Designing for Human Factors:
A Harmonistic Knowledge-Based Proactive Design Approach

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Abstract

The physical construct of a dual ontological product (DOP) is essential for those products which physically interact directly with humans, whereas the product's emotional construct interconnects with human cognition. Multitude of human factor aspects must be considered when designing dual ontological products. To increase the product's impact and reach, designers should also understand the requirements of potential users. There are multiple aspects encompassed within the human factors discipline which merits investigation. However, this doctoral research narrows its scope to three core aspects, namely, ergonomics aesthetic-derived emotions, and persona. These multitude of factors influence each other during product development. For this reason, besides making the designer proactively aware of the product to human factors interaction, the designer must also be supported in finding a harmonised product solution for it to be successful in the market.

The outcome of the problem definition led to the development of a decision consequence-based phenomena model. This is generated from two conditions, the population majority privation phenomenon and the design-stage conflict phenomenon during product design. The population use-phase consequence (PUC) arises when a designer focuses on a specific target user group while neglecting the majority (potential) customers. This unintended consequence will untimely affect the level of product's success in the market. The design-stage conflict consequence (DCC) leads to a factor-biased design. This conflict arises when a particular human factor aspect is given priority, at the early routine design stage, over others considered at a later design stage.

This doctoral research therefore contributes a novel harmonistic design approach framework which proactively supports DOP designers to be aware of design-stage conflicts and consequences of commitments made on human factors in the use phase of the artefact. This harmonistic knowledge-based framework also supports designers to develop balanced product designs from human factors perspective. The proposed framework takes a user-centred approach, placing designers and DOP users at the framework's core. The framework acts as a support to the designer, where it couples

the designer's expertise with the framework's knowledge to proactively support product design decision making.

A prototype computer-based design support tool, constructed on the underlying concepts of the approach framework, has been developed and implemented on a machine learning and harmonistic knowledge-based system. The computer-based tool exploits information collected directly from potential customers to proactively assist, guide, and motivate product designers. The kernel consists of the harmonising engine, where its task is to harmonise possible design provisional solutions to create a unified harmonised DOP product solution.

The prototype support tool has been evaluated with DOP designers. The results obtained from this evaluation have shown that the approach and design computational-based tool meet their goals, are beneficial, and are required in design engineering practice.

Keywords: Dual ontological products; user-centred design; concurrent engineering; design synthesis; life-cycle consequences; machine learning.

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dedicated to

Mum & Dad

for giving me the gift of life, twice

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List of Abbreviations

2D	Two-dimension
3D	Three-dimension
ADAMS	ADjustAble Motorcycle Simulator
AI	Artificial intelligence
AM	Anthropometric measurements
API	Application programming interface
ATT	Rider attributes
BDC	Basic design cycle
CAD	Computer aided design
CAD-IE	Computer Aided Design Interface Engine
CTR	Computer-based tool requirement #
CWK	Current working knowledge
DAF	Designer Assistance Frame
DCC	Design-stage Conflict Consequence
DCI	Data collection instrument
DDDI	Dula Dangerous Driving Index
DESMO	Designing harmonisEd motorcycleS for huMan factOrs
DESMO-APP	APPlication for Designing harmonisEd motorcycleS for huMan factOrs
DIF	Designer Intent Frame
DOP	Dual ontological product
DF	Design factor
DFEP	Design Factor Emotion Profile
EC	Evaluation criteria (criterion)
ED	Ergonomic discomfort
EO	Evaluation objective
EP	Emotion profile
ESD	Engineering systematic design
FP	Focus-group participant
FR	(Approach) framework requirement
GR	General rider
GREP	General Rider Emotion Profile
GU	General user
GUM	General User Modeller
HARMONIOUS	Human fActors haRMonisation Of dual-oNtologIcal prOdUctS

HCD	Human-centred design
HE	Harmonisation Engine
HF	Human factor
hf_{AE}	Aesthetic-derived emotion human factor
$hf_{AE(GR)}$	Aesthetic-derived emotion human factor of the general rider
$hf_{AE(TR)}$	Aesthetic-derived emotion human factor of the target rider
hf_{E}	Ergonomic human factor
$hf_{E(GR)}$	Ergonomic human factor of the general rider
$hf_{E(TR)}$	Ergonomic human factor of the target rider
hf_{P}	Persona human factor
$hf_{P(GR)}$	Persona human factor of the general rider
$hf_{P(TR)}$	Persona human factor of the target rider
$hf_{E\text{-}AE\text{-}P}$	Ergonomic, aesthetic-derived emotion and persona human factors
$hf_{E\text{-}AE\text{-}P}$-CC	Concurrent consideration of the three human factors
hf-Multi X	Design for Multi human factors ($hf_{E\text{-}AE\text{-}P}$)
hf^{1}-Multi X	Design for Multi X means with at least one aspect being hf_{E}, hf_{AE} or hf_{P}
hfKB	human factors Knowledge Base
HIMEP	Harmonised Induced Motorcycle Emotion Profile
IAUF	Information Acquisition and Update Facility
IEF	Inference Engine Frame
ICC	Intra-class correlation
IMEP	Induced Motorcycle Emotion Profile
IPIP	International Personality Item Pool
IRR	Inter-rater reliability
JA	Joint angle (Posture)
KB	Knowledge base
KBS	Knowledge-based system
KDD	Knowledge discovery from data
KIF	Knowledge Interpretation Frame
KM	Knowledge Modeller
KMF	Knowledge Modelling Frame
MA	Motorcycle adjustment
ML	Machine learning
MLS	Machine Learning Service
MOO	Multiple objective optimisation
MT	Main theme
NSGA-II	Non-Dominated Sorting Genetic Algorithm

PDE	Product design element
PDEV	Product design element variant
PDEVEP	Product design element variant emotion profile
PUC	Population Use-phase Consequence
RC	Real Consequences
RE	Recommendation Engine
REP	Rider Emotion Profile
RPU	Research primary users
RTU	Research tertiary users
SE	Support Engine
SS1	(off-the-shelf) Simulation software
SS2	Software script
ST	Sub-theme
SVM	Support Vector Machine
TR	Target rider
TREP	Target Rider Emotion Profile
TU	Target user
UCD	User-Centred design
UDCF	User Data Capture Frame
UI	User interface
VMIE	Visual Model Illustrator Engine

Notation

$\boldsymbol{\mu}$	Average (mean)
$\boldsymbol{\sigma}$	Standard deviation
D	A decision query arising due to a set of alternatives e.g. D = which PDE?
$\{O\}$	A set of decision query (D) options
$D\ \{O\}$	Decision (solution) space: a query (D) being operated on a set of options {O}
$[d]_E\{O\}$	A synthesis decision commitment i.e. the alternative selected from the decision space
$[P_{HB\text{-}S}]$	Positioning of the handlebar in relation to the seat
$[P_{HB.v\text{-}S}]$	Vertical positioning of the handlebar in relation to the seat
$[S_{HB}]$	Handlebar style
$[T_E]$	Type (or power) of the engine
$D_{S_{HB}}\{O\}$	Handlebar style solution space
$D_{P_{HB.v-S}}\{O\}$	Vertical handlebar position solution space
$[d]S_{HB}\{O\}$	A synthesis decision commitment from the handlebar style solution space
$[d]P_{HB.v\text{-}S}\{O\}$	A synthesis decision commitment from the vertical handlebar position solution space
A_H	Anthropometric height
$hf_{AE(GR)}[P_{HB.v\text{-}S}]$	Vertical positioning of the handlebar in relation to the seat from the perspective of the aesthetic-derived emotions human factor of the general rider
$hf_{E(GR)}[P_{HB.v\text{-}S}]$	Vertical positioning of the handlebar in relation to the seat from the perspective of the ergonomic human factor of the general rider
$hf_{P(GR)}[P_{HB.v\text{-}S}]$	Vertical positioning of the handlebar in relation to the seat from the perspective of the persona human factor of the general rider
$\rightarrow[p]\leftarrow$	Indicates that the best handlebar position is level p. The subsequent preferable positions are (p-1) and (p+1), followed by (p-2) and (p+2), and so forth, with position (p-∞) and (p+∞) being the worst handlebar position.
$[d]P_{HB.v\text{-}S}\{p\}$	A synthesis decision commitment of a vertical handlebar position 'p' from the solution space
$PUC_{xR_hf_i}$	PUC consequence (represented as a deviation function), for each human factor (i = E, AE and P) and type of rider (x = TR and GR)
W_{xR}	Rider priority weight, where (x = TR and GR)

DCC_{xR}	DCC consequence (represented as a deviation function), for each type of rider (x = TR and GR)
W_{hf_i}	Priority weight attributed to each human factor, where (i = E, AE and P)
$RE_{xR_hf_i}$	Recommendation of each human factor (i = E, AE and P) and type of rider (x = TR and GR)
θ	Emotion type comprising the following four dimensions: • S – Sober (Serious or Sensible) • G – Glamour (Elegant) • D – Dynamic (Lively) • I – Intimidating (Scary)
r	Emotion intensity
$V_{aesthetic}$	Aesthetic value of an artefact, which is a function of the intensity of various emotions generated by it.
w_x	Weighting assigned to different design factors (DFs).
w_a	Weighting assigned to different product design elements (PDEs).
θ_{rider}	The Rider Emotion Profile (REP) represented in the 4 dimensions of emotion (S,G,D,I).
$W_{rider_{Mx}}$	The weight (rating of the 5-pointed Likert-scale) provided by the participant for a particular motorcycle.
$[Mx]_{S,G,D,I}$	The motorcycle emotion profile derived from experts.
ED_{wrist}	Ergonomic discomfort in the wrist

Glossary of Terms

Term	Definition
Aesthetic-derived Emotions	Emotions derived from visuals or product's aesthetic. The principal aesthetical aspects that elicit emotions are the shape, size, position and colour of a product.
Anthropometry	Measurements and dimensions pertinent to the human body.
Approach	Similar to *means*. It's broader and more flexible, providing general guidance which can be adapted to different situations without specifying particular practices or tools.
Approach framework	An approach framework is like a blueprint, detailed and somewhat prescriptive, offering specific structures for achieving a goal.
Aspects	In this doctoral dissertation, aspects influence the evolution of products, which are based on existing technologies for which support already exist and are in focus during design. Such aspects include: human factors (ergonomics, emotions, persona, etc.); mechanical engineering (functional); aerodynamics (performance); design for manufacturing or assembly.
Behavioural emotional processing level	It deals with the expectations and perceptions that a customer has of a particular product. These are generated and continuously evolve during product use. This is driven by the product's ergonomics and physical feel, or performance such as, function, understandability and usability (Mamo, 2018).
Behaviour	Behaviour refers to the outward actions or reactions of an individual, observable by others, and often influenced by a combination of internal and external factors.
Compiled knowledge	Compiled knowledge consists of experience-based rules, plans, scripts, and cases of previously solved problems with explicit solutions.
Computer-based support tool	Allow human designers who control the design process, while technical means offer support to decision makers by making them aware of consequences associated with design commitments.
Conceptual design stage	In the concept design stage, the focus is on identifying working DOP concepts that can realise and meet the requirements of the target users.
Consequences	In the 'Theory of Dispositions' Olesen (1992) argues that decisions made during the product design activity have dispositions (consequences) on other product life-cycle phases, including the design and use phase.

Current working knowledge (CWK)	Consists of descriptions of DOP elements which are concurrently defined during synthesis decision-making.
Customer	The customer of an artefact is anyone that purchases for the product.
Data	According to Bernstein (2011) and Chandrasegaran et al. (2013), data is the raw, unprocessed facts or figures without context.
Design activity	Designers carry out a number of activities, to facilitate the effective completion of each design stage. (i) Problem analysis, (ii) synthesis, (iii) simulation, (iv) evaluation and (v) decision are the five activities that form part of Roozenburg & Eekels' (1995) basic design cycle (BDC) model. The BDC may be repeated several times in each design stage before arriving at the final design.
Design factors (DFs)	Chandra (2018) categorised PDEs into distinct groupings, referred to as Design Factors (DFs), which encompass Form, contribution to Ride Experience, Colour and Texture, Unity, and Dynamism.
Design decisions	Design decisions is the process involving decision-making and then committing to the decision.
(Decision) Commitment	The result of the decision-making process is a selection of one of the most suitable options, which according to the decision maker is the best alternative satisfying the set criteria (Uzonwanne, 2016).
Decision-making	Decision-making process entails evaluating options (one PDEV) from the array of available PDEVs choices (Hatamura, 2006), based on the goal to be achieved and the criteria by which the choices are to be evaluated.
Decision (solution) space	The alternative choices being considered make up the decision space.
Declarative (product) knowledge	Declarative knowledge, often termed as 'know what' knowledge (Wang & Duffy, 2007), encompasses the ability to describe objects, events, or methods. An example of this type of knowledge could be describing the colour of a motorcycle's fuel tank.
Design knowledge	Tacit and explicit knowledge that allows the designer to execute his/her profession. This includes knowledge about manufacturing processes, material performance, best dimensional tolerances, etc.
Design phase / Design process / Design life-cycle	Design phase / life-cycle referred to the design life-cycle of a product particularly when compared to other life-cycle phases, such as manufacturing and use.
Design stage	Pahl et al.'s (2007) engineering systematic design (ESD) model indicate what problems the designer has to solve and what is the best sequence is therein. The ESD model is structured into four design stages: (i) (planning and) task clarification, (ii) concept design, (iii) embodiment design, and (iv) detail design.

Design-stage Conflict	The design-stage conflict occurs when the designer intentionally commits to selecting PDEVs to meet a particular human factor (e.g. hf_{AE}) requirement, but unintentionally this commitment has a design consequence on another human factor (e.g. hf_E) later on in the design phase.
Design-stage Conflict Consequences (DCCs)	Discrepancy between PDEs committed by the designer during the conceptual (early) stage and those preferred by the designer in the embodiment (late) stage.
Design support	Design support refers to the resources, tools, and activities that aid designers in effectively carrying out the design process. It encompasses a wide range of elements that provide assistance to designers, ensuring that they have the necessary information, methodologies, and infrastructure to produce designs efficiently.
Design support tool	Methods, approaches, simulations, prototypes, and digital tools that could support designers in making well-informed decisions.
Domain / Application knowledge	Domain knowledge serves to define the space of possible solutions to be explored (Smithers & Troxel, 1990; Wang & Duffy, 2007). For example, the design of a motorcycle requires the application of human factors domain knowledge such as knowledge about the handlebar styles and vertical positions.
Dual Ontological Products (DOPs)	Products which have a dual ontological nature (Kroes 2001). They are, at the same time, a physical (objective) construction and emotional / psychological (subjective) construction.
Dynamic knowledge	Dynamic knowledge is used to generate new knowledge structures that are not covered by compiled knowledge, with solutions being implicit. It includes both qualitative knowledge (like common sense reasoning and causal models of processes) and quantitative knowledge (such as physical laws, numerical techniques, and closed-form equations).
Early design process	In this doctoral dissertation the early design process is all the design activities occurring during or prior to the conceptual synthesis design activity.
Emotions	According to Singh (2013) emotion is defined as the response of human being to an artefact on his/her interaction with the artefact.
Ergonomics (hf_E)	The 'physical construct' of DOP is ergonomics. It focuses on the physical interaction between the user and the product. Ergonomics encapsulates anthropometry, product geometry or layout, and posture.
Functional product model	A Functional Model refers to the way a product works and involves technical factors (Pahl et al., 2007).
Form / Physical product model	Refers to the three-dimensional space that a product takes up and relates to the shape of a product such as external dimensions, size, as well as the

	aesthetic qualities that the shape gives (Morris, 2009). Form is regarded as the component that shapes a product's outside appearance and interface.
Formal knowledge	Formal knowledge in product design is embedded in explicit materials like product documents, repositories, problem-solving routines, and computer algorithms.
Generation knowledge	A system that can learn and adapt (knowledge) based on generated new information by the system itself (Russell & Norvig, 2021).
General rider (GR)	The motorcycle general user.
General User (GU)	The design intended for the general populace, where its fundamental purpose is to be used by the majority of people, without adaptations or special designs (Erlandson, 2007; Acosta et al., 2011).
Guidance type	This is a literature review criterion which aims to address whether the support means motivates and supports multi human factors (hf-Multi X),) or whether the support means is oriented towards other aspects or restrict their support to two or less aspects.
Harmonisation	Harmonisation concerns the process of attaining coherence, consistency, or compatibility among aspects which may diverge. Generally, trade-offs are required to reconcile conflicting aspects.
Harmonisation awareness	This is a literature review criterion which seeks to address whether the means provides support for each aspect independently, or if it provides simultaneous and interdependent awareness, based on a harmonised approach between: (i) ergonomics; (ii) aesthetic-derived emotions; (iii) persona through TU; and (iv) persona through GU.
Harmonisation knowledge	Harmonisation knowledge supports designers in balancing multiple human factors and human diversity, such as knowledge about reconciling conflicting aspects to achieve a harmonious design solution and to reach a wider customer base.
Harmonistic Knowledge	Harmonistic knowledge, is comprised of human factor knowledge and harmonisation knowledge.
Human-Centred Design (HCD)	Like user-centred design, HCD focus on the human user and the social problems that a particular community has, but has its focus on the general humans.
Human Diversity	The diverse cognitive, physical, and emotional abilities that can vary between individuals and situations (Pheasant & Haslegrave, 2006).
Human Factors (HFs)	Lee et al. (2017) define human factors as an interdisciplinary approach, encompassing the properties of the human element and examining the manner in which humans engage with products.
Human Factor aspects	Human factors encompass a wide range of physical and psychological disciplines including ergonomics, personality, cognition, emotions and perceptual (Lee et al., 2017; Li et al., 2020; Branaghan, 2021).

Human factors knowledge	Human factor knowledge makes designers explicitly aware of the implications of early design decisions on human factors during the product's use phase.
Human-recognisable form (format)	Revealing the patterns hidden in the data to a format comprehensible to humans (Russell & Norvig, 2021).
Induced Motorcycle (DOP) Emotion Profile (IMEP)	IMEP is the emotions that the motorcycle (DOP) induces to the rider (DOP user).
Information	According to Bernstein (2011) and Chandrasegaran et al. (2013), information is the processed or organised data that provides meaning or context.
Innovative Design	According to Brown (1996) innovative design (class 1) refers to the creation of entirely novel products or major inventions, characterised by significant advancements such as new market creation or company establishment. It is defined by the absence of predetermined knowledge sources and problem-solving strategies, resulting in high uncertainty and requiring substantial creative exploration.
Knowledge	According to Bernstein (2011) and Chandrasegaran et al. (2013), knowledge represents the insights or understanding gained from information, which facilitate informed decision-making.
Knowledge discovery from data (KDD)	Simple relational knowledge (tables) requires a dedicated approach necessary to extract information from data sources and populate the knowledge base. KDD is the whole process consisting of data pre-processing, storing the information in a database, model generation from AI techniques, and storing AI-based models in the knowledge base (Krzywicki et al. 2016).
Knowledge explainability	The concept of knowledge explainability pertains primarily to the inherent processes of AI and the formulation of intrinsic rules. Knowledge explainability refers to the ability to clearly and comprehensively communicate how knowledge is derived. It involves providing transparency into the decision-making processes and logic used to generate that knowledge.
Late design process	In this doctoral dissertation the late design process is all the design activities occurring after the conceptual synthesis design activity, i.e. after a candidate solution, in its entirety, has already been generated.
Means	*Means* designate entities that assist and support in decision-making during the design of DOP. In this dissertation *means* encapsulates models, frameworks, tools, or methodologies.
Multiple Life Phase View	This is a literature review criterion and concerns whether there is an awareness of the product system's consequences across multiple life-phases, such as DCC and PUC, or only for a single phase.

Persona	Drawing from the connotations provided by Brangier and Bornet (2011), and Myers & Twenge (2019), in this doctoral research, the term 'persona' is characterised by the person's personality, experience, behaviour and product use-context.
Personality	Personality refers to an individual's unique pattern of thoughts, feelings, and behaviours that persist over time and across different situations and contexts (Larsen & Buss, 2009).
Phenomena models	These are knowledge models derived from descriptive (based upon observations and analysis) models of the design reality.
Posture	Posture delineates the alignment and orientation of the body, or limbs, in relation to one another and the product (Kroemer et al., 2018).
Population majority (general user) privation	The population majority privation occurs when the designer intentionally commits to selecting PDEVs to meet the target user requirements, but unintentionally this commitment has a consequence on the general user from a human factors' perspective.
Population Use-phase consequences (PCCs)	Use-phase consequences arising when there is a mismatch between the target user and the general user models.
Procedural (process) knowledge	Procedural knowledge, conversely, is referred to as 'know how' knowledge. It pertains to the understanding of how to execute specific tasks, such as the process involved in designing a DOP.
Product	Also referred to as an artefact, is a tangible item created by humans, that can be touched, seen, and experienced by a user (Ulrich et al. 2020).
Product design elements (PDEs)	Components related to each other through 'part of' relationships (Andreasen et al., 2004) which construct a product from. E.g. a motorcycle is composed of various PDEs, including tangible components like the seat, fuel tank and handlebar.
Product design element variants (PDEVs)	Each PDE have a range of variants. E.g. variations of the fuel tank PDE could range from a tear-drop shaped tank to oval or squarish ones.
Product design	"A process performed by humans aided by technical means through which information in the form of requirements is converted into information in the form of descriptions of technical systems, such that this technical system meets the requirements of mankind" (Hubka & Eder, 1996).
Product development	Product development encompasses various activities that transform an idea into a commercial product. These activities span from goal formulation and strategy development during the product planning stage to product design in the strict development stage (Roozenburg & Eekels, 1995).
Product life-cycle / life-view	The total duration that it takes from the moment a need for a product is recognised to the time when the product is finally removed from existence.

Product use-context	The description of context of use provides information about how, and the environment in which the product is anticipated to be utilised. The task context is also addressed with elements concerning the nature and frequency of interactions (Myers & Twenge, 2019).
Real Consequences (RC)	This is equals to the population use-phase consequences (PUCs) plus the design-stage conflict consequences (DCCs). Where these two consequence types will in turn interact together and effect each other.
Reflective emotional processing level	The reflective level is conscious and includes reflective thoughts about the emotional impact of a particular product or feature. This is driven by message, culture, and meaning of a product or its use.
Research Primary Users (RPU)	Those who make direct use of the approach framework or computer-based tool, i.e. designers engaged in the design activities of DOPs.
Research Tertiary Users (RTU)	Those who do not use the approach framework or computer-based tool but are directly affected either positively or negatively by the prescriptive solution, i.e. DOP users.
Rider(s)	Motorcycle user(s).
Rider (DOP user) Emotion Profile (REP)	Is the intrinsic emotion profile of the rider (DOP user) and is moulded by a multitude of factors.
Routine Design	According to Brown (1996) and (Brinkop et al., 1995) routine design (class 3) involves selecting and configuring pre-existing, well-understood design alternatives to meet specific requirements. It operates within a fully specified framework of design goals, subcomponents, and functions, with predefined knowledge sources and problem-solving strategies. Routine design addresses problems similar to previously solved ones, leveraging past designs to develop new configurations. It avoids open-ended exploration or iterative planning, focusing on efficient and reliable optimisation of known solutions.
Simple relational knowledge	At a basic level, one might envision a table with column names and corresponding values in rows, with information being transmitted within this structure. More accurately, though, it represents a collection of attributes, each linked to specific values. Notably, this concept bears resemblance to the manner in which information is stored in a standard Database (Brachman and Levesque, 2004).
Synthesis design activity	Roozenburg (2002) and Ueda (2001) defined synthesis as the combining and assembling of anything, including ideas, parts, processes and activities into a new whole. According to Blessing (1994), in this activity, the designer finds elements suitable for the solution which are then ‘selected’ and 'synthesised' into possible solutions.
Tacit knowledge	Tacit knowledge is tied to the experiences, intuitions, unarticulated models, and implicit rules of thumb of individuals or design teams. It is

	often subjective, gained through long periods of learning and experience, and is difficult to express.
Target Rider (TR)	The motorcycle target user.
Target User (TU)	Birch (2014) defined 'target users' as a group of users based on similarity in their characteristics and similar needs. This dissertation also refers to target users as intended users.
Timing and Activity	This is a literature review criterion and determines if the support means is offered during the early design process, or if such support is provided after a candidate solution, in its entirety, has already been generated.
Use phase	The detailed understanding of the product when it is being used by the users.
Use-phase consequences	Design commitments made intentionally to the solution model may lead to unforeseen consequences during the use phase. In this doctoral research, use-phase consequences include aspects like product usability, safety levels and degree of product attachment.
User	The user of an artefact is anyone that comes in contact with the artefact during its product lifecycle. A user can be someone who is manufacturing the product, transporting the product or even servicing the product. In this dissertation the term 'user' is also used for anyone who uses the artefact during its use-phase.
User-centricity	While fundamentally similar to User-Centred Design, 'user-centric' imply a broader, more holistic approach that extends beyond the field of 'design'.
User-Centred Design (UCD)	A design philosophy that places the user's needs, behaviours, and constraints at the forefront throughout the development process, involving users in all stages to ensure the final product is both usable and tailored to their requirements.
Visceral emotional processing level	This level is an automatic and pre-wired part of the brain that makes rapid judgements of what is attractive or repulsive, good or bad, safe or dangerous. This is driven by aesthetics, style and appearance.

Part A:

Research Overview

1 Introduction

Globalisation phenomenon on product competition

In today's rapidly evolving global landscape, the ongoing process of globalisation has drastically transformed the economy. According to the World Trade Organization (2020), global trade has grown at an average annual rate of 4.3% between 2010 and 2019, demonstrating the increasingly interconnected nature of the global economy. This has, in turn, led to an unprecedented level of product competition. As businesses cope with the challenges posed by this new reality, the demand for innovative and different approaches to product design and development becomes increasingly imperative. Crucially, the creation of products offering exceptional added value and designed with customers at the core has become the cornerstone for success in this highly competitive global market.

Product-added value as a differentiator in product design

Now, more than ever, the world is packed with thousands of different products to choose from. To be successful, a product must offer customers something of added value that sets it apart from other competitive products on the market. By understanding and accommodating the cognitive, physical, and emotional needs of users, designers can create products that are not only more appealing but also more pleasant and safe in use. In fact, considering the interaction between people and products during the design phase has led to a 30% increase in user satisfaction and a 20% reduction in user errors (Hartson & Pardha, 2012).

User-centricity as a differentiator in product design

Another key differentiator during product design lies in embracing user-centricity. Research by Prahalad & Ramaswamy (2004) and Anvari et al. (2015) contends that value is created through the active involvement of users in the product development process. The *LEGO* Group serves as a prime example of this strategy in action, having successfully implemented user co-creation through their *LEGO* Ideas platform. By allowing users to submit and vote on new product

concepts, *LEGO* has effectively maintained its market leadership (Antorini et al., 2012).

The need for novel approaches in product design

In light of the transformative effects of globalisation on product competition, the scientific investigation of novel approaches for developing products becomes essential (Ulrich et al., 2020). The study of real-life cases and the application of cutting-edge research will undoubtedly contribute to the ongoing quest for market success (Pahl et al., 2007; Ullman, 2010) in an ever-changing global landscape.

1.1 Human Factors

A shift towards human factors

It is crucial to recognise that the pursuit of market success is linked to understanding and catering to the needs of consumers in a global context (Cooper & Edgett, 2008). As such, a product cannot be developed in isolation but necessitates consideration of the interactions with the user (Norman, 2013). Lee et al. (2017) describe *human factors* (HF) as an interdisciplinary approach, encompassing the properties of the human element and examining the manner in which humans engage with products.

Human factors related challenges

Designing products for human factors can be a challenging task for product designers. One of the main challenges is to understand the needs and limitations of the users (Dreyfuss, 2003). According to Li (2012) designers often struggle to understand the user's perspective and tend to design products based on their own assumptions and biases.

The importance to design for human factors

Despite these challenges, the motivation to address HFs in product design is driven by the desire to create products that minimise human error (Cross, 2021), reduce the risk of accidents (Wickens et al., 2003), enhance human well-being (Waldemar Karwowski, 2006), are desirable (Norman, 2013) and meet the needs of users (Adikari et al., 2016). According to Norman (2013), designing for HFs creates a positive user

experience, which can lead to increased brand loyalty and customer satisfaction.

Focus on human factor aspects

There are multiple aspects encompassed within the HFs discipline which merits investigation. However, this doctoral research narrows its scope to three core aspects, namely, *ergonomics* (hf_E), *emotions*, and *persona* (hf_P). *Aesthetic-derived emotions* (hf_{AE}) are the aesthetical aspects of the product that elicit emotions, such as shape and form. Ergonomics encapsulates anthropometry, product geometry or layout, and posture. Persona encompasses the personality, attitude, experience, and product-use context.

1.1.1 Human Diversity

Complexity of humans

Humans have diverse cognitive, physical, and emotional abilities that can vary between individuals and situations. The human body is incredibly diverse, and the physical abilities of human beings vary according to their physical dimensions (Pheasant & Haslegrave, 2006). Creating products that satisfy diverse emotional states can pose a significant challenge, as individuals may exhibit a range of emotional responses to the same product (Gross, 2015). Human beings are comprised of different personality types. According to Lee et al. (2017) this can be challenging and argue that designers must consider these differences, in their design decisions. Cultural differences can impact how users perceive and interact with products (Cross, 2021). Furthermore, as the population ages, designers must consider the specific needs of older adults (Fisk et al., 2004), who may have different cognitive and physical capabilities compared to younger users.

Awareness of diversity

The great diversity implies that there can be no image of an *'average'* human, and that compromises must be made (Bakshi & Gupta, 2014). A focus on diversity can lead to more inclusive designs that cater to the needs of diverse user populations (Hosking et al., 2010). Furthermore, addressing human diversity in product design can help to ensure that

products reach a wider market, improve customer satisfaction and drive business success (Waller et al., 2015).

1.1.2 Concurrent Consideration of Multiple Aspects

Concurrent consideration of human factors

Designing for human factors requires a multidisciplinary approach, involving knowledge from diverse domains such as engineering, ergonomics and psychology. This assertion is supported by Agius et al. (2020), in which interviewed product designers explicitly indicated that they concurrently consider human factor aspects during their design activity. This often requires making trade-offs and compromises, referred to as harmonisation in this doctoral research, between multiple human factor aspects. The balancing of multiple aspects is often an area of difficulty for designers.

Harmonisation

Another far greater challenge faced by designers is the need to consider and balance the intricate interdependencies associated with designing for multiple human factors, coupled with the need to accommodate human diversity in the design process (Karwowski, 2005; Jennifer et al., 2015). Designers express difficulties in achieving compromises especially when considering these intricacies with respect to the whole product life-cycle (Koroth et al., 2022). The criticality of harmonising these aspects to cater for the needs of a broader customer base is emphasised by Agius et al. (2020).

1.2 Early Routine Design Process

Early challenges in the design process

When product designers are in the early routine design process, very little is known about the product's solution. However, as the design process proceeds, the design team is forced to make many design decisions which reduce greatly the design freedom (Cross, 2021). This phenomenon is illustrated in Figure 1.1. At the early stage, the designer has the freedom to make changes without great cost penalty and smaller efforts but may lack the necessary knowledge to make the design better (Dieter & Schmidt, 2013). When the design team finally

master the problem, their design is essentially frozen because of the great penalties and larger efforts involved with a change (Dieter & Schmidt, 2013). Besides reducing design freedom, aspects considered at an early routine design process may, later on, come in conflict with other aspects considered at a later design process (Agius et al., 2021).

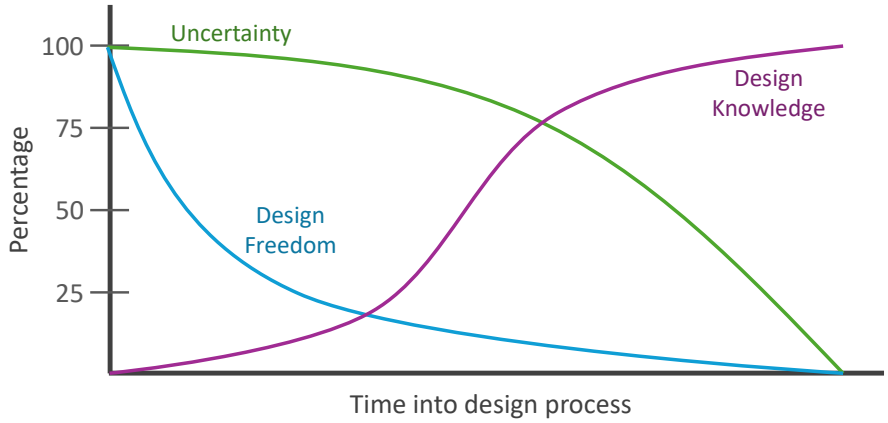


Figure 1.1 – The design paradox between design freedom and design knowledge, adopted from Dieter & Schmidt (2013) *and* Fernández et al. (2002)

Decision-making in product design

Another challenge in the early routine design process is decision-making, which is crucial to the success of the product development life-cycle (Mohd Saad et al., 2013). Uncertainty exists in the early routine design process, making decision-making extremely difficult (Kimura & Grote, 2002). Any lack of effective decision-making at an early routine design phase will affect productivity as well as increase costs and lead times of the product's design life-cycle (Mohd Saad et al., 2013; Yilmaz & Seifert, 2011).

Product life-cycle consequences

According to Olesen (1992), decisions made during product design have consequences on future product life-cycle phases. During early routine design process, designers have to cope with the co-evolution of problems which make it difficult for humans to be aware of them all (Sosa et al., 2007). Design-decision commitments can have significant consequences during the product's use phase, where the designer has no more control over the product (Chitale & Gupta, 2013). Consequently, these decisions, if incorrect, may substantially impact business outcomes. A wrong decision made in the early process of product design can adversely affect production economics, and in most

instances, the costs associated with rectifying such a decision render it economically unfeasible, leading to profit losses throughout the product's lifetime (Ulrich et al., 2020).

Given that the design phase precedes all other product life-cycle phases, it is logical to assume that decisions made during design phase will have repercussions on subsequent product life-cycle phases. Thus, the product design phase is a critical component of the product's life-cycle, with decision-making constituting a vital aspect of this phase.

1.3 Knowledge Support to Designers

Challenges: supporting designers with knowledge

Based on the design paradox (illustrated in Figure 1.1), as product designers progress through the design phase they acquire more knowledge about the possible solutions (Dieter & Schmidt, 2013). It is at the early design phase that designers require the most knowledge, as this stage is decision intensive (Wang et al., 2005; Pahl et al., 2007; Ulrich et al., 2020). According to Mullineux et al. (2005) challenge exist to provide design knowledge at the outset, as the data available in the early phase of a new product design is often limited (M. Li, 2012). Capturing good information and converting it to knowledge is an important task that have motivated a long history of research in design processes and tools (Van Horn, 2012). There is a need for supportive tools and methods for modelling and analysis of evolving design solutions (Albers et al., 2022).

Motivation: supporting designers with knowledge

By equipping designers with knowledge from the outset, they are better prepared to make informed decisions that address user needs, design stage conflicts and explore foreseeable consequences during the product's life-cycle. Early design process knowledge support minimises design errors, reduces costly iterations, and accelerates the overall design cycle. Moreover, it encourages a holistic approach to design, taking into account the interaction between multiple aspects of design. Ultimately, providing knowledge support at the beginning of the design process empowers designers to create superior products

that deliver enhanced user experiences and contribute to long-term organisational success (Schmidt & Luczak, 2000).

1.4 Research Context

Focus on dual ontological products

Physical products have a dual ontological nature (Kroes, 2001). They are, at the same time, a physical construction and psychological construction. The physical construct is essential for those products which physically interact directly with humans, whereas the product's psychological construct interconnects with human cognition, where this can lead to stronger brand relationships, increased customer loyalty (Norman, 2013), increased likelihood of repeat purchases (Schmitt et al., 2015) and recommendations to others (Hassenzahl, 2010). Wearable devices, or products which are characterised by a physical connection between the human user and the product, such as automobiles, exemplify the category of *dual ontological products* (DOPs).

A case study in motorcycles

Delving deeper into DOPs, certain products provide an ideal case for understanding the complex interplay between physical and emotional constructs. It is hard to think about a more intimate experience between a user and a product than the interaction between a rider and a motorcycle (Pirsig, 2006; Schmueli, 2007). Furthermore, there is no aspect of product design that is not reflected in motorcycles (Schmueli, 2007; Cocco, 2013). Although this doctoral research will take the motorcycle artefact as a case of dual ontological product, its scope is beyond the motorcycle domain. This approach serves to offer tangible examples that elucidate abstract principles of DOPs through the use of the motorcycle artefact, without confining the research to this particular product.

1.5 Research Methodology

Design engineering

A research methodology helps in developing and validate knowledge systematically, ensuring that the research is scientific (L. Blessing &

research methodology

Chakrabarti, 2009). Different disciplines have varying methodologies to obtain research results. As this research falls under the discipline of design engineering, only design research methodologies have been considered. A number of methodologies for design research have been proposed, e.g. those described in (Antonsson, 1987; Duffy & Andreasen, 1995; Duffy & O'Donnell, 1999; Eckert et al., 2003; Reich, 1995; Jørgensen, 1992; Blessing & Chakrabarti, 2009).

Adopted research methodology

To methodically address the aforementioned design challenges (Sections 1.1 to 1.3), this doctoral research has employed the research methodology developed by Blessing & Chakrabarti (2009) refined with that developed by Duffy & O'Donnell (1999), which were purposely developed for product development research. These methodologies assisted in taking this doctoral research from empirical studies to the introduction of a new approach to design dual ontological products for multiple human factors. As can be seen through Figure 1.2, both methodologies complement each other, Blessing & Chakrabarti's (2009) *Design Research Methodology* (DRM) is helpful with the overall guidance of this project as well as with the development and testing of solutions, while Duffy & O'Donnell's (1999) methodology is more helpful in the beginning when the design problem is narrowed down by hypotheses to a research problem. Moreover, Duffy & O'Donnell's (1999) methodology is intended to develop computer-based design support.

1.5.1 Design Problem

Phase 1: Design problem definition

Responses were gathered from motorcycle designers *(A)* to capture their design practices and insights from the existing literature *(C)*. This information aided in developing an understanding (Blessing & Chakrabarti, 2009) and facilitated the identification of the design problem *(1)*. This doctoral research specifically focuses on dual ontological product design challenges and to find a harmonisation between multiple human factor aspects coupled with human diversity.

The identified challenges and design problem were presented as a contribution to the design community in the study by Agius et al. (2020). Understanding of the research context, including DOP characteristics, emphasis on specific human factors, and diverse physical and psychological interactions between the product and its users, was attained by conducting focus groups and surveys involving motorcycle riders and stakeholders *(B)* and through literature *(C).*

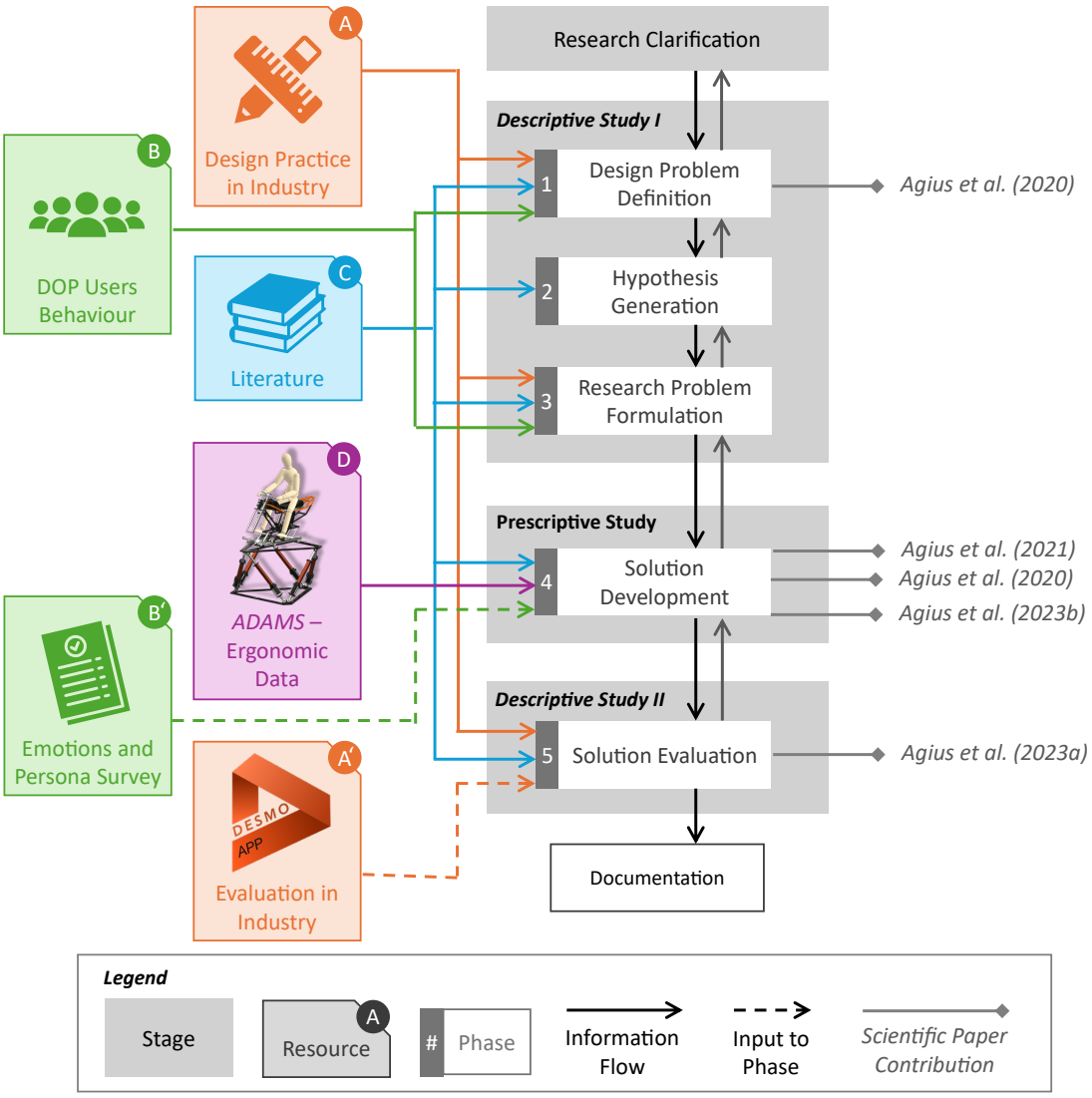


Figure 1.2 – Research methodology, adopted from (Duffy & O'Donnell, 1999) *and* (L. Blessing & Chakrabarti, 2009)

1.5.2 Research Hypothesis

Phase 2: Hypothesis generation

Having delineated the challenges and design problem, the following research hypothesis *(2)* was formulated:

During the design of dual ontological products, designers would benefit from an early routine design support if they are:

- *Made aware of human factor consequences for their decision commitments, and*
- *Guided to harmonise multiple human factor aspects coupled with human diversity.*

Expectation from the hypothesis

Such a support would contribute towards an effective approach to design for human factors and to achieve a harmonious design solution, compared to the current state-of-the-art human factors approaches.

1.5.3 Research Problem

Phase 3: Research problem formulation

Within the research problem formulation *(3)* phase, characteristics of DOPs and human factors, derived during the design problem phase, were established through literature, interviewed designers, as well as from focus group and surveys with motorcycle riders and stakeholders *(B)*. This helped to identify the requirements for an approach which proactively would support product designers. Based on these requirements, criteria were established to critically review design supporting *means* for multi human factors in DOPs.

Inadequate means of supporting human factors

The state-of-the-art collectively highlighted a deficiency in supporting *means* for DOP designers to become aware of human factor consequences that influence users during the product's use phase. Furthermore, designers are not guided to concurrently design and harmonise the three human factor aspects (i.e. ergonomics, aesthetic-derived emotions and persona) during the DOP conceptual synthesis design activity.

Research problem

Based on the above, the research problem that concerns this doctoral research is:

The development of a design approach that supports designers with human factor and harmonisation knowledge arising from the synthesis design activity of dual ontological products.

Subsequently, the research questions were devised to facilitate the development of a suitable solution within a defined research boundary pertaining to the design problem under investigation.

1.5.4 Solution Development

Phase 4: Solution development

The *prescriptive study* phase involves the development of a support (Blessing & Chakrabarti, 2009) for the required solution *(4)*. As specified by the research questions being addressed, human factors knowledge and harmonisation knowledge had to be generated on the specific considerations for dual ontological products.

Requirement of a computer-based tool

According to interviewed designers *(A)*, to deal with the complexity of the product design activity with a manual method would prove to be both labour-intensive and challenging. Consequently, employing computational means, in the form of a computer-based support tool, has been deemed a necessary and feasible solution to address this challenge.

Computational means development framework

Duffy and O'Donnell's methodology (Figure 1.2) is founded on a framework which provides assistance in developing knowledge-based computational support for product design. This framework, shown in Figure 1.3, was used as a foundation to scientifically conduct this research.

Research phenomena

For a computational means to make an impact on the design reality it should be based on knowledge models derived from descriptive models of the reality, termed *phenomena models* (Duffy & O'Donnell, 1999). Phenomena models are based upon observations and analysis of the design reality and hence, reflect design practice *(1)*. The phenomena concerned in this research is that design decisions give rise to human factor *use-phase consequences* and the inherent

characteristics of dual ontological products lead to *design-stage conflicts*. This phenomena model is disclosed in Agius et al. (2021). It has been validated through the examination of two case studies from industry.

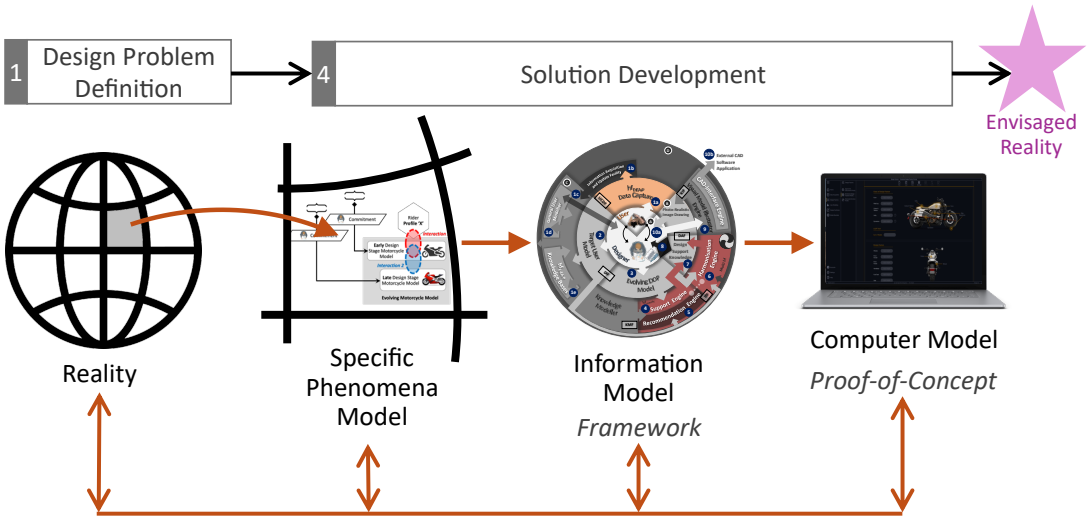


Figure 1.3 – Research framework for developing the computer-based solution, adopted from (Duffy & O'Donnell, 1999)

Research design approach framework

The phenomena model is then developed in more detail into an *information model*, forming a knowledge structure and organised in such a way to form a design approach framework. This approach framework has been titled *HARMONIOUS (**H**uman f**A**ctors ha**RM**onisation **O**f dual-o**N**tolog**I**cal pr**O**d**U**ct**S**)*. This design approach elucidates the manner in which structured human factors knowledge and harmonisation models can be employed to offer knowledge-based support to designers working with DOPs. Furthermore, this knowledge will be supplied in a non-obtrusive manner with respect to the designer's cognitive activities. This research work was disseminated in Agius et al. (2020) through the presentation of a peer-reviewed approach framework specific for motorcycles, a case example of dual ontological products.

Prototype computer-based tool

The computer model which covers *artificial intelligence* (AI) and *multiple objective optimisation* (MOO) technologies, is a realisation of the design approach framework as a proof-of-concept to directly support the designer in the reality situation. Data for the specific

motorcycle computer-based tool was collected from *ADAMS (D)*, a prototype adjustable motorcycle simulator, developed as part of the *RIDE+SAFE* project[1]. This simulator enables the collection of rider postures and ergonomic discomforts in relation to the geometry of the motorcycle. Furthermore, surveys were utilised to collect ergonomic, aesthetic-derived emotional and personality traits of riders *(B')*. The computer-based implementation, encompassing its architecture and functionality, is presented in Agius et al. (2023b). This publication highlights the contribution of artificial intelligence and harmonisation technologies in product design.

1.5.5 Solution Evaluation

Phase 5: Solution evaluation

The prototype tool and approach framework were assessed *(5)* with designers in the evaluation study *(A')* to establish the effectiveness of the proposed human factors and harmonisation design approach. During this study, the extent to which designers were inclined to incorporate the proposed approach framework into their practice was explored. Furthermore, an understanding was gained of how the proposed approach support designers with solutions that would overcome the challenges that they had found during the design problem phase.

From the feedback received, evaluators showed that the approach and design computer-based tool meet their goals, is beneficial and required in design engineering practice (Agius et al., 2023a). As such a degree of validity of the hypothesis put forward during this doctoral research was ascertained.

1.6 A User-Centred Design Philosophy

User-centred design

To address the needs of users more effectively, their consideration should be integrated throughout the entire research process

[1] A project funded by the Malta Council for Science & Technology (MCST), through the FUSION Technology Development Programme 2017 (R&I-2017-003-T).

(Lowdermilk, 2013). Embracing a *user-centred design* (UCD) philosophy has the potential to yield improved research outcomes (L'Astorina & Di Fiore, 2017). UCD places the user and not the system at the centre, by answering questions about the goals and tasks of users, in order to direct the design of a product (Toxboe, 2005). Through the work of Norman's (2013) user-centred design philosophy, designers realised the benefits gained from observing users during product development and testing. This empathetic approach allows designers to understand why users need a particular artefact, in which context the artefact will be used, and if the solution is accepted or needs further improvement (Randall et al., 2003).

Adopting a user-centred design philosophy

As seen from this doctoral's research methodology a user-centred design philosophy was adopted in order to provide the right knowledge to product designers, for whom this approach is being developed. In both *descriptive studies* and *prescriptive study* (see Figure 1.2), designers, stakeholders and product-users were involved in order to understand the reality faced. These participants contributed to populating the computer-based tool with information and subsequently evaluating the tool in question.

1.7 Research Aim and Objectives

Research aim

In view of the described hypothesis, the research context and the challenges that designers encounter, the aim of this research is to:

> *Develop and evaluate a design approach framework and computer-based tool that handles multiple human factor aspects and harmonisation. This design approach framework will serve as a means to proactively support designers during the synthesis design activity of dual ontological products, by revealing human factors decision consequences, and solution specific guidance to harmonise multiple human factor aspects and human diversity.*

Research objectives (RO)

To achieve this aim, the objectives of this doctoral research are to:

i) Characterise the research problem, by:

RO1. (Research Objective 1) Identifying the human factors and design characteristics of dual ontological products.

RO2. Exploring the designers' reality to establish what the design problem is, by an understanding of human factors, diversity and harmonisation.

RO3. Identifying strengths and weaknesses of existing design supporting *means* for multi human factors in DOPs.

ii) Develop a design approach framework to design dual ontological products, by:

RO4. Establishing a phenomena model that provides a formal explanation of how human factor use-phase consequences and design-stage conflicts result from synthesis decision commitments.

RO5. Exploiting the phenomena model explanations to establish a design approach framework describing how human factors and harmonisation knowledge can be modelled and explicitly utilised during design synthesis of dual ontological products, to proactively support designers.

RO6. Identifying the prototype tool's system requirements and architecture for realising and implementing the *HARMONIOUS* design approach framework in a computational-based form.

iii) Evaluate the developed approach and prototype computer-based tool:

RO7. Carrying out an evaluation with relevant DOP designers by demonstrating the computer-based tool prototype with a motorcycle design case scenario.

RO8. Analysing the prototype evaluation results, to establish the strengths and limitations of the novel approach

framework to harmonise the design of dual ontological products for human factors, leading to the identification of future research avenues.

1.8 Dissertation Structure

Part A: Research Overview

To reach the envisaged reality postulated by the research hypothesis, this dissertation is organised into four parts, as shown in Figure 1.4, with the first part (*Part A*) has given an overview of this doctoral research together with its philosophical approach.

Part B: Characterising the Research Problem

Part B of this dissertation provides the research frame of reference within which this doctoral research has been conducted. In Chapter 2, the domain, that this research is concerned with, is discussed, followed by characterisation of dual ontological products and human factors in the literature. The characterisation of DOP is extended to Chapter 3, where a mixed-methods study is employed to understand the characteristics and challenges of DOP stakeholders and DOP users in more detail. Then, in Chapter 4, a qualitative study is demonstrated, as part of the *first descriptive study* (Figure 1.2), highlighting the challenges, and requirements for an approach by DOP designers. Chapter 5 provides the reader with a review of state-of-the-art design supporting *means* for multi human factors in DOP. After identifying the research gap, Chapter 6 concludes *Part B* by highlighting the research problem, research questions and research boundary undertaken in this doctoral research.

Part C: Solution Development

Answering these research questions will in turn lead to the development of the research solution, which is presented in *Part C* of this dissertation. Chapter 7 presents a phenomena model of how synthesis design decisions result in human factor use-phase consequences and design-stage conflicts. The harmonistic design approach framework is then presented in Chapter 8 as a prescriptive solution to the research problem previously identified. Chapter 9 presents a formalisation of the human factors and harmonisation

knowledge model for supporting design of dual ontological products. In Chapter 10, the *HARMONIOUS* approach framework is implemented as a prototype computer-based support tool.

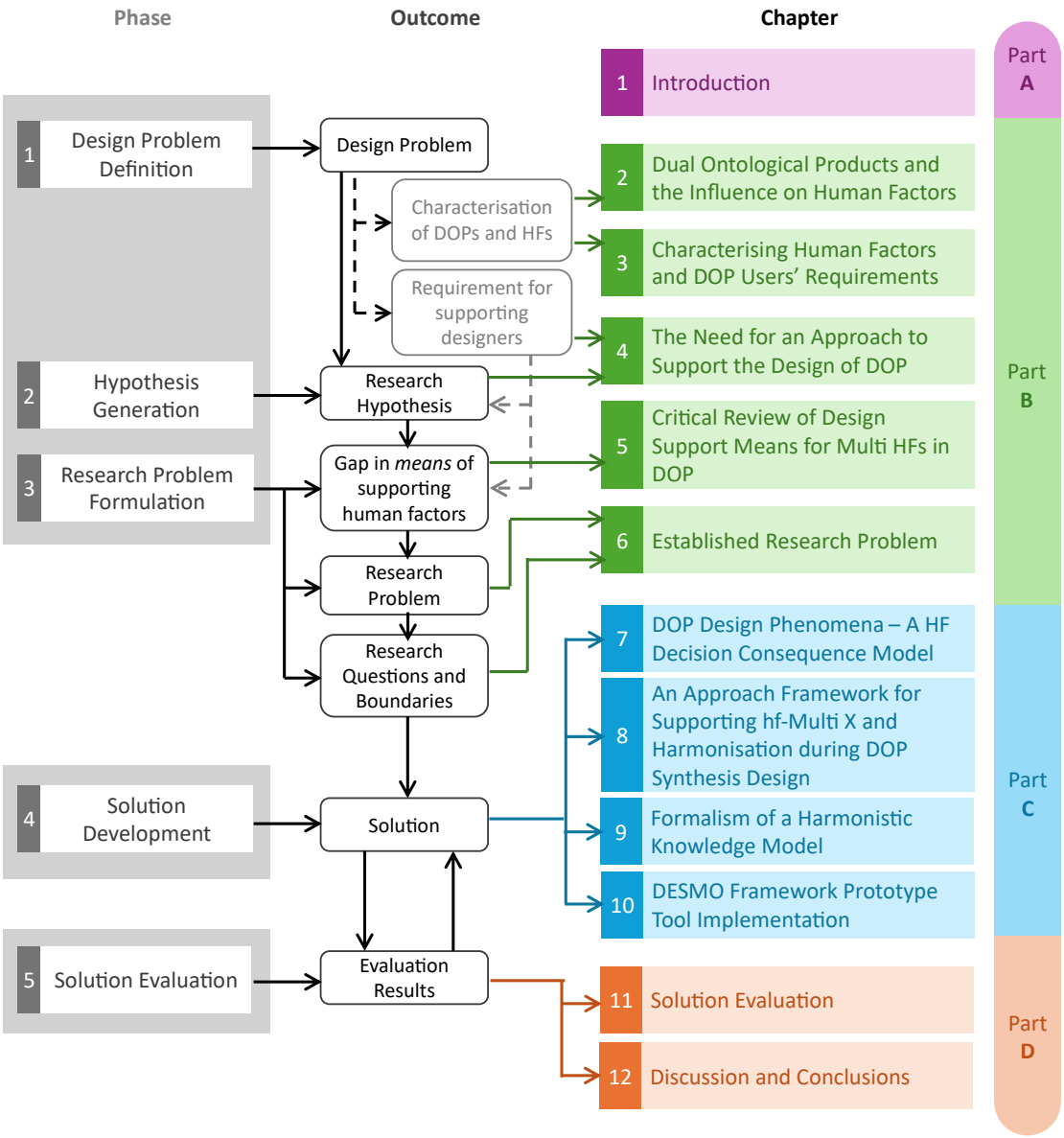


Figure 1.4 – Dissertation structure

Part D: Solution Evaluation and Discussion

The final part of this dissertation presents the *second descriptive study* that critically evaluates the *HARMONIOUS* approach framework and the computer-based tool. The results are analysed and discussed in Chapter 11, together with the benefits and limitations exhibited by the prototype implementation and the recognised improvements. Discussion and conclusions are drawn in Chapter 12 where potential future research work is outlined. This chapter finishes by highlighting the significant contributions to knowledge made in this research.

1.9 *Part A* Conclusions

Part A of this dissertation has established the context and familiarised the reader with the research topics addressed during this doctoral research.

Developing a harmonistic solution from a human factors' perspective

This chapter introduced the challenges that this doctoral research addresses and presented the main aim of this research, which is to develop and evaluate a design approach framework and computer-based tool that make designers aware of human factors related consequences, and to support them early on in the design phase by finding a harmonisation between multiple human factor aspects and human diversity. Consequently, this dissertation will document the activities carried out, adhering to the doctoral research methodology delineated in this chapter, in order to meet this aim.

Dual ontological products and human factors in product design

Part B of this dissertation will follow by providing a characterisation of the research problem for this doctoral research with existing dual ontological product development and human factor theories. This will allow for definition and understanding of the research problem and questions tackled by this doctoral research.

Part B:

Characterising the Research Problem

2 Setting the Scene: Dual Ontological Products and the Influence on Human Factors

This chapter looks at setting the scene for this doctoral research, followed by characterisation of dual ontological products and human factors in the literature. In Section 2.1, the term dual ontological product is defined and explained, Section 2.2 describes the product breakdown structure and Section 2.3 portrays the product life view. In Section 2.4, the focus shifts to human factors in the context of dual ontological products. Chapter conclusions are drawn in Section 2.5.

Defining a product

A product, also referred to as an artefact, is a tangible item created by humans, that can be touched, seen, and experienced by a user (Ulrich et al., 2020). Examples of a product vary from a simple stylus to a much more complex system such as a car.

Multiple product structure viewpoints

In the context of the product development process, several authors (Ehrlenspiel, 1994; Erens & Verhulst, 1997; Andreasen, 1980) have highlighted the existence of numerous product descriptions. Andreasen et al., (1996), in their *'Domain Theory'*, explain how a product can be viewed from different structural viewpoints. This *Product Structure Viewpoint* is illustrated in Figure 2.1.

Focus on specific product structure viewpoints

It is argued (Andreasen, 1980; Mortensen & Hansen, 1999) that product designers have to design based on these multiple system and structure views. As highlighted in Figure 2.1, this doctoral research adopts a scientific exploration of three distinct product structure viewpoints, namely:

2.1 – *Functional Views*

2.2 – *Genetic Views*

2.3 – *Product Life Views*

Each of these viewpoints will be examined in the following sections, Section 2.1 to 2.3 respectively.

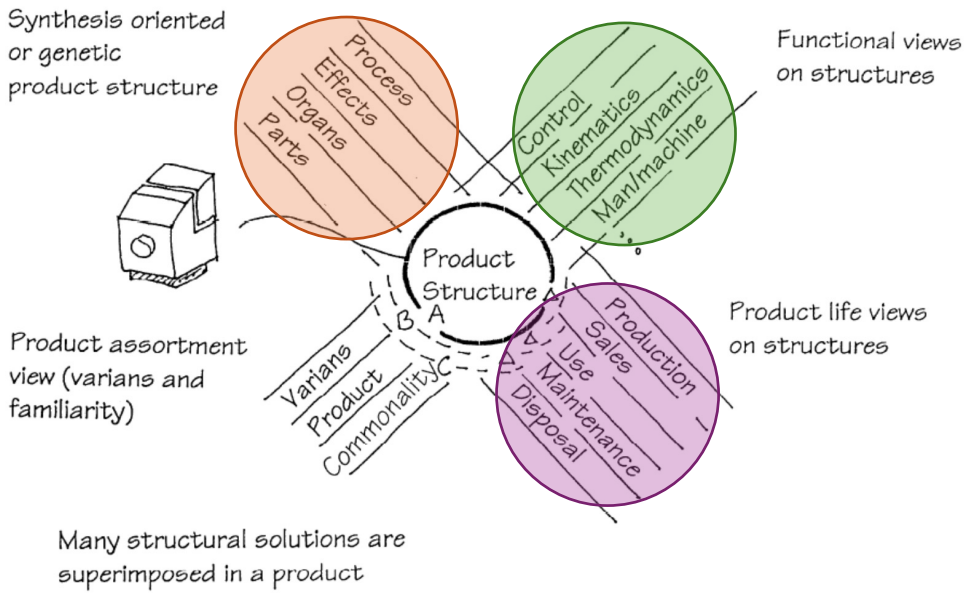


Figure 2.1 – Product structure viewpoints, adopted from Andreasen et al. (1996)

2.1 Dual Ontological Products (DOPs)

Product models

The various product structure viewpoints can be effectively represented through distinct types of product models, as proposed by Erens & Verhulst (1997). A *Functional Model* refers to the way a product works and involves technical factors (Pahl et al., 2007). Functionality is met when a product performs its technical purpose effectively and reliably (Hubka & Eder, 1996). A car's engine serves as an example of a technical product. The *Technology Model* presents a coherent depiction of the utilisation of technologies to guarantee the functionality and performance of a product, although it may not specifically address its production processes. This model focuses on the integration and implementation of various technological elements to support and enhance the operational aspects of the product, ensuring its successful functioning in practical applications. The *Physical Model* or *Form Model* (Ulrich et al., 2020) refers to the three-dimensional space that a product takes up and relates to the shape of a product such as external dimensions, size, as well as the aesthetic qualities that the shape gives (Morris, 2009). Form is regarded as the component that

shapes a product's outside appearance and interface. Eder (2012) argues that expertise in aesthetics and ergonomics are required during the design process to enhance the user experience (Ulrich et al., 2020).

Defining Dual Ontological Products (DOPs)

Focusing on the *Man/Machine* view in the *Functional View Structure* (refer to Figure 2.1), and the *Form Product Model*, products have a dual ontological nature (Kroes, 2001). They are, at the same time, a physical construction as well as a social construction. A similar view was poised by Lin (2018) who stated that the relationship between the product and user can be seen in both physical and perceptive terms. The physical construct is essential for those products which physically interact directly with humans. According to Kroes (2001), the purpose of using a product is not solely determined by physical causes, which is objective in nature, but is also shaped by another factor which is, on the other hand, subjective. The terms *'social'* and *'perceptive'* are broad in scope and encompasses various aspects and, according to Kroes (2001) and Lin (2018), represent an intangible behaviour towards products inherently linked to human beings. This implies that the meaning and significance of the products' use are constructed through intangible interactions which are subjective in nature and susceptible to change over time and across cultures (Kroes, 2001). Solomon (2019), examine these intangible interactions from a sociological perspective and believe cultural context plays a fundamental role in shaping individuals' preferences and what is considered of value. Others (Liu, 2003; Karjalainen & Warell, 2005; Sepahpour et al., 2022) believe that human responses to these intangible interactions are influenced by the emotive symbolic meaning. Different individuals may have different responses to the same product because they carry different symbolic or connotative meanings and as such evoke different emotions (Crilly et al., 2004).

How a product is viewed in this research

For instance, the physical construct of a wrist rest for a keyboard helps reducing discomfort in the wrists during prolonged computer use, but it may be a plain product without any decorative elements or any social

symbolic value. A household decorative product has an emotional impact on an individual's experience, such as creating a sense of warmth or joy when looking at it, but the individual does not physically interact with the decorative product in an ergonomic sense. This doctoral research considers products from a dual ontological point of view. Wearable products such as (smart)watches, hand-held devices like smartphones or where humans are physically connected to the product such as motorcycles, are good examples of dual ontological products (DOPs). DOPs are viewed by individuals in both an objective (physical) and subjective manner. The objective perspective refers to whether or not a product is physically suitable for an individual based on their anthropometric (bodily) attributes. For instance, a person with a smaller hand palm may encounter difficulties when handling large hand-held devices due to the incongruity in size. The subjective view depends on the individual's psychology, which may or not be influenced by the society in which they live.

A case study in motorcycles

As discussed in the introductory chapter, this doctoral research will employ the motorcycle artefact as a case of DOP. Nevertheless, the scope of this research extends beyond the motorcycle domain.

The motorcycle artefact presents a good case for understanding the complex interplay between physical and emotional constructs. Motorcycles are designed with a focus on ergonomics since the comfort of the rider depends on it (Karmegam et al., 2009). Furthermore, riders experience a deep emotional connection with motorcycles as these artefacts are often admired for their aesthetic appeal (Singh, 2013). The shape, colour and finish play a significant role in attracting consumers. The emotional response elicited by the aesthetic appeal of a motorcycle can significantly influence user preference and satisfaction (Singh, 2013; Mamo et al., 2017). The motorcycle artefact presents a significant challenge to DOP designers due to its inherent limitations. There is very limited available adjustment to suit the different needs of riders (Amrutkar and Rajhans,

2011). Therefore, it is imperative to get it right in the design (Amrutkar and Rajhans, 2011). Furthermore, there is no aspect of product design that is not reflected in motorcycles (Schmueli, 2007; Cocco, 2013).

The use of the motorcycle case study approach serves to offer tangible examples that elucidate abstract principles of DOPs, without confining the research solely to the motorcycle artefact as a product.

2.2 Product Breakdown Structure

Genetic product structure

The *Genetic Product Structure* (Andreasen et al., 1996) depicted in Figure 2.1, delineates the various structural domains essential in product design, specifying the constituent elements and sub-elements that construct the product. Furthermore, it articulates the interrelationships among these (sub) elements, as well as the effect that is realised by them and their interactions.

2.2.1 Product Compositional Model

Product design elements (PDEs)

When an artefact is viewed from a constructional perspective, a *Product Breakdown Structure* emerges, as described by Borg et al. (2000). This leads to the realisation of a product's *Compositional Model*. As illustrated in Figure 2.2, the constructional perspective allows for the interpretation of a product being constructed from numerous *product design elements* (PDEs), related to each other through *'part of'* relationships (Andreasen et al., 2004).

Exemplifying (PDEs)

For instance, a motorcycle is composed of various PDEs, including tangible components like the seat, fuel tank and handlebar, as outlined by Chandra (2018). To alter the motorcycle's form, designers may experiment with an assortment of fuel tanks, which represent variations of the fuel tank PDEs. These variations could range from a tear-drop shaped tank to oval or squarish ones, reflecting the specific aesthetics the designer wishes to impart on the motorcycle. In the context of this doctoral research, these are termed the *product design*

element variants (PDEVs), where a non-exhaustive list is demonstrated in Figure 2.2.

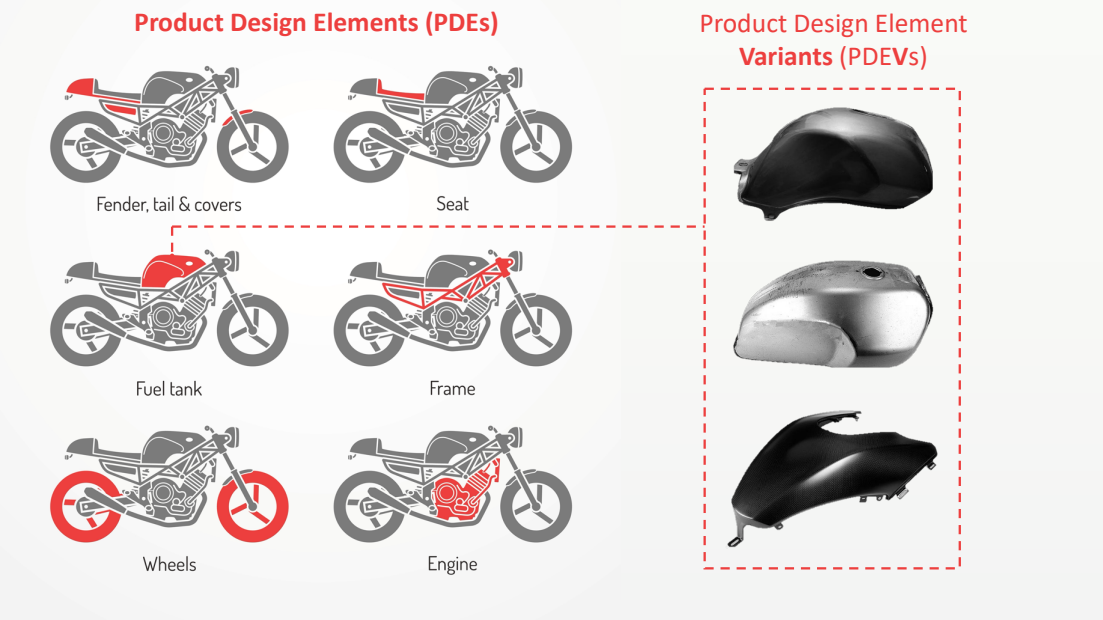


Figure 2.2 – Modelling of a product's structure

2.2.2 *Product's Complexity*

Nature of a product's complexity

In product design, the nature of a product's complexity is often a subject of investigation. The distinction between simple and complex products lies in the quantifiable variance in the number of PDEs, the interrelations amongst these PDEs, and the degree of sophistication in their functionality (Ulrich et al., 2020; Pahl et al., 2007; Dieter & Schmidt, 2013).

Simple products

Products of a more rudimentary nature characteristically encompass a limited number of PDEs, and the interactions between these components are generally uncomplicated. These simpler products are typically designed to execute a single or narrowly defined set of functions (Dieter & Schmidt, 2013). A hammer can be categorised under a simple product. This product is composed of two principal components: the handle and the head. The interaction between these components is relatively direct, and the hammer is designed to carry out a singular primary function: the application of force to a particular object.

Complex products (Multi-PDEs)

In their work, Pahl et al. (2007) delineate a complex product as a system comprising multiple interacting PDEs or subsystems (organs). The interactions between these PDEs and/or subsystems exhibit a strong interdependence between each other (Ulrich et al., 2020), such as in a motorcycle, a complex DOP exemplar. A motorcycle is constructed of hundreds of PDEs, inclusive of the engine, transmission, brakes, fuel tank, handlebar, seat, foot-pegs, and various others. The interplay between these components is complex, collectively enabling a broad array of functions such as propulsion, steering, braking, ergonomic sitting, and eliciting a range of emotions (Ulrich et al., 2020). The design process of a motorcycle necessitates decisions concerning a multitude of PDEs parameters, as well as careful coordination of their interactions (Dieter & Schmidt, 2013).

2.2.3 Genetic Product Structure Viewpoint

Two view philosophies

Over the years, a debate has emerged among philosophers of engineering design concerning the way in which customers perceive the elements of design (Chandra, 2018) for a desired product effect. This scholarly discussion has gradually crystallised into two distinct philosophical camps: the *Gestalt theory* camp and the *structuralist* camp. Both of these view philosophies encompass differing viewpoints on perception and conceptualisation. These are represented in Figure 2.3 for the motorcycle case study.

Structuralist viewpoint

Similar to the product breakdown structure (Andreasen et al., 1996) viewpoint, structuralist thinkers such as Kotnik (2011) and Dürfeld (2011), articulate structure as a pattern that emerges from a network of formal relationships between the elements of a set, integrated with a topological structure. Here, design is perceived as the geometric organisation of elements. This implies that customers or users interpret the totality of the artefact's PDEs as a mathematical construct, delineated in terms of mathematical relationships. Consequently, they see the difference between the whole.

Gestalt viewpoint

Conversely, the *'whole view'* is fundamentally rooted in Gestalt theory, founded on principles of Gestalt psychology (Jäkel et al., 2016). This theory emphasizes the notion that in human visual perception, the whole is bigger than the sum of its elements. That is, the attributes of the whole are not deducible from analysis of the PDEs in isolation and hence, the overall perception of design cannot be deconstructed into various elements. In support of this view, Pratt (2011) postulated that the influence of the whole over the aggregation of its elements is substantial, given the way that the mind manipulates the patterns that humans see.

Reality of genetic viewpoint

The reality or solution to this dichotomy may indeed be found through an amalgamation of these two seemingly extreme positions (Chandra, 2018).



Figure 2.3 – Structuralist and Gestalt viewpoints

Prioritisation of PDEs

Another challenge is prioritisation, as not all motorcycle design elements are equally important (Chandra, 2018). Analysing this from a functional perspective, the components that facilitate the motorcycle's core functionality, enabling it to transport the rider from point A to point B, such as the engine, tyres, and brakes, emerge as the most critical PDEs or sub-systems. Conversely, if comfort is the primary consideration, elements like the handlebar, seat, and footpegs gain

prominence. Yet, when one assesses the motorcycle from an aesthetic standpoint, emphasis shifts to stylistic elements, such as the motorcycle's fairings. Consequently, the prioritisation of these elements is inherently multifaceted and depends on a variety of factors, including the context and the specific needs or preferences of customers (Chandra, 2018).

2.3 Product Life-View

Product life-cycle

In the context of this doctoral research, the product life is delineated as the total duration that it takes from the moment a need for a product is recognised to the time when the product is finally removed from existence. The concept of the product life-cycle is accompanied by various definitions and associated terminology (Eder, 2001). As articulated by Pahl et al. (2007), Eder (2001), as well as Roozenburg & Eekels (1995), the structure view of product life describes the diverse phases that a product undergoes from its inception to ultimate disposal.

Product life models

Tjalve (1979) explains that all products undergo a common life-cycle of creation, utilisation, and eventually discard. Olesen's (1992) product life-cycle model, which is based and an expansion of Tjalve's (1979) model, systematically showed the interactions or meetings with other life-phase systems. This model is illustrated in Figure 2.4.

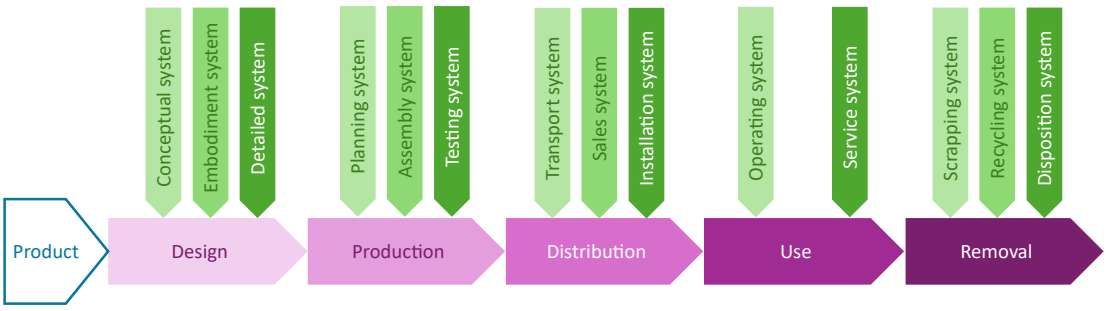


Figure 2.4 – Product meetings with various life-phase systems, adopted from Olesen (1992)

For example, use phase design involves the detailed understanding of the product when it is being used by the users. In this case life-cycle analysis would be used to determine what are the ramifications of the

product being designed, whether it is safe to use or will it evoke the right emotions to the user.

2.4 Human Factors in the Context of Dual Ontological Products

A shift towards human factors

The DOP paradigm conceptualises the product as an extension of the user, physically and psychologically. Accordingly, any examination of such products cannot be conducted in isolation but necessitates consideration of the interactions with the user (Norman, 2013), where the product is not designed solely to be functional but also to be in unison with the user; a *Man/Machine* view from the *Functional View Structure* perspective (Figure 2.1). For a long time, the prevailing view on product design was influenced basically by functional and economic aspects. However, the significance of many products is primarily based on the extent to which their properties align with the individual competencies and requirements of users (Krüger & Wartzack, 2014). In this doctoral research, the user, represented as a human, and the human-to-product interaction, assume primacy and occupies a central position during product design, warranting consideration of human factors (HFs).

Defining human factors

The term *'human factors'* was coined by Alphonse Chapanis (Sanders & McCormick, 1993) in the 1940s, and described as the scientific discipline concerned with understanding the capabilities and limitations of humans while they interact with their industrial work environment. Sanders & McCormick (1993) have added that HFs should be considered during the design of work equipment in order to optimise human well-being and the overall work performance. Since then, the field of human factors has expanded to include various industries and scientific disciplines, with the goal of improving safety and user experience (Wickens et al., 2003). This expansion has brought numerous definitions of the term. However, for this doctoral research, the following definition by Lee et al. (2017), who describe human

factors as the interdisciplinary approach of how humans interact with a system, will be adopted:

> *"The ultimate goal of human factors is towards system design, accounting for those factors that are properties of the human component."*

The term *'system'* in the adopted definition refers to any digital or physical environment such as, technology, consumer products or workplace equipment (Salvendy, 2012; Stanton, 1997; Lee et al., 2017). HFs theory is grounded in the understanding that product designs should be centred around the capabilities and limitations of the human user, thereby enhancing safety and user satisfaction (Wickens et al., 2003). Human factors product design is often employed in the design of products (Salvendy, 2012). Lee et al. (2017) argue that as technology continues to evolve, the importance of HFs in product design is likely to increase, necessitating further research in this field.

Aspects of human factors

With the advent of new technologies and the increasing complexity of human-machine interfaces, a wide range of physical and psychological disciplines including ergonomics, personality, cognition, emotions and perceptual (Lee et al., 2017; Li et al., 2020; Branaghan, 2021), are encompassed in human factors. These are organised and illustrated in Figure 2.5, where the inner ring represents the aspects of human factors, and the outer one represents sub-aspects.

2.4.1 Human Ergonomics

Impact of ergonomics

One of the essential human factors and the *'physical construct'* of dual ontological products is ergonomics (hf_E). It focuses on the physical interaction between the user and the product. During product design, the consideration of ergonomics enables designers to come up with solutions that fit well with the human body, while taking into account the user's posture, anatomy, biomechanical characteristics and physiology (Hall, 2014). The central objective of ergonomics revolves

around the optimisation of human well-being, that is, to reduce strain and prevent injuries. Pain, fatigue and discomfort are all symptoms of products or systems that require the ergonomic attention in their design process (Marek & Pokorski, 2004). By arranging the product to fit the user it is ensured that the design of a product aligns with the capabilities and limitations of the human body (Salvendy, 2012). This includes everything from the dimensions and position of the PDEs.



Figure 2.5 – (Sub) aspects within human factors, organised from Lee et al. (2017); Li et al. (2020); Branaghan (2021)

Ergonomics sub-disciplines

Ergonomics can be segmented into distinct sub-disciplines, each centred on various aspects of the physical interaction between humans and products:

Anthropometry

- *Anthropometry*: This domain addresses the examination of measurements and dimensions pertinent to the human body. Such insights prove invaluable in product design to ensure they

accommodate the physical characteristics of the user's body. Individuals from diverse geographical regions, age groups, or ethnic backgrounds have distinct anthropometric characteristics (Pheasant & Haslegrave, 2006). Consequently, the acquisition of information may necessitate region-specific considerations or tailored in line with specific demographics (Easterby, 2012; Helander, 2005).

Posture

- *Posture*: Within ergonomic studies, posture delineates the alignment and orientation of the body, or limbs, in relation to one another and the product (Elbert et al., 2018). Individuals with different anthropometric characteristics will adopt different postures when interfaced with the same product (Bridger, 2008). Such variations can subject the individual to differential stresses and strains on the musculoskeletal system. Additionally, postural classifications can be classified into static and dynamic (Weerdmeester, 2008). The former pertains to the prolonged posture of a singular position over a period of time. For example, sustained motorcycle riding on motorways for long periods (A. Stedmon, 2013). Extended static postures can lead to increased muscle fatigue and discomfort, primarily due to the consistent muscle engagement to support that posture (Bridger, 2008). Over time, this can lead to musculoskeletal disorders, especially if the posture is poor. Conversely, dynamic posture refers to the posture of the body or limbs when in motion or transitioning between positions (Weerdmeester, 2008). For example, manoeuvring a motorcycle in winding roads (Stedmon, 2013). Dynamic movements help in improving blood circulation, muscle activation, and can mitigate the risks associated with prolonged static postures. Nevertheless, dynamic movements could potentially instigate strains from repetitive motions (Salvendy, 2012).

Biomechanics

- *Biomechanics*: This branch focuses on the mechanical aspects of human actions, encompassing activities such as lifting, pushing, pulling, and bearing loads (Hall, 2014). It is instrumental in task analysis, product design, and the formulation of guidelines promoting practices that diminish injury risks (Kumar, 2007). For instance, the incorporation of assistive equipment in sectors demanding substantial lifting can significantly attenuate the risk of musculoskeletal injuries (Hall, 2014).

Environmental ergonomics

- *Environmental Ergonomics*: This branch is centred on the repercussions of the physical environment on the human body, encompassing factors like illumination, acoustic factors, thermal conditions, and vibration (Elbert et al., 2018). Using the motorcycle as an illustrative context, vibrations can be attributed to engine design and its placement (A. Stedmon, 2013). The overarching aim here is to minimise detrimental implications of vibrations, such as stress and decrease in concentration (Karwowski & Marras, 2006).

Repetitive motion studies

- *Repetitive Motion Studies*: This domain is particularly concerned with activities characterised by recurrent motions (Salvendy, 2012), exemplified by the recurrent actuation of clutch or brake levers in dense traffic scenarios. The primary objective is to reduce the risk of repetitive strain injuries by designing PDEs that diminish discomfort during repetitive usage or by strategically positioning them to alleviate strain (Salvendy, 2012).

2.4.2 Human Emotions and Cognitive Appraisal

Impact of emotions

In today's extremely competitive market the features and specifications of competing products exhibit significant similarity. Consequently, the way products connect with consumers on an emotional level is of paramount importance (Pérez Mata et al., 2013).

Emotions represent a key driver of consumer behaviour and can have a significant impact on product success, as product's emotional construct interconnects with the human cognition, where purchasing decisions are made (Schmitt et al., 2015). Products become a part of users' personality and in turn an expression of their emotions (Singh, 2013). This attachment may be shaped by the visual attributes of the product (colour, shape, material, graphics, etc.) or any other feature of a product that can activate sensory modalities.

Importance of considering emotions during design

Enhancing product attachment is one of the most important strategies for many companies (Singh, 2013; Shigemoto, 2019). Given the importance of crafting products which deliver emotional fulfilment to the user, the literature has emphasised the importance of emotions in product design (Singh, 2013; Farrugia et al., 2013; Mamo et al., 2017), and is crucial for the designer to possess an understanding of such emotions (Norman, 2004). Desmet & Hekkert (2007) claimed that if emotions are considered during the product design, products that resonate with consumers on a deeper, emotional level, can be created. Ultimately, this can lead to stronger brand relationships, increased customer loyalty, increase the likelihood of repeat purchases and recommendations to others (Hassenzahl, 2010).

Contrary to ergonomics, emotions epitomise the "intangible and subjective construct" in the paradigm of DOPs.

Emotion theory

Defining Emotions

Several distinct psychological states are encompassed by the verb *'affect'*, which include: emotions, feelings, moods, sentiments, and passions (Hekkert & Desmet, 2002). Among these, only *'emotion'* suggests a direct relationship between the subject and its affected state (Mamo, 2018). Although commonly misused and interchanged, the terms *'emotion'* and *'feeling'* have distinct meanings (K.R. Scherer, 2000). Feeling specifically comprises of the cognitive appraisal together

with the physiological reactions resulting from an emotional occurrence (Scherer, 2005).

According to Singh (2013) emotion is defined as the response of human being to an artefact on his/her interaction with the artefact. The interface results in stimuli and stimulus congruence and facilitates impression formation which finally affects consumer responses (Van Rompay et al., 2008). There are times when product users know that they are experiencing an emotion, while at other times they may not even be aware of their emotional reaction to a situation (Singh, 2013). Furthermore, emotions can be elicited by internal or external events. External occurrences require evaluation for their relevance to the individual before eliciting an emotional reaction. For instance, when an individual rides a motorcycle, experiencing the *cruiser* seating posture, observing the centrally located dashboard, and sensing the premium textile finish of the seat, might collectively evoke a positive emotion. On the other hand, internal events serve as inherent elicitors of emotion, frequently attributed to physiological or hormonal changes spurred by past memories (Sherer, 2005).

How emotions develop

Observing a product can elicit both conscious and subconscious reactions (John A. Bargh, 2002; Friese et al., 2009; Schoen & Crilly, 2012). By distinguishing between these initial and terminal states, Haug (2016) deduced four potential combinations: *(1) subconscious to subconscious*; *(2) subconscious evolving into conscious*; *(3) conscious to conscious*; and *(4) conscious reverting to subconscious*. These four processes are respectively labelled as *'emotion'*, *'attention'*, *'reflection'*, and *'internalisation'*, illustrated through Figure 2.6:

Subconscious to subconscious

- *Emotion:* This state describes the mechanism where the observation of a product induces emotions, either of a positive or negative nature. According to (Singh, 2013), in an emotional state a person can shift the relationship between individual PDEs and the product as a whole. In such a situation, certain features or PDEs of a product take precedence over others. This

phenomenon provides insight into why certain elements, such as the taillight of a motorcycle, elicit strong emotional responses and driving desires for acquisition without a holistic assessment of the product or contemplation of other competitive alternatives. Upon first observing a motorcycle, the striking design of its sleek, chrome exhaust might instantly evoke a surge of excitement or admiration, influencing one's preference based purely on emotional response.

subconscious evolving into conscious

- *Attention:* This delineates the process through which the individual becomes aware of the emotions produced by a product in the first step. According to Singh (2013), this process instigates certain action tendencies, which in turn manifest as emotions and corresponding physiological reactions, *'feeling'* (Scherer, 2005). After the initial emotional reaction, one becomes consciously aware of the motorcycle's exhaust, noticing details like the reflection of light on the chrome, which deepens the emotional engagement.

Conscious to conscious

- *Reflection:* In this state the individual attempts to understand why these emotions occurred, compare the product with alternate offerings, associate the product with a particular style, among other considerations (Haug, 2016). Subsequently, one might question the practical implications of the motorcycle's striking exhaust—considering factors such as performance and durability, thus engaging in a rational assessment of the motorcycle.

Conscious reverting to subconscious

- *Internalisation:* According to Haug (2016) internalisation is a manner that changes the predispositions towards emotions in relation to analogous products or specific product features. Over time, the initial emotional response to the motorcycle's exhaust becomes embedded in one's overall attitude towards

similar motorcycles, subtly shaping preferences for future selections with similar features.

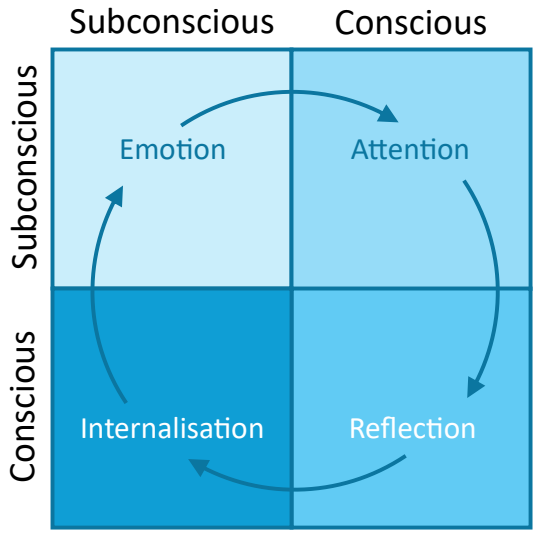


Figure 2.6 – The emotion development model, adopted from Haug (2016)

Three levels of processing emotions

When looking at a product, there are three levels of emotional processing which occur by a human brain. These are the *visceral*, *behavioural* and *reflective* levels (Norman, 2004).

Visceral processing level

According to (Norman, 2004) human biological instinctive reactions to a product occur at the *visceral* level. This level is an automatic and pre-wired part of the brain that makes rapid judgements of what is attractive or repulsive, good or bad, safe or dangerous, and then sends signals to the motor system and alerts the rest of the brain (Haug, 2016). In this context, a product or circumstance can provoke an instinctive reaction, culminating in both an action and the sensation of an emotion. For example, an individual may have a boost in energy with excitement while seeing a new motorcycle from an admired brand. The situation here arouses the individual's instincts, which direct the action (to boost in energy) and experience an emotion (of excitement) (Singh, 2013).

Behavioural processing level

The *behavioural* level pertains to the section of the brain responsible for governing daily behavioural patterns. This is notably essential for the regulation of well-established, routine functions (Norman, 2004). It deals with the expectations and perceptions that a customer has of a

particular product. These are generated and continuously evolve during product use.

Reflective processing level

Unlike visceral and behavioural, the *reflective* level is conscious, and includes reflective thoughts about the emotional impact of a particular product or feature, as well as other reflections of an informative or symbolic nature (Haug, 2016). The reflective level is the most developed of the three levels and the emotions produced at this level are the most prolonged. As illustrated by Figure 2.7, the reflective layer lacks immediate access to sensory inputs, yet it holds the capability to either enhance or inhibit the visceral and behavioural layers (Norman, 2004).

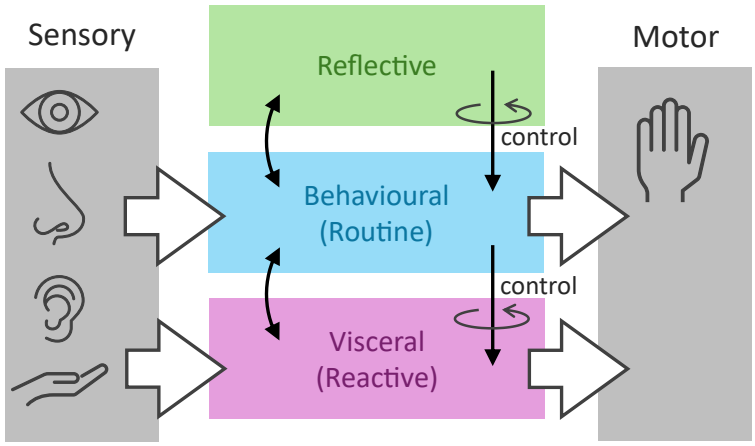


Figure 2.7 – Three levels of processing emotions: Visceral, Behavioural and Reflective, adopted from Norman (2004)

Responses of the three levels

Based on these three layers, Norman (2004) defined three types of responses to designs: *(i) Visceral responses*, which are the initial reactions to a product. Motorcycle aesthetics, style and appearance are the prime features that drive the visceral level (Mamo, 2018). *(ii) Behavioural responses* are driven by the product's ergonomics and physical feel, or performance such as, function, understandability and usability (Mamo, 2018). *(iii) Reflective responses*, which are related to message, culture, and meaning of a product or its use. All three levels of processing work together, and the designer should give importance to all three levels as these can all have a huge impact on the success of a motorcycle design (Farrugia et al., 2019).

Emotional responses to products

How a product influence emotions

According to Crilly et al. (2004), emotional responses to products can be better understood by considering the cognitive (aesthetic, semantic, and symbolic) responses related to products. Desmet & Hekkert (2007) defined six overall types of product-evoked emotional responses that can influence an individual's emotions: functional, experience, branding, aesthetic, social, and symbolic.

Functional

- *Functionality*: If a product functions effectively and fulfils the user's requirements, it can elicit positive emotions like satisfaction and confidence. Conversely, if it does not operate as anticipated or proves challenging to utilise, it might trigger negative feelings such as frustration and irritation (Haug, 2016). In relation to Norman's model, functionality is processed at the behavioural level.

Experience

- *User experience*: The overall experience of utilising a product, including factors like ease of use, convenience, and personalisation, can elicit emotions such as delight or frustration (Singh, 2013). According to Norman (2004), this emotion-evoking aspect can also be analysed within the behavioural level of emotional processing.

Branding

- *Brand identity*: The reputation and image of a brand can evoke emotions such as trust, loyalty, and admiration (Desmet and Hekkert, 2007). This is processed by the reflective level. A user may feel positive emotions towards a product simply because it is associated with a brand they like and trust.

Aesthetics

- *Visual design or aesthetic-derived emotions*: Styling is an integral part of any product design and development process (Singh, 2013). During the styling process, a designer imparts emotive attributes to products. Aesthetics works on the visceral level (Norman, 2013) and especially plays a crucial role in the

potential customer's first encounter with the product. When a potential customer enters a shop to purchase a particular product, they are often drawn to distinctive and prominent product features, such as shape, size, position and colour (Jennifer et al., 2011). These product features enable customers to match their personalities with their vehicles (Jennifer et al., 2011) on the basis of their taste (Haug, 2016).

According to Coates (2003), the aesthetics of a consumer item frequently hold more significance for the recognition and appreciation of the product than its functional capabilities. For instance, the success of products such as the *Apple iPod*, the *Fender Stratocaster* guitar, and the *Dyson* vacuum cleaner may, to a large extent, be related to their aesthetic qualities (Haug, 2016).

Others, such as Coates (2003); Hekkert (2006); Vessel et al. (2012), have postulated that emotions are strongly subjective and are of symbolic nature or social derived. This means that in these instances, the emotion primarily operates at the reflective processing level (Haug, 2016). These are:

Social

- *Social influence*: The influence of others, such as friends, family, or social media influencers, can also evoke emotions towards a product. For example, users may feel a sense of belonging or excitement when using a product that is popular among their social group.

Symbolic

- *Symbolic connotations*: Emotions, as stated earlier, are personal and intentional in character, and can be perceived in various manners. A situation can trigger varied emotions in different individuals due to the distinct symbolic or connotative meanings they hold for them (Crilly et al., 2004). According to Singh (2013) memory also plays a significant role in the cognitive process of generating emotions.

Focus on aesthetic-derived emotions

Singh (2013) stated that although a designed product can trigger definite aesthetic responses in observers, correlating these responses to the characteristics of the product is not an easy task. Therefore, while designing emotions into products, it becomes pertinent to investigate the role played by various aesthetic properties. Moreover, determining which emotion-evoking aspect (outlined above) is dominant during the interaction between product and individual, or which influences the purchasing decision, remains a challenge (Haug, 2016).

To narrow the focus, this doctoral research will address aesthetic-derived emotions (hf_{AE}), prompted by the visual appearance of a product, rather than emotions arising from semantic or symbolic significance to a user. The focus on aesthetic-derived emotions in this doctoral research stems from the sub-aspect's direct and immediate influence by tangible design elements such as shape, colour, and material (Norman, 2004). This characteristic renders hf_{AE} actionable during the product development process, in contrast to semantic or symbolic emotions, which necessitate higher-order cognitive processes and are significantly shaped by personal or cultural contexts. The aesthetic-derived emotions sub-aspect predominantly arise from visual and sensory stimuli, distinguishing it from social or semantic-derived emotions, which are challenging to quantify and not directly observable.

2.4.3 Personality and Behaviour related Challenges

Person characteristics

Personality

Personality refers to an individual's unique pattern of thoughts, feelings, and behaviours that persist over time and across different situations and contexts (Larsen, 2010). Behaviour refers to the outward actions or reactions of an individual, observable by others, and often influenced by a combination of internal and external factors. The

behaviour (with the product) can be positive, negative, or neutral, and often shaped by an individual's beliefs, feelings, and past experiences (Vogel & Wanke, 2016).

Defining and scoping 'persona'

Brangier & Bornet (2011) contend that consumers convey behavioural patterns, personal motivations, and intentions, which help to define goals concerning the use of a product. *'Persona'* can have various connotations, but Myers & Twenge (2022) remark how both personality and behaviour can be seen as key components of an individual's persona. The individual's persona plays a significant role in shaping how an individual interacts with the world and influences the individual's behaviour and decision-making in various contexts (Myers & Twenge, 2022). Drawing from this definition, the term *'persona'* encapsulates the individual's past experience whilst using the product or similar products which form part of the same product family. Furthermore, *'persona'* also encompasses users' product utilisation patterns (product-use context) which are influenced by their personality traits and behaviour. Within the framework of the DOPs paradigm, similar to emotions, the persona is posited as an "intangible and subjective construct".

Drawing from the connotations provided by Brangier & Bornet (2011), and Myers & Twenge (2022), in this doctoral research, the term *'persona'* (hf_P) is characterised by the person's attributes, personality, experience, behaviour and product use-context. The subsequent sections provide a detailed exploration of each characteristic.

Attributes, personality and experience

From a design process perspective, the objective of attributing an identity to a persona is to render the personas credible, easy to remember, and *'human'* (Brangier & Bornet, 2011). The detailed portrayal of these personas should not only enable to understand the fundamental motivations that bring them to life, but also to foresee their behaviour during the product use (Nielsen, 2002). This will be based on elements linked to the following aspects:

- *Biological attributes:* These encompass diverse data including gender, age, and health condition.
- *Sociological and psychological traits:* Aspects such as social class and individual personality traits can significantly influence the selection of products.
- *Experience:* significantly shapes a user's interaction with a product, enhancing familiarity, and confidence in its use. Over time, this familiarity can lead to advanced utilisation, and a deeper trust in the product. However, this can also lead to overconfidence in the product use, with the consequence of risking harm to the user.

Behaviour (with the product)

Behavioural aspects enable the product to be situated in a global perspective, in relation to people's values and beliefs. Behavioural aspects concern, for example, the goals pursued in life, the type of needs at an interpersonal level, and professional ambitions (Nielsen 2002). For example, a particular motorcycle user might exhibit a calm behaviour towards riding a motorcycle, driven by the simple objective of transitioning from point A to B in harmony with the environment. In contrast, another rider might demonstrate a more aggressive behaviour, possibly motivated by a desire to make an impression within a social group or the wider society (Dorn, 2012).

The articulation of objectives pursued by users during product interaction is a fundamental component provided by the persona description (Olsen, 2004; Goodwin, 2005). This extends beyond a simple description of tasks and enables an identification of the motives behind the behavioural patterns. It is also useful to know the goals linked to product experiences. These objectives represent the type of emotions that the consumer wishes to experience through the product, such as pleasure, fear or surprise (Myers & Twenge, 2022). For instance, a motorcycle rider might desire an aggressive riding style to evoke the thrilling sensations (Dorn, 2012). Regardless of the context,

the behaviour anticipated through product utilisation is a paramount detail to be incorporated in the persona's description (Goodwin, 2005).

Context of use

The description of context of use provides information about how, and the environment in which the product is anticipated to be utilised. The task context is also addressed with elements concerning the nature and frequency of interactions (Myers & Twenge, 2022). For instance, considerations might include whether a rider intends to use the motorcycle amidst traffic conditions or for extended journeys. Such information affords a basis for justifying constraints pertaining to the product ergonomic functionality (Brangier & Bornet, 2011).

The need to incorporate persona in design

A clear understanding of personality styles can be helpful in designing products for a specific community of users (Bakshi & Gupta, 2014). Schmitt et al. (2015) and Hancock et al. (2006) argue that the personality and behaviour need to be factored during the product development process. Designers need to conduct extensive research to understand the users' behaviour and personality traits. According to Lee et al. (2017) this can be challenging if the audience is diverse and they argue that designers must consider individual differences, such as personality traits and individuals' behaviour, in their design decisions.

Personas to segment the market

Target user

According to Greengrove (2002), not all users are the same, and markets consist of a number of *'segments'*. Therefore, it is important to differentiate product offerings for different user groups. As posited by Kara & Kaynak (1997), market segmentation aims to divide markets, populated by individuals, into cohorts that are internally homogeneous in characteristics whilst being externally heterogeneous when compared across segments, based on an identified set of variables. Birch (2014) defined *'target users'* as a group of users with similar needs. This is achieved by categorising users into different segments based on similarity in their characteristics and similar needs. Essentially

this entails delineating the market in accordance with the persona, as elucidated by Singh (2013).

Universal design (for general user)

One of the purposes of design is to fundamentally solve problems and to drive a business forward. Null (2013) argues that a business cannot thrive and succeed if it singularly targets one demographic or fails to grasp the challenges faced by all potential customers/users of their product. This emphasis aligns with the concept of universal design, which pertains to the design intended for the general populace. Where its fundamental purpose is the design of products that can be used by the majority of people, without adaptations or special designs (Erlandson, 2007; Acosta et al., 2011). It is considered to be an enduring design focus, one that assumes the range of human abilities as something ordinary, not special (Ostroff, 2001). The endeavour to design with the broad user base in consideration is undeniably of paramount significance, bearing considerable societal implications (Acosta et al., 2011).

Second connotation of persona in dissertation

The principle is therefore to design a product adapted to a persona, so as to satisfy all the consumers it represents (Goodwin 2005). Within the context of this doctoral research, the term *'persona'* is similarly employed to describe specific users (target users), and potential customers/users (general users) (Brangier & Bornet, 2011).

2.5 Chapter Conclusions

Focus on human factor aspects

In the pursuit of creating total human-centric products, it is crucial to acknowledge the significance of considering all aspects encompassed within human factors, as demonstrated in Figure 2.5. Nevertheless, this doctoral research narrows its scope to three core aspects, namely, ergonomics, emotions, and persona, while designing products. As posited in this chapter, these three aspects collectively represent the essence of the dual ontological product paradigm. Hereafter, they will

be termed the *three human factors* formalised as $hf_{E\text{-}AE\text{-}P}$, where *E-AE-P* represents the initials of the respective core aspect:

- ***E**rgonomics (hf_E)* which encapsulates anthropometry, posture, and product geometry.
- ***A**esthetic-derived **E**motions (hf_{AE})*.
- ***P**ersona (hf_P)* which encompasses the personality, experience, behaviour and product-use context.

The reason for focusing on these three human factors arises from their synergistic interaction and all aspects can influence each other. Ergonomics impacts physical comfort and aesthetics, aesthetic-derived emotions influence visual appeal but also the product's ergonomics, and persona contextualises these interactions by integrating user behaviour. By focusing on these aspects, the study captures a holistic picture of user-product interaction. Furthermore, these three aspects are critical to the design of DOPs, which rely on both physical (ergonomics) and psychological (emotions and persona) constructs for their success.

In this chapter, the context for this doctoral dissertation has been established, introducing DOP and its product structure viewpoints, as well as defined HFs, specifying the particular aspects ($hf_{E\text{-}AE\text{-}P}$) that will be in focus throughout this research.

Research primary users (DOP designers)

In this doctoral research, two distinct categories of *'users'* are identified. The first category comprises of the *research primary users* (RPUs), or the designers engaged in the design activities of DOPs. Bonello et al. (2022), defined primary users as those who make direct use of a *'device'*, applicable also to a tool or an approach. Analogously, for this group (research primary users), the research aims to formulate a well-defined prescriptive solution that can serve as a guiding framework for their design activities.

Research tertiary users (DOP users)

According to Bonello et al. (2022), users who do not use a *'device'* (applicable also to a tool or an approach) at all but are directly affected

either positively or negatively by the *'device'* are defined as tertiary users. Based on this definition, the second category involves the *research tertiary users* (RTUs), or principally the DOP users. These individuals stand to benefit from the implementation of the prescriptive solution developed through this doctoral research.

Next chapters

The structure of this research is designed to cater for the diverse needs of both *'user'* categories. The next chapter, Chapter 3, is dedicated to the characterisation of $hf_{E\text{-}AE\text{-}P}$ and specific requirements of DOP research tertiary users. Conversely, Chapter 4 is set to concentrate on the reality exploration of the designers (research primary users).

3 Characterising Human Factors and Dual Ontological Product Users' Requirements

The characterisation of human factors (HF) in dual ontological products (DOPs) seen in Chapter 2 is extended to this chapter. A mixed-methods study is employed to understand the characteristics and challenges of DOP stakeholders and DOP users (research tertiary users) from the perspective of the three human factors ($hf_{E\text{-}AE\text{-}P}$). In this chapter the motorcycle artefact will be used a case of DOP. Section 3.1 presents the objectives set out for the two studies, while Section 3.2 portrays the mixed-methods methodology (encompassing the two studies) to understanding DOP characteristics and $hf_{E\text{-}AE\text{-}P}$ requirements. Section 3.3 reveals the mixed-methods results in detail, through the main three themes. Limitations of both studies are presented in Section 3.4, while Section 3.5 draws out the key findings and conclude this chapter.

Involvement of tertiary users in research

The discovery and problem definition phase stands as a critical juncture that shapes the trajectory of the entire doctoral research (Booth et al., 2009). By involving users in this phase of the research invaluable insights, that go beyond literature alone, can be gained. The process of involving users early on, sometimes referred to as *'co-creation'*, allows for an interactive dialogue that uncovers pain points and complexities that might otherwise be overlooked (Kaisler & Missbach, 2020). Adopting a user-centred design philosophy for DOPs ensures an in-depth understanding of the users' situation and develop a solution that is tailored to meet users' specific needs.

Primary method

A primary investigation (i.e. not from literature) was carried out to comprehend the research tertiary users' and stakeholders' (RTU), or DOP users and stakeholders, interaction with DOP from $hf_{E\text{-}AE\text{-}P}$ perspective. These two studies were not merely aimed at investigating products in isolation. Rather, the scope was to delve into the user experience from a humanistic point of view, and thereby understanding the resulting interaction between $hf_{E\text{-}AE\text{-}P}$ and the DOP during the artefact's use phase.

3.1 RTU-Two Study Objectives

Objective 1 (RTU-O1)

The first RTU objective centred on identifying various challenges that DOP users' experience.

Objective 2 (RTU-O2)

The second objective aimed to attain a comprehensive understanding of the multifaceted interaction, users have with their, or new, DOPs. This involves considering hf_E, hf_{AE} and hf_P as users engage with DOPs.

Objective 3 (RTU-O3)

The third RTU objective sought to discern which $hf_{E\text{-}AE\text{-}P}$ are given precedence by DOP users and to investigate how these factors influence one another.

Objective 4 (RTU-O4)

The fourth objective involved in collecting RTU's requirements, essential for developing a prescriptive solution that can serve as a guiding framework to assist DOP designers (research primary users). Furthermore, this study is designed to provide insights that will substantively contribute the subsequent study with designers found in Chapter 4.

3.2 A Mixed-Methods Methodology to Understand DOP Characteristics and HF Requirements

Deployment of focus groups and interviews as DCIs

Two primary *data collection instruments* (DCIs) were used for the two-fold study investigation. A focus group session, referred to as *Study A*, was held with a group of motorcycle riders (DOP users), who have expertise in the motorcycle industry. Subsequently, a survey was conducted with a wider sample of motorcycle riders, delineated as *Study B*.

Qualitative method (focus group)

A focus group is qualitative research method which is capable of capturing patterns or trends and detect consistency (Langford & McDonagh, 2003). This qualitative approach aimed to collect in-depth understandings into the influence of motorcycles on the three human factors.

Quantitative method (survey)

On the other hand, surveys typically are quantitative methods, designed to formulate broader inferences that can be extrapolated to the population at large (Mertler, 2021). The survey was designed to build upon and substantiate the initial observations made during the focus group session, thereby providing a more holistic comprehension of the motorcycle users' reality.

Mixed-methods

The combination of the two studies is a *mixed-methods* methodology, which deeply explores the challenges and requirements faced by motorcycle riders while generalising these exploratory observations through quantitative analysis (Creswell & Poth, 2018). Such an integrated methodology facilitates a more pragmatic and realistic interpretation of the observed realities (Dawadi et al., 2021).

Validation of observations

The outcome constitutes a robust triangulation method (Timans et al., 2019) (refer to Figure 3.1), which combines a mixed-methods methodology with the concurrent incorporation of existing literature, as presented in Chapter 2. This serves to validate and provide a multi-faceted examination of HFs use phase challenges whilst interacting with DOPs.

3.2.1 Qualitative Study (Study A)

Focus group procedure

Focus group layout

The focus group session took place in a motorcycle workshop-showroom, thereby providing an environment favourable to discussions centred around motorcycles. Throughout the session, physical motorcycles were available for participants to utilise as illustrative examples, thereby enhancing the clarity of their arguments. To ensure robust engagement, visual presentations accompanied each stage of the focus group's session, with individual questions also displayed on a screen to help participants maintain topic focus. The session, lasting for a duration of two hours, was facilitated by a

moderator whose role was to guide discussions and stimulate participant conversation.

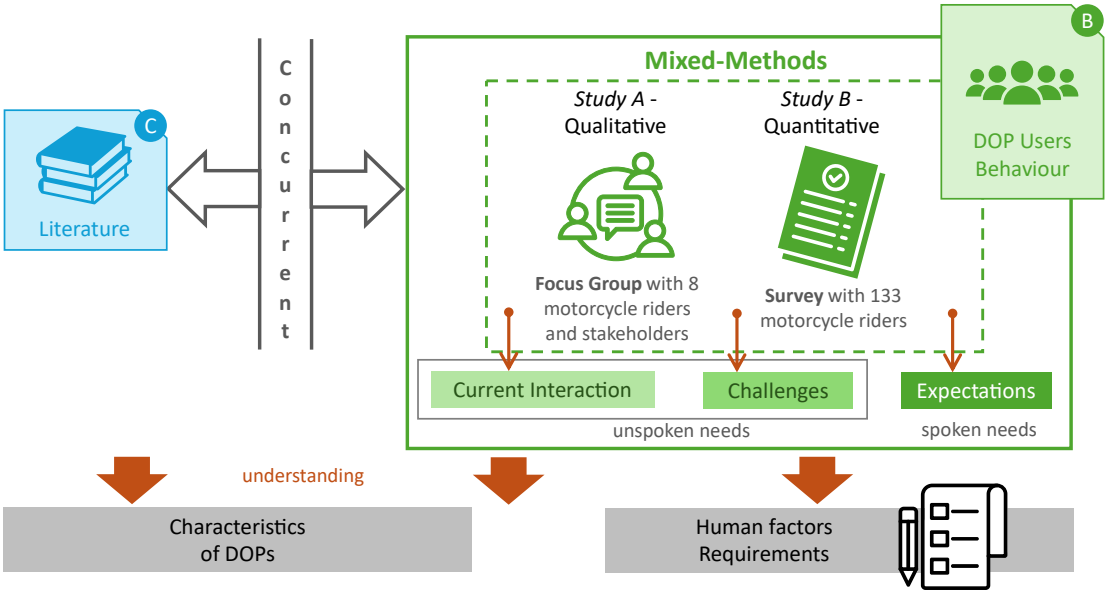


Figure 3.1 – A mixed-methods methodology for understanding DOP characteristics and human factor requirements

Structure of session

A procedure for the effective conduct of the focus group session was established (illustrated through Appendix A - Section A.1). The questions posed during *Study A* centred on:

- Existing interactions and practices of motorcycle riders.
- The challenges faced with current motorcycle designs.
- Riders' expectations and improvements from future motorcycle designs.

These questions are documented in Appendix A.2. Ethical approval for the research was granted by the Ethics Committee of the University of Malta (Application ENG 669/2019, part 3), and informed consent was secured from each participant. The study was divided into two parts. The first part sought to investigate the current situation and challenges that motorcycle users encounter during the use phase from a $hf_{E\text{-}AE\text{-}P}$ perspective. Specifically, this part aimed to understand the different persona views in relation to the motorcycle's ergonomics and aesthetics. The second part focused on discovering participants'

requirements for future motorcycle designs, particularly in relation to the three human factors.

Piloting Study A

Prior to the main study, a pilot test (Ruel et al., 2016) was conducted involving two other researchers to assess the procedure and layout. The questions were transformed into exploratory queries, further elaborated by *'why'* and *'how'* follow-up questions, to facilitate a deeper understanding of customer challenges and requirements. Other improvements observed during the pilot study, and which were incorporated into the full-scale study, included the elimination of question biases and adjustment of phrasing.

Thematic analysis

All focus group sessions were audio-recorded and subsequently transcribed verbatim to enable post-hoc qualitative analysis. Key phrases, sentences, and sections from the transcripts were coded, and the resultant codes were organised into themes as per the methodology outlined by Braun & Clarke (2006) and Vaismoradi & Snelgrove (2019) for thematic analysis. Patterns among these themes were identified using affinity diagramming technique (Otieno, 2023). Affinity diagramming is a technique used to organise and categorise large amounts of data, ideas, or problems into logical groups based on their natural relationships. According to Otieno (2023) This method is particularly useful where sorting through large volumes of qualitative data is necessary to identify patterns and themes.

Inter-rater reliability of the qualitative results

Inter-rater reliability (IRR) served as a measure of the replicability and consistency of the qualitative analysis performed (McDonald et al., 2019). The *Cohen's Kappa index* was employed to assess the degree of agreement between two independent researchers during the thematic coding process. The *Kappa index* was interpreted using the following established criteria: <0.2 signifying poor agreement, 0.2-0.4 as fair, 0.4-0.6 as moderate, 0.6-0.8 as good, and 0.8-1.0 as very good (Collins et al., 2007). The *Kappa index* for this study was calculated to be 0.78,

thereby indicating a good level of agreement between the raters and, consequently, a robust qualitative reliability (Bajpai et al., 2015).

Focus group (*Study A*) participants

Focus group participants

A sample of eight participants, all of whom were frequent motorcycle riders but from diverse occupational backgrounds, took part in the focus group session. This diversity was advantageous in illuminating a broad spectrum of challenges and requirements. Table 3.1 delineates the demographic details of the focus group participants, including their respective occupational backgrounds. The average number of motorcycles owned by the participants were two, with various motorcycle types ranging from scooters to cruisers and sportbikes. Given the extensive experiences of the participants with different kinds of motorcycles, a rich array of feedback was anticipated.

Gender imbalance

As illustrated in Table 3.1 only one of the eight participants in the focus group was female, highlighting a notable gender disparity that is reflective of broader trends in motorcycle riding. Despite the gender imbalance, the inclusion of a female participant was deemed significant for the study. Owing to physiological differences between men and women, the female perspective could offer invaluable insights, thereby enriching the comprehensiveness of the study findings.

3.2.2 Quantitative Study (Study B)

Survey procedure

Semi-structured data collection

In the context of Study B, a survey was conducted in areas in Malta frequented by motorcycle riders, to foster a comfortable environment for data collection. The survey employed a semi-structured questionnaire DCI. This approach was selected for its structured nature, based on predetermined questions, and its capacity for generalisation. Specifically, the collected information could be extrapolated to represent the wider population of Maltese motorcycle

riders, thereby offering insights into the relationship between $hf_{E\text{-}AE\text{-}P}$ and motorcycle use within this demographic.

Table 3.1 – Background of participants

Designation	Role	Background
FP1	Academic and experienced rider	Fluid mechanics and aerodynamics
FP2	Experienced *male* rider	Riding motorcycle for the pas 17 years, sveral experiences wit motorcycles
FP3	Member from transport authority	27 years in the transport authority, also closely worked with the statistics office on vehicular accidents
FP4	Marketing Personnel	Journalist, and drives different motorcycles on a regulaarly basis, especially abroad
FP5	Motorcycle mechachnic and occupational health and safety officer	Health and safety concsultant and voluntary work with Red Cross as a motorcycle first aider
FP6	Experienced *female* rider	Motorcycle rider for the past 15 years and travels frequently with motorcycles
FP7	Motorcycle industry and dealer	Motorcycle expert, technician and dealer
FP8	Motorcycle industry	Experienced motorcycle rider and technician

Questions type

Observations derived from the focus group (*Study A*) informed certain sections of the questionnaire, enabling to gauge broader sentiments among motorcycle riders. In turn, the survey findings also served to contextualise and interpret discoveries from the focus group. The questionnaire incorporated diverse types of variables, ranging from nominal ones, such as true-or-false questions, to ordinal variables captured through Likert-scale responses. Additionally, a segment of the survey solicited open-ended opinions and comments from the participants, capturing other information not directly addressed by the structured questions. The specific questions employed during the questionnaire are documented in Appendix B. As with *Study A*, ethical approval for *Study B* was secured from the Ethics Committee of the

University of Malta (part 1a of application ENG 669/2019), and informed consent was obtained from each participant.

Piloting Study B

Prior to the main survey, a pilot study was conducted with an independent researcher, who is also a motorcycle rider, to obtain impartial feedback on the questions. The feedback expanded the scope of motorcycles considered, with the aim of capturing a wider array of data and understanding diverse rider behaviours across different types of motorcycles and situations.

Survey (*Study B*) respondents

Survey respondents

A convenience sample of 133 motorcycle riders participated in the survey. The age of the riders ranged from 20 to 60 years, with an average age of 42 years ($\boldsymbol{\mu}$=42years) and a standard deviation of 11 years ($\boldsymbol{\sigma}$=11years). Similarly, the motorcycles owned by the respondents were manufactured between the years 1951 and 2019, averaging at the year 2007 with a standard deviation of 11 years. The riders' on-road experience spanned from 1 to 48 years, with an average of 20 years and a standard deviation of 13 years.

Motorcycle types of surveyed riders

Motorcycle power ranged from as low as 8 *brake horsepower* (bhp) for scooters to as high as 193 bhp for super-sport motorcycles, with a average power output of 66 bhp and a standard deviation of 48 bhp. Furthermore, different motorcycle types were categorised into three sub-groups, namely:

- High Power ($\boldsymbol{\mu}$=119bhp): *Sports Tourer, Super Sports, Power Cruiser and Sports Street Naked.*
- Medium Power ($\boldsymbol{\mu}$=64bhp): *Tourer, Adventure Tourer, Chopper and Classic Cruiser.*
- Low Power ($\boldsymbol{\mu}$=27bhp): *Off-Road, Classic/Retro, Standard Street Naked and Scooter.*

Heterogeneity among respondents

Gender representation within the sample was notably skewed, comprising 94% men and only 6% women. This proportion of female

respondents was congruent with that observed in *Study A*. On the other hand, the heterogeneity in age and gender among the respondents, ensured a broad spectrum of perspectives concerning persona, ergonomic, and aesthetic-derived emotions.

Statistical tests concerning *Study B*

Analysis of non-parametric data

Various statistical tests were employed to investigate the three human factors relevant to motorcycle riders, given the differing nature of the test variables. A Kolmogorov-Smirnov test revealed the data to be non-parametric, thereby warranting the use of non-parametric statistical tests (Gibbons & Chakraborti, 2010).

Chi-Square test for association

For analyses involving two categorical variables, such as the dependent and independent variables, the Chi-Square test was utilised (Simpson, 2015). In this context, the group variable encompassed demographic data, such as age, gender, or motorcycle experience. Conversely, the test variable pertained to the riders' views on motorcycle aesthetics and ergonomic characteristic, for example, motorcycle preference or origin of ergonomic discomforts/pains. The null hypothesis (H_0) postulated no association between these categorical variables and would be accepted if the p-value exceeded the 0.05 level of significance (Field, 2018).

Friedman and Kruskal Wallis test for mean rating scores

For rating scores, non-parametric statistical tests were employed. The Friedman test (Field, 2018) served to compare mean rating scores across variables, such as motorcycle power or rider experience, for the same persona characteristic. The Kruskal Wallis test (Field, 2018) was employed for comparisons between groups segmented by attributes such as experience, frequency of use, or preference. For both Friedman and Kruskal Wallis tests, the null hypothesis (H_0) specifies that the mean rating scores vary marginally between the different characteristic categories and would be accepted if the p-value exceeded the 0.05 level of significance (Simpson, 2015).

Spearman test for correlation

Spearman correlation tests (Field, 2018) were conducted to explore relationships between dependent and independent variables of either continuous or ordinal types. The correlation coefficient ranged between 0 and +/-1. The strength of the relationship varies in degree based on the value of the correlation coefficient. Specifically, a value of 0 signified no correlation; a range of 0 to 0.2 denoted a weak correlation; 0.2 to 0.6 indicated a moderate correlation; 0.6 to 0.9 suggested a strong correlation; and 0.9 to 1 denoted a very strong positive correlation (Collins et al., 2007). A coefficient of -1, conversely, indicated a strong negative correlation. The direction of the correlation specified whether an increase in the independent variable would result in an increase or decrease in the dependent variable. In this context, the null hypothesis (H_0) assumed no correlation between the variables under consideration and would be accepted if the p-value exceeded the 0.05 level of significance.

3.3 Mixed-Methods Results (*Study A and B*)

The influence of DOP on $hf_{E\text{-}AE\text{-}P}$

Since all the discussions in the focus group and survey had the aim of discovering how motorcycle customers interact with motorcycles, the primary investigation revolved around how DOP influence $hf_{E\text{-}AE\text{-}P}$. However, three *main themes* (MT) were developed whilst analysing the mixed-methods result. These three themes, derived from the survey questions, are organised as illustrated in Figure 3.2:

Main theme 1 (RTU-MT1)

DOP characteristics (exemplified through the motorcycle artefact) from $hf_{E\text{-}AE\text{-}P}$ perceptive.

Main theme 2 (RTU-MT2)

Lack in current motorcycle design solutions with respect to the three human factors.

Main theme 3 (RTU-MT3)

$hf_{E\text{-}AE\text{-}P}$ requirements for DOP from the perspective of motorcycle users.

Within each of these three main themes, specific *sub-themes* (ST) are enumerated that directly relate to their respective main theme.

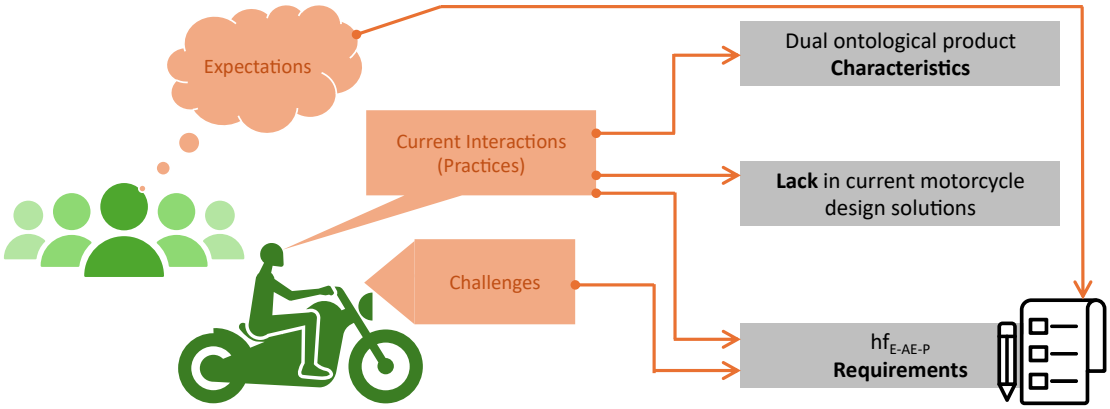


Figure 3.2 – Derived main themes from thematic analysis

3.3.1 DOP Characteristics from the Perspective of the Three Human Factors

ST1 (Sub-Theme 1) – Comparing ergonomic with aesthetic riders' preference

Importance of both aesthetics and ergonomics

According to all of *Study A*'s participants, motorcycle ergonomics is crucial for assuring the comfort and safety of the user. The ergonomically designed features of a motorcycle, such as seating arrangements and handlebar positioning, serve not as a matter of comfort but also as a safety concern. On the other hand, aesthetics operates on a different level. As discussed in Section 2.4.2, the visual appeal, design lines, and overall presentation of the motorcycle become the cornerstone in forming an emotional connection with the artefact.

Minimal inclination to aesthetics

The majority of the focus group participants (87.5%) indicate that once a motorcycle is confirmed to be in operable condition, the subsequent factors that most significantly influence customer choices are aesthetics and ergonomics. This is evident from a particular focus group participant's (FP6) statement: *"When I'm in a showroom to purchase a new motorcycle, the first thing that catches my eye is how it looks, the aesthetics are my initial filter. But after that, it's all about ergonomic comfort. If it's not comfortable, as much as it pains me, I have to explore other options. In the long run, comfort and safety can't be compromised … The personality then dictates what are your liking and if you can sacrifice some comfort for aesthetics or be totally inclined to*

ergonomics." From this study it was also found out that the importance attributed to either ergonomics or aesthetics, varies considerably based on numerous factors such as, the intended use-case scenario or subjective preferences of the individual.

Agreement between studies

In concordance with the findings from the qualitative study, the survey (*Study B* respondents) also reveals a similar riders' preference. As depicted in Figure 3.3, 45% of respondents prioritise aesthetics when purchasing a motorcycle. This is closely followed by ergonomics preference (38% of respondents). The remaining 17% of the sample designated *'other'* aspects as the most important, a category which encapsulates aspects such as performance, fuel consumption, reliability, and availability of parts.

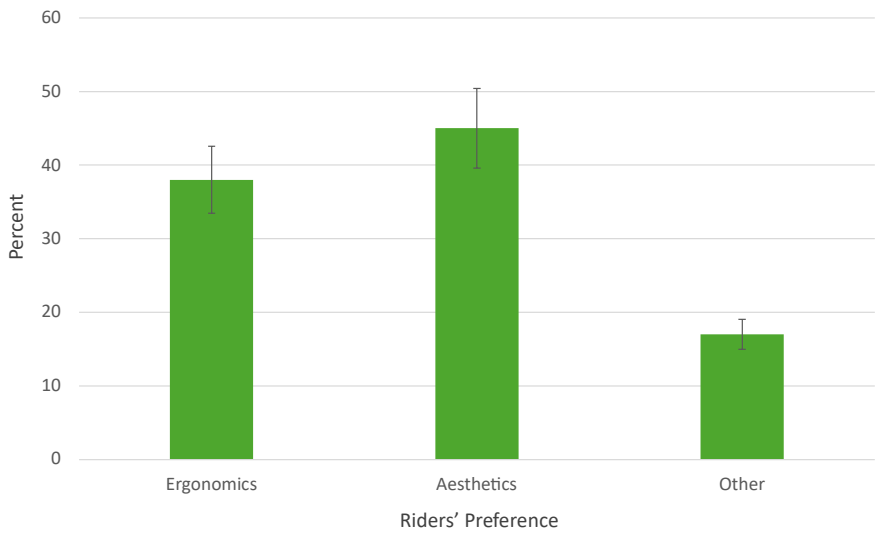


Figure 3.3 – Riders' preference when purchasing motorcycles

Importance of ergonomics and aesthetics compared to 'other' factors

Statistical analysis employing the Kruskal-Wallis test yielded noteworthy insights. The test disclosed a statistically significant difference between the *'ergonomics or aesthetics'* group and the *'other'* group (p-value=0.013). This suggests that respondents do not perceive aspects like performance or fuel efficiency statistically equivalent in importance to ergonomics or aesthetics. This test also demonstrated no statistically significant difference between the preferences for aesthetics and ergonomics (p-value=0.78). Consequently, it is untenable to generalise that aesthetics categorically

supersedes ergonomics, despite their higher percentage of preference among respondents.

Favourable ergonomics lead to positive emotions

In their research works, Hancock et al. (2005), along with Jordan (2002), posited that user emotions should not be overlooked when considering product interactions. They contend that products not only bring ergonomic benefit but also engage users on an emotional level. When a product, in this instance, a motorcycle, possesses favourable ergonomic attributes, it does not only satisfy the user's need for comfort but also has the potential to elicit emotional responses, processed at the behavioural level, as seen in Section 2.4.2. This underlines the importance of accounting for emotions that arise when users interact with ergonomically designed products. Such an approach amplifies the product's capacity to exert a dual positive emotional impact (Jennifer et al., 2011), generated at the visceral and behavioural levels.

ST2 – The influence of persona on ergonomics in motorcycle selection

Multi-dimensional persona-ergonomic factors

According to the majority of focus group participants (75%), there are multi-dimensional persona factors that contribute to ergonomic requirements. Such designs must be inherently flexible to cater divergent needs, particularly those dictated by age and the intended context of use. Motorcycle designs must be sensible to these variations and aim for adaptive solutions that can cater to a broad spectrum of user needs.

Ergonomic impact on old riders

A challenge is determining and meeting the needs of older riders, which represents and increasingly important target population (Karali et al., 2017). The participants stated that more discomfort is present in older riders' limbs compared to younger ones. This is because as riders get older and muscle strength, cognitive abilities, coordination, grip, and general freedom of neck and limb movements deteriorate (Groeger, 2000).

According to Gyi (2012) more data is needed to focus on dynamic and functional anthropometric measurements in vehicle design to accommodate the specific needs of older drivers. Designing vehicles to accommodate the needs of older drivers has social and economic implications for users. Identifying these needs will enable drivers of all ages to be better accommodated by the motorcycle design. In this regard FP2 stated: *"We can maintain our independence, drive for longer periods and remain socially connected for longer."*

Persona-ergonomic characteristics

Study B respondents prioritising motorcycle performance predominantly utilise their vehicles during weekends, as substantiated by Figure 3.4. A Kruskal Wallis test reveals that this statement can be generalised (p=0.008) to the whole population. A strong positive correlation of 0.778 indicates that individuals who use their motorcycle frequently are likely to opt for an ergonomically oriented motorcycle. However, this correlation fails to reach statistical significance, as the Spearman test achieved a p-value of 0.112.

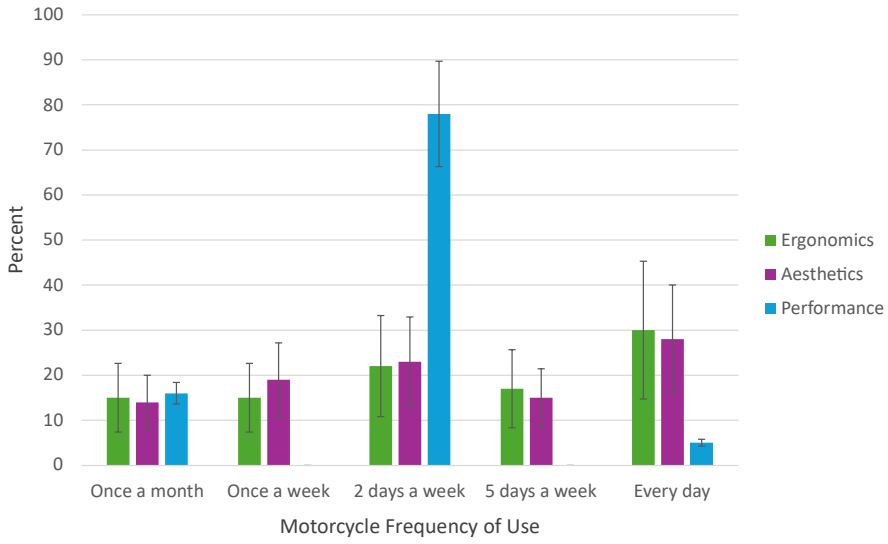


Figure 3.4 – Motorcycle frequency of use with riders' preference

Examination of Figure 3.5 reveals that owners of medium-powered motorcycles are more inclined to embark on extended journeys in comparison to those possessing low-powered counterparts. These medium-powered motorcycles offer superior ergonomic comfort, thereby facilitating longer durations of use. The statistical significance

of this observation is confirmed by a p-value of 0.001. This observation also extends to respondents who own high-powered motorcycles, who similarly demonstrate a tendency for extended journeys when contrasted with those operating low-powered models, like scooters.

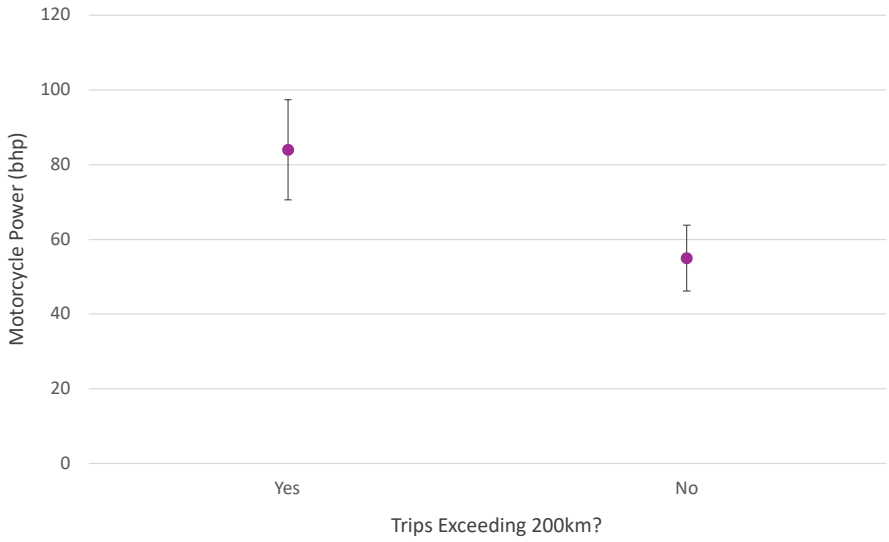


Figure 3.5 – Long-journey trips, exceeding 200km

Respondents valuing motorcycle ergonomics over aesthetic or performance demonstrate a greater tendency for undertaking long-distance trips. As the level of riding experience increases among this cohort, the length of trips tends to get longer. A Spearman test affirms the statistical significance of this relationship with a p-value of 0.004 and presents a moderate correlation coefficient value of 0.46.

ST3 – Interplay between motorcycle aesthetics and rider personality: A reflection of self-expression

Multi-dimensional persona-aesthetic factors

(Bagshi, 2013) stated that a *"motorcycle cannot be seen in isolation from its rider".* A motorcycle and rider together complete a motorcycling experience. Humans perceive expressive or personality characteristics of products (Govers et al., 2004), which help individuals understand and relate to them. This theme explores how the aesthetic features of motorcycles serve as visual stimuli but also as an outward manifestation of the rider's internal psychological landscape. Given the diverse array of motorcycle styles, all *Study A* participants agreed that

individuals select motorcycles that closely align with their personality traits and lifestyle choices.

Personality traits and aesthetic choice

For example, participants exhibiting traits associated with adventure-seeking or risk-taking behaviours are likely to be attracted to motorcycles designed for high-performance and speed, such as sportbikes. These motorcycles often present a sleek and aggressive aesthetic appeal. FP1 stated that: *"I'm a thrill-seeker, always up for an adventure, so a sportsbike with its sleek and aggressive looks just fits who I am. Every time I ride, I'm not just moving from point A to point B; I'm also expressing a part of my identity."* Conversely, participants (like P3) who value tradition and stability might prefer *cruisers* or classic motorcycles that feature more traditional, timeless designs. This, however, assumes that the emotive concern of the individuals exhibiting traits associated with adventure-seeking is to own a sportsbike, while an aggressive motorcycle does not satisfy the emotive concerns of individuals who prefer *cruisers* or classic motorcycles. The differentiation in the emotional experiences of the two focus group participants can be attributed to the differentiation in the appraisal of the motorbike with respect to individual concerns (Bakshi & Gupta, 2014).

Interplay between motorcycle's aesthetics and rider's persona

Survey data offer further insights into the interplay between the expression of the motorcycle and *Study B* respondent's personality. Figure 3.6 distinctly reveals that riders of high-powered motorcycles predominantly prioritise performance when making their purchase decisions. Conversely, aesthetics assumes a position of primary importance for those who own mid-powered motorcycles. For owners of both mid and low-powered motorcycles, ergonomic considerations are the determining factors in their choices. Statistical validation was sought through the Kruskal Wallis Test, which indicates that these observed preferences can indeed be generalised across the population with a significant p-value of 0.003.

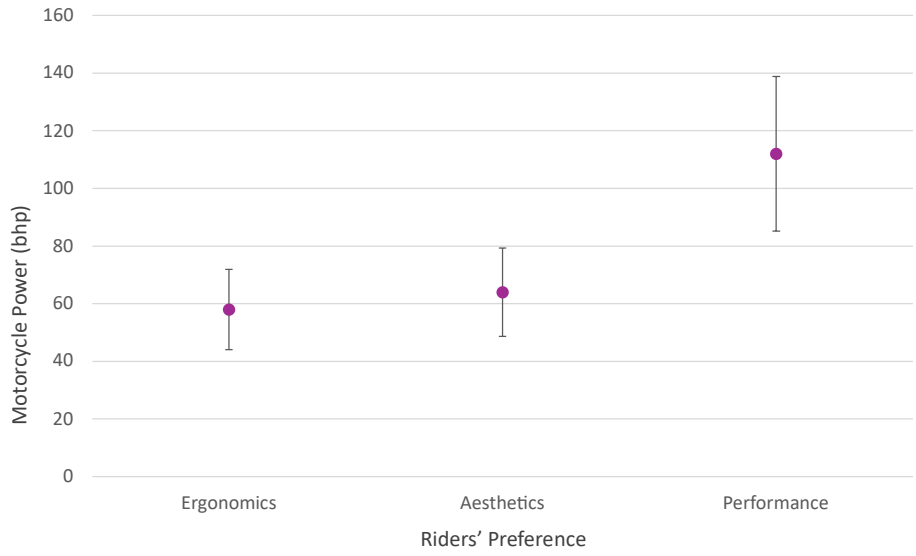


Figure 3.6 – Motorcycle power with riders' preference

Customisation to reflect identity

Customisation options, ranging from paintwork and detailing, further enable motorcycle owners to adapt their vehicles to resonate more congruently with their personal aesthetic preferences and, by implication, their psychological traits.

ST4 – Human diversity: Individual differences and group homogeneity between motorcycle users

Challenges in human ergonomic diversity

The theme of human diversity, both between individuals and across distinct groups, emerged as a subject in the focus group discussions. The human body is incredibly diverse (Pheasant & Haslegrave, 2006), and the physical abilities of human beings vary according to their physical dimensions. According to Bakshi & Gupta (2014), the challenge is to *"create products that meet the ergonomic needs of a broad range of users"*. Given that static measures exhibit substantial variations across individuals, the concept of an *'average'* human becomes elusive, and that compromises must be made (Bakshi & Gupta, 2014).

Challenges in human aesthetic-derived emotional diversity

This diversity extends beyond physical dimensions; emotional responses also vary. Designing products that cater to different emotional states can also be challenging. Focus group participant FP4 stated that: "*individuals may have different emotional responses to the same motorcycle"*, where this difference may be primarily due to the

distinct concerns of riders (Hekkert & Desmet, 2002). Such emotional diversity makes it difficult for a product to elicit the desired emotional reaction across different users, and as highlighted by Gross (2015), when designing products, it is important to consider emotional diversity that cater for different individuals and user groups (Gross, 2015).

Group dynamics

Group dynamics add another layer of complexity. Five *Study A* participants observed that individuals frequently cluster into motorcycle user groups based on shared attributes such as aesthetic preferences, lifestyle choices, or personality traits. These clusters, while relatively homogeneous internally, may demonstrate considerable diversity when compared to other groups. This phenomenon was particularly visible whilst conducting the survey, where motorcycle riders who shared similar aesthetic styles were observed to cluster together.

Aesthetic preferences are not universally shared but are often deeply rooted in cultural contexts. For example, the minimalist, sleek design preferred in some Western countries may contrast sharply with the ornate and vibrant preferences in certain Eastern cultures (Bao et al., 2016). Consequently, what may be regarded as aesthetically pleasing in one country may not evoke the same emotional response in another, posing additional challenges for product designers.

ST5 – Aesthetic trends

Aesthetics, a phenomenon that changes over time

The fluid nature of aesthetics is a multi-faceted phenomenon that has various implications on product design. As highlighted in the previous sub-theme (ST4), individuals often cluster in groups based on shared aesthetic preferences. However, even within these relatively homogeneous groups, aesthetic preferences are not static but are continually shaped and reshaped by an array of factors that change

over time. The user seeks products that are similar in style to the norm, yet are also fresh and creative (Schifferstein & Hekkert, 2011).

Aesthetic trends are ephemeral in nature, often subject to the crazes of fashion cycles, technological advancements, and social changes. As trends evolve, so do the emotional responses they evoke. What was once seen as modern may be considered dated or even retro in a relatively short span of time. This poses challenges for product's long-term appeal like motorcycles, where the aesthetic choices made at the time of purchase may not align with future aesthetic trends.

Shifting emotional engagement

The ever-changing nature of aesthetic preferences has a direct impact on emotional engagement with products. For example, focus group FP7 highlighted that: *"A product designed in line with a current trend might evoke feelings of excitement, relevance, or social belonging. However, as trends shift, the emotional impact of the same design could diminish or even become negative, eliciting feelings of obsolescence or detachment."*

ST6 – Prioritising product design elements (PDEs) in motorcycles

Not every PDE demands equal attention

In examining motorcycles from a macro-view, the analysis is relatively straightforward (Chandra, 2018). However, when delving into the detailed product structure of motorcycles one transitions into a more intricate level. At this level there is an extensive array of motorcycle product design elements (PDEs), and countless possibilities (variants) associated with each element, which influence motorcycles' ergonomics and induced emotions (Chandra, 2018). Nevertheless, not every component demands equal attention, a sentiment echoed by three *Study A* participants. While every constituent of a motorcycle contributes to its holistic essence, the magnitude of their influence varies considerably.

Ergonomic PDEs influencing rider interaction

These are motorcycle elements with which the user interacts most frequently and directly. According to FP8, PDEs of the motorcycle that

the rider interacts with most frequently are: *"The handlebars, seat, and foot pegs. These elements are also important from an ergonomic perspective."* These elements need the most attention because: *"They significantly affect the rider's comfort or fatigue, safety, and behavioural emotion and allow optimal control"* (FP5).

Aesthetic PDEs influencing rider emotions

Aesthetically, PDEs that are most visible or represent the brand's identity become crucial. The shape and design of the fuel tank, the design of the headlight, or the branding on the motorcycle can significantly influence a customer's perception and purchase decision. Participant FP4 specified that: *"The fuel tank is a dominant visual element on most motorcycles. Its shape and design often dictate the lines and flow of the motorcycle, influencing the overall design language."* Spoke patterns, rim designs, and even tire types can change the character of a motorcycle. For instance, the iconic design of Harley Davidson motorcycles evokes a sense of tradition and rebellion (Jolanta, 2015). The headlamp and tail lamp are the *"eyes and face"* of a motorcycle. Their design can influence whether a motorcycle looks retro, futuristic, aggressive, or friendly.

3.3.2 Lack in Current Motorcycle Design Solutions with respect to $hf_{E\text{-}AE\text{-}P}$

ST7 – Post-purchase motorcycle modifications: Motivations and impact

Modifications to address design deficiencies

According to FP7 and FP8, riders often carry out post-purchase modifications to their motorcycle, either for ergonomic or aesthetic purposes. These alterations can be derived from numerous motivations, from instilling individual characteristics, functional adaptations, market variations or evolving user requirements. However, a consensus within the majority of focus group participants (75%) suggests that these modifications predominantly act as compensations for perceived deficiencies in the original motorcycle design. One participant, FP4, commented that: *"I've noticed that many*

fellow riders, including myself, are tweaking certain parts of the motorcycle, especially ergonomic elements like the handlebars, seats, or foot pegs. I can't help but wonder if the original design really captures the comfort needs of people like me and others", while another (FP2) argued that: *"I have seen many riders customising the same motorcycle aesthetically. This makes me think that the original design didn't resonate as much as it should have."*

Modifications to address accident tendencies

Interestingly, an evaluation of accident types, as represented in Figure 3.7, hints at a correlation between post-purchase motorcycle adjustments and accident tendencies. Although there is a noticeable increase in accidents attributed to reckless driving post-modification, this statement cannot be generalised as the p-value achieved is 0.058, which is higher than the 0.05 criterion level. Such modifications predominantly stem from riders' personal preferences, implying the unlikelihood of deliberate motorcycle alterations to increase the chance of accidents. On the other hand, post-purchase modifications on the motorcycle significantly (p=0.000) decrease accidents which occur due to loss of control. In this case this is an indicator that motorcycle coming out from the factory lack ergonomic design solutions.

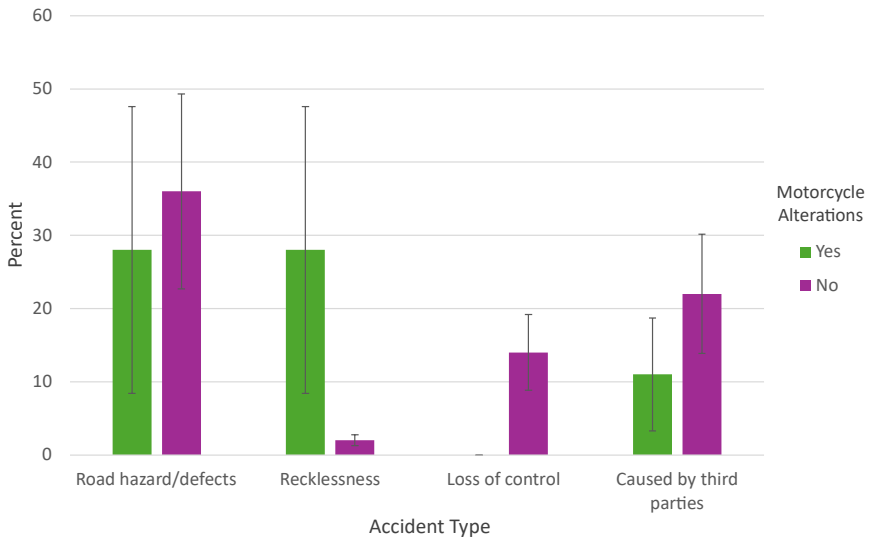


Figure 3.7 – Motorcycle accident types with alterations to riders' motorcycles

Furthermore, the results depicted in Figure 3.8 suggest that survey respondents who prioritise comfort-driven alterations (such as,

adjusting the handlebar, seat, lowering of motorcycle, etc.) display decreased accident tendencies. Conversely, engine modifications aiming to augment performance appear to elevate accident risks. Although these observations are visually true, a Kruskal Wallis test indicates that these observations are not significant (p=0.210).

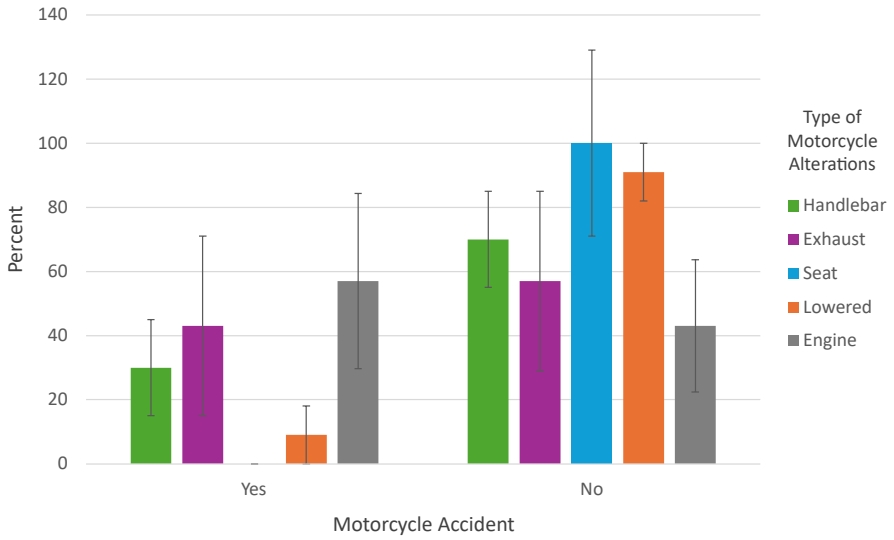


Figure 3.8 – Motorcycle accidents with alteration types

Modifications to improve ergonomics

Figure 3.9 accentuates that the principal reason (50% of respondents) of carrying alterations to the motorcycle is to improve the respondents' posture and reduce ergonomic discomforts, a sentiment confirmed as statistically significant (Kruskal Wallis test, p=0.00). While performance enhancements and aesthetic upgrades are motivators for motorcycle modifications, their prevalence, at 22%, is low compared to ergonomic concerns. This observation is an indicator of the diverse needs, preferences, and changing circumstances of users. The results illustrated in Figure 3.9 are also in agreement with the qualitative analysis, where the increase in alterations to improve ergonomics means that focus group participants are not fully satisfied with the configuration the motorcycle comes in, when purchased.

Performance-driven modifications

Furthermore, the results shown in Figure 3.10 indicate that performance-driven alterations escalate accident propensities from 40% to 60%. In contrast, modifications emphasising safety, comfort, and aesthetics appear to limit accident tendencies.

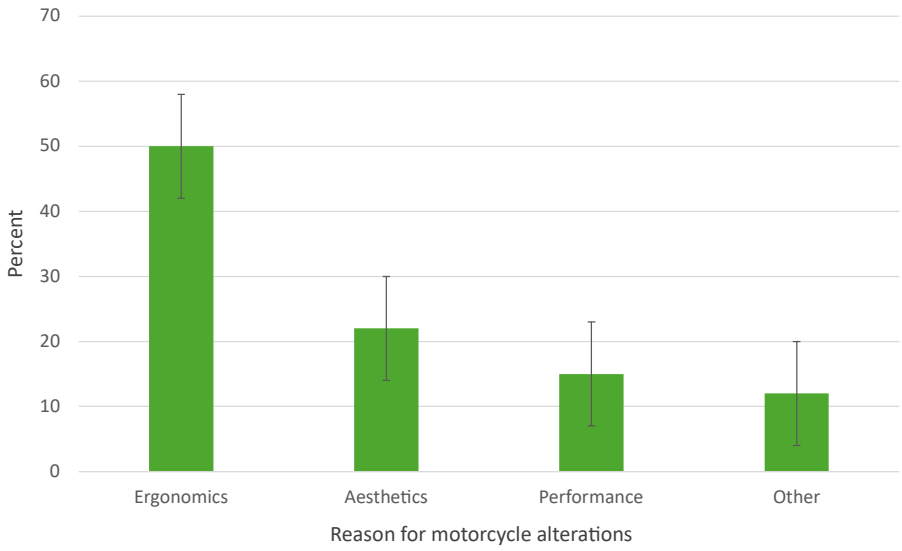


Figure 3.9 – Riders' reasons for making alterations to their motorcycles

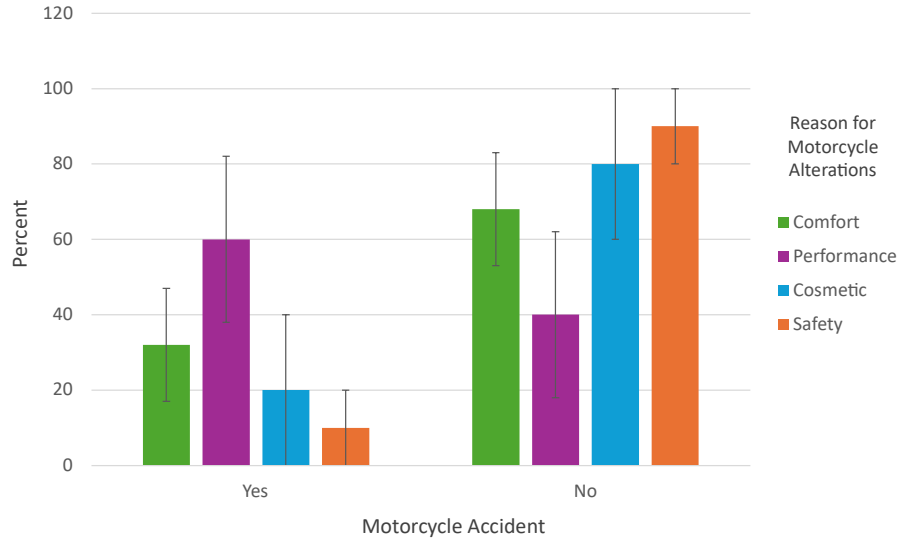


Figure 3.10 – Accidents with riders' reason for making alterations

ST8 – Ergonomic discomforts: Consequences of non-ergonomic oriented design

Riders' ergonomics-derived safety concerns

The motorcycle, as an artefact, inherently presents ergonomic constraints, riding comfort is relevant to the physical fit and adopted riding posture (Amrutkar & Rajhan, 2011). During the focus group session, FP6 highlighted that: "*I had motorcycles where I've personally felt muscle fatigue and pains, which later on developed into an injury. The main reason was because of poor ergonomic posture and uncomfortable seating position.*" In fact, if a rider adopts an unnatural position, the chances of making an error increase by nine times (RoSPA,

2017). This is owed to physical efforts. Stedmon et al. (2012) argue that these scenarios mostly arise because the type of motorcycle dictates who rides it. Stedmon et al. (2012) found that fitting the rider to the motorcycle leads to bad ergonomic consequences.

Body and limbs discomfort manifestation

Surveyed respondents reported ergonomic discomforts manifesting predominantly within their wrists, back, neck, and shoulders, as depicted in Figure 3.11. Back pain emerged as a prevalent complaint among the majority, closely trailed by discomforts in wrists and shoulders. For analytical coherence, the array of reported discomforts, as represented in Figure 3.11, were delineated into four overarching categories:

- *Upper Torso:* Encompassing the neck and shoulders.
- *Arms:* Spanning the arms, elbows, and wrists.
- *Core:* Covering the back, waist, pelvis, and general body fatigue.
- *Legs:* Including the legs, calves, and ankles.

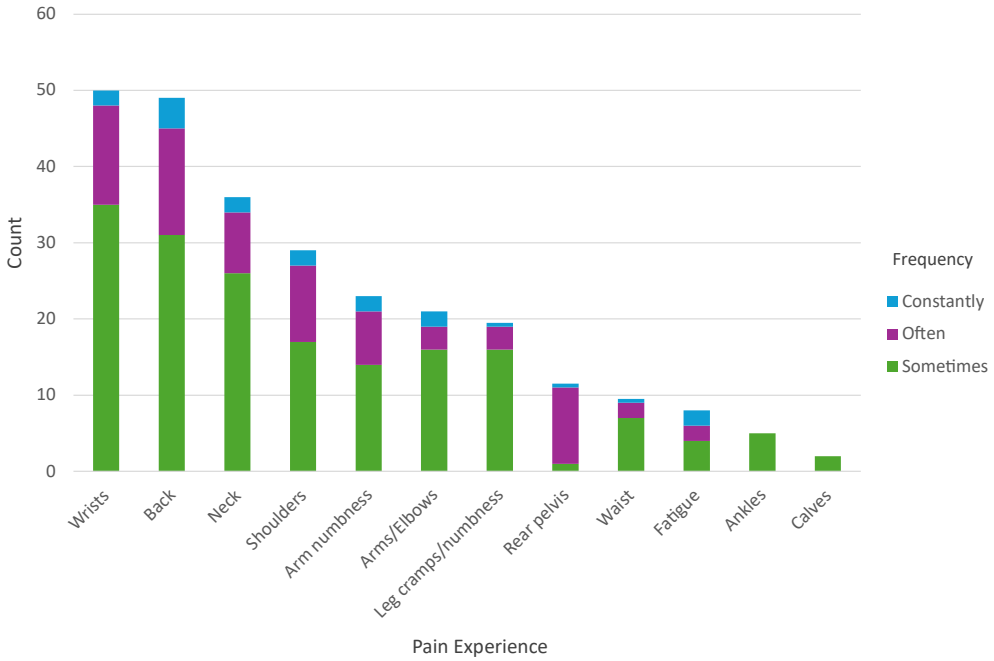


Figure 3.11 – Riders' pain experience and frequency

Motorcycle power's impact on arm discomfort

With a correlation coefficient of 0.242 (moderate correlation), *Study B* respondents are likely to experience ergonomic discomfort or pain/numbness in their arms as the power of the motorcycle increases. A Spearman test reveals that this correlation is significant (p=0.007).

Contrarily, this correlation remained absent for the other limbs that is, upper torso, core and legs.

Ergonomic discomfort with riding frequency

A weak but positive correlation coefficient (0.182) suggests that as respondents increase their motorcycle usage frequency, they invariably experience an increase in ergonomic discomforts and pain/numbness predominantly manifesting within their arms, core, and legs. A Spearman test reveals that these observed correlations are significant ($p<0.05$).

Underlying ergonomic issues related to motorcycle design

A general agreement between the focus group participants and surveyed respondents highlighted that one of the fundamental motorcycle design ergonomic issues is the lack of ergonomic priority. This issue is aptly encapsulated in a statement by FP5: *"Perhaps user testing wasn't diverse enough or the design prioritises other aspects over ergonomics … Designers would need to re-examine their design approach processes to address these concerns."*

ST9 – Consequences of non-aesthetic oriented design

Aesthetic-derived emotion and product attachment complexity

The combination between the product's aesthetic attributes and the emotive expectations of its users can profoundly impact the user experience. Singh (2013) found that the resonance between the aesthetic-derived emotive needs of users and the product's induced emotions leads to stronger product attachment. However, the determination of whether a design will produce a certain degree of aesthetic emotion for customer groups is a complex matter.

Reduced market appeal

To evoke the right emotions is a challenging task (Haug, 2016) and failing in doing so can lead to several consequences. According to FP7: *"For me motorcycles aren't just a simple mode of transport. They represent personal style, freedom, or even status. To me, a design that lacks aesthetic appeal can really diminish the perceived value of the motorcycle.*" Furthermore, motorcycles with strong aesthetic appeal tend to have better resale values. A design that is not aesthetically

appealing might depreciate faster, making it a less attractive long-term investment for consumers.

User experience and attachment

"I've often noticed that for many first-time buyers, the appearance of a motorcycle plays a huge role in deciding whether to make the purchase" (FP7). An unattractive design could deter this segment of the market. Beyond just the look, the aesthetic design can influence how riders feel about their motorcycle, the sense of pride, attachment, or the joy of ownership. As a consequence, non-aesthetic oriented design might not evoke these emotions.

ST10a – Cognitive and human psychology derived consequences

Relation between rider and motorcycle type

All of the focus group participants contended that certain motorcycle types attract certain type of customers or demographics, often aligning with the attitude of the rider, personality, and age. For instance, sportbikes seem to be predominantly favoured by individuals who exhibit *'thrill-seeking'* behaviours.

Personality implications on safety

All participants also agreed that a riders' personalities can significantly influence their safety. Hancock (1995) analysed the demands involved in riding a motorcycle and has indicated that distractions from the primary task can cause dangerous situations. Wickens et al. (1998) defined that the primary task involves in lane keeping and roadway hazard monitoring. Distractions are caused by internal and external influences. Examples of external influences are high-density traffic, filtering (navigating between car lanes during traffic) and junctions. Internal sources of distraction can be split into two, cognitive and motor. Overload of cognitive processing results in a rider's mental fatigue and thus, reducing rider's alertness (Stedmon et al., 2012). As argued by participant FP3 the latter happens when a rider has a lack of experience: *"Teenage motorcyclists having few years of riding experiences are prone to traffic errors and violations of traffic rules. The age and riding experiences have negative correlation with speeding behaviours of riders."* Other cognitive distractions include, personal

concerns, anxiety and lack of attention owing to rider personal characteristics. Motor distractions can manifest themselves through uncomfortable riding positions, physical fatigue, pain or numbness (Hancock et al., 2006).

Experience correlates with motorcycle power choice

Pursuing this line of investigation, the survey results reveal a propensity among riders to opt for motorcycles with greater power as their riding experience increases. A p-value of 0.043 lends statistical significance to this observation. Furthermore, the Spearman test yielded a value of 0.177, suggesting a weak correlation between rider experience and the power of the motorcycle chosen.

ST10b – Accidents as consequences

Relation between accidents and type of motorcycle

Among the *Study A* participants, there was a qualitative consensus (87.5%) suggesting a notable correlation between the type of motorcycles, such as scooter, custom-bikes, racer/sports-bikes, and the occurrence of accidents, with the rider's persona being a salient variable in this association. As with all human beings, motorcycle riders are constantly making decisions. Some of these decisions are taken during the riding, while others are taken outside the riding period. An example of the latter includes the type of journey or type of motorcycle the rider commits to. Some riders reduce or manage risks, while others increase risks, depending on their behaviour and personality (Motorcycle Safety Foundation, 2016).

Experience, behaviour, and accident rates

A rider's road experience is another personal trait that may have an impact on accident occurrence and the severity. Less experienced riders tend to get more overwhelmed and lose their focus from their primary task, while *"experienced riders tend to feel overconfident."* Overconfidence leads to inattention and carelessness (Hancock et al., 2006). Rutter & Quine (1996) found that there was a pattern in behaviour associated with young riders, which resulted in high collision rate. The study showed that this pattern was attributed to risk taking behaviour rather than the level of experience. Riders exhibiting this

behaviour are particularly vulnerable to serious or fatal injuries associated with excessive speed.

Riding experience and accident susceptibility

Substantiating the qualitative findings, Figure 3.12 quantitatively demonstrates the influence of a specific persona attribute, namely riding experience, on motorcycle accidents. An examination of the results in Figure 3.12 leads to the propensity for inexperienced riders to be more frequently implicated in accidents. Although this can be seen visually, the Kruskal Wallis test shows that this variation is not statistically significant (p-value=0.164). Furthermore, survey results show that respondents with minimal experience (0-5 years), as well as those with moderate to slightly extensive experience (15-20 years), exhibit the highest susceptibility to accidents.

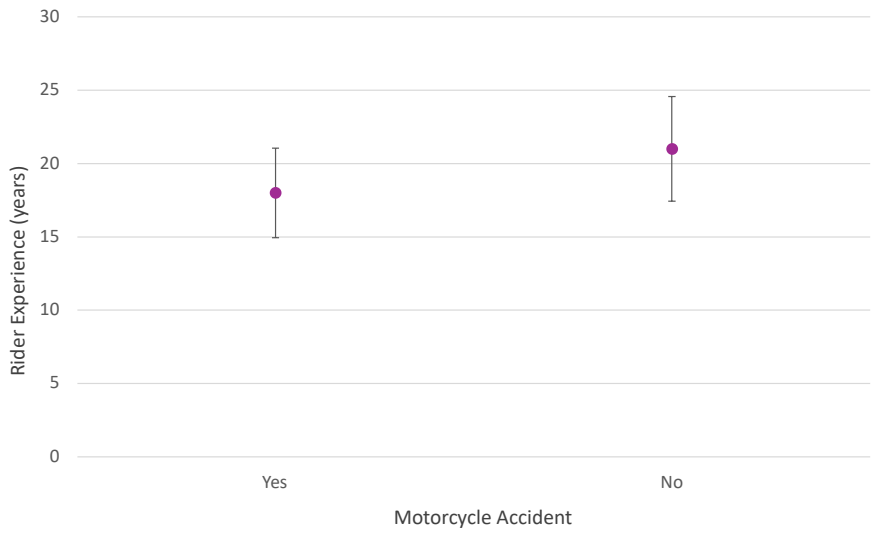


Figure 3.12 – Riders' experience with motorcycle accidents

Accident rates with motorcycle power

Of the surveyed respondents who possess high-powered motorcycles, 40% reported involvement in an accident. This figure is closely mirrored by those with low-powered motorcycles, at 38.8%. Conversely, the mid-power category records the most favourable accident rate, at 22%. Elaborating on this trend, Figure 3.13 delineates the percentage of riders who have experienced an accident in relation to their motorcycles' power output. 36% of all surveyed respondents reported accidents while operating motorcycles with a power range of 0-25 bhp, typically encompassing scooters. This category, albeit with a reduced percentage, is followed closely by the 26-50 bhp range. A further surge

in the accident rate, accounting for 16% of the responses, emerges within the 126-150 bhp bracket, which predominantly includes high-powered motorcycles and sportbikes. The data patterns observed in Figure 3.13 attain statistical significance, as evidenced by the Friedman test yielding a p-value of 0.001 ($p<0.05$).

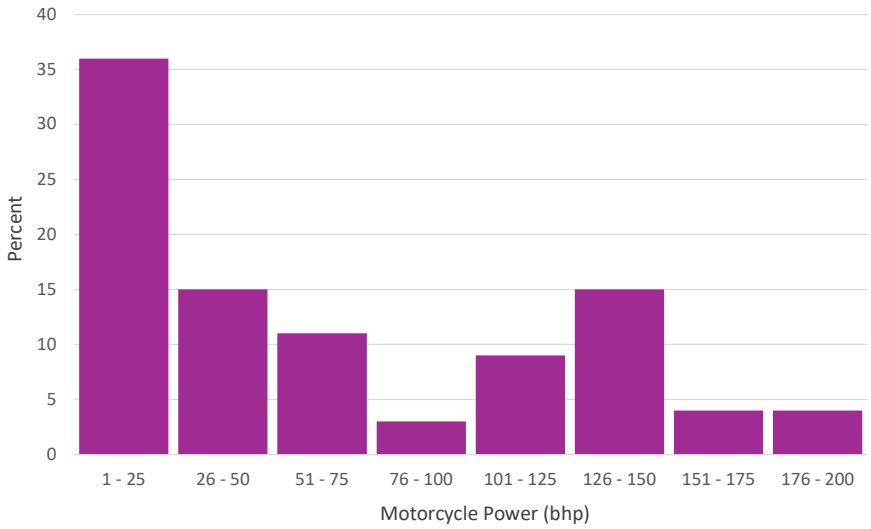


Figure 3.13 – Motorcycle power of riders who were involved in motorcycle accidents

Accident rate: performance vs. comfort seekers

Study B Respondents with a preference for high-performance motorcycles exhibit a susceptibility to accidents, with a notable 78% likelihood of involvement. In contrast, those prioritising ergonomics or aesthetics manifest a substantially diminished accident probability, recorded at 24% and 30%, respectively. A Chi-Squared test indicates that there is statistical difference ($p=0.005$) in accident occurrence, between respondents who prefer performance and those who seek ergonomics or aesthetics. Figure 3.14 suggests that prioritising ergonomic comfort when purchasing a motorcycle emerges as the safest option from the three.

Reckless riding behaviour

Riders who like pure motorcycle performance drive for the thrill and are constantly on the edge. These riders tend to suffer mostly from reckless driving accidents for example, over speeding (45.5% of respondents). In contrast, opting for a comfortable motorcycle suggests a reduced likelihood of loss of control. Figure 3.15 shows that no respondent, who seek comfort, has ever had an accident due to reckless driving. While not as pronounced as among respondents who

prioritise performance, those who seek aesthetics exhibit a moderately elevated recklessness (12.9% of respondents) compared to those who seek ergonomics. While the differences are not conclusively significant, respondents prioritising ergonomics tend to fare slightly better in loss-of-control situations compared to those focused on aesthetics.

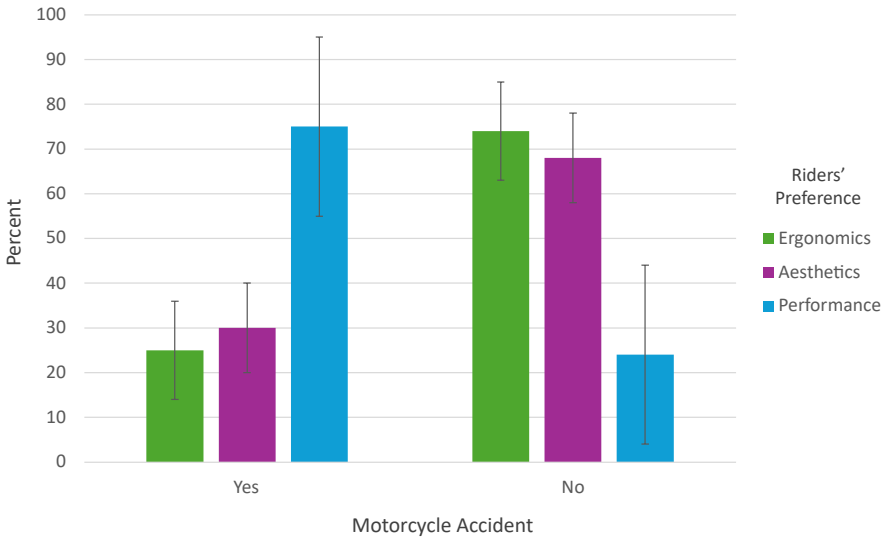


Figure 3.14 – Motorcycle accidents with riders' preference

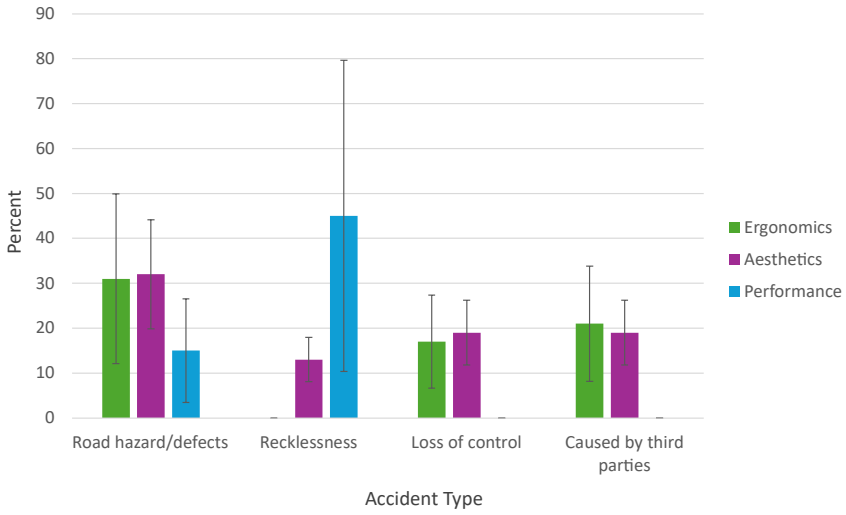


Figure 3.15 – Motorcycle accident types with riders' preference

Persona impact on design and safety

The persona constitutes a significant factor to consider during the product design process. As observed, the persona directly influences the accident rate, a primary safety concern in motorcycles. Harnessing this knowledge can prove invaluable assistance to designers in order to develop safer motorcycles. As a way forward to the current gap, a focus group participant (FP5) asserted that: *"I firmly believe that while design can go a long way in reducing risks, it can't wholly eliminate them.*

Personal behaviours and choices will always play a significant role in overall safety. However, by enhancing motorcycle designs, like incorporating features that address psychological vulnerabilities, and combine it with rider education and awareness, we truly stand a chance at a more comprehensive approach to ensuring the safety of riders."

3.3.3 $hf_{E\text{-}AE\text{-}P}$ Requirements for DOP from the Perspective of Motorcycle Users

ST11 – Emphasis on ergonomic-related design elements

'Rider triangle'

Building upon *sub-theme ST6*, all of the focus group participants and majority of survey respondents (91%) highlighted that from an ergonomics perspective, at the forefront is the *'rider triangle'*, a concept emphasising three pivotal features. As illustrated in Figure 3.16, the rider triangle is an area enclosed between the seating position *(point A)*, the projection of the handlebars *(point B)* and of the foot pegs *(point C)* on the plane of symmetry (Cucinotta et al., 2019).

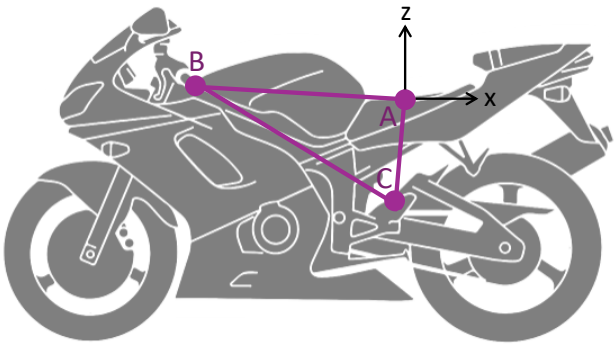


Figure 3.16 – The reference system and rider triangle

The focus group participants and survey respondents pinpointed the following PDEs as central to shaping the rider triangle:

Seat design

- Adjustability in terms of lateral movement and height.
- Tilt functionality, affecting the user's perception of balance and stability.
- Shape and padding specifications, encompassing both contour (flat or cushioned) and material properties (grippy to slippery).

An ergonomically designed seat can reduce pressure points and distribute the rider's weight evenly.

Handlebars

- Height, reach (defined as *'pull back'* distance) adjustments of the handlebars affect the rider's posture, arm comfort, and ability to control the motorcycle.
- Considerations of the *'rake angle'*, or handlebar pitch angle, *'twist angle'* and *'span'* for throttle brake, and clutch reach.

Levers

- The reach, size, and squeeze adjustability of the brake and clutch levers which can have an impact on hand comfort and control efficiency.
- Material composition and tactile sensation they offer.

Footpegs

- Positional considerations such as, height, reach and span.
- The gear shifter and rear brake lever properties, which can influence leg comfort and the ease with which a rider can change gears and brake.

Impact of the 'rider triangle'

These three points can significantly affect the weight distribution of a particular rider (being on the spine or being on the wrists), as well as the position one take on the motorcycle (relaxed reach, stretched reach or crammed). The higher the rider's arms are, the higher the fatigue, due to less blood circulation. This leads to numbness, freezing and loss of grip control. In this regard focus group participant, FP8, commented that: *"A potential solution could leverage this feature, by extracting ergonomic properties of motorcycles and in conjunction with the rider's anthropometry, it suggests the ideal motorcycle ergonomic set-up."*

Role of rider's BMI and weight

According to FP5 and FP8, another important factor to consider is the *Basal Metabolic Index* (BMI) of a motorcycle rider. This is an indicator of the rider's regular lifestyle and as such is an ergonomic-persona parameter. The force being exerted by the motorcyclist during riding increases with flexion angle of wrist irrespective of rider's weight. Nonetheless, Arunachalam et al. (2019) found out that lighter riders

(around 70 kg) exhibit a less pronounced angular shift compared to their heavier counterparts (approximately 100 kg). Along with the BMI, the weight of the rider is another important factor for determining postural comfort of the rider according to FP7.

ST12 – Emphasis on aesthetic-related design elements

Key influential aesthetic design elements

Continuing on *sub-theme ST6*, all of the focus group participants emphasised that like any form of art or design, aesthetics is subjective. However, certain product design elements (PDEs) often stand out as being particularly in determining the visual design of a motorcycle. According to the participants, the following delineates key motorcycle PDEs that influence riders' aesthetic-derived emotions:

Overall form

- The basic shape and outline of a motorcycle can give it a distinctive identity. For instance, the streamlined profile of a sportsbike differs significantly from the rugged appearance of a dirt-bike or the classic form of a *cruiser*.

Colour and finish

- The colour, scheme and surface finish can drastically affect the motorcycle's visual appearance. Special finishes, such as matte, metallic, or pearlescent, can add an extra layer of sophistication.

Fuel tank design

- The fuel tank is often a focal point and can be sculpted in various shapes and sizes, sometimes even featuring intricate artwork or decals.

Seat design

- The design, material, and stitching of the seat contribute not only to comfort but also to the overall look of the bike. A leather seat with detailed stitching can provide a vintage or luxury feel.

Frame and chassis

- The structure of the motorcycle, especially if it is exposed, plays a huge role in aesthetics. Some prefer the raw, industrial look of an exposed frame, while others appreciate a more covered, sleek design.

Wheels and tires

- The design and material of the wheels, as well as the tread pattern and width of the tires, can greatly influence a motorcycle's visual aesthetics.

Headlight and taillight design

- The shape, size, and illumination style (e.g., LED, halogen) can dramatically change the front and rear profiles of the motorcycle.

Exhaust system

- Beyond its auditory contribution, the design, position, and finish (e.g., chrome vs. brushed metal) of the exhaust system can be a significant aesthetic feature.

ST13 – Incorporation of aesthetic trends

Aesthetic trends to ensure market relevance

Tying with *sub-theme ST5*, it was noted that motorcycles, like all products, are influenced by aesthetic trends. The majority of focus group participants (87.5%) specifically requested to *"consider diverse aesthetic trends."* They argued that staying updated with aesthetic trends can give the product a competitive edge in the market, setting it apart from other offerings which might not be as in tune with current design preferences. Furthermore, incorporating contemporary design elements ensures that the product remains relevant in the market, preventing it from appearing outdated or obsolete soon after its release. *"By incorporating the design with current aesthetic trends, the motorcycle is more likely to appeal to a broader audience and enjoy increased sales"* (FP1).

ST14 – Finding a balance

Balancing aesthetics with ergonomic to reach more customers

A successful motorcycle from the eyes of all *Study A*'s participants is one which has the ability to cater for the majority of requirements needed by the majority of riders. In fact, FP7 argued that: *"To cater for many people, you need to optimise ergonomics and aesthetics. In that case you need to find a balance as a way forward to satisfy everybody's needs. While doing this you need to keep the persona in mind for safety*

reasons, consider how the motorcycle will be used and in which scenario."

Form follows function. Or vice-versa?

A classic design principle is form follows function. However, in the modern world, this principle has evolved (Norman, 2013). While functionality (in this case ergonomics) is essential, the form (aesthetics) cannot be an afterthought. In the context of motorcycles, this means that while the artefact must be comfortable, it should also evoke emotions and express a certain style or attitude.

Ergonomics affect emotions

Design is not only concerned with appearance and the aesthetic nature of products; it also recognises the importance of the relationship between the motorcycle and the user, and its impact on the latter in terms of comfort, well-being, and safety. Being ergonomically comfortable and safe, as well as safeguarding well-being, will in turn elicit positive emotions to riders. Moreover, a motorcycle's design can stir emotions, evoke memories, or resonate with cultural or personal aesthetics. Yet, if the design, however striking, results in discomfort during rides, its aesthetic-derived emotions diminish rapidly. The challenge is to design a motorcycle that captivates at first glance and remains comfortable after hours of riding.

ST15 – Listen to users during the motorcycle design process

Voice of the customer

All of the focus group participants emphasised the necessity for designers to listen to customers during the design process of new motorcycles. Incorporating the *Voice of the Customer* (VOC) into the design process is paramount, acting as the cornerstone between business success and customer satisfaction.

Gender anthropometric inclusion

According to FP6, it is crucial to utilise country-specific anthropometric data of motorcycle riders, encompassing both genders, when tailoring designs for a targeted user demographic. Arunachalam et al. (2019) discovered that an anthropometric database, considering both male and female motorcycle riders, is largely absent during design stages. A

majority of countries worldwide lack these specialised databases. Moreover, utilising generic anthropometric data as a representative of specific demographic might pose significant implications (Arunachalam et al., 2019).

Importance of user-centred design in today's market

According to focus group participant FP4, in an age where products and services thrive, being user-centric can differentiate a company from its competitors. Listening to the VOC ensures that products are designed with the user's needs and preferences in mind. Incorporating the VOC ensures that design efforts are not carried out in a vacuum but are aligned with the very people who will use and benefit from the product. It bridges the gap between businesses and users, leading to products that truly resonate and fulfil market needs.

3.4 Limitations of the Study

Study limitations

The findings drawn from these investigations should be taken in the context of the subsequent limitations:

Limitations of *Study A*

Number of focus group sessions

A common approach is to start with two focus group sessions, analyse the outcomes thereof, and subsequently determining the necessity for additional sessions (Krueger & Casey, 2014). Multiple focus group sessions are frequently advocated to validate the consistency of findings and capture a broader range of perspectives (Krueger & Casey, 2014). This can help in identifying patterns or commonalities in feedback. This study did not adhere to this guideline, as only a single focus group session was conducted.

Mitigating the one focus group session limitation

However, to mitigate this limitation, the focus group was not the exclusive method employed. It was complemented with a survey study to harness a broader spectrum of opinions, thereby facilitating a comparison between the two methods. As delineated in Section 3.2 and congruent with Creswell & Plano Clark's (2017) recommendations,

the focus group session was instrumental in formulating the questionnaire carried out in *Study B*.

Size of focus group

Moreover, the session included eight participants. According to Morgan (1997), a typical focus group should comprise between 6-10 participants. With fewer participants, it may be difficult to sustain a discussion; with more, it may be challenging to control the discussion. Guest et al. (2006) argued that with just six participants most basic elements of themes are discovered and therefore, addressing approximately 80% of the challenges and requirements. This focus group session extended beyond the recommended duration (Krueger & Casey, 2014); primarily to ensure comprehensive exploration, given the limitation of the session, and secondly due to the diverse participants' backgrounds and their profound attachment to the subject.

Subjectivity

Thematic analyses inherently involve a degree of subjectivity, as the researcher must interpret the speaker's intentions. To attenuate this influence, recordings were transcribed, read multiple times and codes were themed by another researcher (as outlined in Section 3.2.1) to consider a multiplicity of perspectives. Nonetheless, the *Kappa index* for this study was 0.78 indicating a good level of agreement between the raters and, consequently, a robust qualitative reliability (IRR).

Limitations of *Study B*

Sampling size

Given that each individual survey session spanned approximately 12 minutes, the research was limited to 133 participants. This number does not holistically represent the entirety of the local Maltese riders. As such, with a 95% level of confidence there is a margin of error of +/- 8.5% on the interpretation of quantitative results.

Sampling method

Additionally, due to sampling by convenience, riders were recruited from habitual meeting points rather than employing a nation-wide random sample, a limitation that might have inadvertently introduced

selection bias. One reason for sampling by convenience was the unavailability of local motorcycle riders' database. Nonetheless, challenges and $hf_{E\text{-}AE\text{-}P}$ requirements for DOP were consistent with established literature (Chapter 2) and the findings from the focus group.

3.5 Chapter Conclusions

Characteristics of DOPs

In addition to the characteristics presented in Chapter 2 and based on the arguments presented in Section 3.3.1, DOPs in the context of the three human factors are further characterised by:

DOP-C1. (Characteristic 1) A comparable importance between ergonomics and aesthetics, with the latter holding a marginal precedence in general. The importance shifts depending on the case or scenario.

DOP-C2. An influence of the persona on both ergonomic and aesthetic factors, shaping the overall user experience and perception of the product.

DOP-C3. Human diversity, which exists both among individuals and across different demographic groups.

DOP-C4. Various $hf_{E\text{-}AE\text{-}P}$ implications during product utilisation, if not carefully designed.

Requirements of research tertiary users (RTUs)

Complementing these characteristics, feedback from the research tertiary users (*Study A and B* participants) unveiled several pronounced requirements. These requirements serve as salient factors that need to be examined when designing DOPs from $hf_{E\text{-}AE\text{-}P}$ perspective:

RTU-R1. (Requirement 1) Certain ergonomic and aesthetic PDEs take priority over others due to the dual nature.

RTU-R2. Incorporation of the aesthetic trends. This ensures that the product remains contemporary and resonates with the evolving preferences of customers.

RTU-R3. Finding a balance. Essential to reach a wider user base which in turn influences the product's market success.

RTU-R4. Listening to users during the design process of DOPs, as it ensures that the final output aligns closely with user expectations.

Use phase implications

The results obtained from the two studies presented in Section 3.3, together with Chapter 2, lead to the conclusion that $hf_{E\text{-}AE\text{-}P}$ negative implications are experienced during the DOP's use phase. These results also confirm that these consequences are not only dependent on the product's intrinsic dual nature but are also influenced by the persona and human diversity.

$hf_{E\text{-}AE\text{-}P}$ challenges

Hence the reality described in Section 3.3 results in a number $hf_{E\text{-}AE\text{-}P}$ challenges for designers involved in the product design. In order for designers to develop successful DOPs, they need to be aware of the needs of users such that the artefact provides the right and balanced experience during product use. To minimise or avoid $hf_{E\text{-}AE\text{-}P}$ consequences that surface during the utilisation phase, it Is imperative that the design activity of DOP is adequately supported.

Next chapter

Having characterised $hf_{E\text{-}AE\text{-}P}$ and delineated the specific requirements of DOP users (research tertiary users), the subsequent chapter will focus on exploring the realities faced by DOP designers (research primary users).

4 The Need for an Approach to Support the Design of Dual Ontological Products

This chapter looks at the role of designers during DOP development. A qualitative study is demonstrated, as part of the first descriptive study, highlighting the challenges, and requirements for an approach by DOP designers. This is carried out by first presenting the design problem study objectives through Section 4.1. Section 4.2 portrays the qualitative methodology used to understand the design problem. Sections 4.4, 4.5 and 4.6 disclose the qualitative results. Respectively, these are detailed through three main themes: Design process and impact on multi life-phase system, concurrent considerations and $hf_{E\text{-}AE\text{-}P}$ in design, and designers' (research primary users) expectations from an approach. Limitations of the qualitative study are presented in Section 4.7. Section 4.8 presents the approach framework requirements from DOP designers' perspective, while Section 4.9 concludes this chapter.

Involvement of designers in research

Having delved into $hf_{E\text{-}AE\text{-}P}$ and characteristics of DOPs, established through the literature (Chapter 2) and the mixed-methods study presented in Chapter 3, this chapter focuses on understanding the designers', the research primary users' (RPUs') challenges when developing DOPs from $hf_{E\text{-}AE\text{-}P}$ standpoint. The outcome of this chapter will be used to establish the design problem and requirements for the approach framework development in Chapter 8.

4.1 DOP Design Problem Study Objective

Overall aim of study

The overall aim of this investigation is to determine the requirements for, and expectations from an approach framework to support the design of DOPs from $hf_{E\text{-}AE\text{-}P}$ perspective.

The following are the specific objectives of this investigation:

Objective 1 (RPU-O1)

To explore the designers' (RPUs') current DOP design practices.

Objective 2 (RPU-O2)

To understand $hf_{E\text{-}AE\text{-}P}$ related challenges during the design of DOPs.

Objective 3 (RPU-O3) To identify the design stage and activity that designers find most challenging.

Objective 4 (RPU-O4) To ascertain the type of support designers would need, if any.

Objective 5 (RPU-O5) To identify what designers explicitly envisage from a solution which would assist them in DOP design for $hf_{E\text{-}AE\text{-}P}$.

4.2 A Qualitative Methodology to Understand DOP Design Problem

Descriptive study 1 Figure 4.1 illustrates schematically the *first descriptive study,* based on Blessing & Chakrabarti's (2009) DRM. This study (referred to as *Study C*) is carried out to understand DOP design problem from the perspective of $hf_{E\text{-}AE\text{-}P}$.

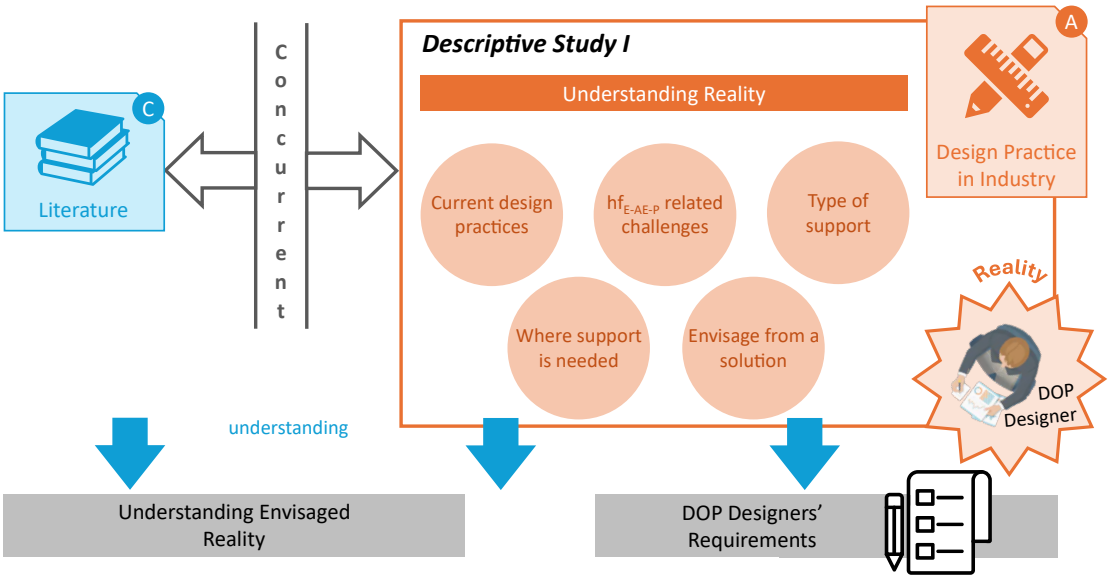


Figure 4.1 – Investigating the design problem

Primary and secondary research methods According to Jørgensen (1992) a study in engineering design research should have two components: the problem base, typically a phenomenon observed in reality, disclosed via a *descriptive study*, accompanied by the theory base. Both components are important (Jørgensen, 1992) as they result in a more holistic understanding of the reality being observed. While the primary component offers direct insights, the secondary component provides context and a broader overview.

Qualitative and quantitative data collection

Difficulties are likely to develop if one chooses exclusively a quantitative approach in a small sample study (Seawright & Gerring, 2008). On the other hand, using a qualitative approach on its own presents challenges in quantifying the observations made (Osborne & Petersen, 2011). Due to such limitations both qualitative and quantitative methods were used. The qualitative part assisting in addressing a range of exploratory questions and uncovering the phenomena relevant to this research (Etz & Arroyo, 2015), whilst the quantitative method offers measurable data and thus outlining the relative importance of the qualitative response. Furthermore, the qualitative analysis will describe what all the participants in the study have in common, as they are experiencing the phenomenon, whilst providing inferences through the quantitative validity (Parry & Kupiec-Teahan, 2010).

4.2.1 Study C Procedure for Understanding the Design Problem

Semi-structure type of DCI

Due to the aforementioned reasons (Section 4.2) a semi-structured interview was used to collect responses from the RPUs, in this case motorcycle designers. The semi-structured DCI combines aspects of structured and open-ended questions. The structured questions are used to obtain *'factual or quantitative'* information, while open-ended questions acquire qualitative explanations and descriptions for the designers' reality being studied (Creswell, 2007).

Structure of semi-structure DCI

The questions were categorised into two main parts (see Figure 4.1). The first set of questions aimed to capture current practices and challenges whilst designing motorcycles from $hf_{E\text{-}AE\text{-}P}$ standpoint (covering objectives RPU-O1 to RPU-O3 listed in Section 4.1). The second part probed designers on what type of support they require which would assist them in DOP design for $hf_{E\text{-}AE\text{-}P}$ (objectives RPU-O4 and RPU-O5).

Procedure of interviews

All interviews were conducted on a one-to-one basis using an online conferencing tool. Interviews lasted between 45 to 90 minutes, as

discussions followed every question to obtain further insights. The semi-structured interview guiding questions used in this study are provided in Appendix C. This was reviewed and approved by the Ethics Committee of the University of Malta (Application ENG 669/2019, part 1b), and informed consent was secured from each participant. Mirroring the approach taken in the studies documented in Chapter 3, a pilot test (Ruel et al., 2016) was conducted ahead of the actual study with designers. This involved in assessing the procedure and making the necessary refinement to the questions with two other researchers.

4.2.2 Qualitative and Quantitative Analysis

Qualitative data analysis method

All interviews were voice recorded and transcribed verbatim for analysis. Key phrases from participants were coded, sorted, and clustered into identified themes by following the procedure of Braun & Clarke (2006) and Vaismoradi & Snelgrove (2019) for thematic analysis. Patterns among these themes were identified using the affinity diagram technique (Otieno, 2023).

Quantitative data analysis method

The quantitative questions utilised were ordinal in nature, adopting a scale ranging from 0 to 3, where 0 signifies *'no priority'*, 1 represents *'low priority'*, 2 indicates 'moderate priority', and 3 denotes *'high priority'*. In case of small sample sizes, achieving statistical significance is challenging since variances are often amplified in limited samples with multiple categories. Consequently, the aforementioned ordinal categories were consolidated into two nominal groups: 0 and 1 were designated as *'no priority or importance'*, whereas 2 and 3 were deemed *'high priority or importance'*. In order to discern any significant disparities between these nominal categories, the test for one proportion method was employed (Sauro & Lewis, 2016).

The identified core themes address the objectives listed in Section 4.1, and the quantitative input from all the participants was used to infer trends among the participants.

4.2.3 Study C Reliability

Inter-rater reliability (IRR) test

In congruence with the thematic analysis approach of the focus group detailed in Section 3.2.1, the inter-rater reliability (IRR) test was employed in this study to gauge the replicability and consistency of two independent researchers while conducting the thematic analysis. The *Cohen's Kappa index* was used to measure the level of agreement, with the same criteria as documented in Section 3.2.1. The *Kappa's index* for this study, carried out with designers, was 0.75. This value suggests a good agreement between the two raters and thus, a good qualitative reliability.

Intra-class correlation (ICC) test

The *intra-class correlation* (ICC) test was employed to evaluate the coherence between the quantitative and qualitative components of the study. The *Cronbach's alpha* was utilised to gauge the validity between these two components. As delineated by Teddlie & Tashakkori (2009), the acceptable alpha values span from 0.70 to 1.0: with 0.7-0.8 indicating acceptable consistency, 0.8-0.95 signifying good consistency, and 0.95-1.0 denoting excellent consistency. The qualitative data was converted into quantitative scores, which corresponded to the frequency of direct citations (from transcripts). Throughout this chapter these will be referred to as (*# refs.)*, where the *#* indicates the frequency of direct participant citation. Both qualitative and quantitative scores were converted into percentages. These percentages served as metric measures of the concept or theme and hence connected to the inter-relatedness of the items within the test. The *Cronbach's alpha* was 0.938, which affirms substantial validity and consistency between the two methods (Tavakol & Dennick, 2011).

4.2.4 Study C Participants

Reason for the selection of participants

The discussion presented in Chapter 2 revealed that DOPs can be exemplified through the motorcycle artefact in this doctoral research, meaning that they have properties attributed to the dual nature. For this reason and because they are most likely to design a product for

riders, motorcycle designers were selected as participants for this study. To anonymise the designers, each participant is given a number and denoted as *D#* (reads as: designer number *#*).

Participants' recruitment

A group of eight motorcycle designers from Europe took part in semi-structured interviews. A convenience sampling was employed for participant recruitment. An internet search was conducted to identify motorcycle design companies. Email addresses were retrieved from these companies' websites. Subsequently, an invitation was sent to each company, outlining the researcher's role and the objective of conducting interviews with motorcycle designers.

From the forty-five invitations disseminated, sixteen responses were received. Of these, eight participants were selected for interviews based on the following inclusion criteria:

- *Affiliation with renowned motorcycle companies*: To ensure adherence to formal design procedures.
- *Engineering graduate*: To confirm familiarity with the design process.
- *A minimum of two years of professional experience*: To maximise the depth of insights, including those derived from prior roles.

Background of participants

Table 4.1 delineates the demographic details of the participants, including their respective occupational backgrounds. The range of their professional experience spanned from 2 to 30 years, with an average of 17 years and a standard deviation of 10 years. All participants have collaborated with leading brands, including *Honda, Yamaha, Suzuki, Triumph, Ducati, Aprilia, MV Agusta, Piaggio (Vespa), Moto Guzzi, KTM, Harley Davidson, and Indian*. Within the industry, all participants created motorcycles that were produced and sold on a large scale. Two of them ventured to establish their own design firms after years of designing for elite motorcycle brands, while the remaining six are presently affiliated with such premium brands. Seven out of the eight

designers mentioned that they have designed motorcycles starting entirely from scratch (or *new product design*), *"from a white piece of paper"* as participant D4 defined it. Additionally, six of these professionals have been integrally involved in the complete motorcycle design process throughout their extensive careers.

Table 4.1 – Background of motorcycle designers

Designation	Highest qualification achieved	Role	Years of Experience	Design type	Design rocess involved in	Own Firm	Country
D1	B. Eng.	Mechanical Engineer	6	New product design	Complete	No	Italy
D2	B. Eng.	Mechanical Vehicular Engineer	14	New product design	Complete	No	Italy
D3	M.Sc.	Product Design Engineer	2	-	Not complete	No	Italy
D4	M.Sc.	CEO & Mechanical Engineer	30	New product design	Complete	Yes	Germany
D5	B. Eng.	General Engineer	11	New product design	Complete	No	Germany
D6	B. Eng.	CEO & Vehicle Design	28	New product design	Complete	Yes	UK
D7	B. Eng.	Vehicle Design	25	New product design	Complete	No	Italy
D8	B. Eng.	General Engineer	20	New product design	Not complete	No	UK

4.3 Understanding the Qualitative Results

Main themes: Understanding designer's challenges and requirements

The main themes, illustrated in Figure 4.2, were identified whilst trying to understand the challenges that designers have during motorcycle design stemming from the dual product nature and $hf_{E\text{-}AE\text{-}P}$. These main themes (MT) are organised into the following three categories:

Main theme 1 (RPU-MT1)

Motorcycle (DOP) design process and the impact on multiple life-phase systems.

Main theme 2 (RPU-MT2)

Concurrent considerations and $hf_{E\text{-}AE\text{-}P}$ in design.

Main theme 3 (RPU-MT3)

RPUs' expectations from an approach supporting DOP (motorcycle) design, from $hf_{E\text{-}AE\text{-}P}$ perspective.

Sub-themes pertaining to main themes

Within each of these main themes, distinct sub-themes (ST) are listed that correlate directly to their overarching subject. The three overarching themes then pave the way for the formulation of the design support framework requirements, as illustrated in Figure 4.2.

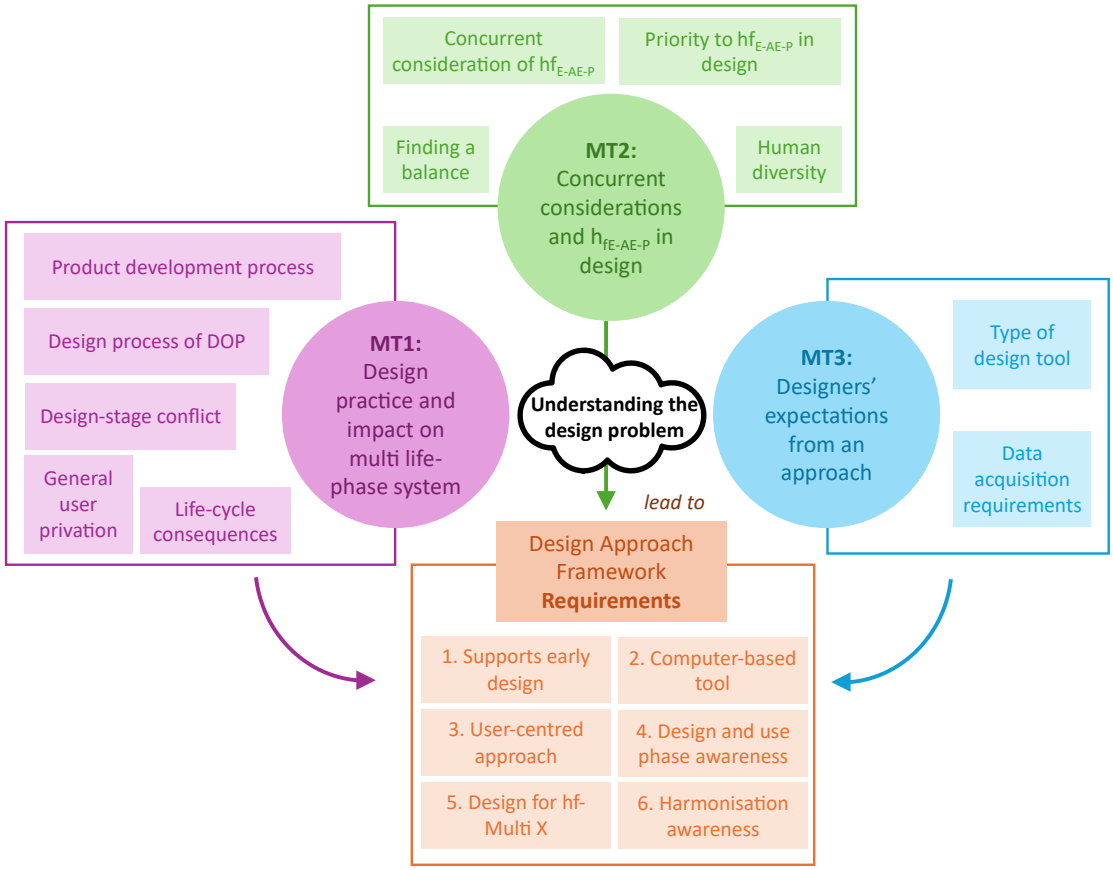


Figure 4.2 – Understanding the design problem through main and sub-themes

Quantitative statistical test methods and criteria

Quantitative findings are provided through descriptive statistics for each question posed to the designers. The mean and standard deviation were derived from the score range of 0 to 3 (detailed in Section 4.2.2). Significance was determined using the one-tailed exact probability test method for the two nominal categories (Sauro & Lewis, 2016). In the forthcoming sections which document quantitative

results (reference to Table 4.2 and Table 4.3), questions highlighted in green denote statistical significance. Amber-highlighted questions signify participants average score above the mean or 1.5, but without statistical significance. Questions in red suggest an average below 1.5, signifying that, designers on average disagreed with the statement.

4.4 Motorcycle (DOP) Design Process and the Impact on Multiple Life-Phase Systems

4.4.1 Product Development Process

Product development

An artefact results from a product development process consisting of a sequence of steps that transform an idea into a commercial product. This process, which is multidisciplinary in nature, is initiated by a company in response to market recognition (Krishnan & Ulrich, 2001). The need for a new product typically arises from customers (Ulrich et al., 2020), and a company will develop it if they believe it is technically feasible and there is a market demand for it.

Product development activities

Product development encompasses various multidisciplinary activities, as depicted in Figure 4.3. These activities span from goal formulation and strategy development during the product planning stage to product design in the strict development stage (Roozenburg & Eekels, 1995). The planning team (Pahl et al., 2007), comprised of marketing and product managers (Ulrich et al., 2020), is responsible for preparing the design brief (Ulrich et al., 2020) or product proposal (Pahl et al., 2007). This document will present the new business idea to the designer, thus triggering the start of the design process (Roozenburg & Eekels, 1995).

The relevance of product planning to designers

As illustrated in Figure 4.3, the designer's role comes into play during the strict development phase (Roozenburg & Eekels, 1995). Nonetheless, Pahl et al. (2007) insist that designers need to understand how the initial list of requirements was generated. This is because they may need to supplement the list with additional requirements or even

"*undertake this phase themselves*", particularly in instances where a structured product planning phase is absent (Ulrich et al., 2020).

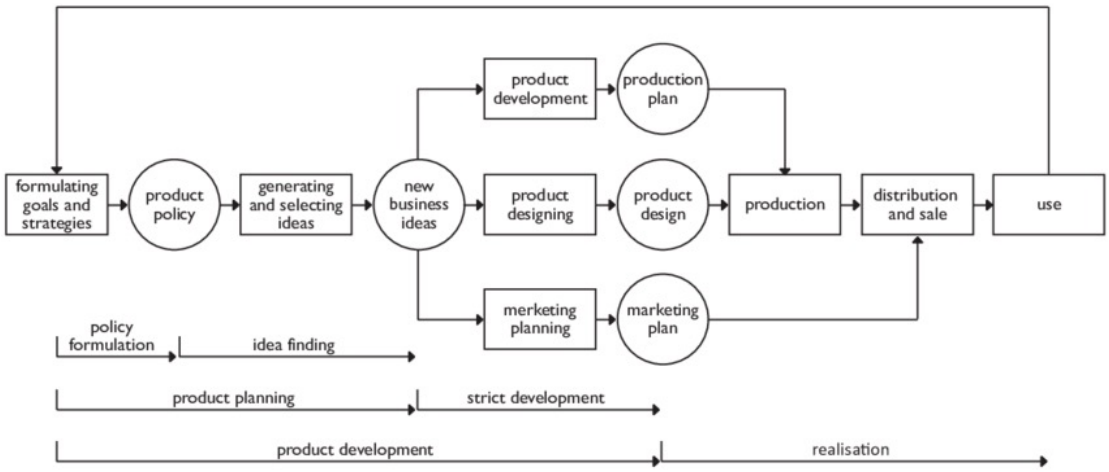


Figure 4.3 – Product development lifetime, sourced from Roozenburg & Eekels (1995)

The central role of design in product development

Design and related terms

Within this doctoral dissertation, the term *'design'* mainly functions as a verb, signifying the process of conceiving an idea and bringing it to life, both functionally and aesthetically (Roozenburg & Eekels, 1995). When employed as a noun, design denotes the resultant artefact, such as motorcycle, encompassing its various organised product design elements (PDEs). Moreover, references to the designer, in this dissertation *'DOP designer'*, encompass the entire collaborative team engaged in product design, including but not limited to industrial designers, electrical and mechanical engineers, and graphic designers. A formal definition of engineering design is provided by Hubka & Eder (1996), articulating design as:

Design according to Hubka & Eder (1996)

> *"A process performed by humans aided by technical means through which information in the form of requirements is converted into information in the form of descriptions of technical systems, such that this technical system meets the requirements of mankind."*

Defining a technical system

Here, a *'technical system'* refers to any human-crafted artefact, also known as an *artificial system* (Simon, 2019). *Technical (or design support tools)* refer to methods, approaches, simulations, prototypes,

and digital tools that could support designers in making well-informed decisions.

Problem-solving process

Hence, design manifests as a problem-solving process where requirements translate into an artefact solution.

4.4.2 Classes of Design

Three classes of design

Brown (1996) categorises design into three distinct classes, as outlined below:

Class 1: Innovative Design

Class 1 encompasses major inventions or the creation of entirely novel products. This category often results in significant advancements, such as the establishment of a new company or the development of a new market. Crucially, neither the underlying knowledge sources nor the problem-solving strategies are predetermined in this context. Consequently, Class 1 design is characterised by a high degree of uncertainty and necessitates substantial creative exploration.

Class 2: Intermediate/Innovative Routine Design

Class 2 pertains to design activities involving substantial innovation, although it is less radical than Class 1. In this category, the knowledge sources are identified in advance, yet the problem-solving strategies remain undetermined. This type of design may emerge during routine activities when new requirements or constraints necessitate the introduction of novel components or techniques. Typically, Class 2 design involves collaboration among multidisciplinary problem solvers and requires a degree of planning.

Class 3: Routine Design

Class 3 focuses on selecting among pre-existing sets of well-understood design alternatives. While the choices at individual stages of the process may appear straightforward, the overall task can exhibit considerable complexity due to the extensive range of possible combinations arising from initial requirements. Unlike Classes 1 and 2, Class 3 design does not involve open-ended exploration or iterative planning. Instead, all design goals, requirements, subcomponents, and functions are fully specified and pre-established. Furthermore, the

knowledge sources (such as available parts or process technology) and problem-solving strategies are also well-defined (Brinkop et al., 1995). One of the problem-soling strategy involves in handling problems similar to previously addressed ones, often leveraging past designs to generate new configurations (Brinkop et al., 1995).

Focus on routine design in this doctoral research

Routine design operates within a structured framework of components and configurations. As outlined in Chapter 2, the genetic product structure facilitates the adaptation of product design elements (PDEs), which collectively form the product and are configured to address varying user needs. This research adopts routine design specifically because it involves products that retain the same underlying structure without pursuing innovative modifications. For instance, in the context of a motorcycle, the design is defined as a configuration comprising an engine-carrying frame with two wheels, steered via a handlebar, and equipped with a saddle for the rider. This approach ensures consistency and reliability in design while focusing on configuring known elements rather than introducing novel innovations.

4.4.3 The Routine Design Process of Motorcycles

Two complementary design models

Design, characterised as a creative, multidisciplinary, and knowledge-intensive process, necessitates a structured approach. The literature on product development design contains an array of models which all shed light on a particular aspect of designing (Roozenburg & Eekels, 1995). This doctoral dissertation explores two complementary design models. The *engineering systematic design* (ESD) model indicate what problems the designer has to solve and what is the best sequence is therein. The *basic design cycle* (BDC) model gives the logical sequence of steps in the problem-solving process within each *stage* of product design. Furthermore, insights derived from the responses of motorcycle designers serve to explain the procedural practices of the DOP design process.

Engineering systematic design (ESD) of motorcycles

The ESD design framework

Pahl et al.'s (2007) engineering systematic design (ESD) framework, which takes a functional decomposition approach to design, is considered the consensus prescriptive model for systematic design in product engineering (Van Boeijen et al., 2014) and is used within the motorcycle design industry employing a stage-gate process. The ESD framework is structured into four design stages: *(planning and) task clarification, concept design, embodiment design, and detail design,* as shown in Figure 4.4. An illustrated example is provided to show how the motorcycle, according to the participants and literature, is currently being developed into a physical artefact.

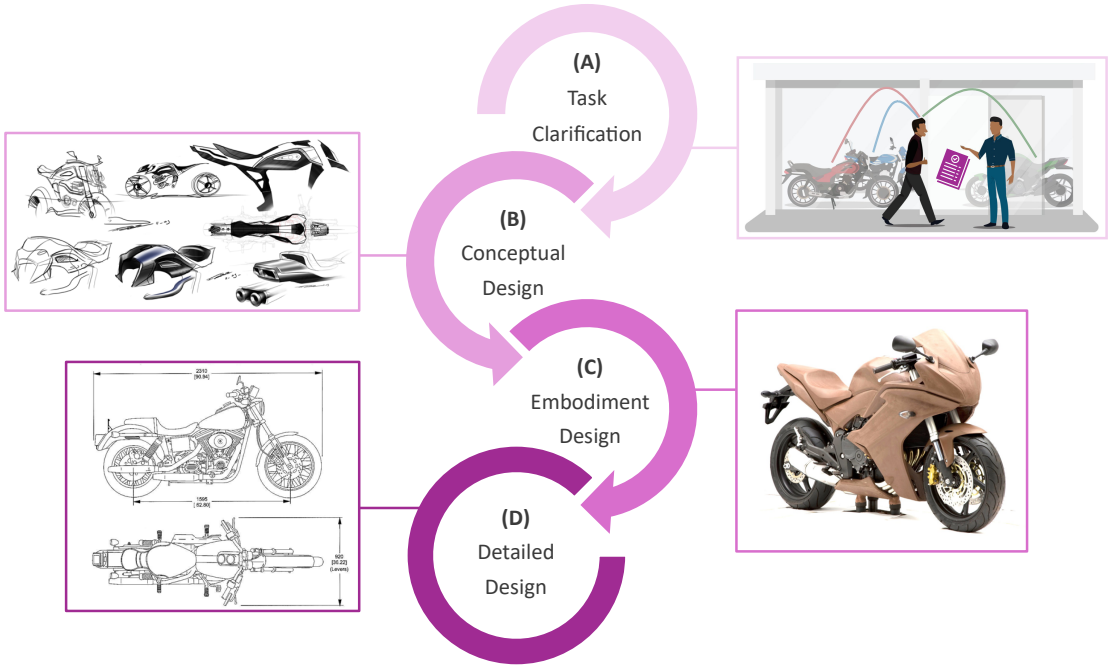


Figure 4.4 – Motorcycle engineering systematic design

Stages in motorcycle design

Task clarification stage

During the task clarification the main aim is to define the product or formalise the problem (Ullman, 2010). In the motorcycle design industry this entails identifying the *target user* (TU). This was substantiated with seven out of the eight (87.5%) interviewed motorcycle designers. In this regard, D1 stated that: *"I always start by asking two questions, for who we are building this motorcycle, and*

where the motorcycle is going to be used." They can be based on real user data *(1 ref.)*, but the majority of participants (75%) stated that these are based on their own experience and assumptions about the target market *(4 refs.)*. Once TUs are identified, target user models are created. This model encapsulates the characteristics of the TUs. It may include information such as demographics, use-case scenario, behavioural specifications and any other requirements which TUs might have (Cocco, 2013).

Conceptual design stage

In the concept routine design stage, the focus is on identifying working motorcycle concepts that can realise and meet the requirements of the TUs *(2 refs.)*. According to the majority of participants *(6 refs.)* the conceptual routine stage is characterised by idea generation through mood boarding and motorcycle sketches. Mood boarding is a visual tool that is widely used in the motorcycling industry. D7 commented that: *"I use the mood boarding method to explore design ideas … Generally, I collate visual motorcycle design elements to convey my ideas for that particular motorcycle."*, while D5 highlighted that: "*At this stage, this method helps me to brainstorm and visualise my ideas without getting bogged down in the details."*

Sketching in conceptual stage

Sketching is another essential tool in the motorcycle industry to ideate the product requirements and to visually communicate the designer's ideas (Mamo, 2018). Depending on the project's focus, the sketches are in the form of *two-dimensional* (2D) drawings if motorcycle ergonomics are of top priority, or illustrations carried out on traditional hand-on-paper renderings or digital artwork if emphasis is made on the motorcycle's aesthetics.

Aesthetics mainly considered in conceptual stage

According to 87.5% of *Study C* participants, aesthetics is mainly considered in the conceptual stage. *"The normal procedure is to start from the aesthetics … This is the first thing that you need to check if it is going to be an aggressive or relaxed or comfortable motorcycle"* (D3). At the end of this stage, one principal solution (product concept) is then chosen from the generated sketches. According to the participants *(3*

refs.) this is carried out by a team which try to match the motorcycle to the target user characteristics, *"generally made through assumptions"* and in other cases *(3 refs.)* they are based on the designer's experience. Many complex variables such as the brand identity, past design solutions, success and failure of motorcycle designs, and market trends often skew the design decisions (Cocco, 2013).

Most important considerations mainly dealt in conceptual stage

Interviewed designers *(4 refs.)* stated that the most important design considerations are dealt with, in the conceptual design stage. This is because in the conceptual design stage one tends to focus the attention on aspects or features that sparks interest the most, as explained well by D6: *"We have completely left the ergonomics in the later stage of the embodiment design, because it is not very important. This is more related to style, so we do not really care about the ergonomics."*

Embodiment design stage

The motorcycle concept selected (principal solution) in the previous stage will be further developed throughout the course of the embodiment stage, where the designer decides on the physical properties and the related function(s) (Pahl et al., 2007).

3D modelling approach in embodiment stage

According to all of the participants, sketches are transformed to *three-dimensional* (3D) form using two methods. D2 reported that: *"It can either take a traditional route through clay modelling, scanning and surface CAD modelling, or by a virtual modelling process where the CAD surface data for production is created without a clay model."* Because of the need to reduce development time and costs, the form/styling model is usually developed in parallel with the engineering functional/mechanical model (Cocco, 2013). Later in this stage the prototypes are evaluated from an economical and technical aspect. By the end of the embodiment design stage the design team will have the definitive layout of the motorcycle. D8 explained that *"We usually get feedback from the users but not too much … The customer comes to try the motorcycle when it is still in the modelling or prototype stage and expresses the views on the handlebar position. For example, he says I want the handlebars a little bit up and then we adjust according to his*

needs. But of course, this will be very late in the design phase of the motorcycle."

Ergonomics mainly considered in embodiment stage

Unlike aesthetics, 62.5% of interviewed participants believed that ergonomic design should be considered in the embodiment stage while the other 37.5% believed that this should be taken into account in conceptual design stage. There were participants who argued that as ergonomics are highly parametrised, they restrain aesthetics and will limit design creativity if considered in the conceptual stage. D4 insisted that: *"In the first stage I do not want to use too much ergonomics because they close our creativity. So, we have to move on with the ergonomics in the second stage."*

Detailed design stage

Details of the motorcycle such as dimensions, surface properties and materials to be used are set in this stage (Mamo, 2018). The final production documentation, such as blueprints of the motorcycle, are created to prepare the design for production.

Design stage assistance required

Support in the conceptual design stage

The participants were asked to select which design stage they required the most assistance in, together with the reason of why. The quantitative result, illustrated in Figure 4.5, shows that seven interviewed designers require assistance mostly in the conceptual stage, while D4 required assistance in both conceptual and embodiment stage: *"I would like to have help in the initial stages where I would be able to sketch a motorcycle really fast and then moving to embodiment using parametric assistance."* Extrapolating this observation to the whole motorcycle design population, there is a 95% chance that more than 74% of all motorcycle designers would like to be assisted in the conceptual design stage.

Designers' challenges in the conceptual stage

The seven designers seek assistance during the conceptual design stage for a variety of reasons, primarily because this stage is critical in determining the direction and viability of the project. D6 stated that:

"The conceptual design stage often involves dealing with ambiguous requirements and uncertain variables. Assistance is needed to navigate through this complexity and define a clear, feasible concept." D1 added that: *"bringing in varied perspectives and expertise can spawn a wider range of innovative ideas and solutions, which is pivotal during the conceptual phase"*, whilst D3 and D5 had a very similar observations: "*Conceptual design is a creative process, but it can be difficult to come up with new ideas. We can be assisted with generating ideas by provided with inspiration or access to a wider range of knowledge."* D7 added: *"We lack assistance to generate new ideas during the brainstorming or helping us with the mood board activity. For example, we could search through a database of existing designs."*

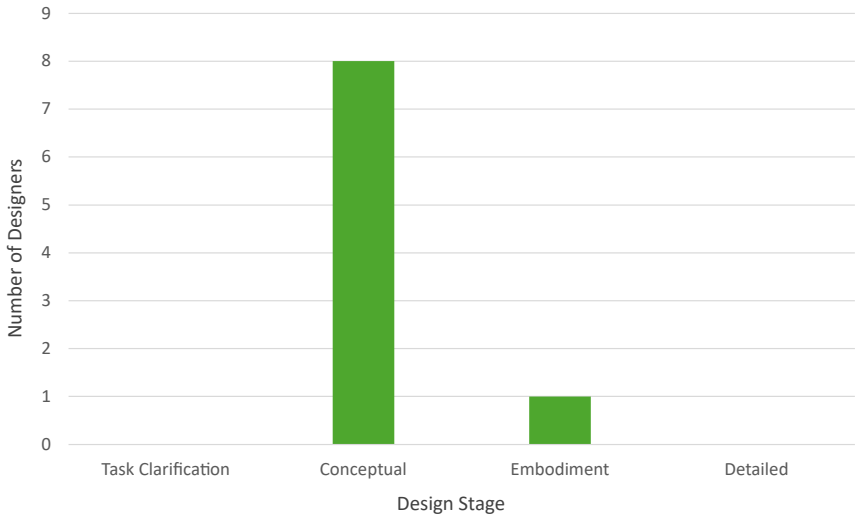


Figure 4.5 – Where do participants require assistance

Overall, the participants looked forward to being offered support at the early stages of the design process to help them make informed decisions, clear doubts, and avoid risks. As a result, such means can speed up the design process because research takes a lot of time.

The basic design cycle (BDC): An activity-based process

The BDC design framework

Designers carry out a number of *activities*, to facilitate the effective completion of each design stage. *Problem analysis, synthesis, simulation, evaluation and decision* are the five activities that form part of Roozenburg & Eekels' (1995) basic design cycle (BDC) model. This

model is presented in Figure 4.6 and may be repeated several times in each design stage before arriving at the final design. Experience, creativity, and external knowledge support each design iteration. Given that overall the participants require assistance in the conceptual stage, the BDC model will be explained by taking this early stage as an example.

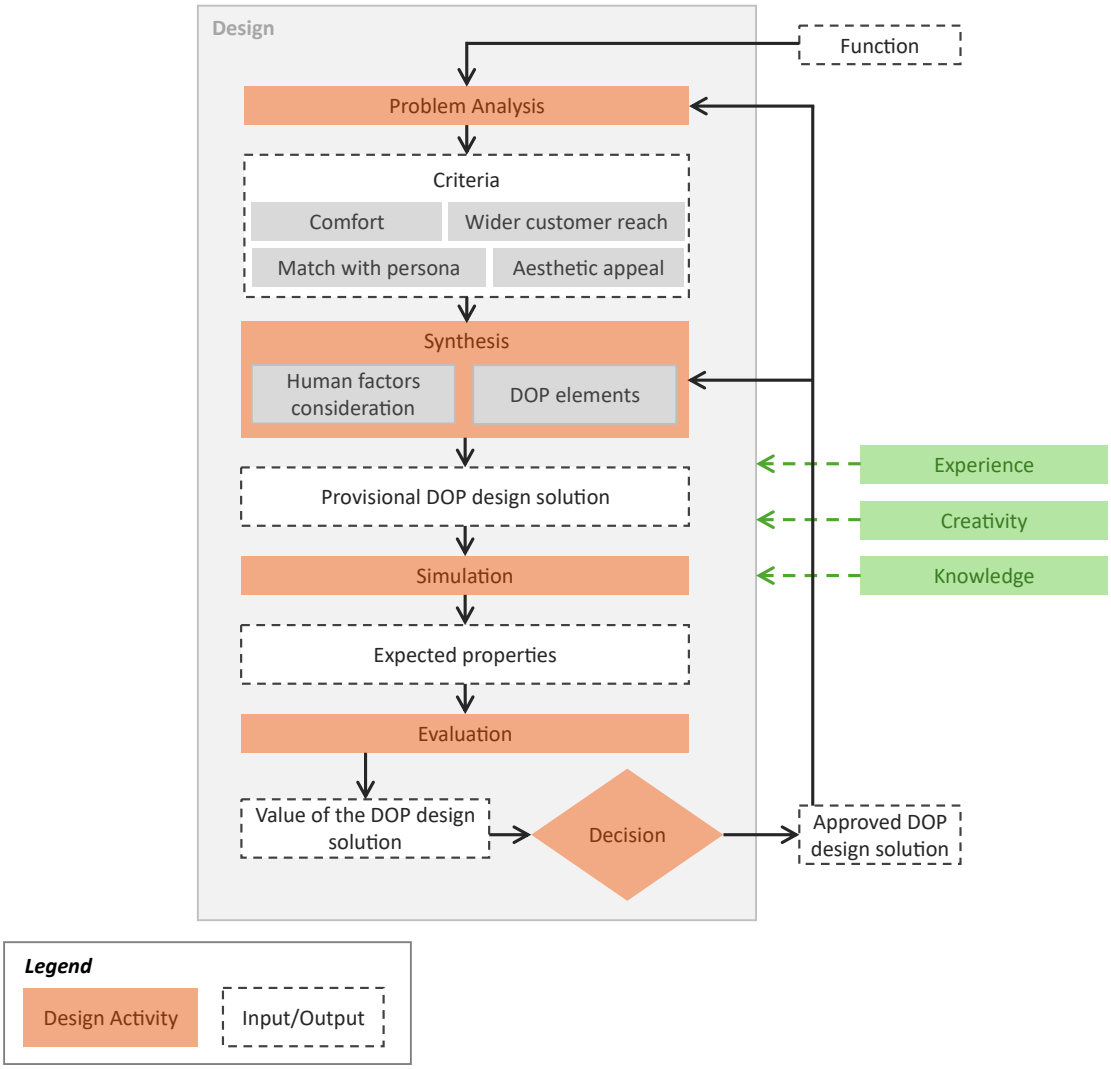


Figure 4.6 – Motorcycle basic conceptual design cycle, adopted from Roozenburg & Eekels (1995)

Problem analysis

The design cycle in the conceptual routine stage begins by the designers analysing the persona of the target user (TU) in conjunction with the use-context. As explained by some of the participants, the general requirement for a motorcycle is to, from $hf_{E\text{-}AE\text{-}P}$ perspective, be at the required comfort, aesthetically appealing and reflects their persona. Another unspoken requirement was the reach of potential customers.

DOP design synthesis

In the synthesis activity the designer develops possible solutions for the motorcycle problems identified in the previous activity. Roozenburg (2002) and Ueda (2001) defined synthesis as the combining and assembling of anything, including ideas, parts, processes and activities into a new whole. According to Blessing (1994), in this activity, the designer finds elements suitable for the solution which are then *'selected'* and *'synthesised'* into possible solutions. In the conceptual routine stage the synthesis activity is manifested by the mood boarding method, as stated by four interviewed designers. It is during synthesis decision-making that the product design elements (PDEs) and their relationships are established. For example, seat position with handlebar height or choosing a particular fuel tank that matches with the evolving motorcycle. Motorcycle designers make selection commitments based on the requirements defined in the previous activity.

Motorcycle conceptual simulation

The next activity of the motorcycle conceptual routine design cycle involves the simulation of the provisional motorcycle solution. In this step, motorcycle designers realise conceptual models of the evolving motorcycle and carry out simulation runs to gain insights into how the actual motorcycle would perform in real-world conditions.

Evaluation

During evaluation of the provisional motorcycle solution, the expected properties are compared to the criteria established during the analysis activity. At the end of this design cycle the designer will decide whether to continue developing the motorcycle design by further elaborating on the provisional solution, or whether to repeat the cycle by trying to modify the motorcycle requirements.

Provisional to final solution

Once the motorcycle designer is satisfied that the motorcycle solution meets the motorcycle requirements and criteria, then the status will be upgraded to that of final motorcycle solution and the project can move on to the embodiment stage.

Support in the synthesis design activity

This doctoral dissertation focuses on decision-making taking place during design synthesis. This was motivated by the fact that this activity occurs during early stages of design. This would enable designers to make changes with relatively less impact on cost and time as the solution is still incomplete and undetailed. Furthermore, five designers explicitly requested to be assisted in the "*brainstorming and mood boarding activity*" at the conceptual design stage.

4.4.4 Multiple Life-Phase Awareness

Early decision-making in product design

Another challenge in the early routine design activity is decision-making, which is crucial to the success of the product development life-cycle (Saad et al., 2013). What is decided in the beginning will be reflected in the subsequent design process. D5 argued that: *"Uncertainty exists in the early design process, making it extremely difficult for us to take decisions. We need to make several assumptions at this point."* Any lack of effective decision-making at an early routine design phase will affect productivity, increase costs and lead time for other stages of the product development life-cycle (Saad et al., 2013; Ulrich et al., 2020).

Design-stage conflict

Conflicts between aesthetics and ergonomics dealt with in different stages

As it transpired from Section 4.4.3, in the conceptual routine design stage, designers are often focused on the motorcycle's aesthetics. For example, a designer might create a conceptual design for a motorcycle with a very low seat height. This conceptual model might look great and evoke the right emotional responses to potential customers, but it would be very uncomfortable to ride. Ergonomics on the other hand, is not considered in the conceptual stage, as highlighted by D4: " *I do not want to focus on the ergonomics in the conceptual stage because it closes our creativity. We then tackle ergonomics in the embodiment stage, where we start thinking about how to make the conceptual design a reality.*" This involves considering the physical constraints of

the product. At this stage, designers may realise that some of the decisions they make in the conceptual design stage are not feasible. For example, they may realise that the low seat height is too uncomfortable. This leads to a *design-stage conflict* between the emotional and physical constructs (product's dual nature) considered in different design stages. The designer may have to make a difficult choice between focusing on one construct or go back to the drawing board. D4 continued saying that: *" … It depends on the case, but if ergonomics is of high priority we go back to the drawing board and see where we can fix. Of course, this will impact negatively the project's cost and timeline."*

General user privation

Consideration of a wide customer base (Population majority consideration)

As indicated in the motorcycle design stage, designers typically focus on crafting artefacts tailored to TU (specific user group), ensuring every feature, aesthetics, and ergonomic attribute resonates with the identified user profile. While this strategy ensures a specialised offering, there exists a substantial risk: by concentrating solely on a narrow customer base, designers might inadvertently side-line a potentially larger, more diverse audience with slightly varying needs and preferences. This exclusion of the general rider (*population user privation*) can culminate in constrained market penetration. D6 remarked that: *"Lately we are seeing a trend where culture and style are concerned. Before Indian and Chinese companies were not interested in motorcycle aesthetics. They saw the motorcycle as a functional tool to travel from one point to another. Now, Indians and Chinese are changing their perspectives of a motorcycle aesthetics and are introducing European motorcycle designs trend concepts … As a designer, my ambition is to craft motorcycles that not only positively impact users but also achieve notable success. The motorcycle does not need to be too much related to a special user as you may lose other potential customers. One way to achieve this is to go beyond the target*

user and listen to as many as riders as you can." A similar observation was made by D7: *"It is also important to be open to the possibility that potential clients who do not fit into the target user category may also purchase the motorcycle. For example, what would happen if I had to make a motorcycle which is ergonomically comfortable for 80% of users but is only aesthetically pleasing to my 10% target users? I would have lost that 70% and unfortunately, I have seen this many times."*

Motorcycle life-cycle consequences

Decisions have consequences

In the *'Theory of Dispositions'* Olesen (1992) argues that decisions made during the product design activity have *dispositions (consequences)* on other product life-cycle phases, including the design and use phase. For example, the choice to instil certain aesthetics to the evolving motorcycle model, has a dispositional mechanism which effects the motorcycle's ergonomic in the embodiment stage. Based on this theory, Borg & Yan (1998) present a phenomena model which explains how product synthesis design decisions interact with life-cycle elements and result in product *life-cycle consequences* (LCCs). Similarly, by considering only target users (TU) in the synthesis activity, a negative consequence can result when the motorcycle eventually meets general riders in the use-phase. Or such consequences may arise due to the concurrent consideration of $hf_{E\text{-}AE\text{-}P}$. For example, committing to a high handlebar set-up during the design phase, might have a negative consequence when the motorcycle is in its use phase, specifically when short riders try to manoeuvre this motorcycle. In this case *$hf_{E\text{-}AE\text{-}P}$ use-phase consequences* emerge from the interaction between riders and the motorcycle.

Design and use-phase consequences

Based on the above premises it is here being argued that the DOP's synthesis design decisions result in a myriad of LCCs. However, as illustrated in Figure 4.7, this research will focus on the *Design-stage Conflict and Population Use-phase Consequences,* (DCCs and PUCs)

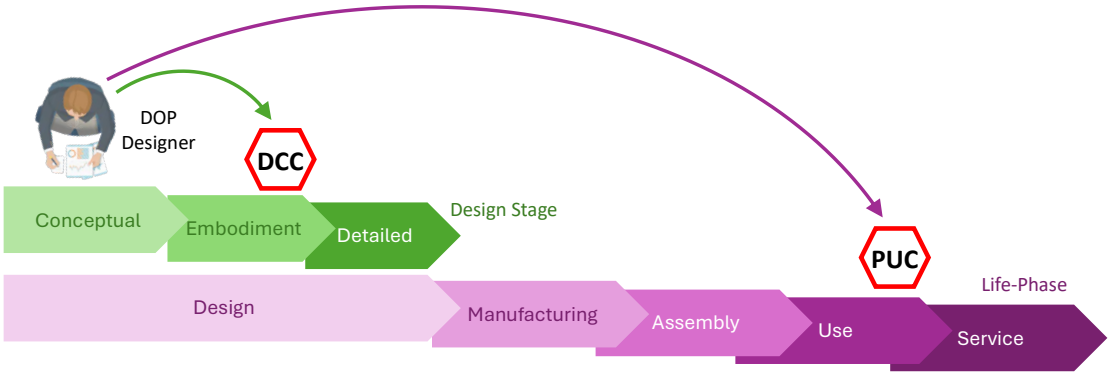


Figure 4.7 – Dual ontological product life-cycle consequences

If these are not handled during the early routine design process, these DCCs and PUCs can lead to challenges and problematic effects (documented in Chapter 3) on intended target users and potential customers.

4.5 Concurrent Considerations and $hf_{E\text{-}AE\text{-}P}$ in Design

4.5.1 Priority to $hf_{E\text{-}AE\text{-}P}$ in Motorcycle Design

Quantitative importance to each human factor aspect

Interviewed designers were asked to evaluate the significance of incorporating $hf_{E\text{-}AE\text{-}P}$ into the process of motorcycle design. Table 4.2 shows that aesthetics, with an average value of 2.00, is prioritised over ergonomics, which has an average value of 1.75 (out of a maximum score of 3).

Particular persona elements, encompassing the road experience, personality and driving behaviour, manifested a lesser priority, with an average rating score of 1.25. While these aspects may not be top-of-mind during the design process, participants emphasised the importance to consider the three human factors and the essential role they play in achieving a motorcycle that is both safer and elicits a stronger emotional response. In descending order of importance based on the ratings, aesthetic-derived emotions stood at 2.92, ergonomics at 2.62, and specific persona characteristics at 2.32.

Table 4.2 – Descriptive statistics of current practises and designers' experiences during design

Question	μ	σ	Significance
Priority to Ergonomics given by designer whilst designing	1.75	0.71	There is a **73% chance** that more than **51% of all motorcycle designers** give priority to ergonomics whilst designing
Importance to consider ergonomic factors	2.62	0.54	There is a **95% chance** that more than **74% of all motorcycle designers** would consider ergonomics important
Priority to aesthetic-derived riders' elicited emotions given by designer whilst designing	2.00	0.93	There is a **95% chance** that more than **51% of all motorcycle designers** give priority to aesthetic-derived riders' elicited emotions whilst designing
Importance to consider aesthetic-derived riders' elicited emotions	2.92	0.31	There is a **95% chance** that more than **74% of all motorcycle designers** would consider aesthetic-derived riders' elicited emotions important
Priority to riders' road experience, personality and riding behaviour whilst designing	1.25	0.89	There is a **90% chance** that more than **51% of all motorcycle designers** do not give priority to riders' road experience, personality and riding behaviour whilst designing
Importance to consider riders' road experience, personality and riding behaviour	2.32	0.73	There is a **73% chance** that more than **62% of all motorcycle designers** would consider riders' road experience, personality and riding behaviour important

Emphasis on ergonomics during design process over other aspects

Qualitative priority to ergonomics

Qualitative findings reveal that participants attributed 68.9% *(20 refs.)* of importance to ergonomics during the designing phase. Conversely, 31.1% *(9 refs.)* assigned a lower priority to ergonomics, favouring aesthetics and performance instead. One participant (D1) noted that: *"We prioritize motorcycle ergonomics because purchasing a motorcycle should ensure comfort during riding. Ultimately, if the motorcycle doesn't provide a good riding experience, its longevity will be compromised."*

Ergonomic market-based priority

Study C participants believed that ergonomics are dependent on motorcycle type, and therefore the market *(13 refs.).* Participants remarked that ergonomics is highly important for long distance travel

motorcycles *(2 refs.)*, but less ergonomic important for short distance travel *(1 ref.)* No ergonomic consideration for super-sports motorcycles *(1 ref.)* is given as the priority in this market segment is performance. Participant D2 mentioned that: *"If you are designing a tourer that is going to be comfortable to ride for hundreds of miles a day, then the seat comfort is extremely important. Whereas if you are designing a motorcycle that is more of low mileage use, then obviously you expect a different level of comfort."*

Priority given to aesthetics whilst designing

Qualitative priority to aesthetic-derived emotions

The qualitative results were in line with the quantitative ones (presented in Table 4.3) and the findings from the research tertiary users documented in Chapter 3. Contrary to the aforementioned discussion regarding ergonomics, when aesthetics and ergonomics are directly compared, a trend emerges among interviewed designers to prioritise aesthetics. Designers *(5 refs.)* revealed that ergonomics often takes a backseat to accommodate aesthetic design. Conversely, some designers *(4 refs.)* contended that even if a motorcycle is designed with optimal ergonomics, if it lacks aesthetic appeal, it will struggle to penetrate the market. D7 remarked that: *"You can develop the best motorcycle in terms of performance or ergonomics, perfect in every way, but if it is not aesthetically pleasing you will have difficulties in selling the motorcycle"*.

Aesthetics seen as a marketability enabler

In today's scenario, companies focus on the emotional benefits of buying and owning a particular product (Walter, 2011). Therefore, one of the most important challenges for designers is to incorporate emotions into products in the early stages of the design process. The importance of designing emotion-laden products can be seen across all cultures and societies. Emotions are considered as central to the design process (M. Kumar et al., 2021). In line with the arguments presented by Singh (2013), D7 expressed that" The *aesthetical features must be*

seen as something positive. Something that can improve motorcycle marketability and not a constraint for motorcycle development."

Lack of knowledge in emotion-driven design

Based on prior observations, it is evident that while the majority (75%) of interviewed designers recognise the critical nature of emotion-driven design and comprehend its benefits, they unfortunately lack the knowledge or tools to implement this methodology during their design process. D6 expressed that: *"Having a clear understanding or deeper insight into our target users' emotions and aesthetic preferences would enable me to design a motorcycle that evokes these emotions. However, we don't possess such expertise and I am not aware of any methods that foster this 'emotive communication' between the user and the motorcycle.*" Knowledge of these emotive qualities would certainly enhance designers' competency in styling products for different ownership experiences (Singh, 2013).

Priority to persona

Certain persona components employed in design

In reference to Section 4.4.3, it has been noted that during the task clarification stage, models are developed with a focus on the target user persona. Participants indicated that they typically incorporate components like anthropometry, age, region, and use-case parameters into the target user model.

Qualitative priority to the persona aspect

From the interviews it was discovered that only two participants consider the target user's experience, personality, and riding behaviour components of a persona during design. D3, a participant which does not consider these components stated that: *"We give to the customer a practical motorcycle. We don't look at the experience and what kind of rider would use the motorcycle."* On the other hand, D5 argued that: *"We look at the personality type because we are designing a motorcycle for a particular customer group. So, with that customer group there would be a person with a personality type that might be strongly representative in one type of motorcycle than within another."* Nevertheless, the majority (62.5%) of participants underscored the

significance of considering these persona components, particularly to mitigate accidents and produce safer motorcycle designs. D7 shared that: *"Occasionally, we may design provocative motorcycles without weighing the repercussions. Integrating these persona components would undoubtedly contribute to a safer product."*

4.5.2 Concurrent Consideration of $hf_{E\text{-}AE\text{-}P}$

Concurrent consideration (CC)

Within *concurrent engineering* (CE), the *US DARPA Initiative in Concurrent Engineering* (Cleetus, 1992) and Borg (1999) presented the *concurrent consideration* (CC) paradigm and defined it as:

> *"A systematic approach to integrated product development where decision-making proceeds with the synergetic consideration of both functional and life-cycle perspectives, and viewed as being related to the 'life-oriented' knowledge available and employed during the execution of an early design activity."*

Concurrent consideration of the three human factors ($hf_{E\text{-}AE\text{-}P}$-CC)

In this doctoral dissertation it is argued that the concurrent consideration presented by Cleetus (1992) and Borg (1999) can be extended to the three human factors *($hf_{E\text{-}AE\text{-}P}$-CC)*. As disclosed in Section 4.4.3 and 4.4.4 the interviewed designers explicitly highlighted challenges when *concurrently considering* $hf_{E\text{-}AE\text{-}P}$ during the design process.

Challenges of $hf_{E\text{-}AE\text{-}P}$-CC

As a consequence of the design-stage conflict and general user privation, decision-making should be carried out through the simultaneous involvement of the three human factors, schematically illustrated in Figure 4.8.

This assertion is supported by the participants *(5 refs.)*, where D5 stated that: *"In a motorcycle, the ergonomics and aesthetics are closely intertwined. The shape of the motorcycle, which contributes to its aesthetic appeal, also influences its ergonomics. For instance, the design of the motorcycle's body can influence the rider's posture, which in turn can affect the rider's comfort and control"*. D4 argued that: *"As*

a sole designer, it is challenging to consider all aspects of motorcycle design, such as ergonomics, aesthetics, and the needs of various potential users, simultaneously. It would be helpful to have a tool that can help designers identify and address potential problems early on. This is especially important for teams where each member is responsible for a different aspect of the design, as this can lead to siloing and a lack of coordination."

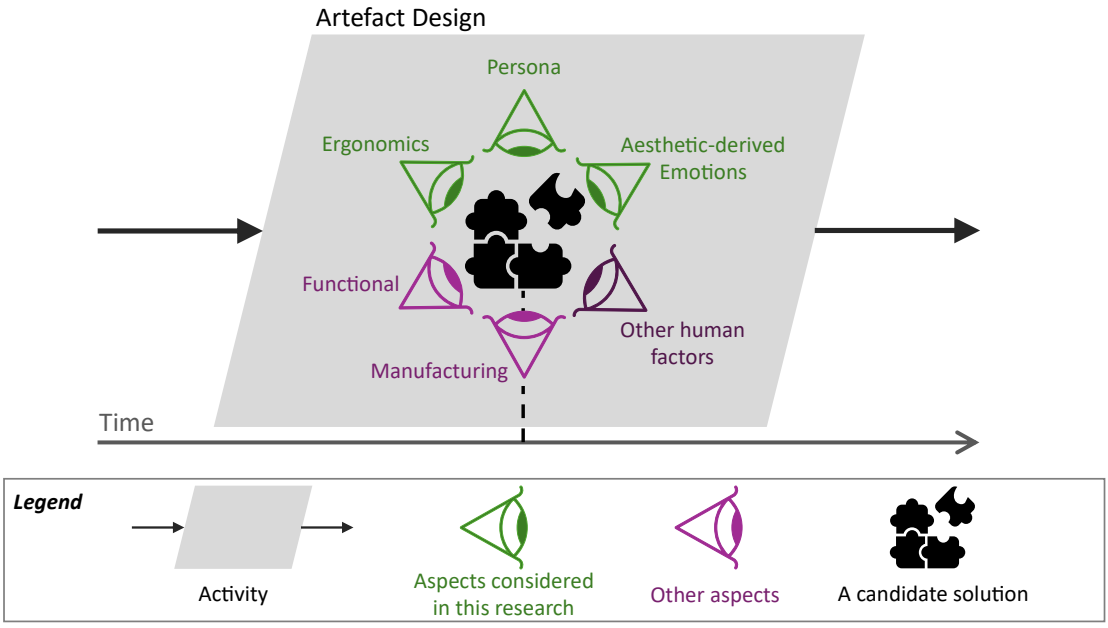


Figure 4.8 – Three human factors concurrent consideration ($hf_{E\text{-}AE\text{-}P}$-CC), adopted from Borg (1999)

Quantitatively: The importance to consider $hf_{E\text{-}AE\text{-}P}$-CC

The qualitative assertions outlined in the previous paragraph align with the quantitative data presented in Table 4.3. From these insights, it can be inferred with a 90% confidence that more than 51% of all motorcycle designers do not consider the interplay between the three human factors. However, with 95% confidence, it can be stated that 74% of all motorcycle designers deem it crucial to concurrently consider these aspects early in the design process.

Multiple 'X' approach to CC

According to Olesen (1995), adopting a functional perspective when considering solution concepts is merely one component of a singular encounter (Andreasen et al., 1996) occurring throughout the entire lifespan of a product, namely, the interaction between the product and its user. Therefore, and as a consequence of concurrent consideration, Olesen (1995), Chal & Linde (1997), Borg (1999) as well as Filippi &

Cristofolini (2010) highlighted the importance of an approach that encourages the *'generation'* of a solution that addresses a multitude of artifact life issues. This approach is referred to as *'Design for Multi-X'*, and as asserted by (Prasad, 1996), the *'X'* signify a range of values pertaining to the entire lifespan of a product, including: manufacture, assembly, use, service, recycling, etc.

Table 4.3 – Descriptive statistics of concurrent considerations during design

Question	μ	σ	Significance
Interplay considerations between multiple human factors in the design	1.25	0.64	There is a **90% chance** that more than **51% of all motorcycle designers** do not consider the interplay between multiple human factors in the design
The importance to consider concurrently human factor aspects early in the design	2.66	0.54	There is a **95% chance** that more than **74% of all motorcycle designers** would give importance to consider concurrently human factor aspects early on in the design

hf-Multi X

The *'Design for Multi-X'* approach is adopted in this doctoral research to *'Design for Multi human factors ($hf_{E\text{-}AE\text{-}P}$)'*, formalised as *hf-Multi X*, as a foundation to address and promote multitude of human factors during the early routine design phase of DOPs.

4.5.3 Diversity Consideration

Challenges of human diversity

In Section 4.4.4, the majority (87.5%) of participants concurred that there are significant benefits when adopting the design for a wider customer base. Three participants (D2, D4 and D6) who have designed a motorcycle that caters to diverse riders, argued that this approach encompasses various challenges, as they must accommodate a wide range of needs, preferences, and physical abilities. D4 explained that: "*In designing a motorcycle for diverse riders, designers need to carry out thorough research and testing, involving a wide variety of potential users in the design and testing processes to ensure that the end product is as inclusive as possible."* Moreover, D2 expressed a notable perspective, arguing that: *"A paramount aspect we must adhere to is*

recognising that a scooter designed for European riders is ergonomically distinct from one intended for use in China due to the differing anthropometry of Chinese individuals. Addressing such pronounced variation by crafting motorcycles tailored for different regions is feasible. However, this necessitates doubling company efforts, which isn't an optimal scenario and isn't entirely within our control. A more complex scenario arises when aesthetics come into play or when there's a high anthropometric variability within a particular region. For instance, the USA, being multi-national, has riders originating from all over the world. In both scenarios, we find ourselves without methods or tools to effectively navigate these issues."

4.5.4 The Concept of Harmonisation

Finding a balance

Hu et al., (2020) explained that products need to fulfil ergonomic requirements whilst at the same time elicit positive emotional experiences by the user. The *'balance'* between function and form is often an area of difficulty for the designer (Hu et al., 2020). If a product is purely functional, it may be lacking in appeal to consumers, no matter how suitable it may be at completing its job. Designers must *'balance'* these two aspects of product design to create products that are both effective and emotionally appealing (Ulrich et al., 2020).

Designers' divergent views

Typically, (form) styling designers and (function) ergonomic engineers will have divergences during this stage of development (Cocco, 2013). Emerging from Section 4.4.4 (design-stage conflict), five participants argue that this is because styling designers try to maintain the original styling of the clay model into the prototype motorcycle, while the ergonomists try to improve the rider's posture. The success of the final product depends heavily on the level of cooperation (*balance*) between these conflicting needs.

Challenges to cope with $hf_{E\text{-}AE\text{-}P}$-CC and diversity

Along the same lines, this doctoral research argues that when designing a dual ontological product (DOP), a significant challenge faced by designers pertains to the intricate interdependencies associated with

designing for multiple human factors, coupled with the need to accommodate anthropometric, emotional, and persona diversity in the design process (seen in Sections 4.5.2 and 4.5.3).

The need to balance human factor aspects and human diversity

To reach as many customers as possible a compromise is crucial *(18 refs.)*. The criticality of striking a *'balance'* between these aspects to cater for the needs of a broader customer base is emphasised by Agius et al. (2020). In this regard, D4 stated that: *"In the end you need to have a motorcycle which has a balance between the stile or aesthetics and comfort. Balance is the key to reach as many customers as possible."*

Difficulty in achieving a compromise

All of the interviewed designers expressed difficulties in achieving a compromise between multi human factors. D6 highlighted that *"It's the designer's role to find a harmonious balance, ensuring one doesn't severely compromise the other aspect. This is a challenge in itself and demands several years of experience to do so effectively."*

The concept of harmonisation

This doctoral research considers two distinct views of the term *'balance'* when considering multiple aspects during design. The first view pertains to the actual balance, which generally describes the state of equilibrium attained when two divergent aspects are made equal. For instance, when designing a product to optimise both ergonomics and aesthetics, balancing these two factors necessitates a proportionate allocation of attention and efforts towards each of them. On the other hand, balance can be viewed as *'harmonisation'*. The concept of *harmonisation* concerns the process of attaining coherence, consistency, or compatibility among aspects which may diverge. Generally, trade-offs are required to reconcile conflicting aspects. During the design phase, this may involve the adjustment or modification of various product design elements (PDEs) in such a way as to align aspects with each other, ultimately leading in a more cohesive and harmonious whole. The concept of balance and harmonisation is exemplified through Figure 4.9.

Focus on harmonisation

Upon establishing clear definitions for the two terms in question, in this doctoral dissertation, the concept of *harmonisation* is employed hereinafter in order to refer to the notion of balance whilst designing for multiple human factors ($hf_{E\text{-}AE\text{-}P}$).

4.6 Designers' Expectations from an Approach Supporting DOP Design, from $hf_{E\text{-}AE\text{-}P}$ Perspective

4.6.1 Knowledge in a Form of Computer-based Support Tool

Type of design tools

Interviewed designers had the option to select what type of design tool they require; (i) manual method, (ii) automated computational tool, (iii) computer-based support tool, or (iv) others.

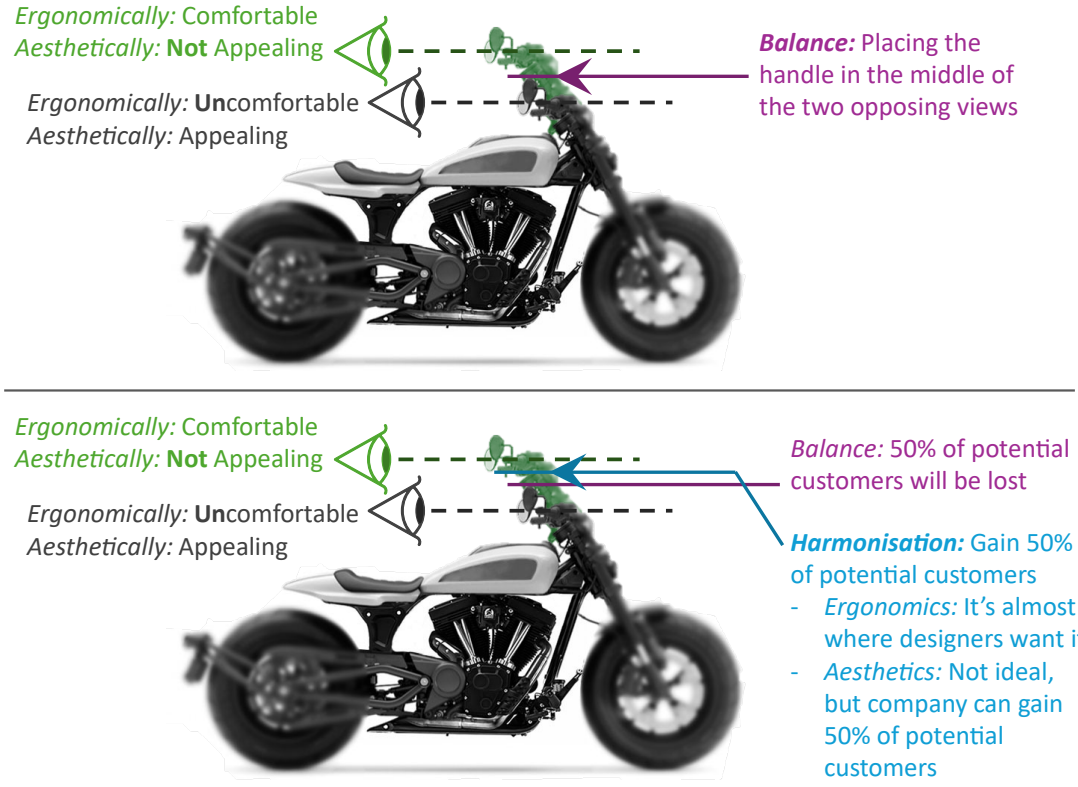


Figure 4.9 – Exemplifying balance and harmonisation in this doctoral dissertation

Need for a computer-based support tool

None of the participants requested a manual method. Given the limitations of human mental processing power (Baddeley, 1986), addressing the intricacy of the motorcycle design process through manual methods would result in a support tool that is not only time-consuming and complex to implement but also challenging to utilise. Only one of the interviewed designers requested to have an automated

computation tool, while the other seven stated that they would like to have a *computer-based support tool*. This result is quantitatively shown in Figure 4.10. Extrapolating this observation to the whole motorcycle design population, there is a 95% chance that more than 74% of all motorcycle designers would like to have a computer-based design support tool.

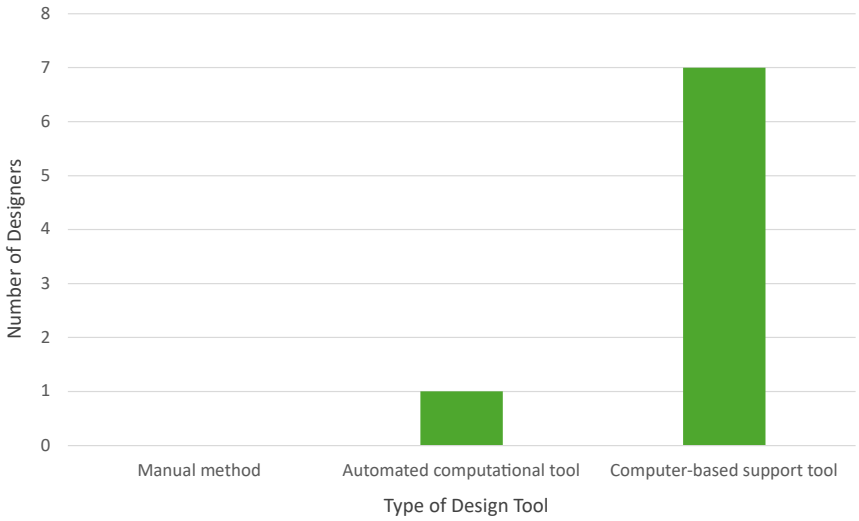


Figure 4.10 – What type of design tool participants require

Computational support

The use of computer-based support tools would allow human designers who control the design process, while technical means offer support to decision makers by making them aware of consequences associated with design commitments. D5 highlighted that: *"We can have something which permits the human factor aspects to communicate with each other whilst leaving us free to be creative and also instil that personal touch in our products"*. D1 explained that: *"In the initial stages I use a lot of tools which take time to import and export. For instance, I use a CAD software to compose the technical aspects of the new motorcycle, such as wheelbase, hight and rake angle. Then I use another software to visualise the aesthetics, and so on. It would be nice if we had to have something consolidated into a single package"*. Pahl at al. (2007) describe that such tools should *"enhance the creativity, engineering knowledge and experience of designers"*. Knowledge needs to be provided at the right time whilst not being intrusive to the designer's cognitive activity (Van Merriënboer & Sweller, 2005; Liao et

al., 2020). Given the aforementioned reasons, the application of a computer-based support tool to implement this method would be aptly suited to address this problem.

Harmonistic knowledge to handle human factors and diversity

The presented responses from interviewed designers and arguments reveal that *harmonistic knowledge* is required in order to handle multiple human factors and diversity in the design activity of dual ontological products. *Harmonistic knowledge*, as defined in this research, comprises two types: *human factor knowledge* and *harmonisation knowledge*.

Human factor knowledge

Human factor ($hf_{E\text{-}AE\text{-}P}$) knowledge makes designers explicitly aware of the implications of early routine design decisions on human factors during the product's use phase.

Harmonisation Knowledge

Harmonisation knowledge supports designers in balancing multiple human factors and human diversity, such as knowledge about reconciling conflicting aspects to achieve a harmonious design solution and to reach a wider customer base.

4.6.2 Data Acquisition Requirements for the Computer-Based Tool

Employment of anthropometry

D1 and D2 stated that they employ anthropometry in their design approach. On the other hand, the other six participants utilise alternative data collection methods for considering ergonomics in design. For these designers, ergonomic insights are derived from measurements of existing motorcycles (3 refs.) or from their accumulated experience and knowledge *(2 refs.)*. Another designer, D3, make use of pre-existing motorcycle geometries as the sole approach *(1 ref.)* to obtain an ergonomic base for the new motorcycle.

Data acquisition needs for the computational tool

Designers have requested an approach that incorporate information gathered from existing motorcycle geometries *(5 refs.)* Specifically, designers have requested a real postural data collection device *(12 refs.)*, implemented in the form of an adjustable motorcycle jig. This jig would help designers acquire real and accurate ergonomic information

of various riders with different ergonomic and persona characteristics. In fact, D2 suggested that: *"You can consider building a hardware that can test the ergonomics of the motorcycle design in consideration. You can regulate the height of the handlebars, the seat, or footpegs position. You can acquire information about different simulations, regarding different geometries with different rider characteristics such as weight, height, dimensions of his arms and legs."* D5 continued saying that before the design commences the company can ask potential users to use an adjustable simulator. If the rider finds the ergonomics satisfactory, it can be used as a base of the motorcycle design model. Otherwise, adjustments are made, until the rider is comfortable with the change.

Integrating a motorcycle simulator with the computational tool

D8 suggested that a computational tool can be developed which recommends the ideal motorcycle in terms of ergonomics posture and personality types. The tool can also recommend driving style based on simulation runs. *"For an adventurous rider, the tool could guide designers to design a small-powered motorcycle, suited for such a user. Thus, alleviating accidents"* (D8). D8 also highlighted that the simulator can be interfaced with a system which recommend the ideal bike in terms of adjustment.

4.7 Study Limitations

Finding participants

The field of motorcycle design is very specific. As anticipated, it resulted to be very challenging in finding participants with relevant background and expertise to contribute to *Study C*. Locally this proved to be impossible as no contacts were available and therefore, this has led to engage experts from abroad. Nonetheless, this also proved to be challenging, with a response rate of 18%. One of the primary concerns with a small sample is the ability to generalise the findings to a broader population. Furthermore, the margin of error tends to be larger in smaller samples, meaning the confidence in estimates might be lower than in larger samples. This is evident through Table 4.2 and Table 4.3.

Small number of participants

Despite these constraints, data saturation was achieved, and the presence of consistent findings in the qualitative analysis suggests that designers, regardless of their diverse countries and backgrounds, share similar perspectives. The main goal of the study was exploratory, that is, to gain a deeper understanding of the designers' reality while designing DOP. Due to the exploratory nature, smaller number of detailed interviews can provide more depth, richness of the data and better insight than a large number of shallow surveys (Creswell & Poth, 2018; Flick, 2018).

In addition to the main research efforts, this study was supplemented by secondary data from various literature sources. This not only helped corroborate the findings but also anchored the study within the context of existing research. The good agreement among multiple researchers during the analysis phase, coupled with the alignment between quantitative and qualitative results, further reinforce the validity of the findings.

4.8 Key Takeaways: Approach Framework Requirements

Design approach framework requirements

Six requirements for a *human factor dual ontological design approach framework* have been identified to enable designers to cope with $hf_{E\text{-}AE\text{-}P}$ related challenges during the design of DOPs. As such, the design support approach framework has to:

RPU-R1. (Research Primary Users' Requirement 1) Support the synthesis activity at the conceptual design stage

Designers' Requirement 1

Designers have stated that the conceptual stage is where most important design decisions are made and therefore, the stage where there is most scope for making improvements. Because decisions made during the early stages of design significantly shape how subsequent stages unfold, it is crucial that designers are equipped with human factors knowledge right from the start. This ensures that

designers receive the support they need to make well-informed decisions, resolve uncertainties, and mitigate risks early on in the design process. As a result, designers can implement changes more easily, with less impact on cost and time.

RPU-R2. Be implemented as a design computer-based support tool

Designers' Requirement 2

Every interviewed RPU expressed a desire for a computer-based tool. Rzevski (1983) and Zhou et al. (2020) outline several reasons why designers should utilise computer-based tools, noting their ability to provide *'tentative design solutions'* by effectively storing, processing, and displaying vast amounts of information, along with the necessary knowledge. Seven of the participants emphasised a preference for a support tool rather than an autonomous application to avoid limiting their creative input and enhance their experience while providing them with the right harmonistic knowledge. Cormier et al. (2014) describe problem abstraction as the process of identifying needs without dictating how solutions should be implemented. It is important that the design process remains a creative, unrestricted endeavour.

RPU-R3. Provide a user-centric design approach

Designers' Requirement 3

Following from Chapter 3, through requirement RTU-R4 (Research Tertiary Users' Requirement 4), DOP users explicitly requested for their voice to be heard during the design process. Potential users' information can be gathered and channelled in the form of human factor knowledge, that can then be accessed by the designers. This information should not be limited to the data gathered during the task clarification stage, which is typically focused on the intended

customer. Instead, it might encompass a broader range of information that is reflective of the general user population and human diversity. Insights derived from studies involving RTUs and RPUs indicate that the approach could encapsulate the following information captured from potential customers:

Collection of ergonomic information

- Collection of DOP potential users' anthropometric information, as well as real-postural and ergonomic interaction information through an adjustable hardware and simulation tool.

Collection of aesthetic-derived emotions

- Collection of potential customers' emotions which are elicited to different DOP styles and aesthetic preferences. This would enable designers to design a DOP that evoke the right type of emotions.

Collection of persona information

- Collection of the persona aspect based on the potential customer's personality, behaviour, DOP use-context and demographics details.

RPU-R4. Provide multiple life (design and use) phase awareness

Design-stage conflict awareness

Design-stage conflict arises due to the product's dual nature, where different human factors are considered in different design stages. Late in the design process, designers may recognise that certain decisions they took in the conceptual stage are not feasible.

Potential customers' requirement awareness

According to interviewed designers, for a product to thrive in the market, there must be a willingness to acknowledge that potential customers outside the target user demographic might also opt to purchase the DOP. Human factor interactions will inevitably occur between the DOP and potential customers. But these interactions are privy to the designer as these happen in the product's use phase, at

which point the designer no longer has control over the product.

Designers' Requirement 4

Given these challenges, DOP designers should be made aware of such interactions and understand their implications on both the intended target users and potential customers (*population majority consideration*) during the product's use phase. That is, designers must be aware of design-stage conflicts and population use-phase consequences, (DCCs) and (PUCs). The effects of these negative consequences should be derived from the use phase issues explicitly identified by RTUs, as discussed in Chapter 3. Equipped with this knowledge, designers will be better prepared to approach the design process with a familiarity to the problems faced by RTUs.

RPU-R5. Design for multi human factors (hf-Multi X)

Designers' Requirement 5

In DOPs, the TU's persona in considered during the task clarification stage, aesthetics primarily come into play during the conceptual design stage, while ergonomic considerations are typically addressed in the embodiment stage. In Section 4.5.2 it was seen that RPUs need to cope with concurrent multiple human factors ($hf_{E\text{-}AE\text{-}P}$). As such, this section argues that design for multi human factors (hf-Multi X) is required as a foundation to address and promote $hf_{E\text{-}AE\text{-}P}$ during the early routine design phase of DOPs. Drawing from the *'Design for Multi-X'* approach (Borg, 1999), the hf-Multi-X approach necessitates to make aware designers of multiple human factor interactions and to provide them with the negative consequences that these interactions will eventually have on the DOP's use phase.

RPU-R6. Provide harmonisation awareness

Designers' Requirement 6

Some DOPs may be ergonomic oriented while others may be aesthetic oriented, some are both. Aesthetics and ergonomics must co-exist harmoniously as both are essential to *attract* (through the visceral emotion level) potential customers and to *keep* (through the behavioural emotion level) users. Providing harmonisation knowledge supports designers in harmonising multiple human factors and human diversity. This knowledge is about reconciling conflicting aspects to craft a cohesive design solution that resonates with a broader spectrum of customers. The approach must, therefore, facilitate designers in maximising their reach to potential customers. According to the interviewed designers, striking the right balance between aesthetics and ergonomics is vital in appealing to a broader customer base. This means that compromises may be necessary to ensure that the final product effectively addresses hf_E, hf_{AE} and hf_P.

Requirement from designers and DOP users

The emphasis on harmonisation awareness is underscored by the fact that the majority of designers highlighted its importance during interviews. Moreover, this awareness aligns with the requirements and expectations of DOP users, through RTU-R3, further solidifying its significance to be incorporated in the approach framework. By supporting designers with harmonisation knowledge into the early routine design process, designers will be better equipped to create DOPs that emotively resonate with users while also adhering to necessary safety and comfort standards. This, in turn, will contribute to the product's success in the market and its acceptance among a diverse range of customers.

4.9 Chapter Conclusions

Consolidating the view of the design problem

In order to fully comprehend the complexities associated with DOPs, an exploration of both designers' (RPUs') and DOP users' (RTUs') perspectives concerning such products has been undertaken. This chapter primarily delves into the experiential reality of designers throughout the design process of these products from the three human factors' perspective. Chapters 2 and 3 were devoted to delineating the $hf_{E\text{-}AE\text{-}P}$ and particular requisites of RTUs. Observations from the three studies (*Studies A to C*), illustrated in Figure 4.11, amalgamate spoken and unspoken requirements expressed by both RPUs and RTUs. Adopting a holistic methodology ensured a comprehensive examination of the issue, wherein a variety of primary and secondary research methods were employed to garner robust insights to adeptly address the challenges at hand.

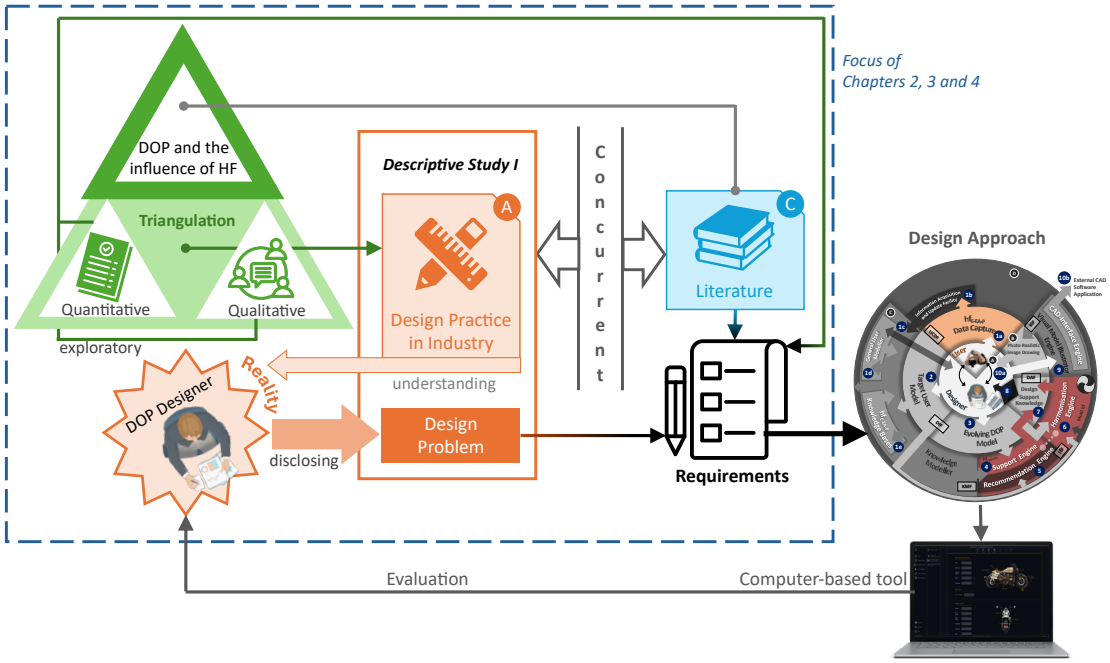


Figure 4.11 – Scoping the design problem within the overall doctoral research

The need to provide support during the design process of DOPs

Based on the arguments and findings presented, this chapter concludes that to design DOPs which appeal to a broader customer base, designers need to be supported during the early routine design process. This support includes human factors and harmonisation knowledge required to achieve a harmonious product design solution. This doctoral research argues that when DOP products from a human

factors' perspective, designers need to be made aware of DCC and PUC arising from their synthesis decision commitments. Moreover, designers need to be guided in order to relax or avoid DCCs and PUCs.

Are DOP designers supported, and how?

fter arriving at this product development problem definition, there is a need to investigate how DOP designers are supported during the design process from a human factors' standpoint. These questions will be answered in the next chapter as different means for supporting human factors are reviewed.

5 Critical Review of Design Support *Means* for Multi Human Factors in Dual Ontological Products

There are several systems, tools or approaches aimed at supporting the different activities in the DOP design process. In this chapter, the purpose is to provide a critical review of the existing research on design support means that have shaped the field of human factors in engineering design and to identify the research gap, with respect to a set of review criteria. Section 5.1 will introduce the critical review. The methodology adopted for this critical review is delineated in Section 5.2. This section encompasses the review criteria and the classification used to structure the review. Relevant literature is critically reviewed in Sections 5.3 to 5.8 and a summary of the findings is presented in Section 5.9. The summary leads to the identification of the gap within the existing body of literature, revealed in Section 5.10.

5.1 Introduction to the Critical Review

Scoping the search: Why focus on hf and DOP

Products and support can be divided into several sub-categories. Particularly in Chapter 2 of this dissertation, the distinction between dual ontological products (DOP) and the general term 'product' has been defined. As argued in Section 2.1, certain products have a dualistic nature, a phenomenon where artefacts are seen from physical perspective and at the same time from subjective (emotional) perspective. This duality implies that these artefacts function as extensions of the user, encompassing both physical and psychological aspects. Such a notion highlights the significance of considering the human element. Given that the focus of this doctoral research is on DOPs, this critical review will predominantly concentrate on human factors (HFs) in the engineering design activities of DOP.

Definition of means

De Araujo & Duffy (1996) have highlighted a prevalent uncertainty in the terminology used to describe entities that aid in product development activities. To clarify this ambiguity within the context of this doctoral research, the term *'means'* is adopted to designate

entities that assist and support in decision-making during the design of DOP.

According to De Araujo & Duffy (1996), two key characteristics are crucial for an entity that supports product development. Firstly, such an entity should facilitate the establishment, implementation, and monitoring of development tasks. Secondly, it requires an operator, which could be a person, a group, or a computer system.

Therefore, entities that exhibit these characteristics—including *methodologies, frameworks, ontologies, models, algorithms or tools*—are considered as a 'type of' *means* to support DOP design.

5.2 Critical Review Methodology

Methodology

A critical literature review was undertaken to systematically identify and assess the existing research on *means* employed in the design activities of DOPs. Adhering to the systematic review guidelines formulated by Kitchenham & Charters (2007) and Xiao & Watson (2019), relevant studies were pinpointed through a systematic mapping procedure.

5.2.1 Review Criteria

Aim of review criteria

The aim of this critical review is to conduct a scientific and impartial analysis of literature and solutions that have emerged in both research and industry contexts. Achieving this aim necessitates a critical evaluation of the underlying *means* according to a specific set of criteria. These criteria have been derived from the overall objective of this doctoral research, which is to develop a harmonistic proactive approach framework to design DOPs for $hf_{E\text{-}AE\text{-}P}$.

Timing and Activity

The first criterion seeks to determine if the support *means* is offered during the early routine design process, specifically during or prior the conceptual synthesis design activity, or if such support is provided after a candidate solution, in its entirety, has already been generated.

Multiple life-phase view

The second criterion concerns whether there is an awareness of the product system's consequences across multiple life-phases, or only for a single phase. Specifically, whether the *means* foresee the design-stage conflict consequences (DCCs) as well as population use-phase consequences (PUCs), for both intended (target) and non-intended (general) but potential customers.

Guidance type

The third criterion aims to address whether the support *means* motivates and supports multi human factors (hf-Multi X), by concurrently considering ergonomics, aesthetic-derived emotions and persona aspects or whether the support *means* is oriented towards other aspects or restrict their support to two or less aspects.

Harmonisation awareness

The final criterion seeks to address whether the *means* provides support for each aspect independently, or if it provides simultaneous and interdependent awareness, based on a harmonised approach between:

i. Ergonomics
ii. Aesthetic-derived emotions
iii. Persona through the *Target User*
iv. Persona through the *General User*

5.2.2 Review Boundaries

Inclusion criteria

The inclusion criteria which collectively characterise the boundary of this review are specified in Table 5.1. These criteria are established to pinpoint research works that adequately address the literature review and to minimise bias, following the guidelines set forth by Kitchenham & Charters (2007).

Clarifying the review boundaries

As previously outlined in the introduction to this chapter (Section 5.1), the scope of this literature review, is on HFs in the DOP engineering design activities. Particularly, this should concentrate on physical DOP development. Consequently, the support *means* under consideration

are not intended to facilitate services, software, education, people management or work environment development, to name a few.

The researcher has identified numerous scholarly works in the domain of HFs for DOPs. To refine the search further, the review focuses exclusively on *means* that concurrently address multiple aspects (i.e., Multi X) and that include at least one of the following aspects: ergonomics, aesthetic-derived emotions, or persona (i.e. *hf[1]-Multi X*).

Additionally, descriptive *means*, which document design practices to analyse and improve decision-making processes, were excluded from this review. Instead, the focus was placed solely on prescriptive *means*—those that provide specific guidelines, rules, or approaches dictating design procedures (Blessing & Chakrabarti, 2009).

Table 5.1 – Inclusion criteria of the literature search

#	Inclusion Criteria
1	Engineering design related
2	DOP development
3	hf[1]-Multi X
4	Prescriptive *means*
5	*Means* published: January 2000 – April 2024
6	Published in academic work (conference proceedings, journal papers, thesis or books)
7	English only written articles
8	Non duplicate *means*

5.2.3 Systematic Scoping

Electronic database searches

Due to different terms used in this field, a search string was used to identify relevant literature within the following electronic databases: Google Scholar[2], IEEE Xplore[3], Scopus[4], ScienceDirect[5], SpringerLink[6]

[2] https://scholar.google.com
[3] https://ieeexplore.ieee.org/Xplore/home.jsp
[4] https://www.scopus.com
[5] https://www.sciencedirect.com
[6] https://link.springer.com

and ACM Digital Library[7]. Figure 5.1 illustrates a flowchart of the review process, detailing the number of articles sourced from each database.

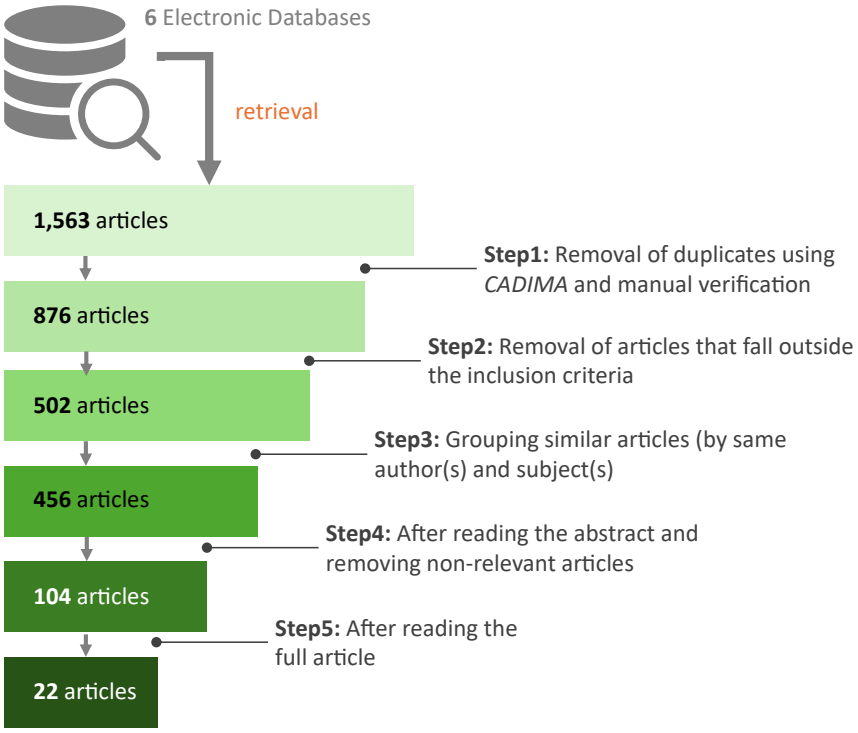


Figure 5.1 – Method employed for systematic scoping

Search string

In *Step 1*, the studies were retrieved using the following search string:

G1. (Group 1) *"engineering design"*

G2. *"support means"* OR *"design support"* OR *"support tool"* OR *"approach"* OR *"framework"*

G3. *"product"* OR *"dual ontological product"* OR *"motorcycle"*

G4. *"human factors"* OR *"ergonomics"* OR *"emotions"* OR *"aesthetics"* OR *"persona"*

G5. *"concurrent"* OR *"simultaneous"* OR *"multi X"* OR *"harmonisation"* OR *"balance"* OR *""*

which were combined as: *G1* AND *G2* AND *G3* AND *G4* and *G5*.

Expanding the search

The search using the term combination in G3, which included *"dual ontological products,"* yielded only two results. Both papers (Agius et al., 2023a and Agius et al., 2023b) originate from the author and pertain

[7] https://dl.acm.org

to the subject matter of this doctoral research. Consequently, the term *"product"* was incorporated to broaden the scope of the search.

Articles incorporated in the critical review

After completing *Step 3* of this scoping activity, the search yielded 456 unique articles. To facilitate the removal of duplicates and the grouping of similar works (by author and subject), the free online software tool *CADIMA* and manual verification were employed during *Steps 2* and *3*, respectively. The process of selecting publications by author continued through *Steps 4* to *5*, as depicted in Figure 5.1. Ultimately, 22 publications satisfied the selection criteria and were incorporated into this critical review.

5.2.4 Review Classification

hf¹-Multi X in DOP design classification

Considering the extensive scope of this research field, the state-of-the-art scientific contributions have been systematically organised using the classification system depicted in Figure 5.2. The *means* under review were categorised according to the classification approach utilised by Power (2002), Burstein & Holsapple (2008) and Sànchez-Marrè (2022) for facilitating decision-making in product development activities.

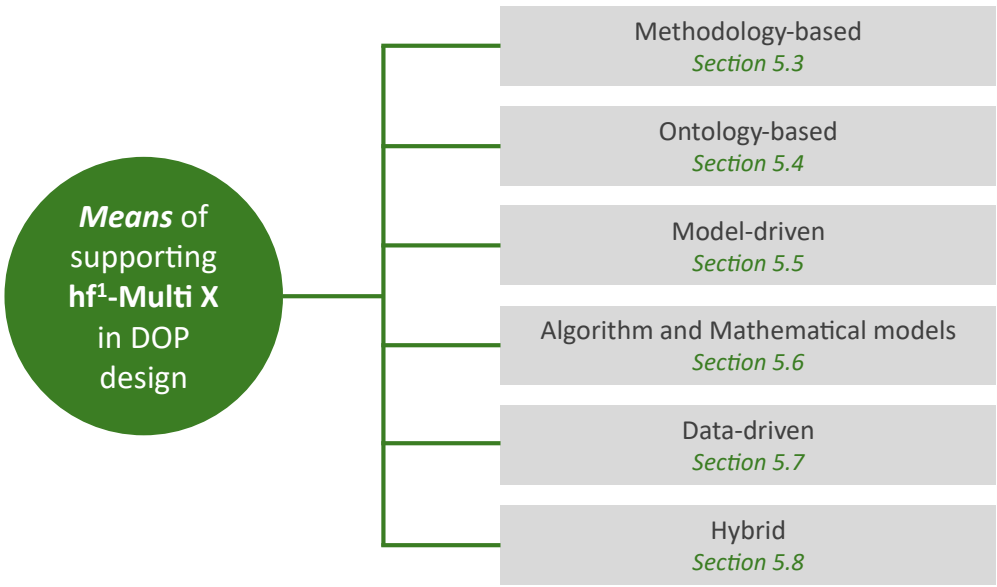


Figure 5.2 – Overview of the state-of-the-art classification

What to expect in the upcoming sections

The following sections provide a detailed description of the research reviewed, structured according to the classification outlined in Figure

5.2. Each category includes sub-sections, which comprise a description of each *means* evaluated, an analysis of how it aligns with the review criteria, and a critical assessment of the support *means*. A concise review (summary) of each *means*, based on the review criteria set out in Sections 5.3 to 5.8, is presented in Section 5.9, alongside Table 5.2.

5.3 Methodology-based *Means*

Engineering design methodologies represent systematic methods through which engineering systems may be developed. Pahl et al. (2007) characterise these methodologies as structured plans of action that coordinate working steps and design phases both contextually and organisationally.

5.3.1 Integrating ergonomics into modified HoQ chart of QFD

Lee's (2005) means description

Lee (2005) proposed a modified *House of Quality* (HoQ) matrix adapted from *Quality Functional Deployment* (QFD) to systematically identify the critical ergonomic design area corresponding to functional user requirements as well as affective (emotion related) needs of user. This methodology is depicted in Figure 5.3. Lee (2005) claims that this approach enables product designers to gain insights on critical design area to be seriously considered for enhancing overall user satisfaction.

DOP used as a case study

A case study of screwdriver design was conducted to demonstrate the applicability of the proposed design methodology, providing information related to the critical product design attributes of a screwdriver, which will help engineering product designers identify what to seriously consider for enhancing overall user satisfaction.

How Lee's (2005) methodology fairs compared to the review criteria

Given that the QFD exercise is conducted during the task clarification design stage, this approach supports the early design. Furthermore, it addresses the ergonomic aspect through the physical interaction between the user and a hand tool, the emotional aspect via the tool's

appearance, and performance, which is quantitatively assessed through tasks performed with the hand tool.

Regarding the life-phase views, this *means* does not make the designer aware of design-stage conflict or use-phase negative consequences (DCCs and PUCs). Furthermore, it does not harmonise any conflicts or multiple aspects together.

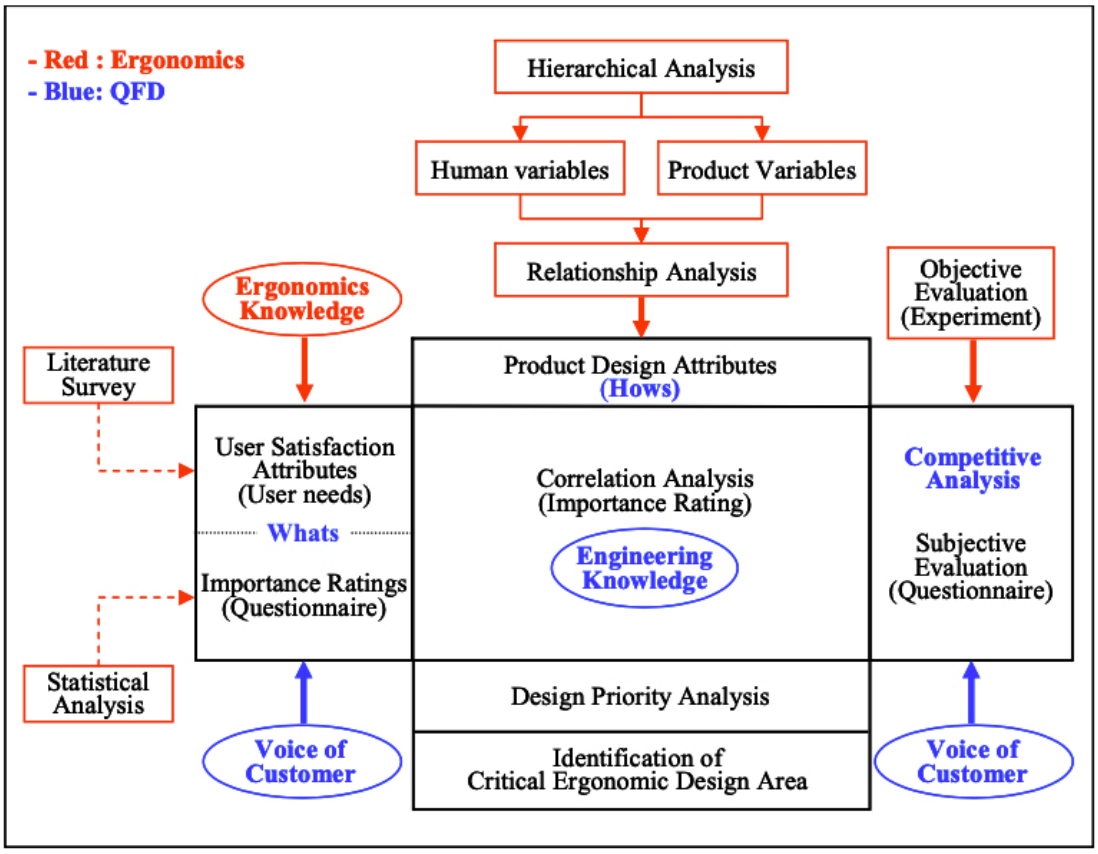


Figure 5.3 – A conceptual model for ergonomic design of hand tools: integrating ergonomics into a modified HoQ chart of QFD, source: Lee (2005)

Strengths of ergonomics integration into modified HoQ

The proposed approach prioritises functional design attributes, ergonomic attributes and user satisfaction attributes right from the very start of the design process. Furthermore, this approach facilitates concurrent consideration with the prominent tool attributes in order not to overwhelm product designers with the extensive and scattered ergonomic data available.

Limitations of ergonomics integration into modified HoQ

While the QFD primarily focuses on translating explicit 'performance' needs, it does not adequately capture 'must-be' (basic) needs and 'attractive' needs, given that the *means* under review focuses on multiple aspects at such an early stage of design. Another identified limitation lies in that this approach lacks validation in practice.

5.3.2 Simultaneous consideration of Design for Emotions (DfE) with defining engineering specifications

Jiang et al.'s (2014) methodology description

Jiang et al. (2014) developed a methodology that bridges *design for emotions* (DfE) and engineering specifications within the early stages of product design. Jiang et al. (2014) leverage a *chaos-based Fuzzy Regression* (FR) approach for modelling customer satisfaction derived from QFD and an *Adaptive Neuro-Fuzzy Inference System* (ANFIS) enhanced *by Particle Swarm Optimisation* (PSO) for DfE modelling. As illustrated through Figure 5.4, these models are then utilised in a multi-objective optimisation framework, solved using a *chaos-based Non-dominated Sorting Genetic Algorithm II* (NSGA-II), aiming to determine optimal settings for both design attributes and engineering requirements concurrently.

DOP used as a case study

A case study on mobile phone design illustrates the methodology, showcasing its potential to significantly enhance customer satisfaction by simultaneously considering emotion design and technical specifications. According to Jiang et al. (2014), the *means* not only promises higher satisfaction but also facilitates a harmonious decision-making process between designers and engineers, offering a structured pathway towards the development of products that are both functionally and emotionally appealing to customers.

How Jiang et al.'s (2014) means fairs compared to the review criteria

As noted in the previous section the QFD exercise is conducted during the task clarification design stage, thus the approach supports the early design process. The support *means* concurrently considers the human factors' affective (emotional) and limited ergonomics together with the technical (engineering specifications) aspects of product design.

Furthermore, this methodology provides a harmonised process, aiming to find a balance between emotional design and engineering specifications.

Jiang et al. (2014) do not explicitly consider multiple life-phase views that is, no unintended consequences are provided for design conflicts or foreseen for the product's use phase. Moreover, the methodology focuses on intended users directly linked to user perceptions and preferences, without understanding the general users.

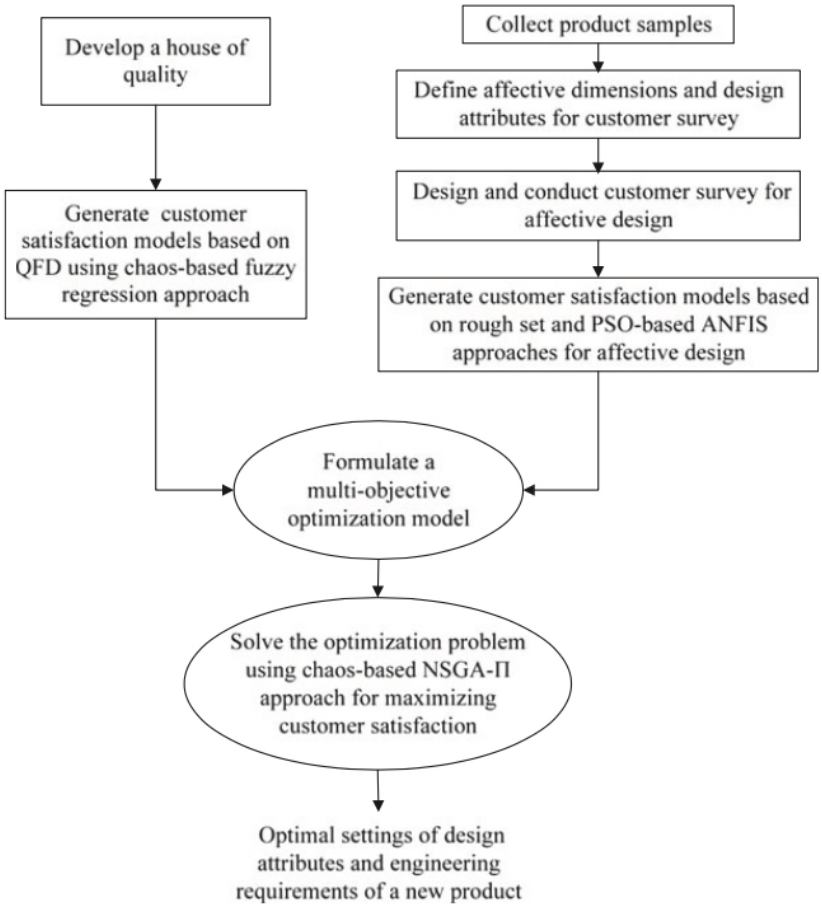


Figure 5.4 – The proposed simultaneous consideration of DfE with engineering specifications, obtained from Jiang et al. (2014)

Strengths of simultaneous consideration of DfE with engineering specifications

The methodology provides a systematic way to simultaneously consider design for emotions and engineering specifications, through

the use of several techniques like *FR, ANFIS, PSO,* and *NSGA-II*, enhancing the product design process's efficiency and effectiveness.

Limitations of simultaneous consideration of DfE with engineering specifications

In the development of the proposed methodology, Jiang et al. (2014) state that it is assumed that the perceptions, needs and desires of customers regarding particular products are static. In reality, since users possess diverse persona, emotively they react differently to the same product, in which these varied emotional responses are not captured by this methodology.

5.3.3 Kansei Engineering-based methodology integrated in a CAD environment

Göloğlu & Zurnaci's (2016) means description

Göloğlu & Zurnaci (2016) present a *Kansei Engineering*-based methodology that helps involve customers in the product design process by taking customer preference into account (conveyed using linguistic expressions). As seen in Figure 5.5, Göloğlu & Zurnaci (2016) integrated a Computer-Aided Design (CAD) environment to serve as a 3D dynamic product representation, with this methodology. The 3D representation is generated by individual customer preferences using fuzzy logic reasoning. This allows a customer user interface (UI) to help facilitate customer decision-making according to individual preferences and emotional needs by visualising a dynamic assembly generation, allowing customers to build their own preferred product interactively.

DOP used as a case study

For illustration, Göloğlu & Zurnaci (2016) demonstrated the methodology by using a case study of an ironing board. An ironing board was chosen because it has a number of categorical design elements to be personalised, thus, allowing companies to provide a great number of solutions for customers.

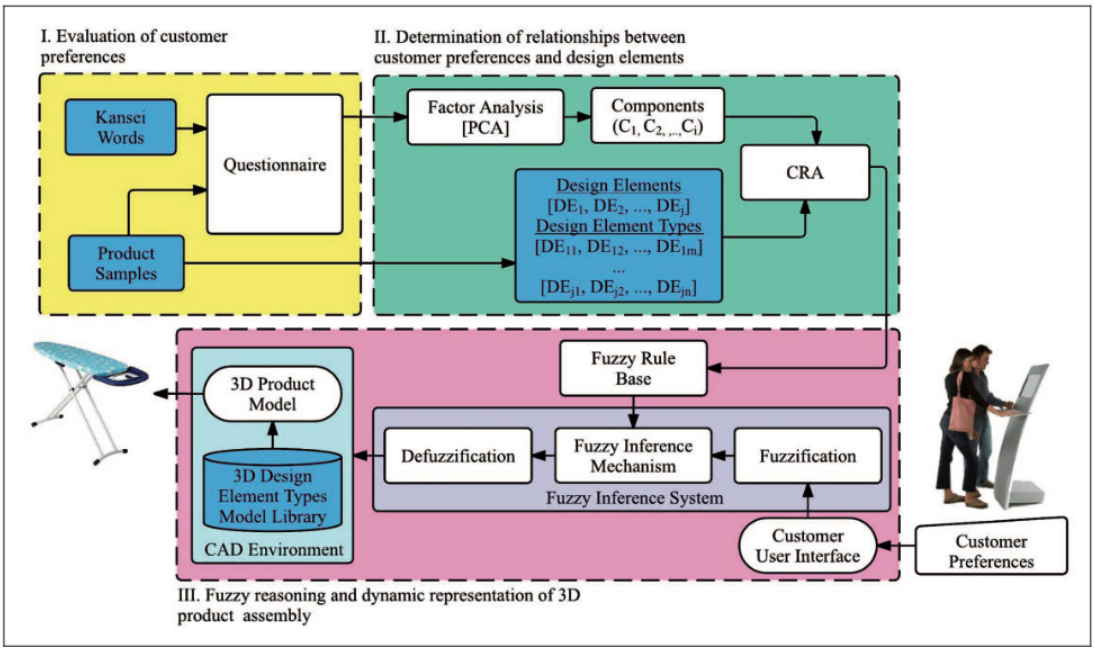


Figure 5.5 – The proposed methodology for product generation based on customer preferences, source: Göloğlu & Zurnaci (2016)

How Göloğlu & Zurnaci's (2016) methodology fairs compared to the review criteria

This methodology guides the human factors' emotional and limited ergonomics, together with the functionality aspects of product design, whilst supporting the use phase life-view of the product. The latter is based on customer preferences through the illustration of a 3D model.

Notwithstanding this, no use-phase negative consequences are provided to the designer or customer through the generated customised product. Furthermore, the work of Göloğlu & Zurnaci (2016) does not provide any reference of what happens between conflicting aspects or how these are resolved through harmonisation. Additionally, Göloğlu & Zurnaci (2016) do not specify during which design stage or activity is this methodology implemented.

Strengths of KE-based methodology integrated by CAD environment

The approach employed by Göloğlu & Zurnaci (2016) is characterised by user-centred design (UCD), as it directly incorporates user preferences. Moreover, this approach results in a 3D customised product based on customer selections, yet it does not involve the customer in the actual design process. According to Göloğlu & Zurnaci (2016) the companies that manufacture assembled products enhance

their production ranges by offering more customer-oriented or fully customised products.

Limitations of KE-based methodology integrated by CAD environment

The methodology proposed by Göloğlu & Zurnaci (2016) does not directly support designers. For instance, it does not provide any indications on what happens when there is a conflict between the considered aspects.

5.3.4 Product development through User Feedback Loops

Kajtaz et al.'s (2015) methodology description

The approach for product development presented in the paper by Kajtaz et al. (2015) emphasises the concurrent execution of functional design activities and user's emotional (addressing aesthetic impression, semantic interpretation, and symbolic association), psychological and persona needs. The user persona serves as a collection of hypotheses about the user's preferences and needs, informed by ethnographic data. As illustrated in Figure 5.6, designers come up with different versions of the product, get feedback from potential users (referred to as *user feedback loops* in this paper), and adjust the design based on the feedback. This allows for the translation of the user's verbal descriptions into visual representations of the product. This cycle repeats until designers find the best fit between the product and the user's emotional and psychological needs.

DOP used as a case study

The *means* has been presented through a case study of designing a cricket faceguard.

How Kajtaz et al.'s (2015) means fairs compared to the review criteria

The support *means* concurrently considers emotional design, encapsulating how it looks (aesthetics), what it represents to the user (symbolism), how it fits into the latest trends with the user persona and functional aspect. Additionally, though not explicitly highlighted there is some level of harmonisation, personified through the feedback loops between functional and emotional/persona design views.

Although Kajtaz et al. (2015) integrate the user in the design phase and therefore, negative use-phase consequences are shared with users and minimised, this methodology is highly bespoke and targeted to an intended user. Therefore, does not factor in the needs of the population majority. Additionally, this methodology is integrated into the later stages of the design process, as Kajtaz et al. (2015) note that their methodology is applied post-sketching and during the evaluation activities.

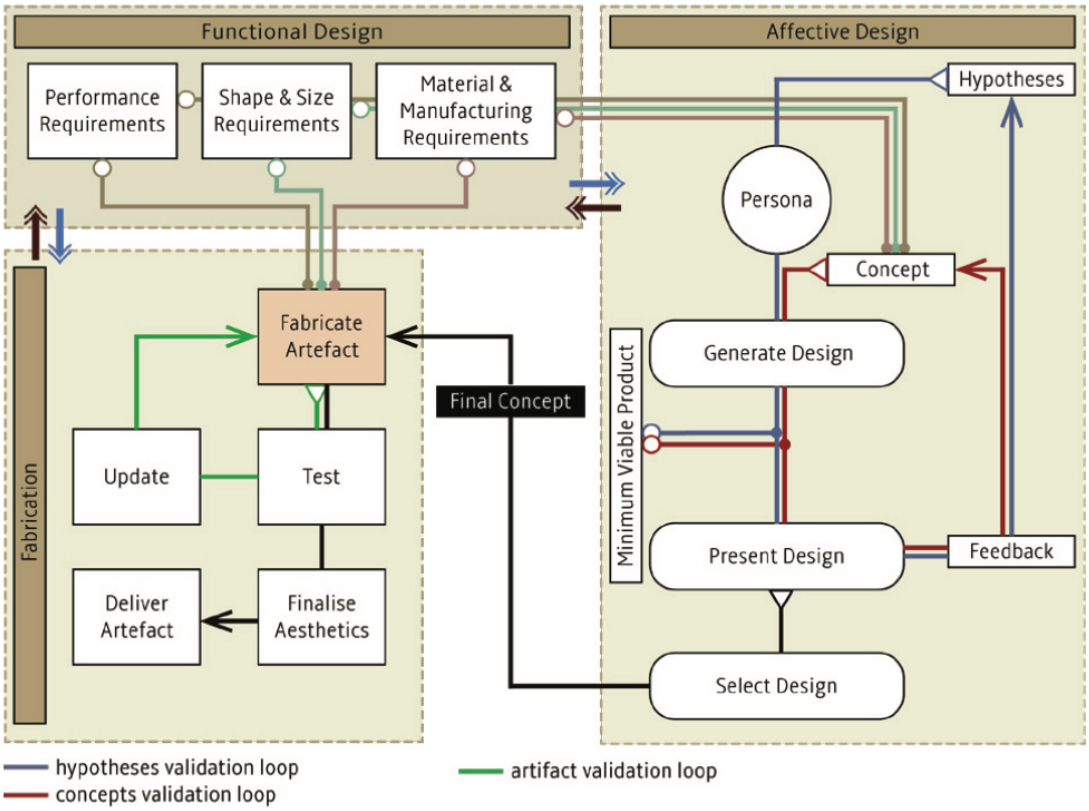


Figure 5.6 – Schematic representation of the proposed methodology, obtained from Kajtaz et al. (2015)

Strengths of product development through User Feedback Loops

According to Kajtaz et al. (2015), this methodology fosters a deep engagement with the user's personal and psychological needs throughout the design process, leading to the creation of products that resonate on an emotional level with the user. This methodology is highly user-centred as feedback is collected directly from the user,

while some activities are run in parallel to reduce product development time.

Limitations of product development through User Feedback Loops

The limitation of the proposed methodology lies in the fact that due to its highly personalised element, it is difficult to implement for mass production, given that feedback from all users who eventually would use the product is required.

5.3.5 The 'Human-Artefact-Context' methodology

HAC methodology description

The methodology developed by Hoyos-Ruiz et al. (2017) integrates ergonomic principles into the engineering design process, focusing on what the authors call *'Human-Artefact-Context'* (HAC) system. This approach aims to ensure a balanced consideration of human (user), artefact (product), and context (persona) aspects throughout the design process. By adopting a UCD approach and emphasising on cognitive and physical ergonomics, Hoyos-Ruiz et al. (2017) seek to improve product efficiency, safety, and consumer well-being. This is achieved by explicitly incorporating ergonomic criteria and user experience considerations from the early stages of design, through concept development, to evaluation and finalisation, as illustrated in Figure 5.7.

DOP used as a case study

This methodology is illustrated using a case study of redesigning an upper body protective vest, demonstrating how ergonomic integration leads to products that are better adapted to user needs and contexts, thereby enhancing usability and overall user satisfaction.

How HAC fairs compared to the review criteria

Hoyos-Ruiz et al.'s (2017) methodology emphasises early integration of the ergonomic and persona aspects, continuing throughout the later stages of the design process. In this paper the ergonomics is about understanding who will use the product and if it would ultimately be comfortable. Whereas the persona in this paper referred to it as *context* is about where and how the product will be used. Furthermore,

Hoyos-Ruiz et al. (2017) argue that these aspects need to be balanced in order to make sure the product is not just useful, but also something people are comfortable using.

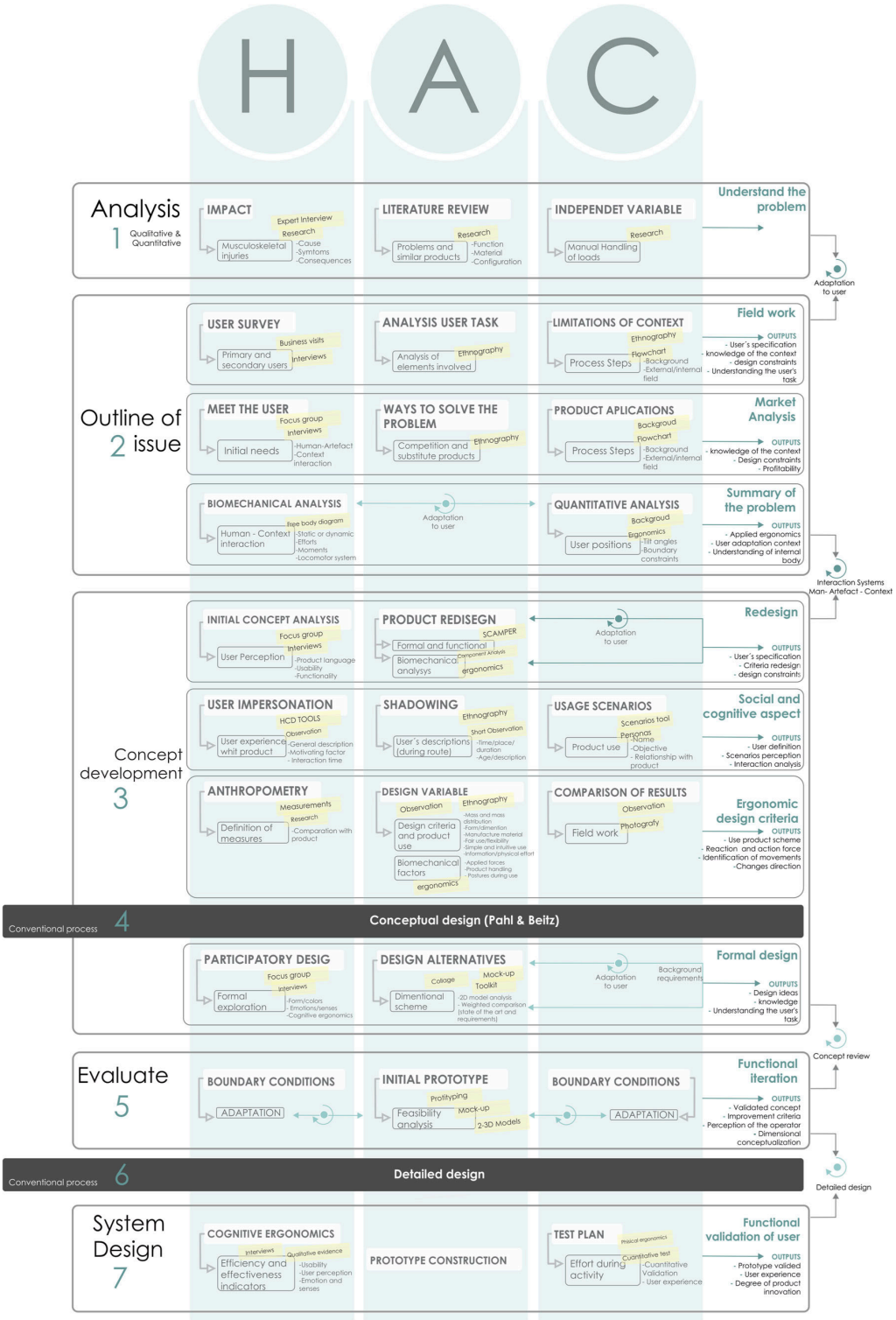


Figure 5.7 – Methodological prescriptive framework V1.1 for product design, source: Hoyos-Ruiz et al. (2017)

Hoyos-Ruiz et al. (2017) contend that harmonisation is essential and thus, their approach raises awareness of potential conflicts during the

design stage. However, they do not address the negative consequences that may emerge, nor do they offer recommendations to mitigate these, or provide negative use-phase consequences. Additionally, this methodology does not take into account the aesthetic emotions of users.

Strengths of the 'Human-Artefact-Context' methodology

The methodology put forward by Hoyos-Ruiz et al. (2017) involves the users directly in the design, asking them what they need, and testing out ideas to make sure they work well, potentially leading to products that are more user-friendly, safe, and goes hand in hand with the target user group.

Limitations of the 'Human-Artefact-Context' methodology

Although the persona aspect is factored through use cases, personality and behaviour are still missing, while general users are not included in this methodology.

5.3.6 The 'Engustrial' design methodology

'Engustrial' description

The *'Engustrial'* design approach developed by Francalanza et al. (2019) merges industrial and engineering design principles to create products that not only meet functional requirements but also resonate emotionally with users. This methodology acknowledges the conflicting priorities that often arise within multidisciplinary product development teams, particularly between industrial designers and engineering designers. By systematically integrating emotional value into the product development process, *'Engustrial'* design aims to enhance consumer satisfaction and market success. Francalanza et al. (2019) structure this methodology into four layers: problem analysis, solution synthesis, evaluation, and solution detailing. As seen from Figure 5.8, during the *first layer (01)*, the engineering and industrial designers work together to jointly analyse a given problem. For example, they

jointly define the needs they foresee using methods such as the QFD method (Francalanza et al., 2019). This ensures that both functional objectives and user emotional responses are considered from the outset, facilitating a more harmonious and efficient design process. In *layer 02*, the team works together to generate a solution satisfying the set of unified specifications generated in *layer 01*. The team members can immediately correct points of divergence (through evaluation in *layer 03*), when the divergence is still minor, making it easier to reach consensus as the solution evolves in *layer 03*. This process proceeds until they reach *layer 04*, where the teams jointly detail the solution in such a way that engineering drawings cater for the emotional aspects built into the solution by the industrial designers such as specific forms, colours and surface finish (Francalanza et al., 2019).

DOP used as a case study

In a similar but a more in-depth study, Fenech (2020) validated this methodology through a case study of professional high-speed video camera enclosure. According to the evaluators, this methodology highlighted its effectiveness in balancing technical constraints with aesthetic and functional considerations.

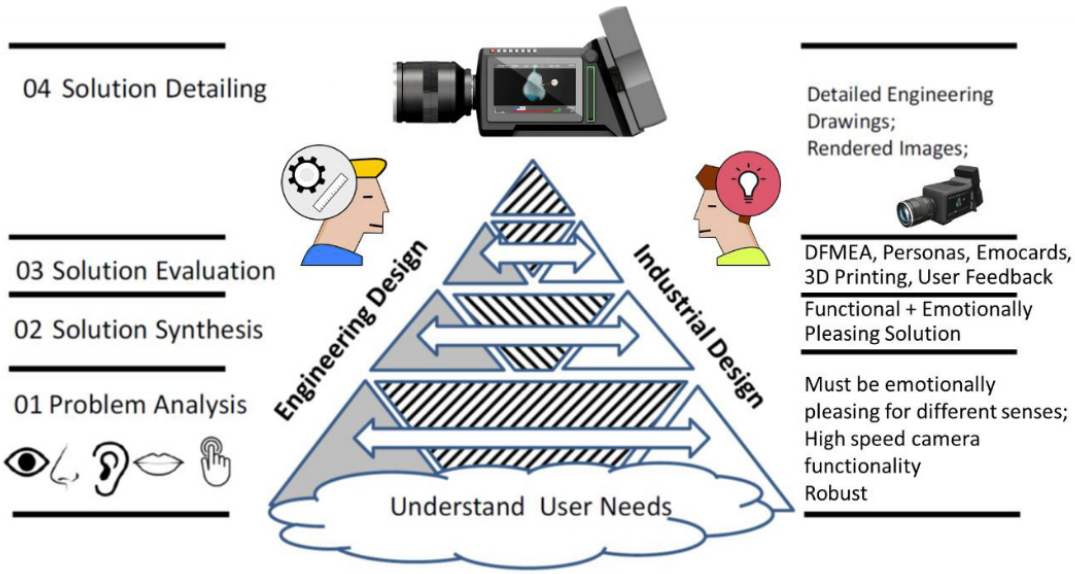


Figure 5.8 – The 'Engustrial' design methodology, obtained from Francalanza et al. (2019)

How 'Engustrial' fairs compared to the review criteria

The *'Engustrial'* design methodology emphasises early (from problem analysis) integration of the emotional (from an industrial perspective)

and functional (from an engineering design perspective) aspects, through the later design process (solution detailing).

Francalanza et al. (2019) postulate that harmonisation is being carried out between the engineering designer and industrial designer, however, there is no explicit explanation how this is achieved in practice. Additionally, Francalanza et al.'s (2019) work does not provide specific and explicit reference to either design- or use-phase negative consequences. This methodology solely focuses on users who are intended to use the product.

Strengths of the 'Engustrial" design methodology

This holistic and integrated approach is proposed as a means to facilitate collaboration between industrial and engineering designers to better meet the explicit and implicit needs of users, thereby creating products that are not just functional but also emotionally engaging.

Limitations of the 'Engustrial' design methodology

Francalanza et al. (2019) do not specify how multidisciplinary teams are to be guided in balancing conflicts, which will lead to potential challenges in harmonising the divergent priorities of such teams and in ensuring that emotional design considerations do not overshadow functional requirements. Additionally, this methodology does not involve direct data collection from users, nor does it include potential customers in its processes.

5.3.7 Design management combined engineering and marketing design approach framework

Shigemoto's (2019) means description

Shigemoto's (2019) work presents an approach to emotional product design, emphasising the role of design management as a pivotal bridge between engineering and marketing disciplines. It highlights how engineering focuses on ergonomics and *Kansei Engineering* to elicit and measure emotions from product interactions, while marketing

explores impulse buying and branding strategies to create delight and emotional attachment to brands. Design management, as depicted in Figure 5.9, coordinates these diverse perspectives, leveraging socio-cultural insights to understand and shape the emotional landscape of product consumption. By synthesising knowledge from these fields, the approach aims to develop products that not only meet functional needs but also resonate emotionally with users, enhancing satisfaction and loyalty.

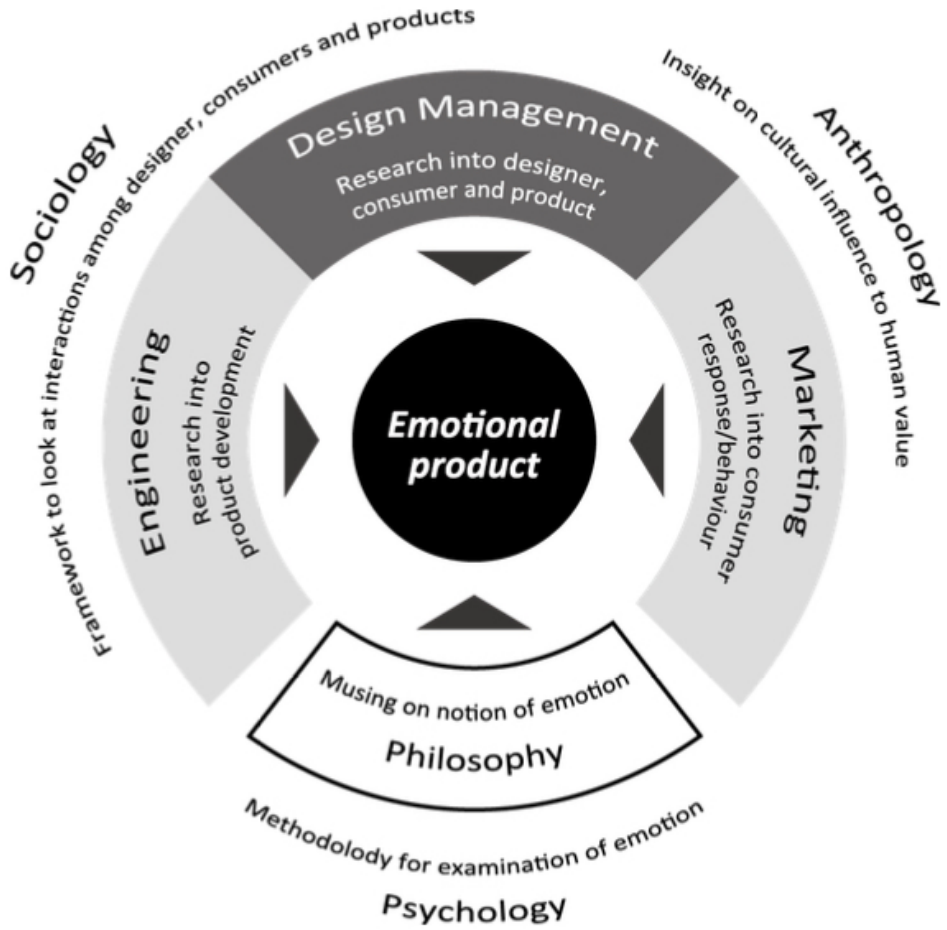


Figure 5.9 – Design management combined engineering and marketing design approach framework, source: Shigemoto (2019)

DOP used as a case study

Shigemoto's (2019) work does not focus on a specific DOP. Instead, it offers a methodology that is applied across various product categories to achieve emotional engagement through design. The paper outlines a framework for emotional product design and calls for further research in this direction, suggesting an exploratory stage rather than a detailed empirical validation of the proposed framework.

How Shigemoto's (2019) framework fairs compared to the review criteria

Shigemoto (2019) argues that it is important to take the aspects, highlighted in the framework (perceived meanings and elicited emotions), into account in the early stage of product development. Through this framework, Shigemoto (2019) seeks to elicit emotions from the consumer, whilst *Kansei Engineering* attempts to quantitatively capture human sensory interaction with products. The use of the marketing domain (through impulse buying and branding) explores how to create emotional engagement between companies and consumers. The last aspect is design management, which according to Shigemoto (2019) is as an artificial and creative process that aims to coordinate diverse physical factors in order to embody a conceptual solution to a social need.

Given it is just a framework, Shigemoto's work does not determine which life-phase views will be influenced by this research, nor does it clarify whether there will be an awareness of design-stage conflicts or population majority considerations provided to designers. Moreover, Shigemoto (2019) suggests that design management coordinates the various aspects, but does not specify how awareness of harmonisation is to be achieved or whether it will indeed occur.

Strengths of the combined design management, engineering and marketing design approach framework

This framework offers a novel perspective on design management that facilitates the integration of engineering, ergonomics and marketing insights to enhance emotional engagement with products.

Limitations of the combined design management, engineering and marketing design approach framework

The design framework proposed by Shigemoto (2019) has not been realised in a proof-of-concept, nor has it been validated through a case study or within industry practices. Consequently, the assertions made

by Shigemoto (2019) lack practical exemplification and remain less comprehensible within the context of product design.

5.4 Ontology-based *Means*

An ontology provides a framework to formalise and construct models using reusable domain knowledge. For this reason, ontologies are often referred to as knowledge models (Sanya & Shehab, 2014) that underpin knowledge bases (Wong et al., 2012). They are invaluable for organising information, developing knowledge-based systems, enhancing communication, advancing software development, and facilitating problem-solving. As such, ontologies serve as foundational elements for software tools (Zheng et al., 2021).

5.4.1 Knowledge-based Intelligent Advisory System

Knowledge-based Intelligent Advisory System description

In a series of papers: Kaljun & Dolšak (2006); Kaljun & Dolšak (2011); Kaljun et al. (2011); Kaljun & Dolšak (2012a) and Kaljun & Dolšak (2012b) explain the developed *intelligent advisory system* based on expert design knowledge management. This system is composed of two sub-systems, aesthetics and ergonomics, which are applied simultaneously and interdependently on the same design project. This *knowledge-base system* (KBS) derives and proposes recommendations for both ergonomic and aesthetic design improvements, and also to harmonise possible design solutions in order to find the optimal balance between the two aspects as illustrated in Figure 5.10. This *means* leverage the knowledge-based ergonomic and aesthetic aspects to create a framework that supports designers in optimising product design for both functionality and user experience. These ontologies serve as a foundation for encoding design knowledge, by categorising aesthetics into a number of elements. These comprise art elements, principles of art, and semantic elements, as well as ergonomic elements into guidelines derived from anthropometric, biomechanical,

and cognitive data. Based on these elements, the framework provides a holistic view of the factors that influence product design.

DOP used as a case study

Multiple case studies of hand tools (such as: side cutter, pipe cutter, Allen keys) and power hand tools (such as: portable driller and pneumatic driller) were employed on which design recommendations were conducted (Kaljun & Dolšak, 2006; Kaljun and Dolšak, 2012b). This was accomplished to demonstrate the applicability of the proposed intelligent advisory system. However, only the ergonomic recommendation engine was considered when implementing the framework into a prototype tool. The aesthetic recommendation engine or the harmonisation of the two engines were not considered as part of these case studies.

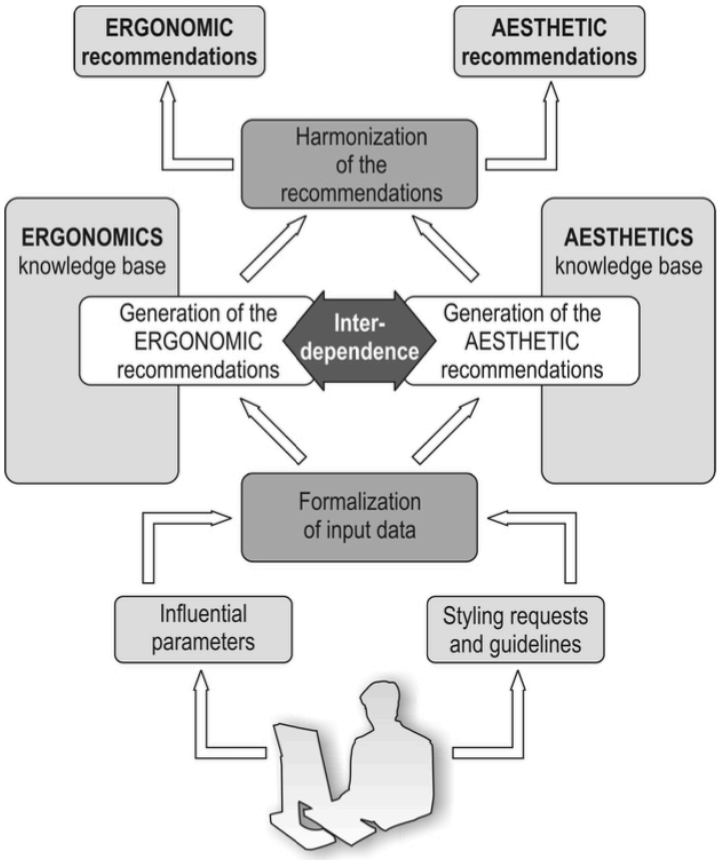


Figure 5.10 – The architecture of the proposed intelligent system, obtained from Kaljun & Dolšak (2011)

How this knowledge-based system fairs compared

This structured approach enables designers to consider a wide range of aesthetic and ergonomic influential factors. These include intended user needs, preferences, and physical requirements, from the earliest

to the review criteria

stages of the design process. Highlighting the importance of addressing these factors from the beginning of the product development. The process continues through to the CAD integration activity, where guidance is offered. Moreover, the *advisory system* provides use phase support and recommendations to improve or minimise negative ergonomic use-phase consequences.

Although Kaljun & Dolšak (2011) highlighted the harmonisation, as reflected in Figure 5.10, the authors do not divulge what methods were used for harmonisation, or how the conflicts between these two aspects were handled. Additionally, the *intelligent system* does not take in consideration the persona and the views of potential customers who might eventually use these hand tools. Consequently, no support is provided for the PUCs or how these can be minimised.

Strengths of the Knowledge-based Intelligent Advisory System

This system offers designers real-time advice and recommendations on how to enhance the ergonomic and aesthetic value of their products. For instance, the system suggests adjustments to a product's form, materials, and dimensions based on user ergonomic standards. This *advisory system* not only evaluates designs against ergonomic and aesthetic criteria but also providing recommendations for improvement.

Limitations of the Knowledge-based Intelligent Advisory System

Kaljun & Dolšak's (2011) system is presented with pre-defined rules captured from literature (predictable behaviour) and therefore, does not capture the different emotions elicited by users for the same product. The system does not take into consideration the designer's evaluation of the system's proposed recommendations. Moreover, this system generates recommendations to improve an already existent product, rather than support the designer during the synthesis of a new

product design. Furthermore, it lacks a proof-of-concept, and thus an evaluation of the harmonisation between aesthetics and ergonomics.

5.4.2 Human and Life-Phase Systems Meetings (HLSM) framework

HLSM framework description

The *Human and Life-Phase Systems Meetings (HLSM)* consequence knowledge approach framework developed by Farrugia & Borg (2016) offers a means to enhance product development by integrating emotional and direct-production consequences into decision-making processes. This hybrid approach leverages KBS to proactively guide decision makers, facilitating the anticipation of manufacturing operators' emotional impacts and the exploration of alternative design commitments to mitigate undesirable emotions. As seen in Figure 5.11, the framework is structured around the synthesis of product components and life-phase system elements, focusing on the transformation of these elements across various life-phases including manufacturing, assembly, and inspection. The *HLSM* approach explicitly models and simulates the interactions between human operators and product components or technical systems, aiming to improve business metrics such as cost, time, and quality, while also considering the emotional well-being of factory workers. The *HLSM* approach framework was later implemented in a prototype computer-based tool *FEDE* (Foresight of Emotional and Direct Effects).

DOP used as a case study

A validation of this approach was carried through the case study of a high-end luxury chair's seat cushion’s assembly. Furthermore, according to the evaluators who assessed *FEDE* in the design practice, stated that the approach demonstrates its capability to provide comprehensive insights into the emotional and technical dimensions of product development (Farrugia, 2017), paving the way for more empathetic design practices.

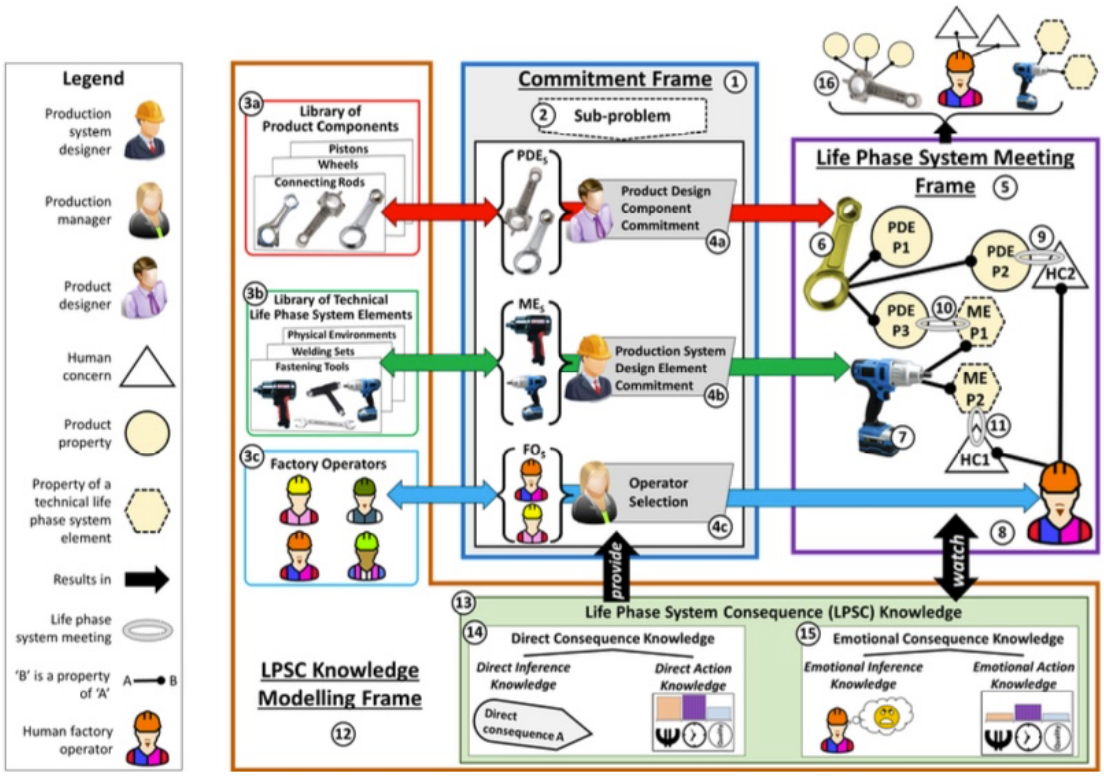


Figure 5.11 – Human and Life-Phase Systems Meetings (HLSM) consequence knowledge approach framework, source: Farrugia (2017)

How HLSM fairs compared to the review criteria

Farrugia & Borg (2016) argue the importance of having *FEDE* assisting the early design process, specifically in the synthesis design activity, to capture and address potential issues later on in the product's manufacturing phase. Making designers aware of these unintended consequences will reduce the need for costly modifications later in the product development cycle. Farrugia & Borg (2016) state that the emotional consequence effects are cost, time and quality.

Farrugia & Borg (2016) focus on the manufacturing phase of the product's life-cycle. Consequently, this model does not factor in consequences arising in the design and use phases of the product's life-cycle. Furthermore, this model does not feature any interactions which occur between different design stages and thus, no harmonisation awareness is provided.

Strengths of the HLSM framework

The framework outlined by Farrugia & Borg (2016) facilitates decision-making throughout the manufacturing life-phase of a product. It

enhances awareness of how design decisions affect human emotional states, encourages the exploration of alternative design commitments, and proposes solutions to mitigate consequences during the manufacturing phase. Consequently, this approach contributes to both quality improvement as well as product cost and time to produce reduction.

Limitations of the HLSM framework

The emotional consequence model does not take into consideration the ergonomic and persona aspects. These two aspects together with the emotional aspect give rise to various consequences. It can dictate the level of safety of a particular machine operator while interacting with a particular product or machine (due to the ergonomics and operator's persona). Additionally, *HLSM* does not consider variable behaviour owing to the various personas, which occurs when the same product interacts with various machine operators having different emotions, anthropometric data and persona.

5.4.3 Rider Inspired Design for Emotion (RIDE) framework

RIDE framework description

The *Rider Inspired Design for Emotion (RIDE)* framework developed by by Farrugia et al. (2019), represents an approach to sportsbike design, designing both emotional satisfaction and aerodynamic performance (illustrated in Figure 5.12). *RIDE* seeks to guide designers in creating sportbikes that not only excel in performance but also resonate emotionally with riders. Through empirical studies, including wind tunnel tests and emotional analysis, the research identifies key design guidelines that encapsulate the essence of aerodynamic efficiency and emotional appeal. *RIDE* was implemented in knowledge-based computer-based tool where data is directly collected from a side elevation 2D sketch of a sportsbike, to provide insights into rider emotions facilitating a design process that is deeply attuned to human experiences.

DOP used as a case study

RIDE was validated with experts in the field of motorcycles, where it emerged that the design support tool is useful as it contributes to reduce the length of the design process as well as improve the user-motorcycle product emotional attachment during the artefact's use phase (Mamo, 2018).

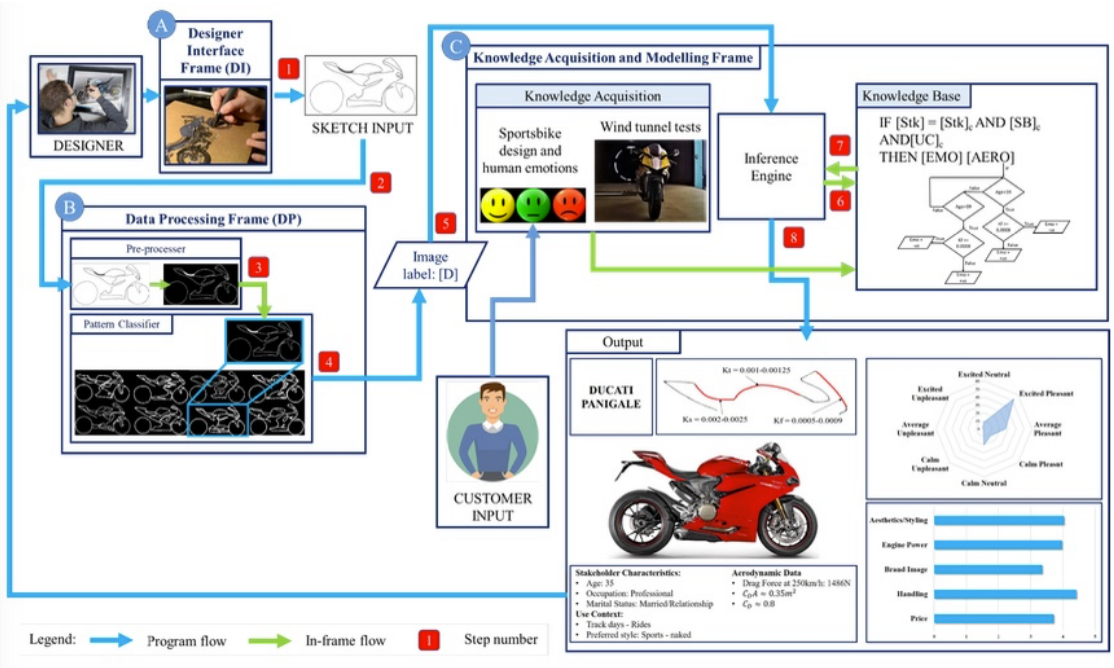


Figure 5.12 – The Rider Inspired Design for Emotion (RIDE) framework, obtained from Mamo (2018)

How RIDE fairs compared to the review criteria

Mamo (2018) underscores the importance of early incorporation of emotional and aerodynamic aspects during the conceptual (sketching) design process. Through the *RIDE* framework, Mamo (2018) provides support exclusively during the use phase of the motorcycle's design.

The model developed by Mamo (2018) does not capture the ergonomic and persona aspects such as riders' anthropometry, personality type or use-context. Consequently, there is no relation between the rider's personality and experience, postural data and emotions elicited to different motorcycle designs. As noted previously, the designer receives support solely during the motorcycle's use phase, resulting in a lack of support for addressing design-stage conflicts. Additionally, the approach does not accommodate the needs of the majority population, nor does it provide a harmonised solution to resolve conflicts between

aspects and the needs of both target and general motorcycle user groups.

Strengths of the RIDE framework

RIDE integrates emotional analysis through a pattern analyser with aerodynamic optimisation, which according to Mamo (2018), provides a holistic design approach, and enhances the emotional and performance quality of sportbikes.

Limitations of the RIDE framework

Due to the nature of the aerodynamic aspect, the model is limited to sportsbike designs or motorcycles who are designed for performance. Additionally, the framework developed by Mamo (2018) overlooks the designers' decision-making commitments at both the early and late stages of the design process. As a result, in Mamo's (2018) approach, there is no consideration of interactions between aspects considered early and late in the design process.

5.5 Model-driven *Means*

The objective of *Model-Driven Engineering* (MDE) is to delineate a system through a range of graphical models that are comprehensible to both designers and computers. Modelling approaches are widely employed in software applications due to their effectiveness in converting abstract models of complex systems into more tangible models without any loss of information. The literature reviewed in this section illustrates the application of such approaches during the design phases of product development.

5.5.1 Geometric representation of industrial and design engineering

Schachinger et al.'s (2005) means description

According to Schachinger et al. (2005) when creating products, there's a gap between how engineers and designers work. They often use different tools and think in different ways, which makes it hard for

them to understand each other. As such, the model proposed by Schachinger et al. (2005) aims to integrate industrial and engineering design aspects through a common product structure that includes technical, and ergonomic dimensions. This would help designers involved in making a product to be on the same page from the start. This integration is facilitated by real-time interactive spatial visualisations using virtual reality (VR), enabling a comprehensive representation of product information from requirements and functions to design solutions and architecture. This helps catching problems early and make it easier for engineers and designers to work together. By leveraging VR technology, the model allows for enhanced communication and collaboration among different stakeholders in the product development process, addressing the challenge of differing mental models and expectations. The approach supports the visualisation of abstract data and descriptive, analytical, and explanatory visualisations to improve understanding and decision-making in product design.

DOP used as a case study

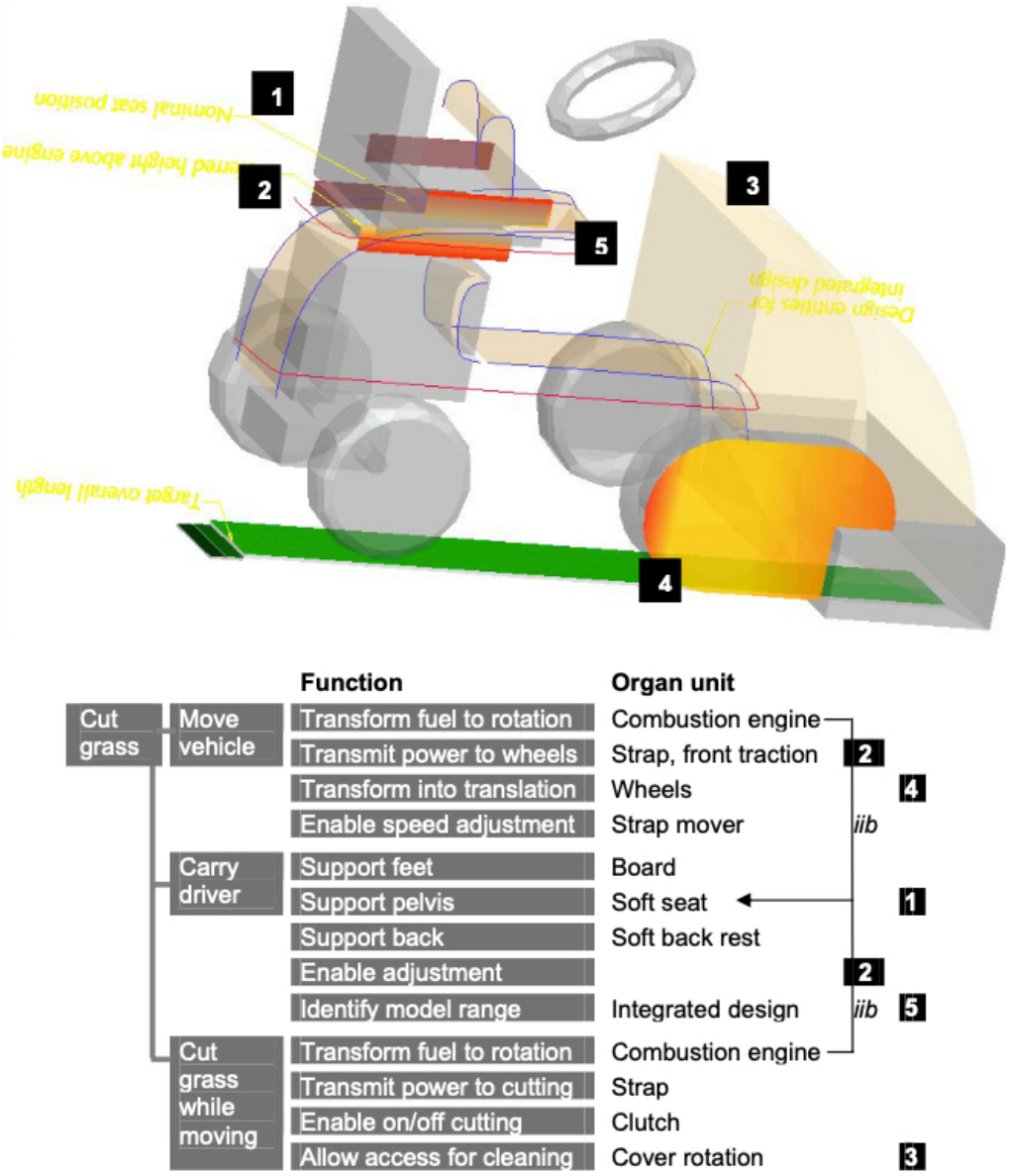
The model is exemplified through two case studies: an automotive interior cockpit unit and a ride-on lawn mower (illustrated in Figure 5.13). Through these two cases studies it is demonstrated that the model provides versatility in its application, as it facilitates the integration of diverse design aspects and promoting a holistic view of product development.

How Schachinger et al.'s (2005) model fairs compared to the review criteria

The model developed by Schachinger et al. (2005), though not explicitly, it assists engineering and industrial designers in identifying design conflicts between ergonomic and functional aspects. This assistance is provided by superimposing the ergonomic and functional 3D models onto a single model. Consequently, designers are able to visually ascertain the points of divergence between the two models.

The model is introduced late in the design process, since the product needs to be embodied in a CAD modelling software and visualised through a VR for the stakeholders to identify conflicts. Moreover,

although the engineering and industrial designers try to find a balanced product design solution, the model developed by Schachinger et al. (2005) does not offer any support guidance on how the features are harmonised together.



		Function	Organ unit	
Cut grass	Move vehicle	Transform fuel to rotation	Combustion engine	
		Transmit power to wheels	Strap, front traction	2
		Transform into translation	Wheels	4
		Enable speed adjustment	Strap mover	iib
	Carry driver	Support feet	Board	
		Support pelvis	Soft seat	1
		Support back	Soft back rest	
		Enable adjustment		2
		Identify model range	Integrated design	iib 5
	Cut grass while moving	Transform fuel to rotation	Combustion engine	
		Transmit power to cutting	Strap	
		Enable on/off cutting	Clutch	
		Allow access for cleaning	Cover rotation	3

Figure 5.13 – VR model and function-means tree including form entities, source: Schachinger (2005)

Strengths of the geometric representation of industrial and design engineering

This model enhances collaboration and knowledge integration among stakeholders, supports comprehensive visualisation of the 3D envelope of form entities, and promotes an integrated approach to product

design. As such, with this model the industrial and engineering designers have the ability to visually see any conflict between aspects.

Limitations of the geometric representation of industrial and design engineering

Although the model provides visualisations of any conflicts occurring between the ergonomic and functional aspect, no unintended consequences are provided on how this will affect the user. In addition, no recommendations are given on how the design conflicts are minimised or harmonised together.

5.5.2 Collage modelling tool

Collage modelling tool description

The study by Liao et al. (2019) introduces a *means* for evaluating product variants based on users' emotions, perceived ergonomics (i.e. ergonomics gauged from an image) and usefulness through an online tool that employs a *two-axis interactive collage*. This method enables users to express their preferences and perceptions of different wearable product variants by comparing them against emotion-related descriptive words (such as *delightful, comfortable, useful*). The goal is to uncover the emotional associations users have, with the product's form and visible characteristics, thereby providing insights into user comfort, delight, and perceived product usefulness. By focusing on the emotional impact of wearable products, this *means* offers a valuable perspective on design that goes beyond the traditional functional and usability considerations (Liao et al., 2019).

DOP used as a case study

Although Liao et al. (2019) illustrated the modelling tool through wearable products, such as spectacles, rings and bracelets, the detailed validation of the tool's effectiveness in influencing design decisions or improving product success was not explicitly discussed.

How the collage modelling tool fairs compared

While somewhat limited and open to interpretation, the *collage modelling tool* developed by Liao et al. (2019) manages to visually represent the conflicts between two human factor aspects, aesthetic-

to the review criteria

derived emotions and ergonomics. Similarly, while not explicitly guiding designers, the tool provides a step towards harmonisation. This involves comparing product variants on a 2D axis, where one axis represents ergonomic rating score and the other represents the emotion-based aesthetic rating. These rating scores are directly derived from user feedback. However, through this approach it is not possible to compare more aspects simultaneously given the limitation of the 2D axis plot, unless a higher dimensional framework is developed.

Nevertheless, this tool does not provide any insight into the use-phase consequences for either intended or general users, nor does it offer recommendations for design improvements to minimise design-stage conflicts or mitigate general user privation negative consequences during the product's use phase. Furthermore, the model is integrated late in the design process, as product variants need to be generated first, occurring after the conceptual synthesis activity.

Strengths of the Collage modelling tool

This *collage modelling tool* creates new opportunities for refining design concepts or objectives to more closely align with users' emotional needs and ergonomic preferences. It offers a rapid, straightforward, and visual method for comparing various aspects. Additionally, as product variants are directly *evaluated* by users, this modelling tool effectively captures the users' perspectives.

Limitations of the Collage modelling tool

The reliance on visual and perceptual *evaluations* via an online tool does not fully encompass the range of user interactions with wearable devices, particularly in terms of tactile sensations and long-term usage experiences. Moreover, these *evaluations* are conducted solely based on images of the product, thus lacking both context and detailed description.

Should none of the variants meet user approval or surpass a specified threshold on the 2D value axis, designers must return to the initial stages to develop additional alternatives. This process becomes increasingly complex as the number of product variants grows, especially given the absence of guidance on selecting the most appropriate solution(s).

5.6 Algorithms and Mathematical-model *Means*

Algorithms provide a step-by-step procedure for solving problems and optimising solutions. Meanwhile, mathematical models offer a foundational framework that represents and predicts the behaviour of systems without the immediate need for physical prototypes.

5.6.1 Algorithm integrating Rhino and Grasshopper

Nayak's (2015) algorithm description

Nayak (2015) presents an algorithm, illustrated in Figure 5.14, which is able to change the value of aesthetic and ergonomic norms of consumer products through a semi-automated process. Nayak (2015) applies basic design rules with the assistance of *Grasshopper* design module, a graphical algorithm editor, tightly integrated with *Rhino*'s 3D modelling tools. Aesthetics is decomposed into its essential elements like form, colour, texture and proportion. A product image is introduced as an input to the algorithm. Ergonomic anthropometric data is also applied as per target specific design process. The aim of Nayak's (2015) algorithm is to bring the automation in the field of product concept design. According to Nayak (2015), the introduction of the algorithm introduces automation in the design phase that saves time for similar product families.

DOP used as a case study

This algorithm has been illustrated through a case study for the design of a water bottle, though no evaluators from the industry practice were involved.

Manual process

1. **Procedure to obtain the basic form of the product:**
- Import image to Rhino
- Determining the contour lines of the image
- Allocate the outer surface while avoiding the inner and other textured surface lines

Automatic process

1. **Procedure to obtain the basic form of the product:**
- Exploding the lines in grasshopper and applying the Golden ratio to lines
- Determination of central axis according to the counter lines
- Plotting corresponding points to regenerate product volume
- Selection of the operation to obtain basic form like revolve, extrusion, scale, Sweep etc.

2. **Define proportion of the product**
- apply as much golden ratio relations without changing its fundamental form.
- Arguments provided to apply Gestalt Principles

3. **Anthropometric design procedure**
- Creating gripping surfaces and other ergonomic design requirements, according to hand anthropometric data

4. **Define texture of the product**
- Different surfaces with different purpose like artistic, functioning and ergonomic surfaces are provided in the algorithmwith easy manipuable forms, position, size and quantity

5. **Defining color of the product**
- Applying color properties and arguments as per masculine/ feminine preferences

6. **Manufacturing considerations**
- Manufacturing data like draft angle, minimal corner radius, finishing texture, arguments are provided

Figure 5.14 – The developed algorithm, obtained from Nayak (2015)

How Nayak's (2015) means fairs compared to the review criteria

Nayak's (2015) algorithm is employed during the early phase of the design process, to take into account the aesthetics and ergonomics aspects.

However, it does not make the designer aware of any of the product's life-phase views. Additionally, Nayak (2015) does not delineate how resolution is achieved for design conflicts, nor does it clarify whether or how harmonisation is accomplished.

<u>Strengths of the algorithm integrating Rhino and Grasshopper</u>

Given that the designer inputs an image file and the algorithm outputs a CAD file, this semi-automated process is streamlined, saving time when designing similar product families. Additionally, by adjusting various aesthetic and ergonomic variables, the designer creates

multiple types of product configurations, thereby generating a range of different ideas.

Limitations of the algorithm integrating Rhino and Grasshopper

The algorithm developed by Nayak (2015) operates based on predefined rules extracted from literature, reflecting predictable behaviour, rather than aesthetic-derived emotions sourced directly from (potential) customers. Thus, it fails to capture the varied emotions elicited by users towards the same product. The algorithm and the parameters within *Grasshopper* are tailored for a specific product family. If a designer wishes to semi-automate the design of a different class of products, a new algorithm is required and must be reprogrammed each time. Moreover, this semi-automatic process may limit designers' creative freedom by diminishing the role of traditional sketching, which is typically used to incorporate topological values into the design.

5.6.2 Multifactor fusion method for product form optimisation

Zhou et al.'s (2023) means description

Zhou et al. (2023) proposed an algorithm (seen in Figure 5.15) to optimise product form that integrates aesthetics and ergonomics using computational aesthetics, *entropy* methods, ergonomic evaluations, and *non-cooperative game theory*. The algorithm starts by establishing a quantitative aesthetic index system for product form, utilising computational aesthetics, that is, use of mathematical equations to objectively quantify and evaluate aesthetic aspects. The *entropy* method is then applied to derive objective weights for these aesthetic indices, ensuring a comprehensive evaluation that overcomes subjective biases. Concurrently, ergonomic evaluation is conducted by comparing actual design parameters with established ergonomic standards, highlighting the algorithm's emphasis on user comfort and functionality. Sensitivity analysis is used to identify key design parameters that significantly impact the product's aesthetic and

ergonomic performance, streamlining the optimisation process. By employing *non-cooperative game theory*, the method treats aesthetic and ergonomic *evaluations* as competing players in a game, seeking a *Nash equilibrium* (Zhou et al., 2023). This algorithm allows for a multifactorial fusion of design elements, ensuring that the final product is not only aesthetically pleasing but also ergonomically sound.

DOP used as a case study

The algorithm is exemplified through the design optimisation of a hand-held translator device (electronic device for language translation), showcasing its practical applicability and effectiveness in achieving a harmonious balance between aesthetics and ergonomics.

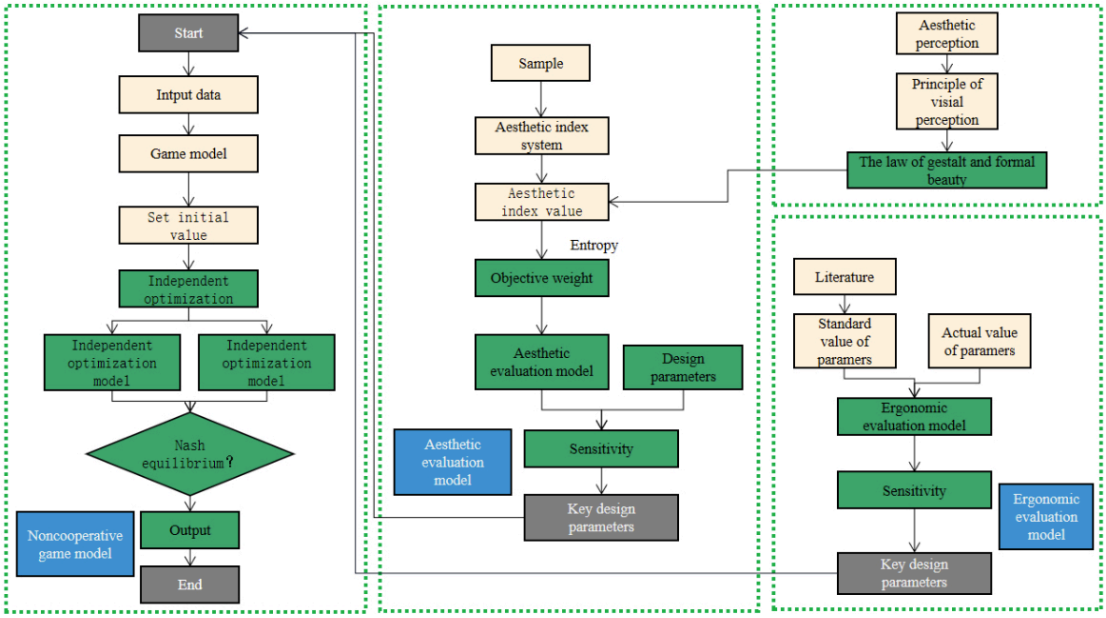


Figure 5.15 – The multifactor fusion method for product form algorithm, source: Zhou et al. (2023)

How Zhou et al.'s (2023) algorithm fairs compared to the review criteria

As indicated above, the algorithm features a harmonisation module to harmonise the two human factors: aesthetics and ergonomics, through a *non-cooperative game theory* form of optimisation.

The algorithm is integrated in the late design activity process, specifically in the evaluation design activity. Moreover, Zhou et al. (2023) do not provide awareness of unintended consequences or recommendations for mitigating design-stage conflicts or population majority use-phase adversities.

Strengths of the multifactor fusion method for product form optimisation

Traditionally, methods for solving multi-objective optimisation problems have difficulties such as high computational effort and poor convergence (Zhou et al., 2023). Zhou et al. (2023) introduces the *non-cooperative game theory* into the process of product form optimisation design by combining its strong advantages and robustness in solving multi-objective optimisation problems with a less computational effort.

Limitations of the multifactor fusion method for product form optimisation

The authors reported that the algorithm cannot consider a series of dynamic postures that are closely related to the human movement process, since it reduced the accuracy and reliability of the ergonomic *evaluations*. Data is captured from literature and not directly from users. As such, Zhou et al. (2023) do not consider the attitude and behavioural interaction of the user with the product, and the proposed solution is of an evaluative type.

5.7 Data-driven *Means*

Contemporary research extensively concentrates on the automatic extraction of information directly from users, highlighting the importance of efficiently capturing their needs, particularly in contexts where big data is prevalent. Developments in this area have been directed towards predictive and generative AI technologies. These initiatives begin by extracting information from large data sources, with computers being trained to make predictions to support designers or generate design solutions.

5.7.1 A user-centred virtual product based on Kansei Engineering

Chuah & Teh's (2008) data-driven support system description

This research by Chuah & Teh (2008) introduces a data-driven design support system that employs *Kansei Engineering* to develop spectacle designs that resonate with users' emotional and ergonomic expectations. Web-based *Kansei* survey is used to collect data from a wide variety of users. Through the application of desktop VR, the data-driven approach allows users to interact with and *evaluate* 3D models of spectacles, based on predetermined emotional and ergonomic criteria (i.e. predicting spectacles form based on the user-selected *Kansei* words). This system whose graphical user interface is illustrated in Figure 5.16, aims to facilitate designers in creating spectacles that not only meet the ergonomic needs of teenagers but also appeal to their aesthetic preferences and emotional sensitivities. The data-driven emphasises a UCD process, highlighting the importance of incorporating user feedback early in the design stage to ensure the final product aligns with the users' desires and requirements.

DOP used as a case study

Chuah & Teh (2008) describe empirical pilot case studies of virtual spectacles used to test the design support system.

How Chuah & Teh's (2008) means fairs compared to the review criteria

This data-driven approach emphasises early integration of ergonomic (comfort, usability) and emotional (aesthetic appeal, feel, and look) aspects in the spectacle design process, particularly through the use of a *Kansei Engineering*-based design support system from the initial stages of design.

The data-driven approach fails to provide the designer with awareness of both the design (DCCs) and use phases (PUCs), lacking both support and recommendations. Additionally, this approach does not incorporate the persona human factor, and there is no explanation provided regarding harmonisations or whether trade-offs are considered.

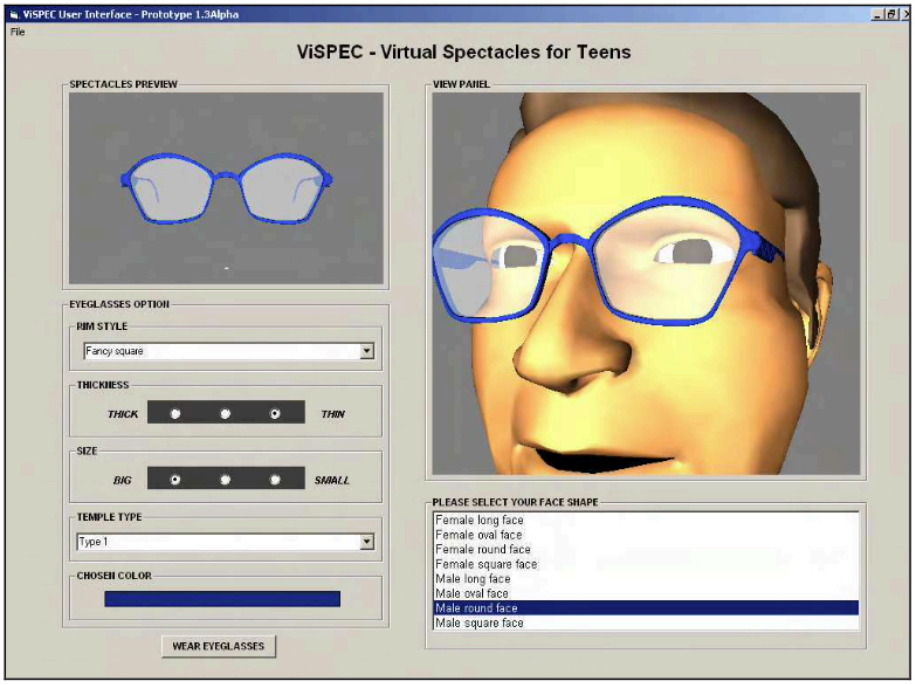


Figure 5.16 – The ViSPEC user interface prototype, obtained from Chuah & Teh (2008)

Strengths of the user-centred virtual product based on Kansei Engineering

The integration of *Kansei Engineering* and virtual reality presents a novel approach to spectacle design, enhancing user involvement in the design process and potentially increasing user satisfaction by aligning product characteristics with user preferences.

Limitations of the user-centred virtual product based on Kansei Engineering

Chuah & Teh (2008) suggest that the implementation of the system requires specialised technical knowledge and resources. Moreover, as described in the preceding paragraph, the terms used, capture both emotions and ergonomics. This implies that the ergonomic value assigned by participants is based on perception, rather than on any discomfort experienced when wearing the spectacles over a prolonged period.

5.7.2 Means based on learning from users through Artificial Neural Networks (ANNs) and balance through Genetic Algorithms (GAs)

Tseng et al.'s (2012) means description

The *means* developed by Tseng et al. (2012) integrates *Artificial Neural Networks* (ANNs) and *Genetic Algorithms* (GAs) to optimise product designs by concurrently considering stylistic form and functional requirements. Through survey data, consumer perceptions of stylistic attributes such as sportiness, ruggedness, and beauty are quantitatively modelled using ANNs. These models then guide the optimisation process, managed by GAs, to generate designs that not only meet functional performance criteria but also appeal to consumer stylistic preferences. This data-driven approach facilitates a balance between often competing design goals.

DOP used as a case study

By enabling computers to account for and optimise stylistic form judgments alongside traditional functional evaluations, the *means* showcase its application through vehicle exterior design examples. Vehicles, particularly car designs, are used to demonstrate the applicability of the proposed *means*.

Tseng et al.'s (2012) data-driven means fairs compared to the review criteria

Although Tseng et al. (2012) do not specify where this *means* can be introduced in the design process, it is deduced that its utilisation window is in the early design phase given that the *means'* outputs artificial generated conceptual sketches.

The *means* simultaneously and interdependently support aesthetic and functional aspects, striving for a harmonised process that mediates between these aspects and reconciles conflicts between functional requirements and stylistic preferences. However, Tseng et al. (2012) neither highlight nor explain how these conflicts are managed. Moreover, the data-driven *means* do not address use-phase consequences (PUCs) nor do they offer recommendations for design improvements.

Strengths of the 'learn from users through ANNs and balance through GAs' means

This data-driven *means* helps companies understand what their customers really want in the look and feel of a product, not just how it works, given that data is directly collected from potential customers.

Limitations of the 'learn from users through ANNs and balance through GAs' means

The *means* operates autonomously, which, while efficient, potentially stifles creativity by not allowing room for designer input or innovation. It also fails to offer any support or recommendations to the designer, which helps in mitigating adverse outcomes or in suggesting viable alternatives. Furthermore, the inability to identify and address design conflicts within the method restricts its capability to optimise design processes and outcomes effectively.

5.7.3 Product Concept Generation based on Deep Learning and Kansei Engineering (PCGA-DLKE)

PCGA-DLKE means description

The *PCGA-DLKE* data-driven approach developed by Li et al. (2021) assists industrial designers by automatically generating product concepts that align with users' emotional preferences whilst perceiving the level of comfort from a generated image. This approach employs *Kansei Engineering* for establishing an emotion-based recognition model that leverages *deep convolutional neural networks* to mark users' emotional and perceived ergonomic preferences. As seen in Figure 5.17, a product design *Generative Adversal Network (PD-GAN)* model generates product conceptual images for quickly creating designs that meet consumer emotional and ergonomic needs. Furthermore, an improved *fast neural style transfer network* facilitates the adaptation of products to users' style preferences.

DOP used as a case study

Li et al. (2021) illustrated this data-driven approach through two case studies of designing hand-held electric tools (drills and screwdrivers) and bicycle helmets, though no evaluators from the industry were involved.

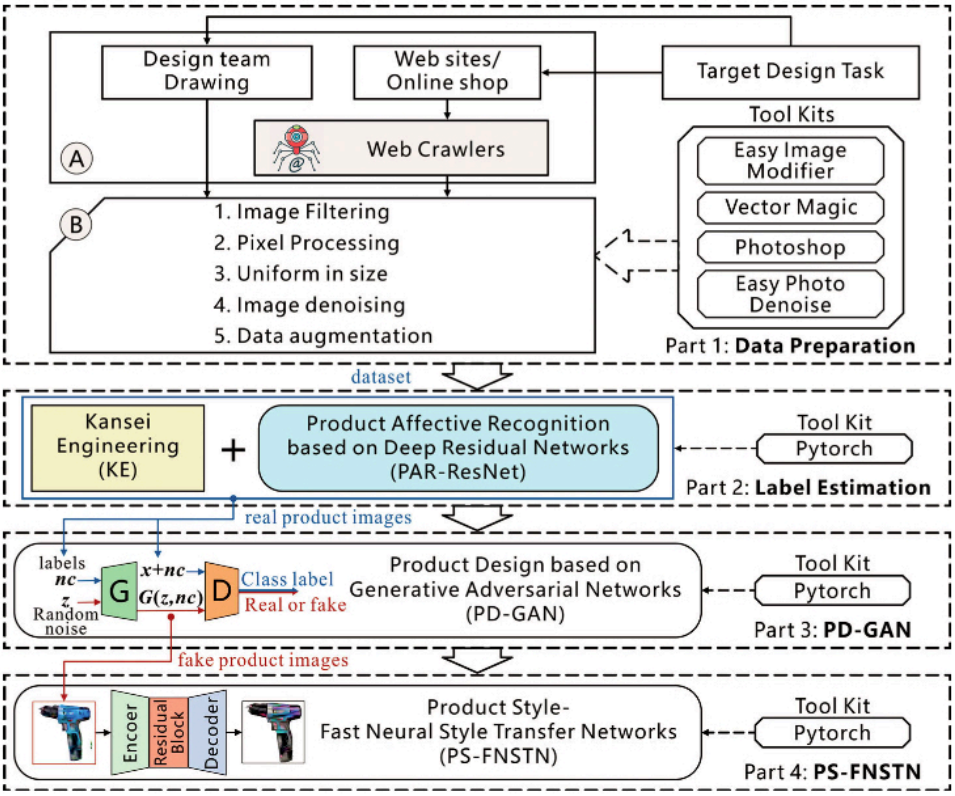


Figure 5.17 – The product concept generation approaches framework based on deep learning and Kansei Engineering (PCGA-DLKE), source: Li et al. (2021)

How PCGA-DLKE fairs compared to the review criteria

Owing to the characteristics of the data-driven approach, the *means* is used during the initial activities of the conceptual design stage as it proficiently generates product variants with varied emotional and ergonomic characteristics for intended users. Additionally, it implicitly provides a design-stage view through a visual method. However, it offers no guidance on how to minimise conflicts at the design stage.

Since the designer is required to select a scale of emotions and ergonomics, and the tool generates an image based on these values, it does not automatically harmonise the concepts nor does it support the requirements of the general user.

Strengths of the PCGA-DLKE

This approach not only streamlines the design process by producing viable product concept, reflective of emotional considerations but also enhances *Kansei Engineering* and *generative AI* by allowing designers to explore various conceptual designs efficiently.

Limitations of the PCGA-DLKE

The downside of *PCGA-DLKE* is that ergonomics are perceived, that is, the user has to perceive the product's ergonomic from an image and not from an real and physical product interaction. Furthermore, given the nature of the *generative AI* approach it may replace the designers' creativity.

5.8 Hybrid *Means*

The approach that employs a combination of one or more approaches outlined from Sections 5.3 to 5.7 is defined herein as a hybrid *means*.

5.8.1 Experimental tests with a CAD framework approach

Barone & Curcio's (2004) hybrid means description

The study carried by Barone & Curcio (2004), focuses on a CAD based system for ergonomic analyses of motorcycles. This hybrid *means*, depicted in Figure 5.18, integrates a CAD framework with a methodology for motorcycle design, a widely used anthropometric database and specific behavioural model (persona) defined by an experimental procedure correlating driving postures and vehicle configurations. Barone & Curcio (2004) suggest that the developed design framework is able to represent 3D models of vehicle configurations and equipment, 3D human models of various anthropometries and *evaluative* techniques to assess reach and postures. Vehicle designers are able to use a single analysis tool to predict and assess postural comfort, from the earliest stages of the design process.

DOP used as a case study

In the study conducted by Barone & Curcio (2004), there is no indication that the hybrid motorcycle approach was evaluated in collaboration with designers.

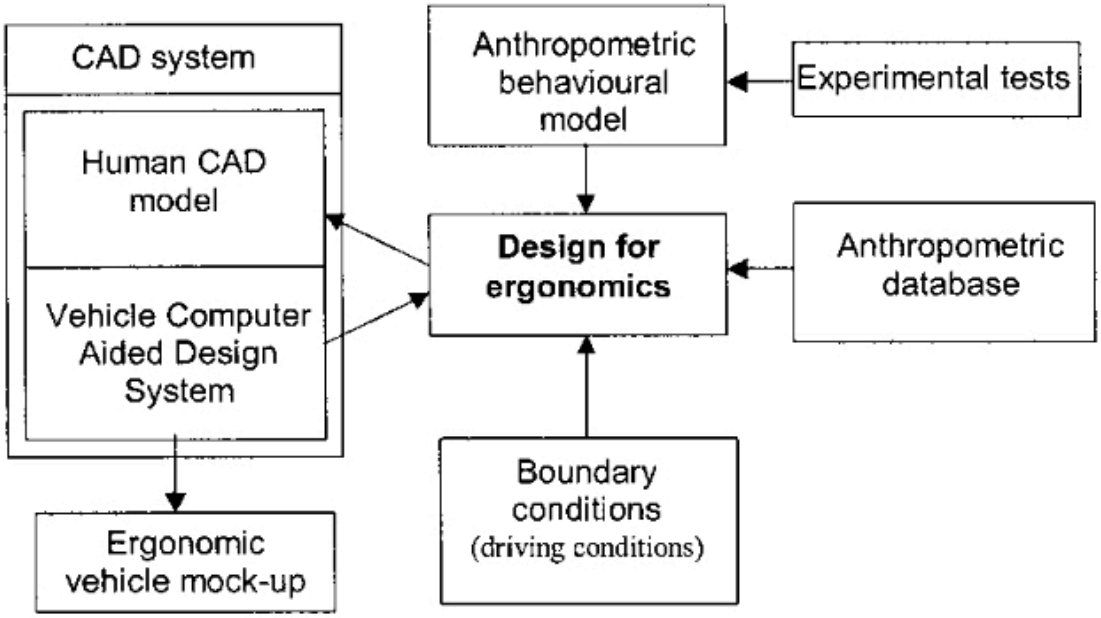


Figure 5.18 – Scheme of the ergonomic and behaviour analysis, obtained from Barone & Curcio (2004)

How Barone & Curcio's (2004) hybrid means fairs compared to the review criteria

The *means* focus on the ergonomic human factor with a limited consideration of the persona. The latter is represented by context analysis to understand product vibration. This *means* allows changing the reference population, while keeping the same human body sets and recalculating their relative weight for the population under study. This aspect allows to test the motorcycle for various body sizes and weight. As such, use-phase awareness supports the designer for both target and general riders.

The inclusion of CAD human models and the use of the framework in a CAD environment means that the support is given at the embodiment design stage and therefore support is offered late in the design process. Furthermore, Barone and Curcio's hybrid *means* is not able to handle design-stage conflicts between the highlighted human factors. Also, Barone & Curcio (2004) do not specify if their hybrid approach guides designers towards a harmonised solution.

Strengths of the experimental tests with a CAD framework approach

Evaluating the comfort feeling on motorcycles, by considering the posture, the loads and performance tested with users during the design phase, instead of after the first prototype.

Limitations of the experimental tests with a CAD framework approach

Given the use of 3D CAD human models/manikins to assess ergonomic posture, this approach is usually limited to the analysis of static posture and static work. The quality of knowledge gained through physical experiments can be superior compared to a digital human modelling (DHM) approach (Högberg et al., 2019). With DHM there is a limit of what can be captured, while through physical experiments it is possible to better understand some micro ergonomic aspects, which are difficult to analyse in simulation studies Barone & Lo Lacono (2015).

5.8.2 Human Anthropometric Data Requirements Investigation and Analysis (HADRIAN)

HADRIAN description

The hybrid *means*, combining data-driven with model-driven approach, presented by Marshall et al. (2015), incorporates ergonomic user needs into product design through personas and user datasets. Personas, defined as descriptive models of archetypical users based on user research, serve to embed a psychological understanding of users within the design process. They encapsulate users' goals, motivations, and behaviours, aiding designers in envisioning users' requirements. However, according to Marshall et al. (2015) personas alone do not provide all the necessary technical details, especially concerning physical attributes and capabilities. This gap is bridged by user datasets and the *HADRIAN* system, illustrated in Figure 5.19, which offers detailed anthropometric, strength, and performance data (Marshall et al., 2015). The system facilitates the simulation of design interactions

through 3D virtual model fitting trials, allowing for an *evaluation* of product accessibility and user inclusivity.

DOP used as a case study

Marshall et al. (2015) demonstrate their research through case studies, specifically detailing the use of the *HADRIAN* system to assess accessibility in real-life scenarios, rather than concentrating on particular products.

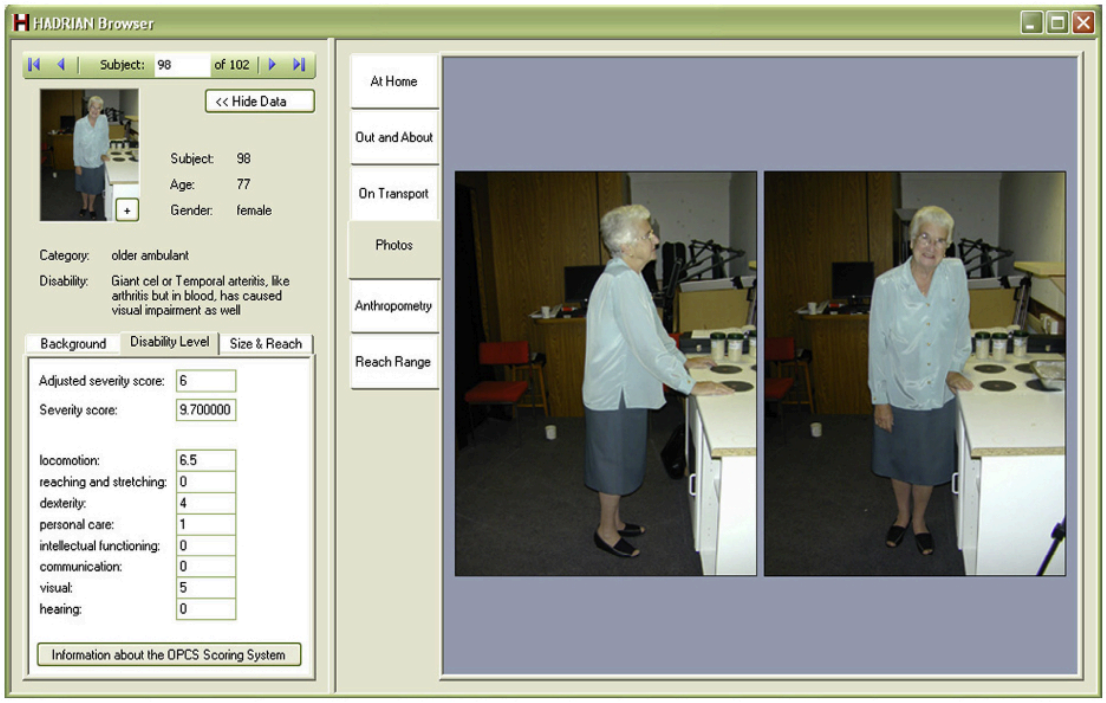


Figure 5.19 – An individual presented in HADRIAN, source: Marshall et al. (2015)

How HADRIAN fairs compared to the review criteria

HADRIAN is employed at the task clarification stage, prior to product conception, to ascertain requirements and understand how the persona interacts both physically and psychologically. However, *HADRIAN* is also used in the simulation activity when the product concept is embodied and designers want to see how the user group interacts with it. The *means* presented by Marshal et al. (2015) supports the product's use-phase view, where indirectly makes aware of unintended consequences through simulation. *HADRIAN* provides designers with support to understand how different users with physical and psychological inabilities behave in real world.

On the other hand, *HADRIAN* does not highlight recommendations for design improvements or design-stage conflict between persona and

ergonomics. Therefore, no harmonisation guidance is provided by this approach.

Strengths of HADRIAN

HADRIAN offers a comprehensive understanding of users' needs, where it combines psychological and physical data for inclusive design. In addition, it facilitates empathy with users and supports early design evaluation through a UCD approach.

Limitations of HADRIAN

The reliance on archetypal users do not fully capture the range of user abilities and needs, and detailed technical information on specific accessibilities will be insufficiently detailed in personas (Marshall et al., 2015).

5.8.3 Interactive virtual prototyping (iVP) based on Perceptual Mock-Up (PMU)

iVP-based PMU means description

Bordegoni et al. (2014) present an emotional engineering hybrid *means* that integrates user emotional responses directly into the product design phase through *interactive virtual prototyping (iVP)*. This approach allows for the simulation of product interactions in a virtual environment, enabling designers to assess and optimise user ergonomics and emotional reactions to the product before it is physically realised. At the prototype design stage, a *'Perceptual Mock-Up' (PMU)* is created (Bordegoni et al., 2014). This is a simplified virtual model that simulates the controller's essential features and how users interact with it. Designers then adjust this virtual model, based on feedback from actual users, tweaking the design until it matches the emotional and physical feeling of the target user, through the *iVP-based PMU*. This approach is illustrated in Figure 5.20. Through this *means* a correlation is made between the physical characteristic of the virtual prototype, the values of the parameters defining its behaviour,

and the kind of satisfaction and emotional reactions elicited in the designer.

DOP used as a case study

The *means* developed by Bordegoni et al. (2014) was validated in the industry with one expert designer using a real case of a refrigerator.

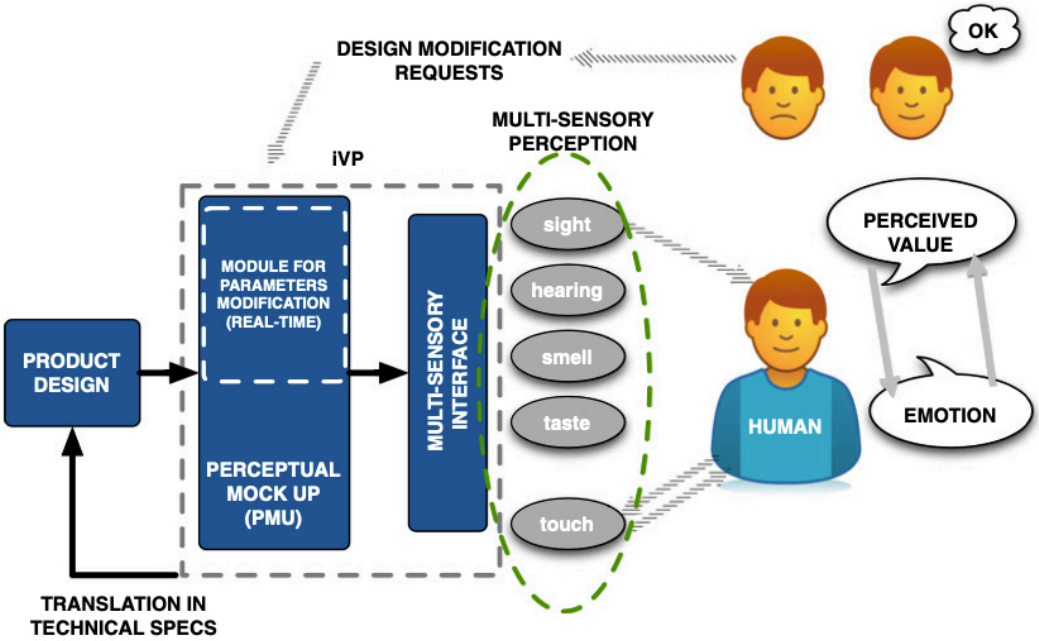


Figure 5.20 – iVP based on PMU for the evaluation of the user experience, obtained from Bordegoni (2014)

How the iVP-based PMU fairs compared to the review criteria

The *iVP-based PMU* integrates users in the design process and therefore simulating the use phase. From users' feedback, parameters are altered to optimise the product. For example, a suitable placement of the door handle is found that satisfies the ergonomic and visual aesthetic needs. So, indirectly this is a type of harmonisation that the user, together with the designer, are finding. However, this hybrid approach is highly bespoke and therefore very specific to the user group who are interacting with the prototype, thus no general user consideration and no support for PUCs.

Given the fact that the virtual prototype needs to be embodied and that the physical mock up needs to be build, this pushes this hybrid *means* to the simulation embodiment design activity, which is rather late in the design process.

Strengths of the iVP-based PMU

This hybrid *means* enables users to interact directly with the *iPV* during the use phase, ensuring immediate feedback and direct user involvement, which contributes to rapid iterations and improvements. This direct interaction is complemented by the *means*' ability to significantly reduce costs through the *PMU*, making the development process more accessible and economical. Furthermore, the flexibility to customise the virtual prototype according to individual user needs, not only maximises emotional connection, but also increases user satisfaction by tailoring the product to specific preferences and requirements.

Limitations of the iVP-based PMU

While *iVPs* allow for early-stage testing and iteration, there are aspects of physical interaction and emotional response that are not fully replicated in a virtual environment. The transition from a virtual prototype's perceived experience to a physical product's actual experience will introduce discrepancies. Furthermore, the effectiveness of *iVP*s for emotional engineering rely heavily on the technology used for virtual prototyping, including the realism of virtual environments and the accuracy of multi-sensory simulations. Any constraints in these technologies will limit the depth and accuracy of user experience insights.

5.8.4 Human factors deconstruction hybrid approach

Chandra's (2018) means description

The hybrid *Kansei Engineering*-based methodology, depicted in Figure 5.21 was developed by Chandra (2018). This methodology aims to quantify aesthetics through mathematical modelling in motorcycle design. It bridges the primary subjective perception of aesthetics and limited integration to rider experience through ergonomics and functional design with objective, quantifiable measures. By

deconstructing down aesthetics into components such as emotions, *user experience, form and unity* Chandra (2018) provides a *means* for analysing and *evaluating* motorcycle designs based on mathematical models. This approach allows designers to systematically assess the aesthetic appeal of motorcycles, considering both the ergonomic experience and emotional impacts of product design elements (PDEs). For instance, according to Chandra (2018) a well-designed ergonomic product that is comfortable and easy to use elicits positive emotional responses.

DOP used as a case study

Chandra (2018) validated this hybrid *means* in the design of different motorcycle types and styles with several evaluators in the motorcycle industry practice.

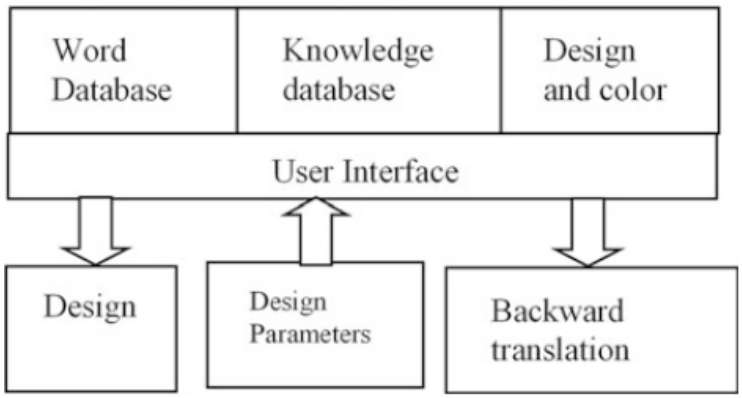


Figure 5.21 – Kansei Engineering-based approach, source: Chandra (2018)

How Chandra's (2018) hybrid means fairs compared to the review criteria

Given that the approach is about the deconstruction of motorcycle elements into emotions and vice-versa, the method is suitable for the synthesis design activity.

On the other hand, the method falls short in identifying and resolving conflicts that arise during the design process, nor does it provide strategies for harmonising elements to enhance the overall design. There is also a notable absence of provisions for refining the design to avert potential negative emotional impacts during the use phase.

Strengths of the human factors deconstruction hybrid approach

Chandra (2018) put forward a systematic and quantifiable approach to evaluate ergonomics and aesthetics in motorcycle design, facilitating a

deeper understanding of how PDEs influence user perception and emotions.

Limitations of the human factors deconstruction hybrid approach

While grounded in quantifiable measures, Chandra's (2018) *means* possesses limitations due to its inability to encompass the inherently subjective domain of aesthetic appreciation, which is notably diverse across individuals. This quantitative focus overlooks the critical aspect of persona, which is essential for creating designs that resonate with target and general users on an emotional level.

5.8.5 Application for Computer-Aided Design of Emotional Impressions and Physical capacities (ACADE+P) hybrid approach

ACADE+P description

The *ACADE* hybrid methodological and data-driven approach (refer to Figure 5.22) first presented by Zöller & Wartzack (2017), then refined to *ACADE+P* Buker et al. (2021), seeks to bridge the gap between usability (from a persona perspective) and emotional design in product development. Recognising the importance of integrating functional and emotional aspects, *ACADE+P* outlines a systematic method for incorporating users' persona capacities and emotional impressions into the design process. This methodology consists of several steps: defining users and product characteristics; *evaluating* the product against users' capacities and emotional expectations; and deriving data-based recommendations for design improvements. By utilising *semantic differentials* for profiling both the product and the user, *ACADE+P* allows an understanding of how a product's design influences user perception and interaction on an emotional and physiological level.

DOP used as a case study

Although the presented hybrid *means* uses a keyboard product as a case study to exemplify the approach, the authors state that *ACADE+P* is not evaluated.

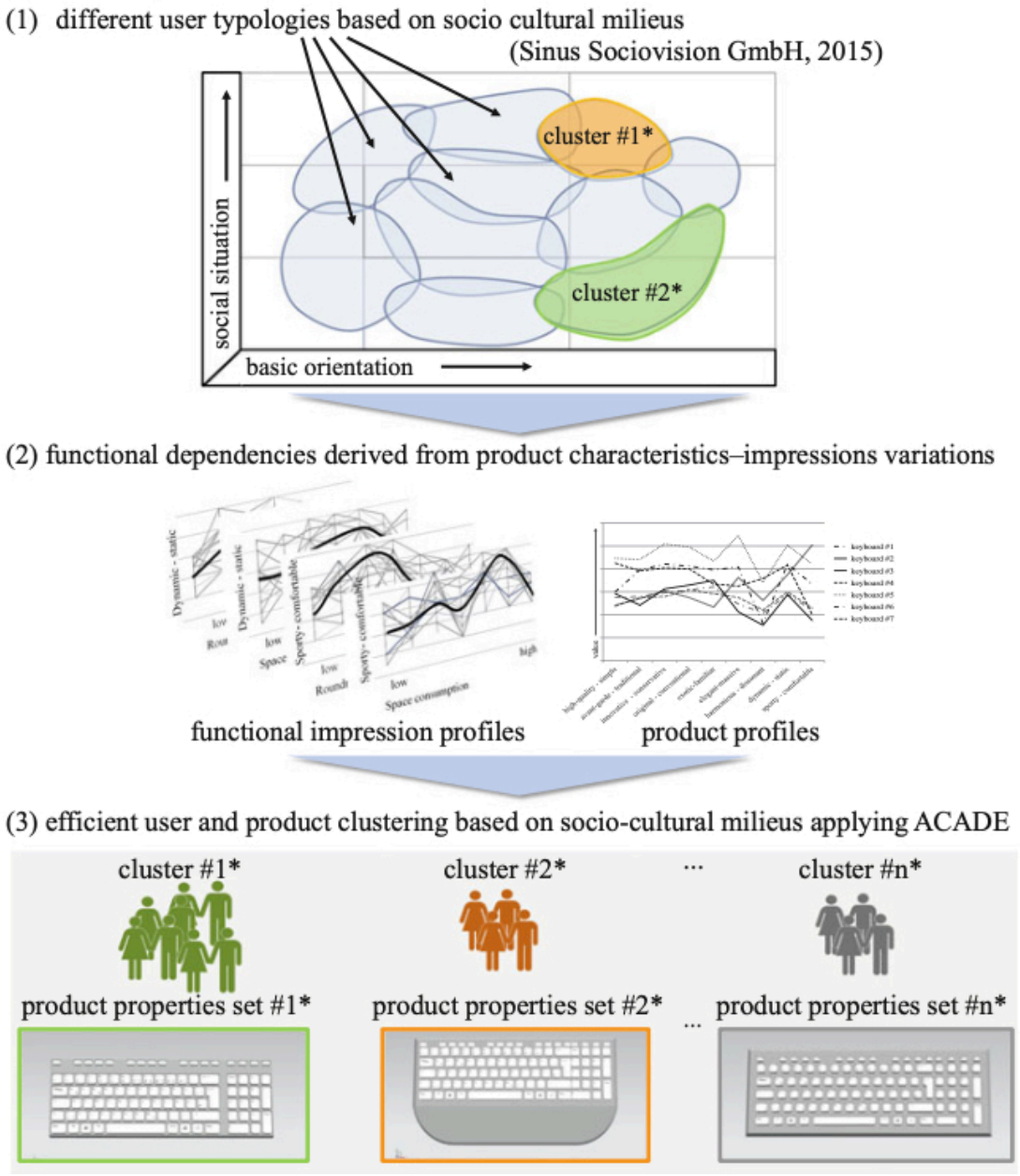


Figure 5.22 – The ACADE+P hybrid approach, obtained from Zöller & Wartzack (2017)

How ACADE+P fairs compared to the review criteria

ACADE+P exemplifies a shift towards a more holistic view of product design supporting the target and the population majority product's use phase.

Notwithstanding the above, no support and recommendations are given to minimise design stage-stage conflicts between different aspects. No reference to harmonisation is either made in Buker et al. (2021) or Zöller & Wartzack (2017). The approach adopted by *ACADE+P* is to have clusters of users (seen in Figure 5.22) with their optimised product variants, but what product will be developed is not specified in neither of the paper. Furthermore, embodied CAD 3D models need to

be administered to the users, as part of a structured survey. This indicates that *ACADE+P* is more suitable in the later design stages.

Strengths of the ACADE+P

The main strong point of the *means* developed by Buker et al. (2021) and Zöller & Wartzack (2017) lies in its robust UCD philosophy, emphasising the creation of products that resonate deeply with users. It proficiently segments different personas and allocates the most suitable product variation to each whilst considering socio-cultural clusters. Therefore, tailoring experiences that cater to the nuances of diverse user groups.

Limitations of the ACADE+P

ACADE+P fails to offer recommendations that could improve the product or minimise negative consequences in the product's use phase. Particularly no guidance concerning design-stage conflicts is provided to the designers using *ACADE+P*.

5.9 Summary of the Review Findings

Current state of means supporting design of DOP

This literature review was motivated by the challenges designers face during the conceptual synthesis design activity. As discussed in Chapter 4, there is a need for *means* that proactively provides human factor and harmonisation knowledge on DCCs and PCCs during early DOP design synthesis. The characteristics of the reviewed *means* are consolidated in Table 5.2. From the review criteria employed, the following key observations are made on how DOP design is currently being supported from a multi human factors (hf[1]-Multi X) perspective.

5.9.1 The means provide a combination of early and late support during the DOP solution analysis activity

Timing and Activity

Whilst the majority of the *means* provide support at the early routine design process, facilitating in the task clarification or conceptual

sketching, only Farrugia & Borg (2016) and Chandra (2018) provide proactive support during the conceptual synthesis design activity of DOPs.

5.9.2 DOP designers are not made aware of both DCCs and PUCs resulting from DOP decision commitments

Multiple life-phase views

Half of the *means* reviewed do not provide any awareness of either the design or use phase of DOPs, while Farrugia & Borg (2016) do support designers with insights pertinent to the product's manufacturing life during the synthesis design activity. Furthermore, only a minority of these single life-phase views, such as Barone & Curcio (2004), recommends the designer to mitigate or avoid negative consequences for both the intended and general user. Additionally, none of the *means* reviewed support multiple life-phase views nor provide recommendation to minimise negative consequences of:

i. Human factors considered at a later design stage and activity (DCCs)
ii. DOP's use phase for both intended and non-intended users (PUCs)

5.9.3 None of the means concurrently considers ergonomics, aesthetic-derived emotions and persona together ($hf_{E\text{-}AE\text{-}P}$)

Guidance type

A key boundary of the literature search was to focus on *means* that consider multiple aspects concurrently (i.e. Multi X), with the requirement that at least one of these aspects belonged to $hf_{E\text{-}AE\text{-}P}$ (i.e. hf^{1}-Multi X). Although some of the *means*, such as the work of Hoyos-Ruiz et al. (2017), Shigemoto (2020), Kaljun & Dolšak (2011), Marshall et al. (2015) and Buker et al. (2021), reviewed do concurrently consider two of these human factors, none simultaneously address ergonomics, aesthetic-derived emotions, and persona together.

5.9.4 The means do not facilitate guidance towards a harmonised solution encompassing all $hf_{E\text{-}AE\text{-}P}$

Harmonisation awareness

The literature review reveals that the majority of the *means* offer limited harmonisation, such as Francalanza et al. (2019), Schachinger et al. (2005) and Liao et al. (2019), or fail to provide any balance or trade-off among the aspects considered. Other *means* reviewed achieve harmonisation between at most two aspects, example Bordegoni et al. (2014), Tseng et al. (2012) and Zhou et al. (2023). Consequently, none of the *means* reviewed promote awareness of harmonisation for the following:

i. Ergonomics
ii. Aesthetic-derived emotions
iii. Persona—Target User
iv. Persona—General User

5.10 Chapter Conclusions

Critical review

This chapter has provided a critical literature review, establishing that numerous *means* have been developed within research to support Multi X DOP design. These existing design support *means* encompass a broad spectrum of assistance and further underscore the necessity for supporting DOP design from an hf-Multi X perspective.

Research gap

With respect to the established four review criteria, it can be concluded that there is a research gap in the literature, diagrammatically depicted in Figure 5.23. This illustrates that none of the *means* reviewed contribute directly to proactively support DOP designers by making them aware of DCCs and PUCs with multi human factors ($hf_{E\text{-}AE\text{-}P}$) and harmonisation knowledge during the DOP conceptual synthesis design activity. The research problem associated with this gap will be formulated in the subsequent chapter and addressed in *Part C* of this doctoral dissertation.

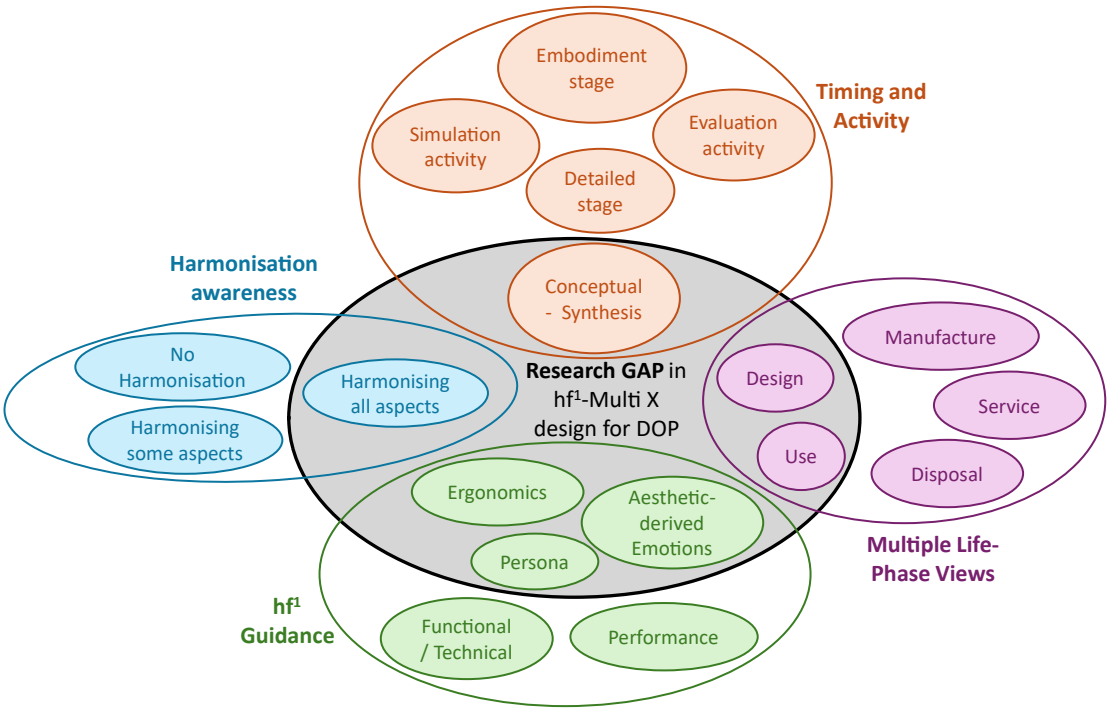


Figure 5.23 – Doctoral research gap

Table 5.2 – Summary of reviewed state-of-the-art

Year	Authors	Review Criteria: Timing and Activity *(E) Early* *(L) Late* *(N) None / Not Specified*	Review Criteria: Life-Phase Views *(D) Design* *(M) Manufacturing* *(U) Use* *(W) Disposal* *(O) Others* *(N) None / Not Specified*	Review Criteria: hf[1] Guidance *(E) Ergonomics* *(AE) Aesthetic-derived Emotions* *(P) Persona* *(O) Other*	Review Criteria: Harmonisation / Balance / Trade-off *(A) All* *(S) Some* *(N) None / Not Specified*	Notable + Strengths / - Limitations	Validation evidence / [DOP used]
Methodology-based approach							
2005	Lee	(E)	(N)	(E), (AE) and (O) - Performance	(N)	+ Prioritises functional, ergonomic and user satisfaction attributes right from the very start of the design process. - It does not adequately capture 'must-be' (basic) needs and 'attractive' needs given that the approach focuses on multiple aspects at such an early stage of design.	Not validated in practice [Hand tools through screw drivers]
2014	Jiang et al.	(E)	(N)	(AE), (O) – Functional and limited support on (E)	(A)	+ Systematic way to simultaneously consider design for emotions and engineering specifications, through the use of several techniques. - Needs and desires of customers captured by this methodology are static. In reality, these are dynamic.	Illustrated through 1 case study but not evaluated in practice [Mobile phones]
2016	Göloğlu & Zurnaci	(N)	(U)	(AE), (O) – Functional and limited support on (E)	(N)	+ 3D customised product based on customer selection, without letting the customer be involved in the design process.	Illustrated through 1 case study but not evaluated in practice

Year	Authors	Review Criteria: Timing and Activity	Review Criteria: Life-Phase Views	Review Criteria: hf[1] Guidance	Review Criteria: Harmonisation / Balance / Trade-off	Notable + Strengths / - Limitations	Validation evidence / [DOP used]
						- It does not provide any indications on what happens when there is a conflict between two human factor aspects. - Based on DOP which are simple and modularised.	[Ironing board]
2015	Kajtaz et al.	(L)	(U)	(AE), (P) and (O) - Functional	(S)	+ Highly user-centred and activities are run in parallel to reduce product development time. - Highly personalised and therefore difficult to implement for mass produced products.	Presented through 1 case study but not evaluated in practice [Personalised cricket faceguard]
2017	Hoyos-Ruiz et al.	(E) to (L)	(D) - Limited	(E), and limited support on (P)	(A)	+ Users directly involved in the design, potentially leading to products that are more user-friendly, safe, and goes well with the target users' group. - Personality and behaviour are missing, while general users are not included in this methodology.	Illustrated through 1 case study of a preliminary conceptual redesign but not evaluated in practice [Wearable carrier vest]
2019	Francalanza et al.	(E) to (L)	(D) - Limited	(AE) and (O) - Functional	(A) - Limited	+ Facilitate collaboration between industrial and engineering designers to better meet the explicit and implicit needs of users. - Potential challenges arise in aligning divergent priorities of multidisciplinary teams and ensuring that emotional design does not compromise functional requirements.	Validated the methodology with evaluators in practice [Professional high-speed video camera]
2019	Shigemoto	(E)	(N)	(AE) through (E), (O) – Marketing	(N)	+ Perspective on design management that facilitates the integration of engineering, ergonomics and marketing insights to enhance emotional engagement with products.	No validation carried out

Year	Authors	Review Criteria: Timing and Activity	Life-Phase Views	hf[1] Guidance	Harmonisation / Balance / Trade-off	Notable + Strengths / - Limitations	Validation evidence / [DOP used]
				and Design management		- Not implemented in a proof-of-concept or validated through a case study or in the industry practice.	
Ontology-based approach							
2006 - 2012	Kaljun; Kaljun & Dolšak; Kaljun et al.	(E) to (L)	(U) – for ergonomics	(E) and (AE)	(A) – only in framework	+ This system offers advice and recommendations for improvement on how to enhance the ergonomic and aesthetic value of products. - Does not capture the different emotions elicited by users for the same product. - Generates recommendations to improve an already existent product rather than support the designer during the synthesis of a new product design.	Demonstration through several case studies only for the ergonomic recommendation engine [Hand (power) tools]
2016; 2017	Farrugia; Farrugia & Borg	(E)	(M)	(E) and (O) – business performance (cost, time and quality)	(N)	+ Enhances awareness of the impact of design decisions on human emotional states, facilitates exploration of alternative design commitments and recommends solutions to minimise manufacturing use-phase consequences. - Does not consider variable behaviour which occurs when the same product interacts with various machine operators having different emotions, anthropometric data and persona. In such a case balance of the aspects is key to reach as many customers as possible, and not only those customers for whom the product is intended.	Validated the framework with evaluators in practice [high-end luxury chair's seat cushion assembly]
2018	Mamo	(E)	(U)	(AE) and (O) - aerodynamics	(N)	+ RIDE integrates emotional analysis through a pattern analyser with aerodynamic optimization, which enhances the emotional and performance quality of sportbikes.	Validated with evaluators in the industry practice

Year	Authors	Review Criteria: Timing and Activity	Life-Phase Views	hf[1] Guidance	Harmonisation / Balance / Trade-off	Notable + Strengths / - Limitations	Validation evidence / [DOP used]
						- Due to the nature of the aerodynamic aspect, the model is limited to sportsbike designs and performant motorcycles. - No interaction is considered between early and late design stage motorcycle models.	(though not being motorcycle designers)
Model-driven Approach							
2005	Schachinger et al.	(L)	(D)	(E) and (O) - functional	A - limited	+ Enhances collaboration and knowledge integration among stakeholders, supports comprehensive visualisation of the 3D envelope of form entities. - No recommendations are given on how the design conflicts are minimised or harmonised together.	Exemplified through 2 case studies but not evaluated in practice [automotive interior cockpit unit and a ride-on lawn mower]
2019	Liao et al.	(L)	(D) - limited	(AE), (E) and (O) - usability	(S) - limited	+ Fast, simple and visualising method to compare aspects together. - Nature of tool does not capture the full spectrum of user interactions with wearable devices, particularly tactile and long-term use experiences. - Rating is carried only on imagery of the product and therefore lacks context and description.	Validation not specified [Wearable products]
Algorithm and Mathematical-model Approach							
2015	Nayak	(E)	(N)	(E) and (AE)	(N)	+ The process is lean that saves time when the designer is designing similar product families.	Illustrated through 1 case study but not evaluated in practice

Year	Authors	Review Criteria: Timing and Activity	Review Criteria: Life-Phase Views	Review Criteria: hf[1] Guidance	Review Criteria: Harmonisation / Balance / Trade-off	Notable + Strengths / - Limitations	Validation evidence / [DOP used]
						- The algorithm and Grasshoper's parameters are for particular product family. In case designer wants to semi-automate a different class of products a different algorithm is required. Therefore, reprogrammed each time	[Water bottle]
2023	Zhou et al.	(L)	(N)	(E) and (AE)	(A)	+ The noncooperative game has strong advantages and robustness in solving multi-objective optimisation problems with a less computational effort. - The algorithm cannot consider a series of dynamic postures that are closely related to the human movement process, since it reduced the accuracy and reliability of the ergonomic evaluations.	Exemplified through 1 case study but not evaluated in practice [Hand-held electronic device for language translation]
Data-driven Approach							
2008	Chuah & Teh	(E)	(N)	(E) and (AE)	(N)	+ The integration of *Kansei Engineering* and desktop virtual reality presents a novel approach, enhancing user involvement in the design process. - The product's value of ergonomics that participants give is perceived and not because the spectacles feel uncomfortable when worn for a certain period of time.	Described through 1 empirical case study [Spectacles]
2012	Tseng et al.	(E)	(N)	(A) and (O) - functional	(A)	+ Understand what customers really want given that data is directly collected from potential customers. - It operates autonomously, which, while efficient, potentially stifles creativity by not allowing room for designer input or innovation.	Validation not specified [Vehicles, particularly cars]

Year	Authors	Review Criteria: Timing and Activity	Life-Phase Views	hf[1] Guidance	Harmonisation / Balance / Trade-off	Notable + Strengths / - Limitations	Validation evidence / [DOP used]
						- It also fails to offer any support or recommendations to the designer, which will help in mitigating adverse outcomes or in suggesting viable alternatives.	
2021	Li et al.	(E)	(D) - limited	(E) and (AE)	(N)	+ Enhances *Kansei Engineering* and generative AI by allowing designers to explore various conceptual designs efficiently. - Ergonomics are perceived. -The nature of the generative AI approach it may hinder the designers' creativity.	Illustrated through 2 case studies but not evaluated in practice [hand-held electric tools (drills / screwdrivers) and bicycle helmets]
Hybrid Approach							
2004	Barpne & Curcio	(L)	(U)	(E) and (P) - limited	(N)	+ Evaluating the comfort during the design phase instead of after the first prototype is developed and tested with users and for performance conditions. - Given the use of 3D CAD human models/manikins to assess ergonomic posture this approach is usually limited to the analysis of static posture and static work.	Validation not specified [Motorcycle context]
2015	Marshall et al.	(E) and (L)	(U)	(E) and (P)	N	+ An understanding of user needs, combines psychological and physical data for inclusive design through a user-centred design approach. - The reliance on archetypal users does not fully capture the range of user abilities and needs.	Demonstration through various case studies, without focusing on specific products
2014	Bordegoni et al.	(L)	(U)	(E) and (AE)	(A)	+ Enable users to interact directly with the iPV during the use phase	Validated with one expert in the industry practice

Year	Authors	Review Criteria: Timing and Activity	Review Criteria: Life-Phase Views	Review Criteria: hf[1] Guidance	Review Criteria: Harmonisation / Balance / Trade-off	Notable + Strengths / - Limitations	Validation evidence / [DOP used]
						+ Flexibility to customise the VP according to individual user needs. - Physical interaction and emotional response that are not fully replicated in a virtual environment. - Effectiveness of iVP for emotional engineering relies heavily on the technology used for virtual prototyping. Any constraints in these technologies limit the depth and accuracy of user experience insights.	[Refrigerator]
2018	Chandra	(E)	(U)	(E) – limited, (AE) and (O) – limited functional behaviour	(N)	+ A systematic and quantifiable approach to evaluating ergonomics and aesthetics. - Inability to encompass the inherently subjective domain of aesthetic appreciation, which overlooks the critical aspect of persona.	Validated with evaluators in the motorcycle industry practice
2021	Zöller & Wartzack; Buker et al.	(L)	(U)	(AE) and (P) – through persona usability	(N)	+ Robust user-centred design philosophy, thereby ensuring tailored experiences that cater to the nuances of diverse user groups. - Fails to offer recommendations that could improve the product or minimise negative consequences in the product's use-phase.	Exemplified through 1 case study but not evaluated in practice [Keyboard]

6 Established Research Problem

The aim of Part B of this dissertation was to present the characterisation of the research problem and provides a context for this doctoral research. For this purpose, Section 6.1 delineates the principal findings from Chapters 2 through 5, along with the research problem, as derived from the arguments put forward in these chapters. Subsequently, Section 6.2 introduces the research questions that emerge from this problem. In Section 6.3, the boundaries of the doctoral research are defined. Finally, the conclusions for Part B are presented in Section 6.4.

6.1 Research Problem Formulation

Chapter 2: DOPs and the influence on human factors

Certain products have a dualistic nature, a phenomenon where artefacts may be perceived from both a physical perspective and at the same time from a subjective (emotional) perspective. Chapter 2 has established that these products are an extension of the user (both physically and psychologically), where the human-to-product interaction assumes primacy. This has necessitated the consideration of human factors, specifically on three aspects: ergonomics, aesthetic-derived emotions, and persona.

Chapter 3: Characterising human factors and DOP users' requirements

In Chapter 3, two studies employing a mixed-methods approach were presented. Both studies focused on discovering the challenges and needs associated with $hf_{E\text{-}AE\text{-}P}$ in DOPs from DOP users (research tertiary users) perspective. Both studies served as an extension to the body of literature, detailed in Chapter 2, complementing the characterisation of such products. Chapter 3 has identified $hf_{E\text{-}AE\text{-}P}$ negative consequences which may be experienced during the product's use phase. In Section 3.3.3, RTUs requested to be listened during the design process. Such involvement allows DOP users to offer designers deeper insights into their interactions with the product, thereby ensuring that the resulting solution aligns more closely with their expectations.

Chapter 4: DOP designers' needs and challenges

In Chapter 4 the focus shifted to exploring the designers' (research primary users') challenges, and expectations from an approach framework, when designing DOPs from $hf_{E\text{-}AE\text{-}P}$ standpoint. Chapter 4 identified six requirements which collectively encapsulate the challenges and needs of designers for a human factor dual ontological support framework:

Support the synthesis activity at the conceptual design stage

- Decisions made during the early stages of design significantly influence how subsequent stages unfold. Designers requested to be equipped with human factors knowledge right from the start.

Be implemented as a design computer-based support tool

- Designers emphasised a preference for a support tool to avoid limiting their creative input and enhance their experience while providing them with the right knowledge at the right time.

Provide a user-centred design approach

- Chapter 4 highlighted that potential customers' information needs to be gathered and channelled in the form of human factor knowledge. This encapsulates a broad range of ergonomic, aesthetic-derived emotions and persona related information, reflecting potential customers' human diversity.

Provide multiple-life (design and use) phase awareness

- DOP designers argued that they need to be made aware of design-stage conflict consequences (DCCs), whilst understanding their implications on both the target users and potential customers during the product's use phase, i.e. population use-phase consequences (PUCs).

Design for multi human factors (hf-Multi X)

- The results in Chapter 4 reveal that designers need to cope with concurrent multiple human factors. In Chapter 4 it was argued that design for multi human factors (hf-Multi X) is required to make aware designers of $hf_{E\text{-}AE\text{-}P}$ interactions and to provide them with the negative consequences, that these interactions will eventually have on the use phase.

Provide harmonisation awareness

- Providing harmonisation knowledge supports designers in balancing multiple human factors and human diversity. This knowledge is about reconciling conflicting aspects to develop a cohesive design solution that resonates with a broader spectrum of customers.

Chapter 5: Designers lack adequate means of being supported on multi human factors in DOPs

Based on the critical review of state-of-the-art means, Chapter 5 determines that none of the reviewed *means* contribute directly to proactively support DOP designers by making them aware of DCCs and PUCs with multi human factors ($hf_{E\text{-}AE\text{-}P}$) and harmonisation knowledge during the DOP conceptual synthesis design activity. Consequently, this reveals a significant gap in research, which will become the central point of investigation for the remainder of this doctoral research.

The research problem

The design problem and the gap in the literature, highlighted in the aforementioned paragraphs, were used to formulate the research problem and therefore, this doctoral research is concerned with:

> *Developing a synthesis design approach that supports designers with human factor knowledge in order to be made explicitly aware of design-stage conflicts and population use-phase consequences, whilst providing them with harmonisation awareness to arrive at a balanced dual ontological products design solution.*

6.2 Research Questions

Research questions for the second part of this dissertation

The research problem presented above introduces a number of research questions that have to be addressed in the second part of this doctoral dissertation to facilitate the development of a suitable solution:

RQ1. How are DCC and PUC generated from design decisions for products of dualistic nature?

RQ2. How to develop a design approach that supports designers with human factor and harmonistic knowledge arising from the synthesis design activity of DOPs?

RQ3. How can DOP users be understood by DOP designers and how can this information be transformed into meaningful human factors knowledge?

RQ4. How can this harmonistic knowledge be modelled and structured in a computational form, in order to be implemented in a design support computer-based tool?

RQ5. To what extent are designers willing to use such an approach in their practice, and why?

6.3 Doctoral Research Boundary

Research boundary

There are a myriad of aspects to the DOP design activity, which are linked to DOPs and human factors. Each aspect presents its unique set of research problems and necessitates distinct solutions. This doctoral research will concentrate on the following design aspects, as part of a research boundary, to channel development efforts towards a focused approach based on human factors:

Early support and new product design

RB1. Given that the designers need specific support during the conceptual synthesis design activity, this doctoral research will focus on early routine design decisions which have implications on subsequent design stages and product's use phase. Furthermore, this boundary deliberately excludes the modification of existing products or starting from an existing base product. Instead, it focuses on *new product design* (NPD) where the only pre-requisite is the user model defined during the task clarification stage.

Focus on human factors

RB2. As per the title and aim of this doctoral research, the developed solution focuses on human factors (HFs) during design of DOPs. As described in Chapter 2, there are other

aspects which can influence the evolution of such products, which are based on existing technologies for which support already exist. Within the scope and time limitations of this doctoral research, the developed solution will not consider aspects such as: mechanical engineering (functional) design; aerodynamics (performance), design for manufacturing / assembly of DOPs, to name a few; or their interaction with human factors.

Constraining to the three human factors ($hf_{E\text{-}AE\text{-}P}$) and specific sub-aspects

RB3. As outlined in Chapter 2, human factors encompass a broad range of aspects. This doctoral research will address DOP design specifically from an ergonomic, emotion and persona ($hf_{E\text{-}AE\text{-}P}$) viewpoint, excluding the other human factors delineated in Chapter 2. Within these three domains of human factors, the research will be limited to specific sub-disciplines: aesthetic experiences and emotions that arise from the product's visual design; and persona, defined by the person's attributes, personality, experience, behaviour and product use-context. The arguments put forward for selecting these particular sub-disciplines is provided in Chapter 2.

Focus on one type of scale-based market

RB4. A variety of scale-based markets exist. In delineating the boundaries, this doctoral research will not cater for bespoke products or designs intended for very small, niche groups. Instead, the market type will be strictly applicable to more universally designed products that address broader market needs. The designers interviewed for this research, as discussed in Chapter 4, all have experience with mass-market products, and as such their insight were all relevant to the context of large-scale market segments.

DOPs exemplified through motorcycles

RB5. As it has already transpired from Section 2.1, the scope of this doctoral research will be confined to dual ontological

products (DOPs). Furthermore, this doctoral research will exemplify DOPs through the motorcycle artefact.

Design driven by a single designer

RB6. This doctoral research specifically examines the design process driven by a single designer rather than one involving collective decision-making by a team. The emphasis on a single-designer perspective stems from the unique epistemological structure of design knowledge at an individual level, often characterised by a cohesive mental model and integrated decision-making processes. A single designer's mental model encompasses tacit knowledge, enabling a unified approach to synthesis, in contrast to team-based designs which introduce diverse mental models that necessitate negotiation and reconciliation

6.4 *Part B* Conclusions

Research aims

The design problems of $hf_{E\text{-}AE\text{-}P}$ in the context of DOPs have provided an understanding of the product development problem being tackled by this doctoral research. Designers lack adequate $hf_{E\text{-}AE\text{-}P}$ and harmonisation support to design products of dual nature. Furthermore, the characteristics of DOPs from the perspective of $hf_{E\text{-}AE\text{-}P}$ have been identified and this led to the definition of the requirements for a proactive design approach. The strengths and weaknesses of existing *means* supporting multi human factors have been identified. *'Part B: Characterising the Research Problem'* has therefore met the established research objectives RO1 to RO3 in Section 1.7 and provided a frame of reference for this doctoral research.

What to expect in Part C

In *Part C* of this dissertation, the focus will shift to the solution for the established research problem, as seen through Figure 6.1.

Chapter 4 reinforced the case for supporting DOP designers, and most importantly to do so during the synthesis decision-making activity. As such, analysis is required to further detail the synthesis decision

making-activity. This will be undertaken in the following chapter (Chapter 7). Chapter 8 presents a UCD approach framework that takes the DOP designers' and DOP users' requirements and models them into a harmonistic design support for DOPs. Chapter 9 models the human factors ($hf_{E\text{-}AE\text{-}P}$) and harmonisation knowledge pertaining to the approach framework. In Chapter 10, the information and knowledge models are implemented as a prototype computer-based support tool.

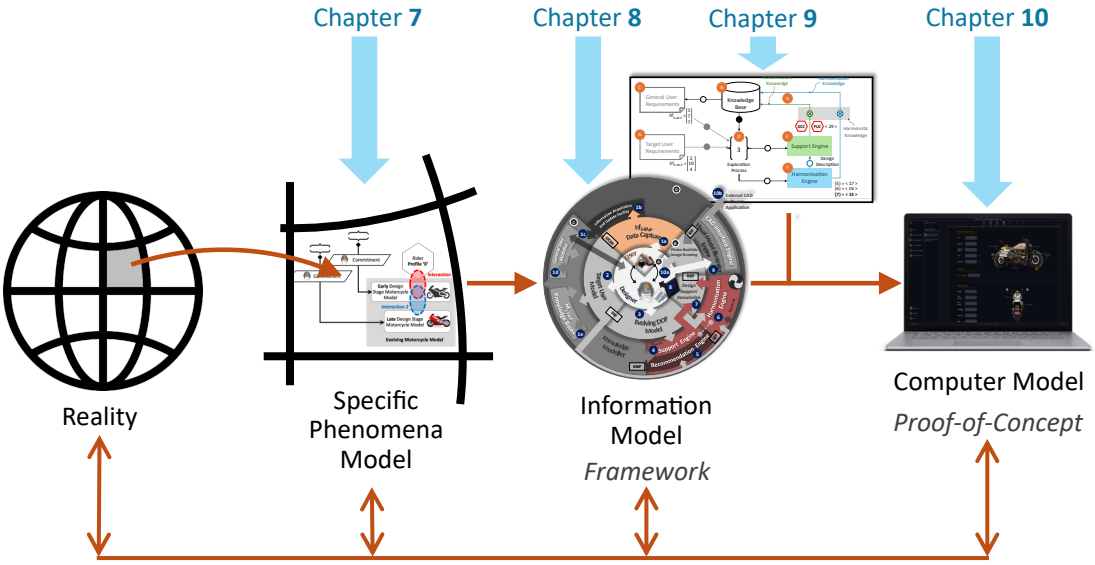


Figure 6.1 – Research framework for developing a computer-based design support tool, adopted from Duffy & O'Donnell (1999)

Part C:

Solution Development

7 Dual Ontological Product Design Phenomena – A Human Factor Decision Consequence Model

The conclusions of Part B have clearly highlighted the need to support DOP designers. Specifically, by making them aware of the Design-stage Conflict and Population Use-phase Consequences (DCCs and PUCs). These consequences result from designers' human factors ($hf_{E\text{-}AE\text{-}P}$) design decisions, occurring in the synthesis design activity. This leads to the research question "How are DCC and PUC generated from design decisions for products of dualistic nature?" This chapter addresses this question by exploring the synthesis decision-making activity (Section 7.2), and how it should be applied to DOPs (Section 7.3). A phenomena model that explains how design synthesis decision commitments result in DCCs and PUCs is presented in Section 7.4, validated through two industry-based case studies in Section 7.5. Finaly the significance of the DOP design phenomena and the chapter conclusions are presented in Section 7.6 and 7.7, respectively.

7.1 Methodology to Develop and Validate the Phenomena Model

Development and validation of the design phenomena

The methodology adopted for the development and subsequent validation of the dual ontological design phenomena model is illustrated in Figure 7.1. This methodology is comprised of two parts. The first part focuses on how the phenomena through the understanding of the designers' reality is uncovered. The second part centres on how the constructed phenomena model is validated.

7.1.1 Method used to Understand the Phenomena During DOP Design

Derivation of the design phenomena

This method leverages Chapters 4 and 3 to comprehend, respectively, the synthesis decision-making process and the consequences of commitments undertaken during the design phase. It uses the method outlined in Section 4.2, which was conducted with motorcycle designers (RPUs).

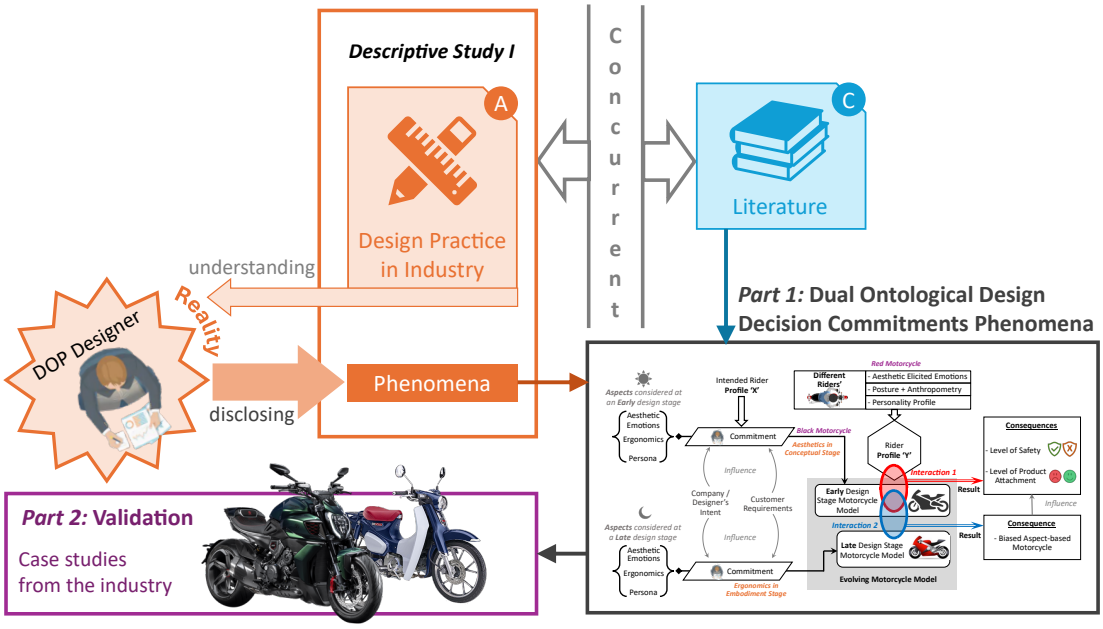


Figure 7.1 – The method used to develop and validate the phenomena model

7.1.2 Method used to Validate the Developed Phenomena Model

A comparative case validation method

In their scholarly work, Barth et al. (2011) and Eisenmann et al. (2021) argued that the method of *comparative case studies* serves a critical role in validating theoretical models. This approach is instrumental in validating a formulated model through comparison with established case studies in the industrial sector. As indicated in Figure 7.1, the comparative case study approach was employed to corroborate the developed dual ontological phenomena model with real motorcycle case studies, which made success, in the motorcycle industry.

Method to find successful motorcycles

A systematic review of literature was undertaken to ascertain the motorcycle designs that achieved success. Scientific journals are typically recognised as sources of scholarly knowledge, whereas magazines are more often associated with conveying pragmatic insights from the industrial field (George, 2008). To this end, articles from esteemed motorcycle magazines, showcasing the 'best motorcycles' as per industry experts, were chosen for analysis. These articles identified successful motorcycle designs according to experts in the field. Table 7.1 enumerates the five chosen motorcycle magazines and their corresponding articles that were included in this study.

Two motorcycles that stood out

Each motorcycle featured in the 'best motorcycle' lists, as per the articles detailed in Table 7.1, was recorded. Two particularly notable motorcycles, ranking highly in these lists, were the *Honda Super Cub* and the *Ducati Diavel*. Illustrations of these motorcycles can be found in Figure 7.2 and Figure 7.3, respectively. Notably, both motorcycles were referenced in three out of the five magazines reviewed. This objectively suggests that the designs of the *Honda Super Cub* and the *Ducati Diavel* are held in high regard within the motorcycle market and industry. This method effectively mitigated any bias in choosing successful motorcycles for the two case studies.

Table 7.1 – Reputable motorcycle magazines and their corresponding articles on the best motorcycles

ID	Magazine	Article Title	Reference
1	Cycle World	Ten best motorcycles	Cycle World (2019)
2	Rider Magazine	25 Best motorcycles of the past 25 years	Rider Magazine (2016)
3	HiConsumption	The 30 greatest motorcycles of all time and 10 best cruiser motorcycles	HiConsumption (2018; 2019)
4	Gear Petrol	The 51 most iconic motorcycles of all time	Gear Petrol (2013)
5	Ride Apart	The 5 best cruisers on the market	Ride Apart (2020)



Figure 7.2 – The Honda Super Cub

Why are these motorcycles successful?

In addition, the *Ducati Diavel* won *'Best of the Best at Top Design 2019 Awards'* (Gear Petrol, 2019; Ride Apart, 2019). The *Ducati Diavel* classified first for the significant contribution to its segment, aesthetic appeal, functionality, and ability to evoke strong positive responses. Conversely, the *Honda Super Cub* holds the distinction of being the most produced motor vehicle in history. By 2017, *Honda* announced

sales of over 100 million units (Cycle World, 2018), solidifying its status as one of the most successful motorised vehicles ever manufactured.



Figure 7.3 – The Ducati Diavel

What is the design process of these two motorcycles?

These assertions underline the distinctive features of both the *Honda Super Cub* and *Ducati Diavel* motorcycle designs, setting them apart from other motorcycles. Having established the two case studies from the industry, a literature search was carried out to discern the design process employed to develop the two motorcycles. To gain an unbiased perspective of the internal design process, interviews found in literature were gathered from designers employed at *Honda* and *Ducati*. The design processes according to *Honda* and *Ducati* were then compared to the developed phenomena model.

7.2 Decision-Making in Product Design

Challenges of early decision-making

As highlighted in Section 4.4.3, a constant challenge in the design process of products is decision-making. Decision-making is a key factor influencing the overall success of the product development life-cycle, as noted by Yu et al. (2022). Choices made at this stage have a lasting impact throughout the subsequent design stages. The presence of uncertainty in the early routine design process complicates more decision-making (Kimura & Grote, 2002). Ineffective decision-making at this early phase can adversely affect productivity and escalate costs and lead times in later stages of the product development life-cycle, as highlighted by Yilmaz & Seifert (2011) and Mohd Saad et al. (2013).

What factors influence decision-making?

In order to provide an explanation of how Design-stage Conflict and Population Use-phase Consequences (DCCs and PUCs) are generated during the DOP design synthesis activity, this section begins by illustrating the decision-making in the early routine design process and the factors influencing these decisions.

7.2.1 Factors Affecting Decision-Making

Alternatives

Transpiring from Chapter 4, DOP designers are engaged with the modification and selection of two kinds of alternatives as shown in Figure 7.4. These are: *(A)*, product design element variants (PDEVs) considered at the early routine design process with a focus on particular human factor, for example hf_{AE} (aesthetic-derived emotions); and *(B)*, the PDEVs considered at a later stage with a focus on another human factor, for instance hf_E (ergonomics). As shown in Figure 7.4, decision-making involves multiple choices. Each of these PDEVs (choices) may have a certain probability of being selected, depending on what the designer wants to attain for a particular intended user model. The decision-making process entails evaluating one option from the array of available choices (Hatamura, 2006).

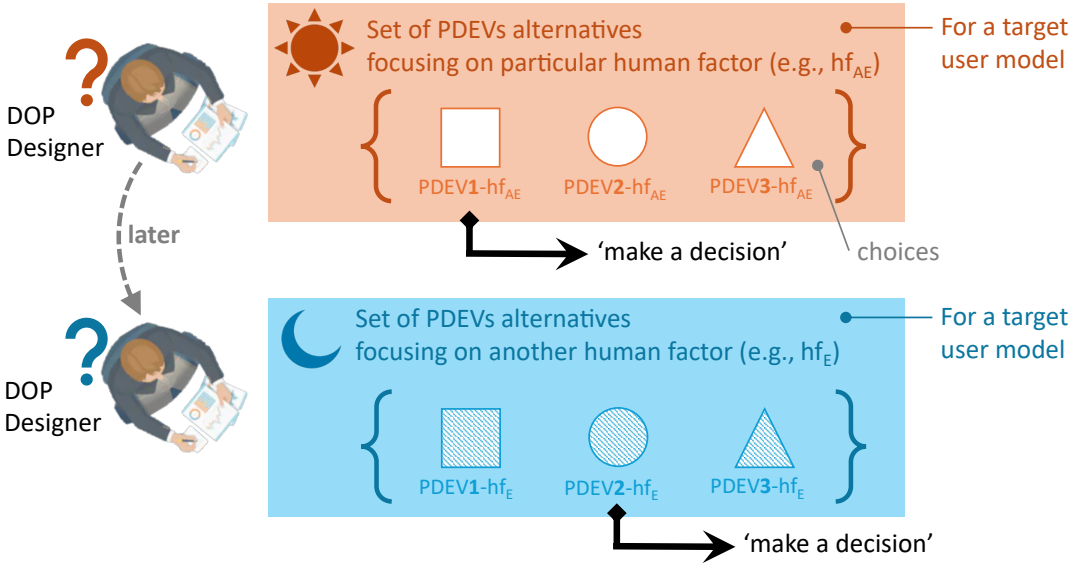


Figure 7.4 – Making a decision from a set of alternatives in dual ontological scenario

Rational decision-making

Decision-making is a fundamental cognitive process where it encompasses the evaluation of available options and the selection of a

course of action. In making a decision to select one of the options there are several factors to be considered. A *rational decision-making model* (illustrated in Figure 7.5) describing a series of formal steps that decision makers consider during the decision-making activity (Uzonwanne, 2016; Kahneman, 2011).

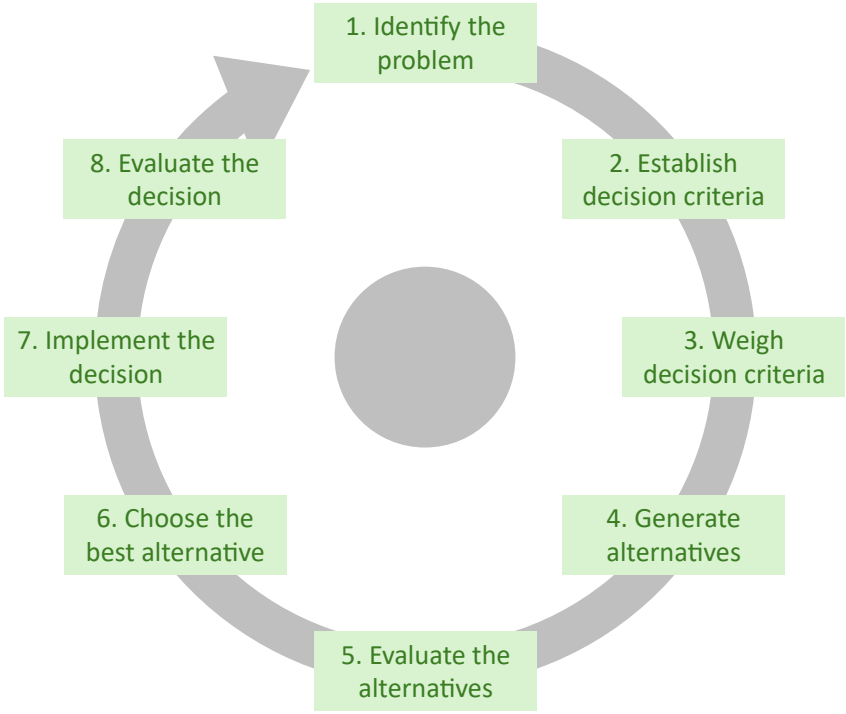


Figure 7.5 – Rational decision-making model, adopted from Uzonwanne (2016) and Kahneman (2011)

Identify the (sub) problem

A decision-making activity begins with the need to solve a particular problem, sub-problem or situation that requires a decision. An example of a sub-problem encountered during the early motorcycle design process, can be related to the selection of the style and handlebar height position for a target user model.

Decision-making criteria

In order to make a suitable decision and solve this problem, information is required about the goal to be achieved and the criteria by which the choices are to be evaluated. These are tied to which factors the designers feel that they are important to them and to the company (Kahneman, 2011). Different criteria have to be taken into consideration, for instance, what design aesthetic-derived emotions the company wants to portray for the new motorcycle, and what are the aesthetic preferences of the intended user.

Weigh decision criteria

The decision maker needs to decide how important each factor (highlighted in the previous step) is to the decision. If each is equally important, then there is no need to weight them, but if the designer wants to satisfy the requirements of the intended users, the designer might weight them heavily and keep the other criteria, that is, what the designer wants to portray, with medium importance.

Decision space

Fundamental to the decision activity are the choices to be considered, as without a choice there is no decision. The alternative choices being considered make up the decision space. The decision space is closely related to the problem specification. These are dependent on the sub-problem being considered and limit the feasible decision space. Continuing with the motorcycle example, if the sub-problem is to decide on the handlebar height, then the choices are high, mid and low-positioned handlebar. The handlebar forward and backward different positions are not included in the feasible decision space but considered in another motorcycle design sub-problem.

Knowledge in decision-making

As explained by Kahneman (2011), decision makers use their explicit (domain) knowledge in the field, but also their experience, preferences, and tacit knowledge to arrive to a solution. As an example, designers may have a good experience working with low-positioned handlebar, hence they would prefer to select a handlebar position close to that choice.

Evaluate the alternatives

Weighing the pros and cons of each choice and considering potential risks and consequences is carried out in the evaluation step. It is also imperative that at this step, the alternative choices are evaluated against the criteria that was established in *Step 2* (refer to Figure 7.5).

Choosing the best alternative and implement the decision

The result of the decision-making process is a selection of one of the most suitable options, which according to the decision maker is the best alternative satisfying the set criteria. This is known as the decision commitment action (Uzonwanne, 2016).

Decision evaluation

The outcome of this decision will be related to the next decision made. At a later design stage this decision comes to the designer who focuses on ergonomics (as illustrated in Figure 7.4). This designer, focusing on ergonomics, evaluates the original decision and may have a different view in order to meet the goal and satisfy the intended user-ergonomic requirements of the motorcycle.

7.2.2 Synthesis Decision-Making Activity

Synthesis decisions

According to Roozenburg & Eekels (1995), the synthesis activity is where designers create tentative design proposals that address the identified problem or need. The term 'synthesis' is defined as the identification of PDEs that constitute a product and their relation to each other (Mortensen & Hansen, 1999). The reader is referred to Section 2.2 on the *product breakdown structure* of DOPs in this doctoral research.

Synthesis in the conceptual stage

As explained in Section 4.4.3, the synthesis activity will be carried at least once during the conceptual stage and once during the embodiment design stage. As seen from Section 4.4.4, during the conceptual stage, synthesis is focused on developing the basic aesthetic concept of the product. Synthesis in this stage is very much about creative and abstract decision-making, without the increased constraints of technical specifics or detailed practical considerations (Ulrich et al., 2020).

Synthesis in the embodiment stage

Embodiment design is a later stage in the product design process, where synthesis becomes more detailed and specific. It involves refining and developing the selected concept from the conceptual design stage into a more concrete and practical design. According to interviewed designers (see Section 4.4.3) this involves determining the general dimensions of the DOP, including its components.

Synthesis as a decision-making activity

Based on the arguments provided in this section, DOP designers (visual product designer, ergonomics engineer or user experience designer) in

their different roles, make decisions to select decision variables from a range of choices at different stages of design. As explored in Section 4.4.4 and illustrated in Figure 7.4, the decision-making outcome may be different depending on the stage and focus of each human factor aspect. These selected decision variables are synthesised together to develop solutions which meet the target users' requirements. The synthesis activities in the different roles, can therefore be considered as decision-making activities.

The role of knowledge in synthesis decision-making

Rodgers & Clarkson (1998) contend design synthesis, as a complex, multidisciplinary decision-making task, that demands extensive knowledge. Borg (1999) further asserts that during the design synthesis activity knowledge of commitment consequences is required in order to satisfy multi product life-cycle issues.

Synthesis of what?

As disclosed in Section 4.4.3, interviewed DOP designers stated that in addition to selecting PDEVs from an array of choices at different stages in the design process, they also decide for who (intended / target user) the new DOP is intended. The latter is carried during the task clarification design stage. Farrugia (2017) argued the importance to also consider the human participant in the life phase-system meeting. In this doctoral research the human component of the life-phase system is embodied by the user model, a pivotal aspect of the decision-making process in product design, particularly in view of the use phase user-artefact meeting.

As illustrated in Figure 7.6, a key challenge for decision makers is to choose product design elements (PDEs) that not only cater to the correct target user model, but also appeal to a broad customer base. As seen from Section 4.4.3 at the task clarification stage, interviewed designers are not aware of what the general user characteristics' may be, as they rely on their experience and assumption to model the intended target user. This PDEs selection is based on predicting the potential consequences that arise from the interaction between the user and the product during its use phase. Chapter 3 provides a

detailed enumeration of these consequences, highlighting the interactions between different motorcycle types and various persona.

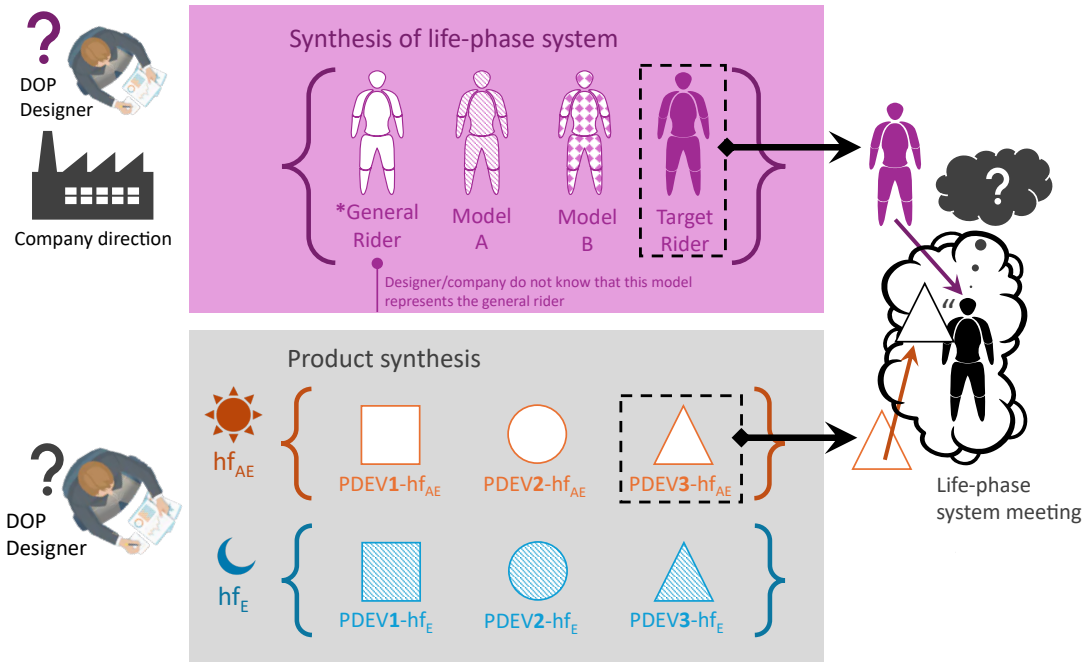


Figure 7.6 – Participants of a life-phase system meeting, adopted from Andreasen & McAloone (2008)

7.2.3 *Synthesis Decision Commitment Model*

Understanding the synthesis decision-making activity

In order to examine the mechanism underlying the synthesis decision-making activity and how this results in decision consequences, this doctoral research employs the *synthesis decision commitment model* proposed by Borg (1999).

Borg & Yan (1998) illustrated the design synthesis decision-making activity across various product life-phases, including use phase. A generalised representation of Borg's synthesis decision commitment model is depicted in Figure 7.7.

Commitment action

In the synthesis design activity, designers encounter specific sub-problems that necessitate decision-making. As Borg et al. (1999) describe, faced with multiple options, the designer undertakes a decision-making process to select a suitable option from the *solution space, D{O},* to address the sub-problem. The decision to commit is influenced by various requirements, such as explicit user demands. Additional factors influencing this decision include the context of the

decision-making, the designer's or the representing company's intentions and preferences. Moreover, complex variables like brand identity, historical design solutions, the success and failure of previous product designs, and market trends often skew design decisions (Cocco, 2013). Following these considerations, the designer would explicitly select one of the options and *commits* $[d]_E\{O\}$ this element to a solution model, resulting in a decision commitment.

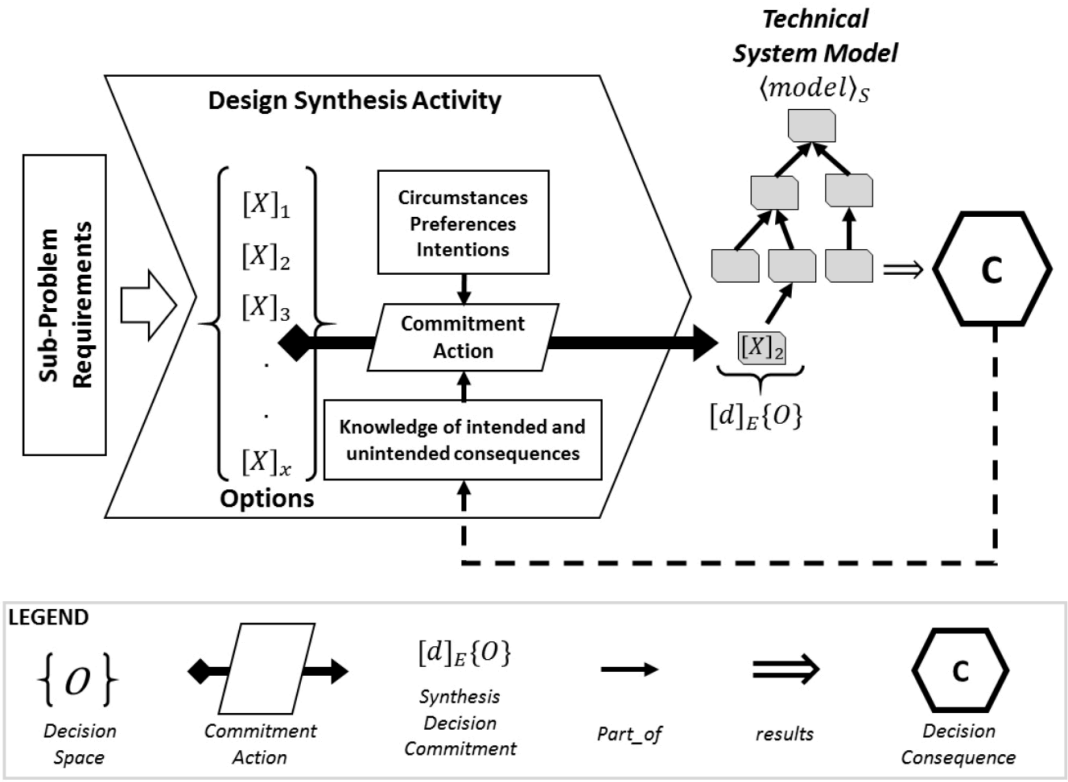


Figure 7.7 – Synthesis decision commitments model, from Borg & Yan (1998)

Exploration of synthesis decision commitments

The commitment made during the synthesis process is subsequently integrated into an evolving artefact model, which represents the solution in development, through a *part_of* relationship. In synthesising a solution, designers may commit to a particular solution that leads to certain consequences (Holt & Barnes, 2010).

Consequences and decision-making

According to Olesen (1992), design decisions have consequences when the artefact meets with different life-phase systems of products, namely design, manufacturing, use and disposal. In this sense, Borg (1999) describes decision-making in design as consequential, emphasising that the selection of an alternative is contingent upon the anticipation of its future consequences. Thus, during design synthesis,

designers have to cope with the co-evolution of problems, which complicates the task of maintaining awareness of all potential issues. This complexity primarily involves attempting to foresee the outcomes arising from a range of alternative options.

Consequences awareness

As indicated in *Step 8* of the rational decision-making model (illustrated in Figure 7.5), if made aware of these consequences, designers may backtrack the synthesis decision commitment temporarily, in order to investigate an alternative commitment and its potential impact on the solution's performance.

7.2.4 Characterising Use-Phase Consequences

Aspects of consequences

As seen from the previous section (Section 7.2.3), decision commitment describes the act of selecting alternatives based on a prior decision-making process. In this doctoral research, consequences include aspects like product usability, safety levels and degree of product attachment, which are shaped by the decisions commitments made during design.

The dimensions of consequences

Borg (1999) delineates the consequences arising from synthesis decisions along two dimensions: *intent* and *desirability*. For the purposes of this doctoral research, *desirability* is reinterpreted as 'effect on product use'. The first dimension describes whether a consequence has been *intended* or *unintended*. The dimension ‘effect on use’ characterises a consequence in relation to the *good (positive)* or *negative (problematic)* impact on users from a human factors’ perspective.

Scenarios arising from synthesis decision commitments

As explained by Farrugia (2017) and illustrated in Figure 7.8, synthesis decision commitments lead to four scenarios:

1. *Intended consequences* are the specific, planned outcomes that the designers aim to achieve with a product. These consequences are central to the purpose and function of the product, and as highlighted in Section 4.4.3, they are

considered in the early routine design stage and guide the entire design process.

2. *Unintended consequences* are those consequences that the designer is not aware of when committing to the design decision.
3. *Good consequences* from a user's point of view, refer to the positive impact that arise when the product is used. These consequences typically evoke positive emotions, safety re-assurance (which are essential for the product's success) and user satisfaction.
4. *Negative or problematic consequences* from a user's standpoint, are the adverse outcomes, drawbacks, or harmful impacts that arise when a product is used, whether as intended or not. These consequences can detract from the product's overall value, pose risks to users or others, and can have a low level of attachment.

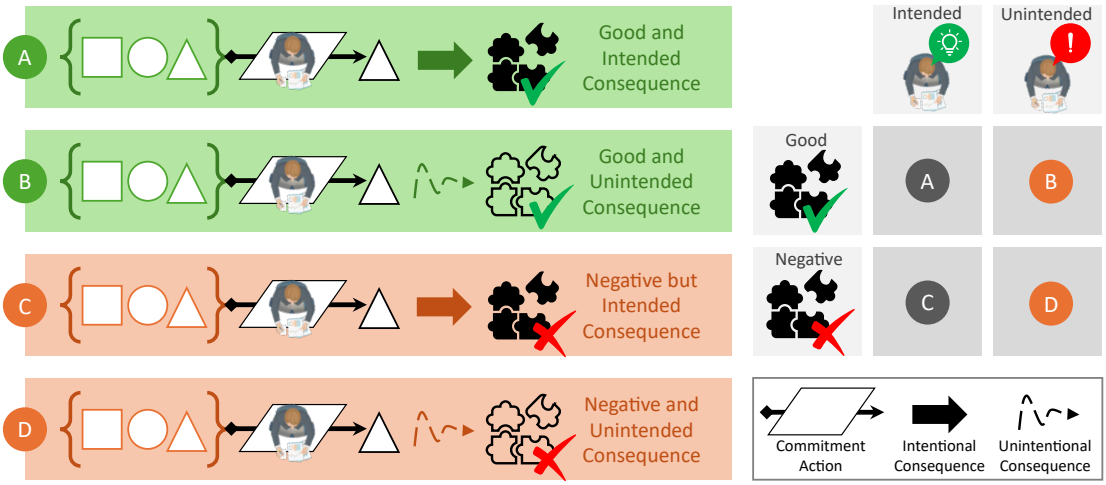


Figure 7.8 – Synthesis commitment and consequence scenarios, adopted from Farrugia (2017)

Scenario A

The first scenario is when given a set of alternative solutions, a designer makes a synthesis decision commitment to purposely achieve an intended good consequence. For instance, lowering the motorcycle ride height, aligning with the targeted needs of the motorcycle's intended user.

Scenario B

A designer may commit to a decision with the intent of realising a specific, beneficial outcome, which, in turn, unexpectedly leads to another positive consequence. For example, lowering the handlebar height to enhance ergonomic comfort while unknowingly also eliciting positive aesthetic-derived emotions by the target user. Additionally, there are instances where a product evolves in an unanticipated direction, not initially considered during the design process. Despite this deviation, the product may coincidentally yield a positive effect during the interaction with the user.

Scenario C

A different scenario is when a designer might deliberately commit to a decision that leads to a negative or problematic consequence during the use phase of a product. While such a scenario is theoretically possible, it is generally considered unprofessional to engage in such practices. On the other hand, this scenario may sometimes be adopted as a strategic business decision aimed, for example, at positioning the product within a specific market segment.

Scenario D

In certain situations, a designer may commit to a decision with the objective of attaining a beneficial, intended outcome, only to inadvertently trigger an unintended problematic consequence. This unanticipated outcome can subsequently exert unforeseen effects on the business performance and the overall success of the product. In an effort to enhance aesthetics, a motorcycle designer might choose a striking, futuristic body design intended to attract younger customers. However, this aesthetic choice could inadvertently alienate traditional riders who prefer classic styles, potentially impacting the product's market appeal.

The importance to reveal unintended consequences

The unintended consequences (*scenarios 'B' and 'D'*) are those outcomes of which the designer is not consciously aware at the time of making synthesis decision commitments. Therefore, commitments made intentionally to the solution model may lead to unforeseen consequences during the use phase. It is crucial for designers to be informed about such unintended use-phase consequences. This is

because, if an unintended use-phase consequence is explicitly made known to the designer and is then considered as:

- Good: it provides additional knowledge that may assist a designer to reinforce the commitment being made.
- Negative: it provides additional knowledge that may motivate a designer to seek alternative solutions aimed at avoiding or minimising human factor use-phase consequences. It is therefore this type of unintended decision consequences that the designer needs to be made aware of for design guidance.

7.3 Synthesis Decision Commitments in DOP Development

Synthesis decision-making DOP development

As highlighted in Section 4.4.3, DOP designers would like to be supported during design synthesis, in which a critical activity is decision making. It is in this activity of the design process that the designer develops solutions which address the $hf_{E\text{-}AE\text{-}P}$ requirements.

As argued in Section 7.2, the activities of intended user modelling and the evolving product model can be considered as synthesis activities, irrespective of the design stage at which these activities occur. The model proposed by Borg (1999), referred to in Section 7.2.3, will be applied to the decision-making activities of DOPs.

7.3.1 Synthesis Decision Commitments of Intended Use

Intended use synthesis decision commitment model

The subsequent section elaborates on the different aspects of the motorcycle synthesis decision-making model, with a specific emphasis on the rider as the intended user of the motorcycle. Examples are provided for clearer illustration. In order to better understand the intended use synthesis decision-making activity and the knowledge required to make human factor-oriented decisions, this doctoral research presents a formal model of motorcycle synthesis design for intended use. This model, depicted in Figure 7.9, is adapted from Borg (1999).

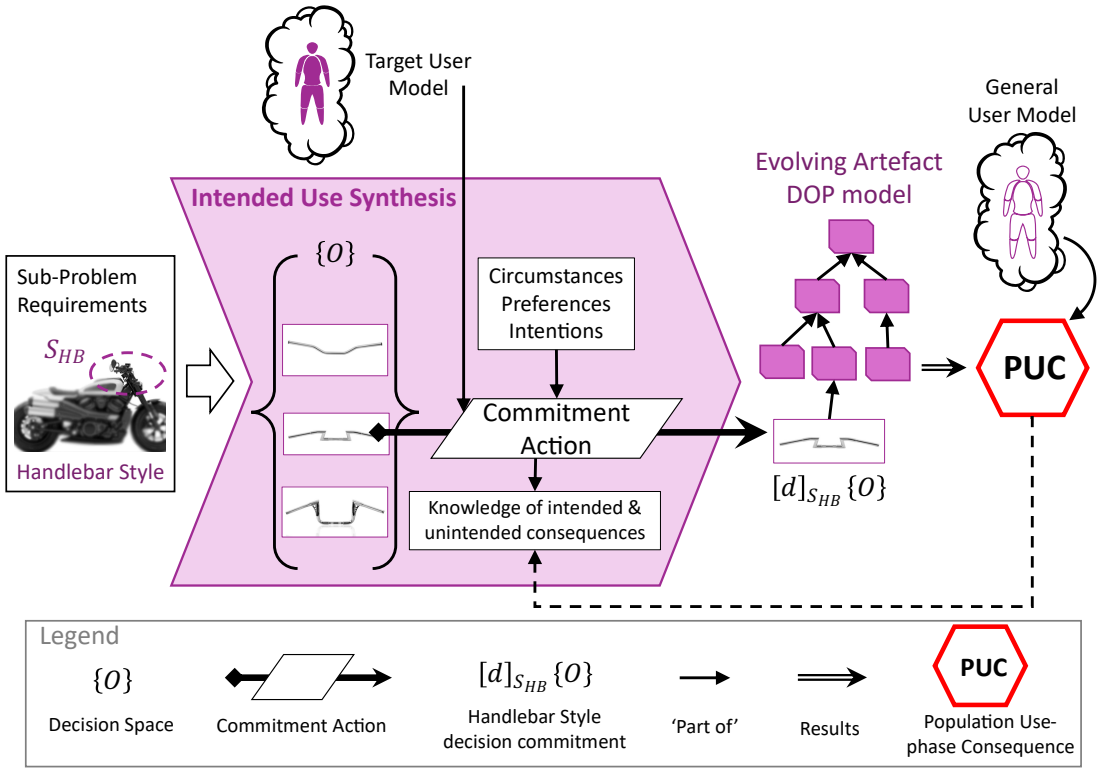


Figure 7.9 – Intended use synthesis decision commitment model

Intended use synthesis requirements

Aesthetic-derived emotions sub-problem

The motorcycle synthesis activity with a focus on intended use begins when the designer is presented with a sub-problem requirement, such as the need to select a *handlebar style* [S_{HB}] for the motorcycle under consideration. The handlebar style pertains to the domain of aesthetics, which is one of the human factors considered in this doctoral research.

Intended use $hf_{E\text{-}AE\text{-}P}$ synthesis requirements

Since this doctoral research considers an $hf_{E\text{-}AE\text{-}P}$ approach, the synthesis activity can also extend to include hf_E and hf_P sub-problems, which ultimately contributes towards defining the requirements of the totality of motorcycle synthesis design activity.

Intended use ergonomic and persona-based design decision query

In the context of motorcycle design, the nature of the decision query varies, based on the specific sub-problem requirement being addressed. For instance, if ergonomics are being considered, the decision query might involve the *vertical and horizontal positioning of the handlebar in relation to the seat* [$P_{HB\text{-}S}$]. Conversely, if the consideration is centred on the persona of the rider, the decision query

could relate to the *type (or power) of the engine* $[\mathrm{T_E}]$, or again to the *positioning of the handlebar relative to the seat* $[\mathrm{P_{HB\text{-}S}}]$. The choice of engine type can influence the perceived personality of the motorcycle, catering to riders who are either thrill-seekers or more cautious. Meanwhile, the handlebar positioning affects the motorcycle's use-context, determining its suitability for either long or short trips.

Intended use synthesis decision space

Decision space

In the synthesis activity, the motorcycle designer is presented with the decision space, encompassing a spectrum of options (variants) for that specific PDE. The designer has the opportunity to commit to these options and integrate them into the development of an evolving motorcycle solution, in order to solve the specific sub-problem at hand.

Exemplifying the decision space

For instance, when choosing handlebars for a specific motorcycle model, the designer might consider various styles, such as *'Tracker', 'Clubman', or 'Z-bar',* as depicted in Figure 7.9. This range of choices is represented by $D\{O\}$ and can include diverse types of PDEs.

Motorcycle PDEs from a $hf_{E\text{-}AE\text{-}P}$ factors perspective

As highlighted in Section 2.2.1 tangible PDEs cover elements like style, position (which is both an aesthetic and ergonomic property) and configuration (for example, the evolving motorcycle's engine power), along with intangible elements like colour schemes (Chandra, 2018). Considering the emphasis on $\mathrm{hf_{E\text{-}AE\text{-}P}}$, this doctoral research will specifically address those PDEs that either directly or indirectly impact the users' ergonomics, aesthetic-derived emotions, and persona. A more detailed exploration of these aspects will be presented in Chapter 9.

Intended use synthesis decision commitments

Aesthetics motorcycle synthesis

During the synthesis decision-making activity, the designer makes commitments $[d]_{\mathrm{E}}\{O\}$ in order to satisfy the set of motorcycle requirements. This involves making a decisive choice from among the *handlebar styles available in the solution space* $D_{S_{HB}}\{O\}$. Through this

commitment actions, the designer selects the 'Z-bar' style, where it is then added to the evolving motorcycle model.

Decision influence by intended use

As illustrated in Figure 7.9 and explained by Borg & Yan (1998), the decision-making commitment of a designer is shaped by various factors including the context of the decision, as well as the intentions and preferences of the designer or the representing company. This doctoral research, drawing on the insights presented in Sections 4.4.3 and 4.4.4, argues that designers in this activity are particularly attentive to a specified target user group, ensuring that every motorcycle's PDE aligns with the identified intended user model. To exemplify this, consider a scenario where the intended user model identified during the task clarification stage is *profiled as 'X'*, characterised by specific persona traits, anthropometric properties, and a predisposition (elicits positive emotions) towards motorcycles with aggressive aesthetics. In this context, the 'Z-bar' handlebar, known for its aggressive features as contrasted with the more natural appearance of the 'Tracker' (Anderson, 2023), becomes a suitable choice. The designer leans towards the 'Z-bar' handlebar style in the solution space, as it aligns with the emotional preferences of the target user profile.

Solution exploration

A designer may navigate through multiple exploratory paths, each leading to different solutions, termed a *solution portfolio*. Each solution within this portfolio possesses unique characteristics and performance metrics. These aspects must be thoroughly analysed and evaluated in subsequent design activities (*Step 8* of the rational decision-making model) to determine which solution should be ultimately adopted and implemented.

Intended use synthesis decision consequences

Intended use synthesis decision consequences

As argued by Borg & Yan (1998), decision commitments result in consequences. As detailed in Section 7.2.4 there are two types of

consequences; these are intended or unintended consequences which can generate either good or negative effects.

Intended consequences

Scenario (A) emerges when a designer's decision commitment results in an intended and positive outcome later on during the use phase of the motorcycle under development. This aligns well with the designer's objective, where the motorcycle appeals to a rider with profile 'X' (who elicits positive emotions towards motorcycles with aggressive aesthetics), is purchased and enjoyed. Scenario (C) involves a decision commitment leading to a negative but intended consequence. While this is theoretically feasible, it is generally improbable as responsible designers typically strive to avoid such outcomes.

What if the general user wants to use the product?

Recalling Section 4.4.3, interviewed designers stated that generally the intended target user is modelled based on their own experience and assumptions about the target market. But at the same time, they wish to create a successful motorcycle which is capable to satisfy the requirements of a larger group, i.e. the general rider (as termed in Section 2.4.3) and *profiled as 'Y'* in this example. This suggests that designers may lack specific data to distinguish between targeted and general riders.

Unintended consequences – General rider privation

Considering the above paragraph, scenario (B) describes situations where the decisions made lead to good but unintended consequences. This might occur when a designer selects aggressive aesthetic PDEVs with the intention to satisfy target user profile 'X', not realising that the general rider (profile 'Y') also favours such aggressive aesthetic styles. As such, when the motorcycle is realised, this situation led to unexpected success in sales. This is because the motorcycle appeals not only to the target rider but also resonates with the general rider, contributing to the motorcycle's success.

Scenario (D) presents a situation where a decision leads to a negative and unintended consequence. This is exemplified in Figure 7.9, where the general rider population does not favour aggressive aesthetics, yet

the designer, without this knowledge, chooses elements that embody an aggressive aesthetic style. Essentially, this occurs when there is a mismatch between the target user (profile 'X') and the general user (profile 'Y'). In the context of this doctoral research, such outcomes are identified as *Population Use-phase Consequences (PUCs).*

7.3.2 Synthesis Decision Commitments of Dualistic Nature

Dualistic nature synthesis decision commitment model

Similar to the approach in Section 7.3.1, the subsequent section provides a detailed examination on the different aspects of the motorcycle synthesis decision-making model, particularly focusing on human factor considerations across different stages of design. This doctoral research introduces an additional formal model, for DOP synthesis design, as illustrated in Figure 7.10.

Dualistic nature synthesis occurring at the conceptual stage

Following Section 4.4.3, here the highlight will primarily be on the conceptual design stage. A majority of the interviewed designers indicated that at this stage, they focus on the most important aspects of the product. In this context, the emphasis is on the aesthetics of the motorcycle and the emotions it evokes. Therefore, aesthetics (hf_{AE}) will be the central consideration during the conceptual synthesis activity.

As argued by Rozenburg & Eekels (1995), and as has already been presented in Section 4.4.3, the synthesis design activity, is not limited to the conceptual stage, but also is carried out in the embodiment stage. Subsequently, during the embodiment stage, the focus shifts to ergonomics (hf_E), the second human factor aspect. This model will facilitate to better understand the conceptual synthesis decision-making activity and the knowledge required to make dualistic human factor-oriented decisions.

Other $hf_{E\text{-}AE\text{-}P}$ scenario

This doctoral research considers an $hf_{E\text{-}AE\text{-}P}$ approach. While not explicitly exemplified in this section, it acknowledges the possibility within the conceptual synthesis activity that a designer might initially

prioritise ergonomics in the conceptual stage, subsequently shifting focus to aesthetics during the embodiment stage.

As an example, assumption: intended target user model = general user

Furthermore, for the purpose of this example, it is assumed that the intended user model identified by the designer and the actual user in the use phase are the same. In this instance, the target user model is presumed to be identical (exact match) to the general user.

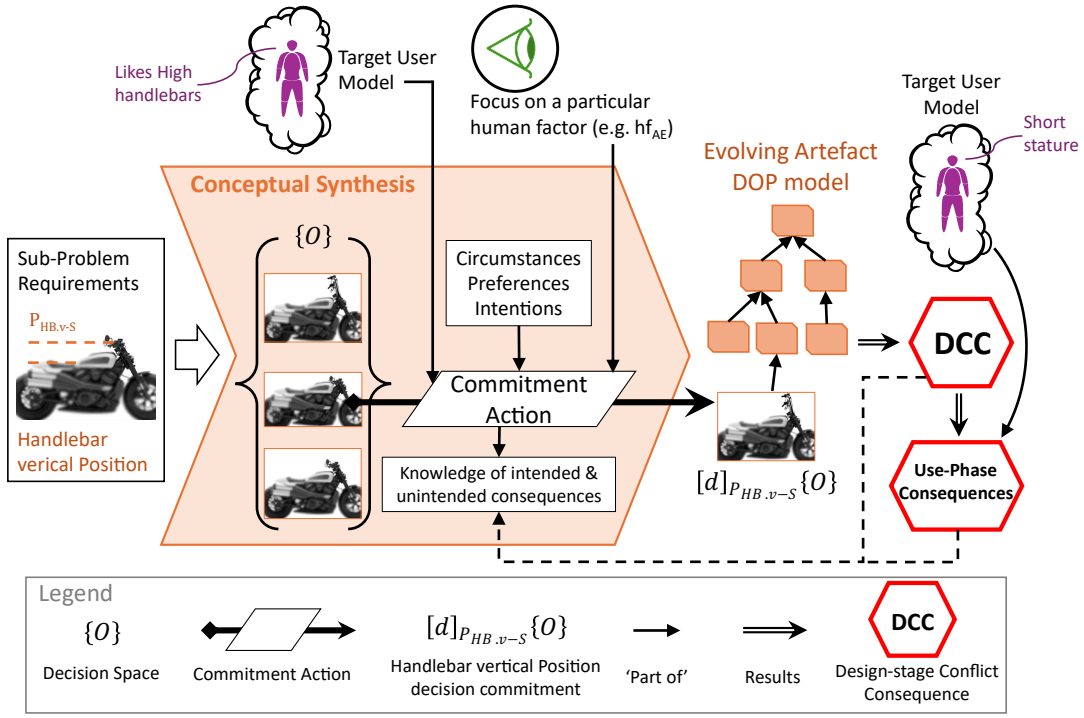


Figure 7.10 – Dualistic nature synthesis decision commitment model

Dualistic nature synthesis requirements

Aesthetic-derived sub-problem during the conceptual synthesis activity

The motorcycle conceptual synthesis activity begins when in this case the designer is presented with an aesthetic-derived sub-problem requirement, such as the need to set the *vertical positioning of the handlebar in relation to the seat* [P$_{HB.v-S}$]. As will be indicated in Chapter 9, position of PDEs in relation to others effects both the motorcycle's aesthetics and ergonomics.

Dualistic nature synthesis decision space

Decision space

In the synthesis activity, the motorcycle designer is presented with the decision space, encompassing a spectrum of options for the [P$_{HB..v-S}$] PDE.

Exemplifying the decision space

For instance, the designer might consider various vertical handlebar positions, such as *'high-positioned', 'mid-positioned',* or *'low-positioned'*, as depicted in Figure 7.10.

Dualistic nature synthesis decision commitments

Aesthetics motorcycle synthesis

During the synthesis decision-making activity, the designer makes commitments $[d]_{\mathrm{E}}\{O\}$ in order to satisfy the set of motorcycle conceptual requirements. This involves making a decisive choice from among the *vertical handlebar position in the solution space* $D_{P_{HB.v-S}}\{O\}$. Through this commitment actions, the designer selects the 'high-positioned' handlebar, where it is then added to the evolving motorcycle model as illustrated in Figure 7.10.

Decision influence

As detailed in Section 7.3.1, the decision-making commitment of a designer is shaped by a variety of factors. In this case, designers are particularly focused on a specific target user group, ensuring that each PDE of the motorcycle is congruent with the intended user model, identified as profile 'X'. As illustrated in Figure 7.10, this type of rider elicits positive emotions for 'high-positioned' handlebars, while expressing aversion to 'low-positioned' handlebars. However, it is noted that a 'high-positioned' handlebar might not be ergonomically suitable for this particular target user, especially if the user is anthropometrically short in stature, potentially leading to difficulties in manoeuvring the motorcycle. From an ergonomic perspective, a 'low-positioned' handlebar would be more comfortable. Despite these ergonomic considerations, the 'high-positioned' handlebar is deemed an appropriate choice by the designer. This is because since the focus in this conceptual stage is the aesthetic human factors aspect, it aligns well with the aesthetic preferences of the target user.

Circumstance-based decision influence

To execute the position decision effectively, the prevailing circumstances require the designer to also commit to incorporating a specific style within the motorcycle solution. Consequently, after the commitment to a particular handlebar position level, the designer then

selects a corresponding style that aligns with this position. The spectrum of style options available is dependent upon the position level previously determined. For instance, if the designer commits to a 'high-positioned' handlebar, then the designer has the option to commit to 'high-handlebar' styled handlebars, such as *'Ape-hangers'* (Anderson, 2023).

Level of commitment

As elucidated by Andreasen (1980) in the *Theory of Domains*, decision commitments lead to concretisation and detailing. A decision can be characterised by varying degrees of commitment. A minimal commitment involves less detailing and concretisation, such as specifying a general positional level of a handlebar (high, medium, or low). In contrast, a more detailed and concrete commitment might involve specifying the exact dimensions of the handlebar's vertical position. This allows the designer to make decision commitments at different levels of detailing.

Level of commitment across design stages

During the conceptual stage, the principle of minimal commitment is prevalent. This can be seen in the example provided earlier in this section, where minimal position commitment is made during the conceptual design of a motorcycle. Conversely, the embodiment stage, which is more parametric in nature, as described by Pahl et al. (2007), is characterised by increased concretisation and detailing. Therefore, if a high-positioned handlebar is chosen during the conceptual stage, its exact measurements should correspondingly reflect this decision later in the embodiment stage.

Dualistic nature synthesis decision consequences

Dualistic nature synthesis decision consequences

As illustrated by Figure 7.10, owing to the dualistic nature of DOPs, decisions commitments made during the conceptual stage have consequences in subsequent stages of design, such as the embodiment stage.

Good consequences

A good consequence emerges when a conceptual decision commitment made by one designer, *'designer A',* leads to a favourable outcome during the embodiment design stage handled by another designer (*'designer B'*), regardless of whether it was an intended or unintended consequence. In such a case, the objectives of both designers align. For example, designer 'A' might choose a 'high-positioned' handlebar primarily for aesthetic reasons, which, intended or unintended, also proves to be ergonomically optimal. Consequently, in the embodiment stage, designer 'B' is able to specify an exact dimension that reflects this 'high-positioned' choice.

Problematic consequences – Design-stage conflict

Problematic consequences describe situations where the decisions made lead to either intended or unintended negative consequences. This is exemplified in Figure 7.10, where designer 'A' commits to a 'high-positioned' handlebar. However, this decision, made with or without awareness, poses issues for short riders, discovered in the embodiment stage. During the embodiment stage, designer 'B' is then required to specify dimensions that correspond to this, short rider-adverse, 'high-positioned' handlebar. This situation typically arises from a discrepancy between PDEs committed by the designer during the conceptual (early) stage and those preferred by the designer in the embodiment (late) stage, which may not be feasible due to the product's progression from the conceptual stage. In this doctoral research, such outcomes are termed *Design-stage Conflict Consequences (DCCs)*.

Use-phase consequences

Similarly to the observations made in Section 7.3.1 and as depicted in Figure 7.10, the commitments made during the synthesis decision activity across various design stages lead to a myriad of consequences, which are in turn felt during the product's use phase. These may lead to an ergonomically uncomfortable motorcycle or no product emotional attachment by the target users. Such consequences may also inhibit the success of the motorcycle in question. A detailed list of these use-phase consequences is given in Chapter 3.

Knowledge during synthesis

For this reason, Rodgers & Clarkson (1998) contends that synthesis design, as a complex and multidisciplinary decision-making activity, requires a significant amount of knowledge on both the intended and unintended consequences.

7.4 Dual Ontological Design Decision Commitments Phenomena

Product life-cycle consequences (LCCs)

According to Duffy & O'Donnell (1999), *"phenomena models are based upon observations and analyses of the design reality and hence, reflect design practice."* Borg (1999) introduces a phenomena model that explains the generation of *life-cycle consequences* (LCCs) from product and life-phase synthesis design commitments. The model by Borg (1999) delineates the impact of LCCs on the product life-cycle.

PUCs and DCCs

Conversely, the research presented in this doctoral dissertation identifies mechanisms by which *general user privation* and *design-stage conflict* arise throughout the product life-cycle, stemming from decision commitments made in the synthesis of DOPs.

DOP phenomena

The study with designers detailed in Chapter 4, along with the synthesis decision commitment models outlined in Section 7.2 and the research conducted by Agius et al. (2021), serve as the foundation for explaining how Population Use-phase Consequences (PUCs) and Design-stage Conflict Consequences (DCCs) emerge from decision commitments in the synthesis design activity of DOPs. What follows therefore is a formal model, represented in Figure 7.11, that explicates how DOP synthesis decision commitments result in PUCs and DCCs. This model will be dissected into two sections:

- Population Majority Privation Phenomenon
- Design-Stage Conflict Phenomenon

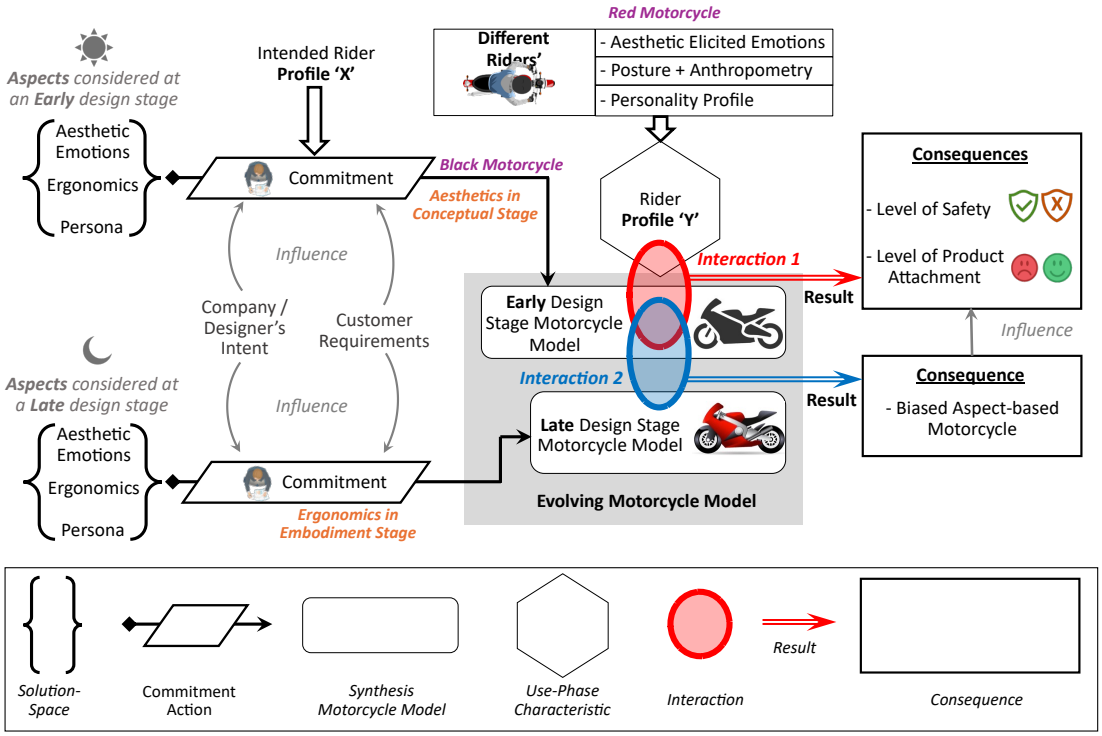


Figure 7.11 – Dual ontological product design decision consequence-based phenomena model

7.4.1 Population Majority Privation Phenomenon

Solutions-space composed of DOP PDEs which influence $hf_{E\text{-}AE\text{-}P}$

The design process is a decision intensive activity (Borg et al., 1999). For early DOP design, the designer has various options from the solution-space. In this doctoral research, the solution-space contains dual ontological PDEs which influence $hf_{E\text{-}AE\text{-}P}$, that is, the user's ergonomics, aesthetic-derived emotions and the persona while interacting with the product.

Committing to a particular PDEV

During the product design synthesis, the designer commits to a particular PDEV, where the designer's decision is influenced by various factors. As explained in Section 7.3.1 the designer makes commitments with the intended consequence of satisfying a specific problem requirement. For example, during DOP design the designer would make a commitment to select a particular PDEV with the intended consequence that the selection satisfies the target user's human factors requirements.

Consequences in successive life-phases

As indicated by Borg (1999) decision commitments introduce consequences. This research will follow on the argumentation made by

Borg et al. (1999), that is, *"the artefact model is governed by the commitments resulting from synthesis decisions in the design process."* Olesen (1992) also explained that, *"due to the phenomena of propagation effects, consequences resulting from a design–decision commitment can affect multiple life-phases, which make it difficult for designers to be aware of them all."* Design-decision commitments can have significant consequences during successive life-phases, where the designer has no more control over the product.

Problematic consequences affecting general user

If the target user is anthropometrically, emotionally and have the same persona as the general user then the DOP requirements satisfy those of the general user. On the other hand, if the general user varies off from the target user on the three human factor characteristics, then the product requirements do not satisfy those of the general user.

Therefore, if during design synthesis the designer makes a decision commitment to select PDEVs which do not satisfy the general user's requirements, this will result in a problematic consequence when ultimately the general user will interact with the DOP during its use phase.

Population majority privation

The *population majority privation* occurs when the designer intentionally commits to selecting PDEVs to meet the target user requirements, but unintentionally this commitment has a consequence on the general user from a human factors' perspective. Where these consequences will untimely have a direct effect on the product's success and the level of user's ergonomic comfort or safety, product emotional and persona-attachment.

Interaction

As illustrated in Figure 7.11, the phenomena model explicitly illustrates how PUCs result as an interaction between the committed dual ontological PDEV, which is now part of the product solution, and the general user requirements.

Case scenario of population

A case scenario of unintended problematic consequence (PUC) arises when a designer commits to a dual ontological PDEV which does not

majority privation

elicit positive emotions to the general user. As an example, consider a designer which committed to a PDEV intended for a particular rider (profile 'X'). During the manufacturing phase, this PDEV results in an attribute. This attribute will interact with the general user's human factor characteristics (profile 'Y') during product's use, giving rise to a consequence. Given that the PDEV does not satisfy the requirements of the general user, this interaction gives rise to a low level of product attachment.

7.4.2 Design-Stage Conflict Phenomenon

Solutions-space at the early stage

During the DOP design synthesis, a designer commits to a particular PDEV. As explained in Section 7.3.2 the designer makes commitments with the intended consequence of satisfying a specific human factor in focus, considered at an early routine design stage.

Decision propagation

Extending the explanation of Olesen (1992) and Borg et al. (1999) on the phenomena of propagation effects, decision commitments can also affect later design stages.

Problematic consequences affecting $hf_{E\text{-}AE\text{-}P}$ considered at later stage

If a specific human factor (e.g. hf_{AE}) in focus, considered at an early routine design stage aligns with another human factor (e.g. hf_E) considered at a later design stage, then the early product requirements satisfy those of the later considered human factor (e.g. hf_E). On the other hand, if hf_{AE} and hf_E diverge, then the early product requirements do not satisfy the human factor (hf_E) considered at a later design stage.

If during the conceptual design synthesis, the designer makes a decision commitment to select PDEVs which do not satisfy the requirements at the embodiment stage, problematic consequences will arise from the interaction between a human factor aspect committed at an early routine design stage and another aspect considered at a later design stage.

Design-stage conflict

The *design-stage conflict* occurs when the designer intentionally commits to selecting PDEVs to meet a particular human factor (e.g.

hf_{AE}) requirement, but unintentionally this commitment has a design consequence on another human factor (e.g. hf_E) later on in the design phase. Following Section 4.4.3, important and critical aspects are considered in the early routine design stage. Therefore, a biased DOP design consequence will arise as a particular human factor aspect will be given priority over others considered at later stages. These consequences will untimely affect the level of user's ergonomic comfort or safety, product emotional and persona-attachment.

Interaction

As illustrated in Figure 7.11, the phenomena model explicitly illustrates how DCCs result as an interaction between the PDEVs committed in the early routine design stage, which is now part of the product solution, and the later stages' human factor requirements.

Case scenario of design stage conflict

A case scenario of unintended problematic consequence (DCC) arises when a designer considers and commits to only aesthetics in the conceptual design stage. Once the conceptual design has been approved in the evaluation activity, the designer moves to the embodiment stage. Here, the committed aesthetic features will interact with the adverse-to-aesthetic ergonomic features, as the latter is considered in the embodiment design stage. This gives rise to a problematic unintended design consequence, reflecting a conflict between the two aspects. Given that the aesthetic-oriented PDEV does not satisfy the ergonomic requirements, this interaction gives rise to a low level of comfort and/or safety once the DOP is in its use phase.

Real Consequences (RC) = PUC + DCC

As seen in Section 7.3.1 and 7.3.2, the two phenomenon concerned in this doctoral research are that DOP design decisions generate unintended consequences arising from interactions between the product and (potential) customers during the use phase, as well as interactions within design stages (during the product's design phase). As illustrated in Figure 7.11, these two interactions will in turn have an effect on each other, giving rise to further consequences and denoted as (this research's) *Real Consequences (RC)*. These consequences will

untimely affect the level of a myriad of human factor aspects during product (potential) use as highlighted in Chapter 3.

7.5 Validation of the Developed Phenomena Model

Comparative case studies validation

As explained in Section 7.1.2, this section will disclose the validation of the developed dual ontological phenomena model, through a comparative case study approach. This describes how real motorcycle case studies achieved success in the motorcycle industry by proactively minimising unintended and negative (problematic) consequences.

7.5.1 Population Majority Privation Phenomenon: Honda Super Cub Case Study

Industrial design practice

In an interview (Honda, 2018), *Jozebo Kimura*, an industrial designer who was part of the *Super Cub* design team (led by Honda and Fujisawa), explained how this motorcycle was conceived. In accordance with the developed phenomena model (Figure 7.11), the standard design practice is to carry out customer analysis. Amongst other factors in this analysis, intended riders are identified and the motorcycle would be developed according to their needs. However, the phenomena model highlights that this approach often leads to unintended problematic consequences during the product's use phase. Consequences will arise when different riders' human factor characteristics (other than the intended riders, such as the general rider) interact with the developed motorcycle. This manifest itself in a low level of product attachment or low level of ergonomic comfort/safety.

Honda Super Cub design process

From the interview, *Kimura* noted how *Honda* and *Fujisawa* gave special attention to this problematic consequence, which is schematically demonstrated in Figure 7.12. *Kimura* stated that in that time *Fujisawa* conducted extensive local and overseas customer requirement analysis, capturing the general requirement of a larger population: *"The new motorcycle would be neither a moped nor*

scooter. Instead, it would be something that the people really desired. An entirely new concept in handling ease and styling that would be unique." Besides conducting research on what the general public needed as a motorcycle type, size, their intention of use, and the motorcycle's aesthetics, the design team also enquired about their persona. This can be verified from the interview (Honda, 2019) where *Goto* (one of the *Super Cub* development team) stated: *"The team wanted answers to numerous questions, one of which was why women did not ride bikes in the city. The development team travelled the country in search of answers ... interviewing women and tape recording them."* Based on the requirements gathered from the general public, the team agreed to focus their efforts to produce a popular small motorcycle for the masses. *"The design brief was to develop a chassis and bodywork of a size and shape that even women could easily get on, off, and ride ... with a friendly aesthetics according to the requirements of many. Therefore, the colours which were the most familiar and popular with most Japanese were chosen ... as the Super Cub was designed to be a vehicle for the masses, the design team wanted to use familiar colours"* stated *Kimura* in his interview. *Kimura* added that: *"Although in those times many mopeds' tyres in Europe were between 610 and 660 mm, the Honda design team took out a survey to determine the average size of Japanese public. Then they extracted the most appropriate size that could ensure easy mounting and dismounting, and which provide good foot grounding and excellent riding performance. The calculated tyre size was found to be 530 mm."*

Listening to the general riders' requirements

One of the top requirements of the general public was to have a motorcycle which is easy to use, to concentrate better on the road. As such, the *Honda* design team invented the clutch-less gearbox to meet the general public's requirements. The *Super Cub's* semi-automatic four-speed transmission is great for learners, and enjoyable for experienced riders. In regions outside of Japan, such as Asia, Europe and the USA, the *Honda Super Cub* series has evolved to accommodate

the unique culture and diversifying customer needs, building products close to the general public for each country.

Foreseeing the unintended population majority privation consequences

The above statements provide a degree of evidence that made the *Honda Super Cub* a successful motorcycle design. By foreseeing the unintended consequences, that is, by surveying the general public instead of the intended riders *Honda* managed to develop a motorcycle which in 60 years managed to sell 100 million units.

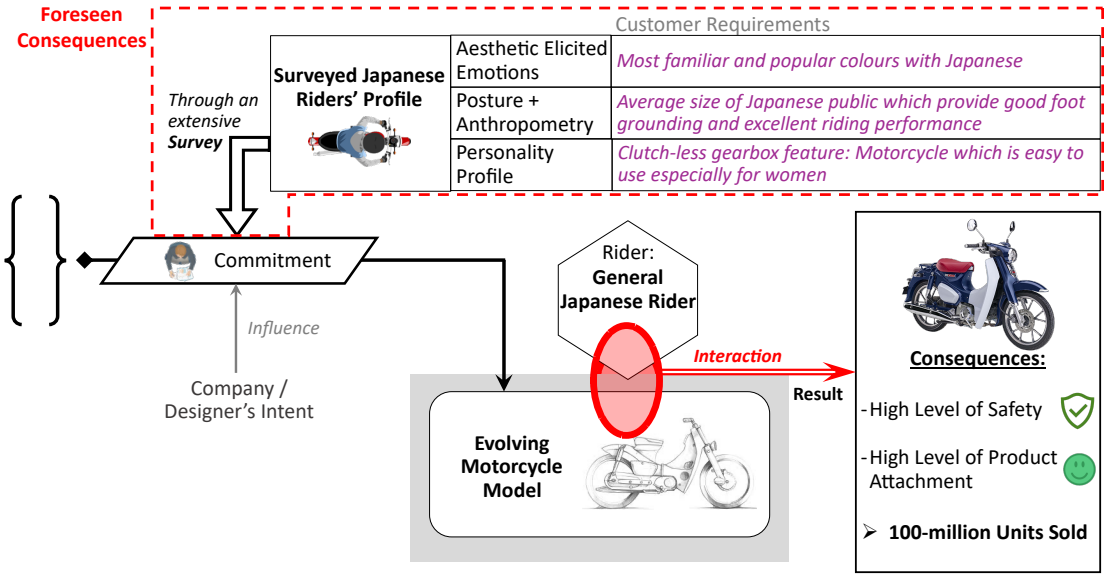


Figure 7.12 – Phenomenon model for the Honda Super Cub case study

7.5.2 Design-Stage Conflict Phenomenon: Ducati Diavel Case Study

Ducati Diavel's design process

An interview to *Andrea Ferraresi*, the design director of *Ducati*, was conducted by Digital Trends (2019) to understand how the *Ducati Diavel* went from a sketch to a production model. According to *Ducati's* design director the design phase of the *Diavel* is similar to the standard product design process with minor but significant divergence. *Ferraresi* stated that: *"Like with any other project, the design phase of the Diavel started by incorporating market analysis, competitor analysis and customer analysis data."* This is in accordance with Figure 7.11 and implies that designers made design decisions based on the influence of specific customers' requirements, and market trends on ergonomics and aesthetic-derived emotions. The design brief was then transferred

to the design department, where a sketch was used to conceptualise the ideas for the *Diavel*.

Refining conceptual design for ergonomics before the embodiment stage

According to the phenomena model many designers focus on a certain aspect in the early (conceptual) design stage. Ultimately, this yield in unintended consequences during the use phase of the product. Riders may not purchase the motorcycle because although it is aesthetically pleasing for them, it may be uncomfortable. Or although it is comfortable riders do not feel emotionally attracted to the motorcycle. In the case of the *Diavel*, the design team diverged from the standard design process. This is schematically demonstrated in Figure 7.13. As claimed by *Ferraresi*, after finalising the conceptual sketch of the *Diavel* and before going to the embodiment stage, the design team have set the height of the seat, handlebars and footpegs, amongst other parameters. This added process modified the original sketch from an aesthetics point of view. The process of altering the sketch for aesthetic and ergonomic reasons was iterated until the design team was satisfied with the results. That is, achieving a compromise between ergonomics and aesthetics. The elimination of the problematic interaction between the early and late design stage models of the *Diavel* indicated that design stage unintended consequences were addressed, making the *Diavel* a successful motorcycle. Confirmation of the harmonisation that the *Diavel's* design team managed to achieve, through their design decisions, are in the riders' comments: *"The Diavel is so comfortable that it is like a touring bike, but with a greater style and attitude unlike any motorcycle I have ever seen"*; *"The Ducati Diavel has a sitting position and ergonomics that are really comfortable, I drove for three hours without stopping. But the driving factor for purchasing this motorcycle were its striking aesthetics"* (Agius et al., 2021).

Foreseeing the unintended design stage conflict consequences

The above statements provide a degree of evidence that made the *Ducati Diavel* a successful motorcycle design. By foreseeing the unintended consequences, that is, by considering both the aesthetics and ergonomics in the early routine design stages, and by finding the

right balance between the two aspects, *Ducati* managed to develop a motorcycle which has won *'Best of the Best at Top Design 2019 Awards'*.

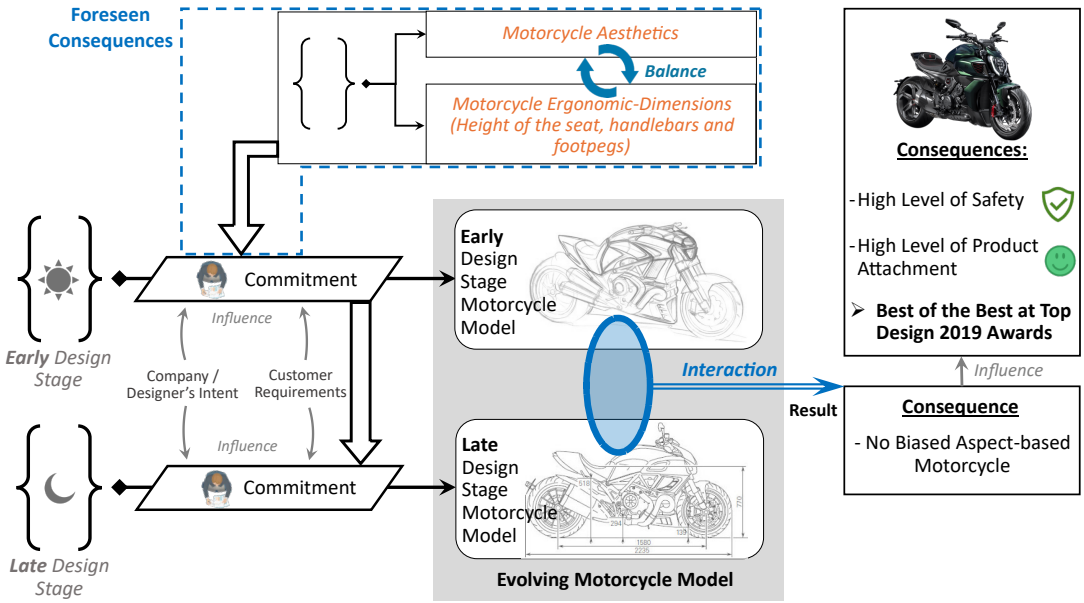


Figure 7.13 – Phenomenon model for the Ducati Diavel case study

7.6 Significance of the DOP Design Phenomena

Significance DOP phenomena model

Based on the arguments provided in this section, during DOP design synthesis, the designer selects a PDEV from a decision space, and commits this to the DOP solution. Even though unintentionally, the decision commitment may result in problematic consequences that negatively affect the product's $hf_{E\text{-}AE\text{-}P}$ during the interaction with user, and result in a population majority privation and design-stage conflict. These consequences are designated as PUCs and DCCs.

Understanding the mechanisms of how population majority privation and design-stage conflict are related to DOP synthesis decision commitments can therefore be used to support the design process of these products. By knowing what synthesis decision commitments have been made, the resulting PUCs and DCCs can now be inferred. Furthermore, by becoming knowledgeable of PUCs and DCCs, designers can then explore different product solutions in order to handle population majority privation and design-stage conflict.

Foundation for a consequence knowledge-based approach

The DOP phenomena model is also significant as it provides a foundation of how to make human factor and harmonisation knowledge explicit within a design approach framework. Furthermore, it also establishes a basis as to what synthesis decisions commitments need to be captured in order to generate a knowledge model of PUCs and DCCs.

Highlights significance of consequence knowledge approach

These PUC and DCC knowledge allow decision makers to be explicitly aware of their synthesis decision commitments and the impact on the three human factors during the use phase. Furthermore, revealed PUC and DCC knowledge allows designers to explore alternative decision commitments in order to avoid and minimise such consequences during the design synthesis of such products.

Needs for integrated and harmonisation synthesis approach

The phenomena model presented in Section 7.4 underline that:

1. In order to support knowledge about DCCs, a design for multi human factors (hf-Multi X) during the synthesis activity at the conceptual stage needs to be provided.
2. In order to support knowledge about PUC, harmonisation awareness needs to be provided.

Without providing hf-MultiX and harmonisation at the early routine design process it would not be possible to draw inferences about human factor consequences affecting (potential) customers during the use phase of the DOP.

7.7 Chapter Conclusions

A phenomena model explaining PUC and DCC generation

This chapter presented a DOP phenomena model explaining how population majority privation and design-stage conflict can occur from two different conditions; PUCs and DCCs. This was directly derived from actual DOP designers in the field. This was further substantiated by the literature with two case studies of real motorcycle designs, which made success in the industry. These were employed to validate the developed DOP phenomena model. Validating with case studies

was essential for a robust scientific model. Knowledge of DOP synthesis decision consequences is not always known. This explains why supporting designers in explicitly becoming knowledgeable of PUCs and DCCs resulting from synthesis decision commitments, assists them in handling of population majority privation and design-stage conflicts.

Exploiting the phenomena to support DOP design

Therefore, to support the DOP design process and facilitate hf-Multi X and harmonisation, with reference to Figure 7.14, an approach is required to make designers aware of PUCs and DCCs. The next chapter consequently presents an approach framework to support DOP design which exploits the population majority prevention and design-stage conflicts disclosed in this chapter.

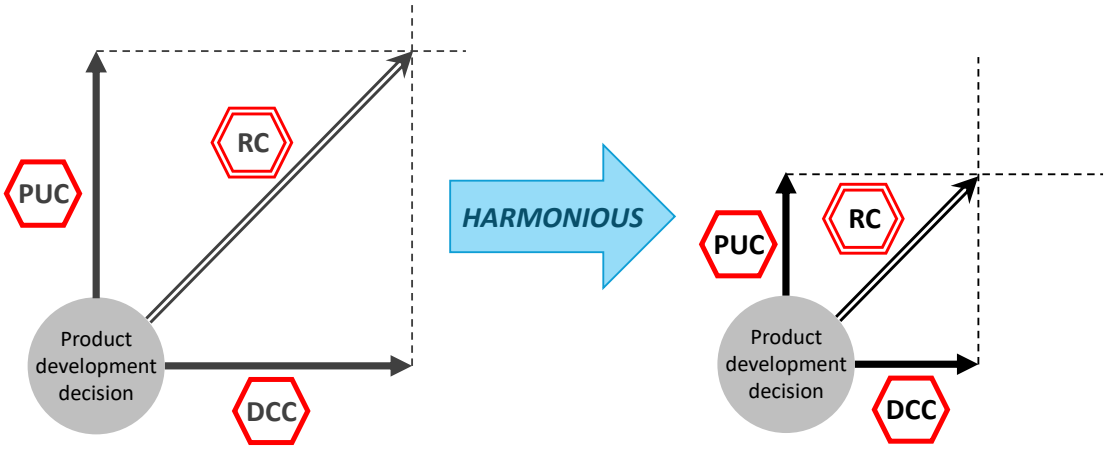


Figure 7.14 – Purpose of the HARMONIOUS design approach framework

8 An Approach Framework for Supporting hf-Multi X and Harmonisation during DOP Synthesis Design

This chapter represents the culmination of the research work presented in the earlier chapters of this doctoral dissertation. Its primary objective is to present a prescriptive solution based on the findings accumulated to this point; an approach for supporting the dual ontological product (DOP) design process and assisting designers in handling population majority privation and design-stage conflicts from a human factors' ($hf_{E\text{-}AE\text{-}P}$) perspective. This chapter will therefore disclose the concepts of how to utilise knowledge to facilitate design for multiple human factors (hf-Multi X) and harmonisation to make designers aware of Design-stage Conflict and Population Use-phase Consequences (DCCs and PUCs), during the DOP design process.

In view of this, Section 8.1 revisits the requirements set by DOP users (as discussed in Chapter 3) and designers (from Chapter 4), along with insights derived from Chapter 7 concerning DCCs and PUCs. To address these requirements and mitigate or minimise DOP challenges, Section 8.2 introduces the proposed approach framework for DOP design, including its underlying frames. Section 8.3 then describes an archetype of this approach framework, demonstrating its application in exploring motorcycle design solutions which handles population majority privation and design-stage conflicts. A preliminary validation of the current form of the approach framework and its soundness, as evaluated by motorcycle designers, is presented in Section 8.4, while Section 8.5 concludes this chapter.

8.1 Design Approach Framework Requirements

Compiled requirements and how these will be met through an approach framework

The objective of this section is to revisit and consolidate a list of requirements identified by DOP users (research tertiary users or RTUs) and DOP designers (research primary users or RPUs) that need to be met by the design approach framework. These will be termed as *approach framework requirements*, abbreviated as *FR#*. The section will not only disclose these requirements but also detail how they will be addressed within the framework. This list of FRs will serve as the

foundational basis for the construction of the prescriptive approach framework.

Requirements of DOP designers

To cope with the three human factor related challenges during the design of DOPs, six requirements for a $hf_{E\text{-}AE\text{-}P}$ dual ontological support approach framework were identified in Chapter 4. In the following consolidated list, these are termed as *research primary users' requirements*, abbreviated as *RPU-R#.*

Requirements of DOP users

Furthermore, interviewed DOP users (in Chapter 3) unveiled four use phase related requirements which intertwine with those of the designers. These requirements are also included in the consolidated list below, where they are referred to as *research tertiary users' requirements*, abbreviated as *RTU-R#.*

Therefore, in the context of DOPs, the design support approach framework has to:

RPU-R1

FR1. Support the synthesis activity at the conceptual design stage.

Addressing FR1

FR1 is addressed by constructing the approach framework to assist in the synthesis activity, specifically by facilitating the decision-making process. This is achieved by enabling designers to decide on product design elements (PDEs) from a library and adding them to the evolving DOP model.

A pre-requisite for this approach framework, utilised at the conceptual design stage, involves having a defined target user (TU), determined during the DOP task clarification design stage. To facilitate this, the approach framework has a component that enables designers to model the target user, derived from the task clarification.

RPU-R2

FR2. Be implemented as a design computer-based support tool.

Addressing FR2

FR2 is addressed by modelling the approach framework on a *knowledge-based system* (KBS) architecture, composed of a

database, knowledge base, inference engine and a *user-interface*. This configuration is intended to facilitate the implementation of the approach framework into a proof-of-concept computer-based tool.

To avoid limiting designers' creative input without dictating how solutions should be implemented, the approach framework is equipped with *'support'* components. These components are designed to assist rather than impose *'restrictive-solution'* approaches.

Studies of Kim et al. (2009) and Zhuang et al. (2017) have established that engineering design is a mental process. Human mental processing capabilities limits the amount of knowledge that can be processed by designers (Clarkson, 2007; Wickens et al., 2021). The evolving demands of product development, characterised by their inherent uncertainty and complexity, further strain these mental processing capabilities. Additionally, the processing speed of the human mind is constrained, particularly when compared to the capabilities of a computer.

Consequently, having the approach framework modelled on computational architecture, is deemed a necessary and feasible solution to address these challenges.

RTU-R1

FR3. Highlight certain PDEs which take precedence over others, due to the dual nature.

Addressing FR3

FR3 is addressed by enabling the approach framework to utilise the previously identified library (in FR1) with human factors related PDEs. Furthermore, to prioritise certain PDEs over others, a weighing mechanism is incorporated in the evolving DOP model component.

RPU-R3 & RTU-R4

FR4. Provide a user-centred design (UCD) approach during the DOP design process. This is carried through:

FR4a. *Collection of (potential) users' anthropometric information, as well as real-postural and ergonomic interaction information through an adjustable DOP hardware simulation tool.*

FR4b. *Collection of (potential) customers' emotions which are elicited to different DOP styles and aesthetic preferences.*

FR4c. *Collection of the persona, based on the (potential) users' personality, behaviour, DOP use-context and demographics details.*

RTU-R2

FR4d. *The incorporation of market trends.*

Addressing FR4

FR4 is addressed by positioning the designers (RPUs) of the approach framework and DOP users (RTUs), at the core of the approach framework. This central placement underscores the framework's UCD philosophy. Recognising the vital role of (potential) customer input for a UCD approach, a dedicated component within the approach framework is designed for gathering information related to the three human factors. To meet FR4d, $hf_{E\text{-}AE\text{-}P}$ PDEVs from the library are based on the current market trends.

RPU-R4

FR5. Provide multiple life (design and use) phase awareness, specifically through the DCCs and PUCs awareness.

Addressing FR5

FR5 is addressed by equipping the approach framework with a *'support'* component, which serves reveal the design-stage conflict and population use-phase consequences (DCCs and PUCs) of commitments made during the DOP synthesis design activity. Additionally, the design framework incorporates a *'recommendation'* component. This component enables DOP

designers to explore alternative choices aimed at mitigating or minimising DCCs and PUCs.

RPU-R5

FR6. Provide design for multi human factors (hf-Multi X) assistance, which handles design-stage conflicts.

Addressing FR6

FR6 is addressed by allowing the approach framework to act as a bridge between the early and late design stages. This facilitates the concurrent consideration of multiple human factors at the conceptual DOP design stage. Achieving this involves advancing certain critical PDEs and parametrisation, which are typically addressed in later stages, to earlier design stages. The adoption of hf-Multi X is key, enabling the concurrent consideration of the three human factors. Moreover, human factor design knowledge ensures that designers are explicitly made aware of the implications of early routine design decisions on human factors during the product's use phase.

RPU-R6 & RTU-R3

FR7. Provide harmonisation awareness, which handles population majority privation and conflicts between the three human factors.

Addressing FR7

FR7 is addressed by integrating a general user (GU) modeller into the approach framework. This modeller is derived from the information collected from (potential) customers.

Importantly, the approach framework includes a harmonisation component which assists designers in achieving balance among potential provisional DOP design solutions. The harmonisation knowledge supports designers in balancing multi human factors and human diversity, such as knowledge about reconciling conflicting aspects to achieve a harmonious design solution and to reach a wider customer base.

Harmonistic knowledge

The presented arguments reveal how harmonistic knowledge can be employed to offer support to designers working with DOPs, in order to handle multi human factors and diversity in the design activity of these products. In this doctoral research harmonistic knowledge is comprised of human factor knowledge and harmonisation knowledge. This knowledge needs to be supplied in a non-obtrusive manner with respect to the DOP designers' cognitive activities. Furthermore, this knowledge needs to allow them to explore a number of different and evolving DOP solutions from a human factors' perspective.

8.2 *HARMONIOUS*: A Harmonistic Knowledge-based DOP Design Approach Framework

Approach purpose

This section introduces the harmonistic knowledge-based dual ontological product design approach, developed as part of this doctoral research. The purpose of the approach framework is to:

hf-Multi X early support

- Support the DOP design when the artefact solution model is still provisional. This support is intended to help DOP designers to proactively design for hf-Multi X, by concurrently considering the three human factors and explore different DOP solutions as early as possible.

Knowledge derived from DOP users

- Provide knowledge, derived from data gathered directly from DOP (potential) customers in a timely manner which will enable DOP designers to consider and explore alternative commitments that will have different impacts on human factors during the DOP's use phase.

Foreseeing and minimising DCCs and PUCs

- Offer the necessary support when the integrated solution model is still evolving to help proactively foresee the population majority privation consequences and design-stage conflict consequences. Furthermore, revealed DCC and PUC knowledge allows designers to explore alternative decision commitments in order to avoid or minimise these consequences.

Multi-aspect harmonisation

- Guide DOP designers towards a harmonised synthesis product solution, which balance conflicts arising among $hf_{E\text{-}AE\text{-}P}$, as well as the needs of both target and general users.

Approach framework: HARMONIOUS

The formulation of this approach is an outcome of the framework requirements (FR) gathered during the *first descriptive study* and addressed in Section 8.1. It also builds on the philosophy underpinning the phenomena models discussed in Sections 7.3 and 7.4. This approach has been further elaborated into an information model, forming a knowledge structure, and organised in such a way to form a design approach framework. Figure 8.1 illustrates the DOP design approach framework, titled *HARMONIOUS (**H**uman f**A**ctors ha**RM**onisation **O**f dual-o**N**tolog**I**cal pr**O**d**U**ct**S**)*, which from a human factors perspective, supports the dual ontological product design process, by proactively providing harmonistic knowledge.

8.2.1 Layers of the HARMONIOUS Approach Framework

Information model framework

Referring to Figure 8.1, *HARMONIOUS* is composed of four layers: u*ser layer (A); user interface layer (B); knowledge layer (C), and information management layer (D)*.

User layer (A)

The approach framework is based on UCD principles, where the primary and tertiary users are placed in the framework's core as they are an essential aspect. Every other aspect of the approach framework (layers and frames) revolve around the users. The *user* is sub-divided into two groups; DOP users (RTU) and designers (RPU). The communication between the DOP users and designers is a vital requisite for a UCD approach. The approach framework acts as a host for the communication to occur. *HARMONIOUS* captures human factors related factual user information (Requirement FR4, in Section 8.1). Contrary to the current reality, the approach framework empowers designers to use the knowledge derived from this information, and assist them in identifying DCCs and PUCs, which in turn have an impact on DOP users during the product's use phase.

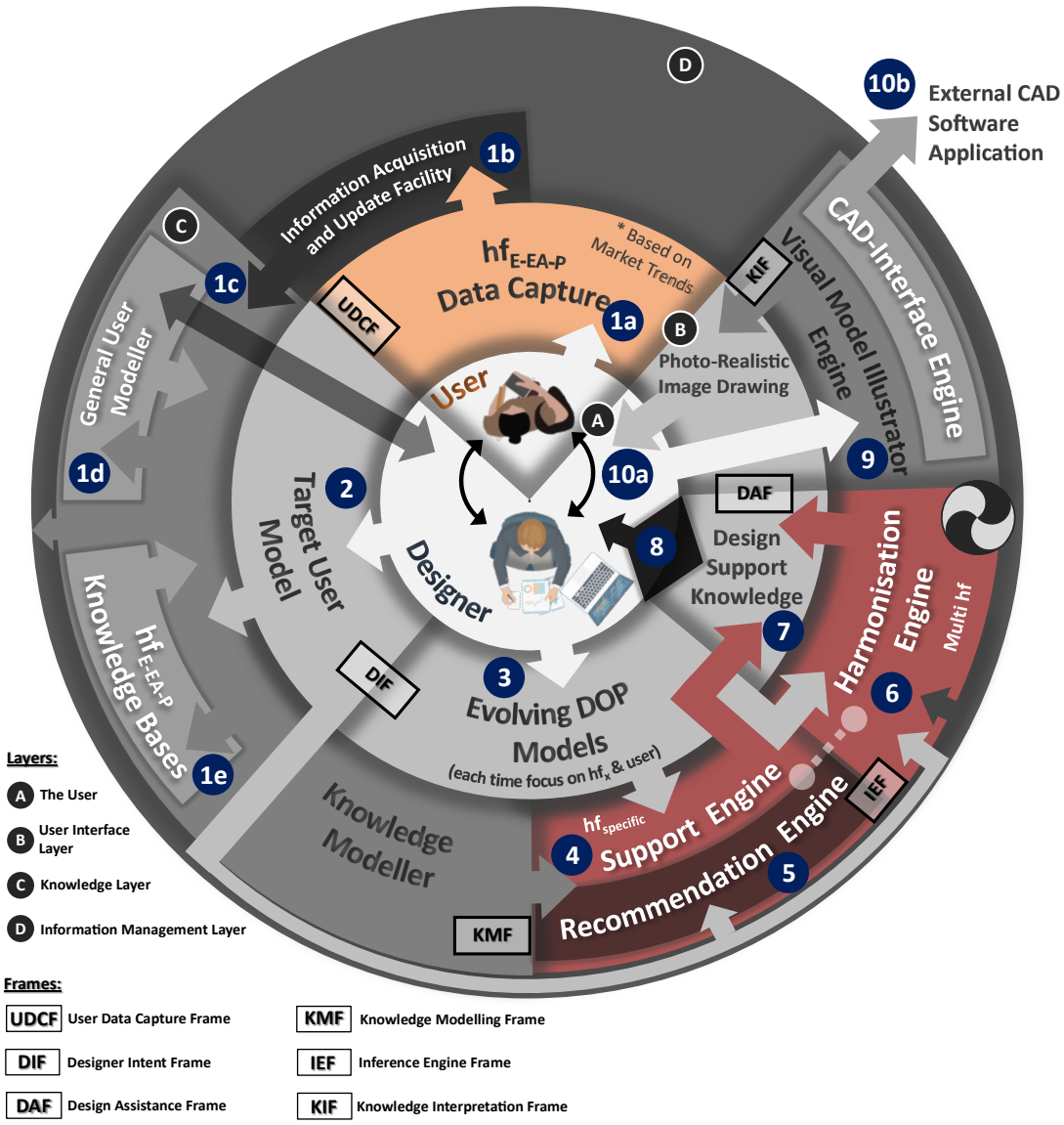


Figure 8.1 – A high-level representation of the HARMONIOUS approach framework

User interface layer (B)

The second layer in this approach framework is the user interface (*front-end*), responsible for all of the communication between the user and the *HARMONIOUS* framework's *back-end*. This layer allows the designer to access the harmonistic knowledge and highlights the type of inputs or outputs RPUs and RTUs are expecting to interact with.

Knowledge layer (C)

The third layer of the approach framework is the knowledge layer, acting as the backbone of *HARMONIOUS* and provides the intelligent support to augment the synthesis decisions made by designers. Central to this layer is the *knowledge base*, encompassing essential human factors-related knowledge designed to assist designers in their activity. This layer contains domain specific knowledge captured from DOP

users via the *knowledge acquisition module*. Within this layer, the *knowledge management* sub-layer is responsible for keeping the system up to date with the latest and relevant harmonistic knowledge.

Information management layer (D)

The fourth layer concerns information management. This layer is responsible for creating, managing, and updating the *information*. This layer includes the *database*. The database contains relevant information used by the framework. Together with the knowledge layer, the information management layer forms the back-end of the approach framework.

8.2.2 Frames Characterising HARMONIOUS

Supporting frames

The approach framework is based on six frames. Detailed descriptions of each frame, including their roles and functions within the four layers of the *HARMONIOUS* framework, are provided in the following sub-sections.

User Data Capture Frame (UDCF)

Collection

The *User Data Capture Frame* (UDCF) is designated to collect inputs from DOP users concerning aspects related to $hf_{E\text{-}AE\text{-}P}$. The UDCF is constructed in accordance with the fourth approach requirement (FR4) stipulated in Section 8.1.

Beyond $hf_{E\text{-}AE\text{-}P}$

In this doctoral research, emphasis is placed on three specific human factors: ergonomics, aesthetics, and persona ($hf_{E\text{-}AE\text{-}P}$). However, the *HARMONIOUS* framework is designed with flexibility, allowing for the incorporation of additional human factors beyond these three core aspects. For instance, a fourth factor (as outlined in Section 2.4 through Figure 2.5) could be integrated, thereby expanding the (UPGF) to accommodate inputs related to the fourth human factor.

Accepted data collection instruments

This frame employs a diverse array of techniques for gathering data related to human factors. These methods range from surveys and interviews, which are instrumental in gauging DOP user behaviours and

attitudes, particularly on subjective matters, to more objective means of data collection. Objective human factor data can be acquired through several measurement techniques, including the use of hardware simulators, as well as digital human models (DHM) such as *human builder* (Högberg et al., 2019) and manikins within CAD software applications. Alternatively, sensor-based technologies offer a means to objectively record information pertinent to human factors. Another method is to use established standards in human factors which provide an existing database of information. Most importantly, in accordance with FR4d the collected information reflects current market trends.

Information Acquisition and Update Facility

These observations are captured by the *Information Acquisition and Update Facility* (IAUF). Each time an observation is made, the IAUF updates the framework with the new observation, categorising each entry as a 'record'. This process is not merely a singular action but a continuous cycle of updates. Owing to the ever-evolving nature of trends, it is imperative that the IAUF, with support from the UDCF, remains consistently updated with the latest information from DOP users on the necessary human factors.

Knowledge Modelling Frame (KMF)

KMF = KM + hfKB + GUM

The *Knowledge Modelling Frame* (KMF) encompasses three components: the *Knowledge Modelle*r (KM), the *human factors Knowledge Base* (hfKB), and the *General User Modeller* (GUM).

Knowledge Modeller

The IAUF send the (updated) information to the KM, thereby enabling the generation of new knowledge from the gathered information. As will be explained in the following chapter, the derivation of knowledge is achieved through a *knowledge discovery from data* (KDD) approach. This process epitomises the internal mechanism by which the KM operates. Consequently, the KM is capable of utilising various KDD algorithms to construct predictive models—effectively transforming

raw data into structured knowledge—without the necessity for any explicitly defined rules.

Human factors Knowledge Base

The knowledge models generated by the KM are stored in the hfKB. As such, the hfKBs encapsulate the knowledge necessary for understanding, formulating and solving problems. The dimensionality of the hfKB is contingent upon the specific aspects of human factors delineated in the UDCF. Consequently, for the purposes of this dissertation, it is posited that there exist three distinct knowledge bases (KBs), namely hf_EKB, $hf_{AE}KB$ and hf_PKB. Each KB serves as a repository for domain-specific knowledge garnered through observation. In addition to factual and heuristic knowledge, these KBs also house structured rules and logic derived from patterns within the domain. These are intended for subsequent utilisation by the inference engine. Within the *HARMONIOUS* framework, the KM represents the accumulation of different human factor aspects captured observations to construct or expand the knowledge base.

General-User Modeller

The GUM is tasked with the generation of the general user model, utilising inputs from the KM, the captured information from IAUF and instructions from the DOP designer. This process involves representing human factors qualities which represent central tendencies. In instances where a specific human factor is represented by continuous data, the average (50^{th} percentile) measurements of the population sample are employed to reflect the central tendency. The mode is utilised for data of a categorical nature, to represent notable (central tendency) characteristics associated with that particular human factor. Through specific instructions, the designer is able to adjust this central percentile, ranging from the 5^{th} percentile mark to the 95^{th} percentile mark, thereby accommodating a broad spectrum of user representations.

Designer Intent Frame (DIF)

DIF = Target User + Evolving DOP models

The *Designer Intent Frame* (DIF) is situated within the user Interface layer and is characterised by two components: the *Target User Model* and the *Evolving DOP Model*.

Target User Model

HARMONIOUS becomes operational subsequent to the completion of the task clarification stage (FR1), by which point the DOP designer would have delineated the target user's human factor requirements, as formulated during the task clarification stage. These requirements are conveyed to the designer through a design brief, established either by the designer or as per the specifications desired by the organisation. Consequently, the designer employs the DIF to construct a model of the target user for whom the DOP is specifically designed, in accordance with the agreements reached during the task clarification stage.

Evolving DOP Model

It is at the Evolving DOP Model juncture that the actual synthesis activity commences (FR1). Here, designers engage in a DOP decision-making activity. Within this space, they commit to synthesis decisions with the objective of fulfilling the DOP requirements. This involves in the selection of DOP PDEVs from a reusable library, to construct the envisaged DOP model. Further elaboration on the constituents of the reusable library will be provided in Chapter 9. Here the designers engage in the concurrent DOP design synthesis of hf-Multi X approach in accordance with requirement FR6.

Inference Engine Frame (IEF)

IEF = SE + RE + HE

To be adequately supported DOP designers require both human factors and harmonisation application of knowledge, accomplished through the *Inference Engine Frame* (IEF). The IEF is the main processing element of the *HARMONIOUS* framework and is composed of three engines, the *Support Engine* (SE), the *Recommendation Engine* (RE), and the *Harmonisation Engine* (HE). These engines communicate with

each other and utilise the necessary knowledge from the hfKB to formulate the consequences, recommendations and harmonisation.

Support Engine (SE)

Decision commitment consequences

The role of the SE is to evaluate the DOP decision commitments being made and their effects on the provisional DOP solution model. This is used for the interaction modelling that occur between the committed target or general user (TU or GU) models and the DOP solution decisions (FR5).

Provide PUC and DCC

Once the designer commits the SE will infer the PUC and use-phase consequences derived from the various interactions occurring with the target and general user models. DCC knowledge is inferred when a decision committed to the provisional DOP solution model interacts with other human factor aspects considered at a later design stage.

Recommendation Engine (RE)

Alternative to minimise problematic PUCs and DCCs

The RE is utilised to guide and motivate the DOP designers in exploring different decision commitments during the DOP design process. The RE assists the designer in exploring alternative decision commitments or solutions which can be utilised to mitigate, alleviate or eliminate the problematic human factor consequences (FR5). To assist the designer in setting up the DOP to better suit the TU/GU for different human factors perspective, the recommendations constitute of the evolving DOP features leading to the minimum human factor problematic consequences. Additionally, the RE suggests modifications to the evolving DOP's PDEs, with the aim of developing a DOP model that fosters a better level of ergonomic comfort and safety, as well as product-emotional and product-persona attachment.

Providing clear explanations of recommend-ations

Furthermore, to ensure that the DOP designers can trust the framework's provision of appropriate support, it is crucial to provide clear explanations to the DOP designer regarding how the recommendations from RE were deduced, along with any pertinent

background and theoretical knowledge. In *HARMONIOUS* this is carried out by providing knowledge of which decision commitments generated the respective human factor problematic consequence and provides guidance on which PDEV should be employed to address this issue.

Harmonisation Engine (HE)

Harmonise solutions committed up to this point

The Harmonisation Engine is the kernel of this frame and the approach framework. The HE is utilised to harmonise possible design solutions in order to create a provisional balanced solution (approach framework requirement 7 – FR7). Information is gathered directly from the potential design solutions committed up to this point by the designer. To achieve this harmonisation, *HARMONIOUS* can use various mathematical algorithms. These are discussed in greater detail in Chapter 9.

Provide support and recommend-ations to the harmonised solution

The harmonised solution may have some shortcomings as it cannot fulfil all the human factors requirements considered in the framework, due to the compromises made. Therefore, the HE leverages the SE to provide human factor and use-phase consequences, and RE to mitigate, alleviate or eliminate the problematic interactions between human factors of both TU and GU. *HARMONIOUS* is capable of offering multiple harmonised solutions for the evolving DOP model.

Support approach

Given that the approach framework is a design support approach, it is within the designer's discretion to either accept or disregard the recommendations provided by *HARMONIOUS*, and the final decision commitment rests in the designer’s hands.

Knowledge Interpretation Frame (KIF)

KIF = VMIE + CAD-IE

The purpose of the *Knowledge Interpretation Frame* (KIF) is to interpret the final committed DOP model composed of the synthesised PDEs. This frame enables various interpretations of the model, which may

involve the use of the *Visual Model Illustration Engine* (VMIE) or the *Computer Aided Design Interface Engine* (CAD-IE).

Visual Model Illustration Engine

The VMIE is tasked with rendering the 2D visuals and geometry of the final committed DOP model. It produces a *realistic, to-scale visual representation* based on the final harmonised solution, incorporating actual dimensions to depict the geometric aspects of the solution and detailed illustrations to convey the visual appearance of the DOP. As highlighted in Section 4.4.3, traditional paper-based freehand sketching remains a prevalent method among designers during the conceptual stage for generating new ideas. As such the output of the VMIE is helpful for the designer in subsequent design activities, serving as a foundation for the initial concept sketches of the DOP model.

3D CAD base model

The CAD-IE functions as an *application programming interface* (API), facilitating communication between *HARMONIOUS* and various Computer Aided Design (CAD) software applications. Through exporting the DOP model's characteristics via the API, external CAD software is able to reconstruct the DOP model, whether as a sketch, a 2D drawing, or 3D spatial features in a CAD geometric format.

Designer Assistance Frame (DAF)

Design support knowledge to designer

The *Designer Assistance Frame* (DAF) is responsible for projecting the design support knowledge carried out by the IEF and KIF frames. This comprises:

a) The formalised knowledge consisting of the commitment harmonised solution together with DCC and PUC consequences identified by the SE, and
b) The recommendations for improving or mitigating these consequences as advised by the RE.

Additionally, this frame supplies the designer with the *realistic Image-drawing* generated by the Visual Model Illustration Engine (VMIE).

8.3 *DESMO*: An Archetype of *HARMONIOUS* Framework

Archetype framework: DESMO

As discussed in Section 8.1, the scope of *HARMONIOUS* extends to any product domain that falls within the paradigm of dual ontological products. However, as explained in Chapter 2, this doctoral research utilises the motorcycle artefact as a representative case of DOPs. To illustrate the framework in a more exemplified and less abstractive way, an *archetype* of the *HARMONIOUS* framework, titled *DESMO (**D**esigning harmonis**E**d motorcycle**S** for hu**M**an fact**O**rs)*, has been developed. This archetype serves to provide a more *tangible* demonstration of the approach framework's application.

DESMO for the motorcycle use case

DESMO inherits directly from the *HARMONIOUS* approach framework and is tailored specifically for the motorcycle product domain. As such the purpose of *DESMO* is to support the conceptual design synthesis process of motorcycles, particularly focusing on: ergonomics; aesthetic-derived emotions; and persona ($hf_{E\text{-}AE\text{-}P}$). It provides harmonistic knowledge to assist motorcycle designers in becoming explicitly aware of the consequences caused by their synthesis decisions. A detailed version of the archetype framework is provided in Figure 8.2.

Peer-reviewed related to DESMO

This archetype framework was peer-reviewed and presented as a contribution to the design community in the research work by Agius et al. (2020).

Motorcycle Design exploration through a Use Case Scenario of the *DESMO* framework

Illustration through a hypothetical example

As depicted in Figure 8.2, *DESMO*, like *HARMONIOUS*, encompasses a sequence of ten principal steps. A *hypothetical use case* will be presented to exemplify *DESMO*. For simplification purposes, this example will focus on a single PDE of the motorcycle: the vertical distance between the handlebar and the seat $[P_{HB.v\text{-}S}]$, a continuation of the example already seen in Section 7.3.2. Furthermore, a scale from

1 to 10 is adopted in this example where '1' signifies the lowest possible position of the handlebar and '10' denotes the highest. Within the context of the synthesis space, this is represented as $P_{HB.v\text{-}S}$ {[1], [2], …, [9], [10]}.

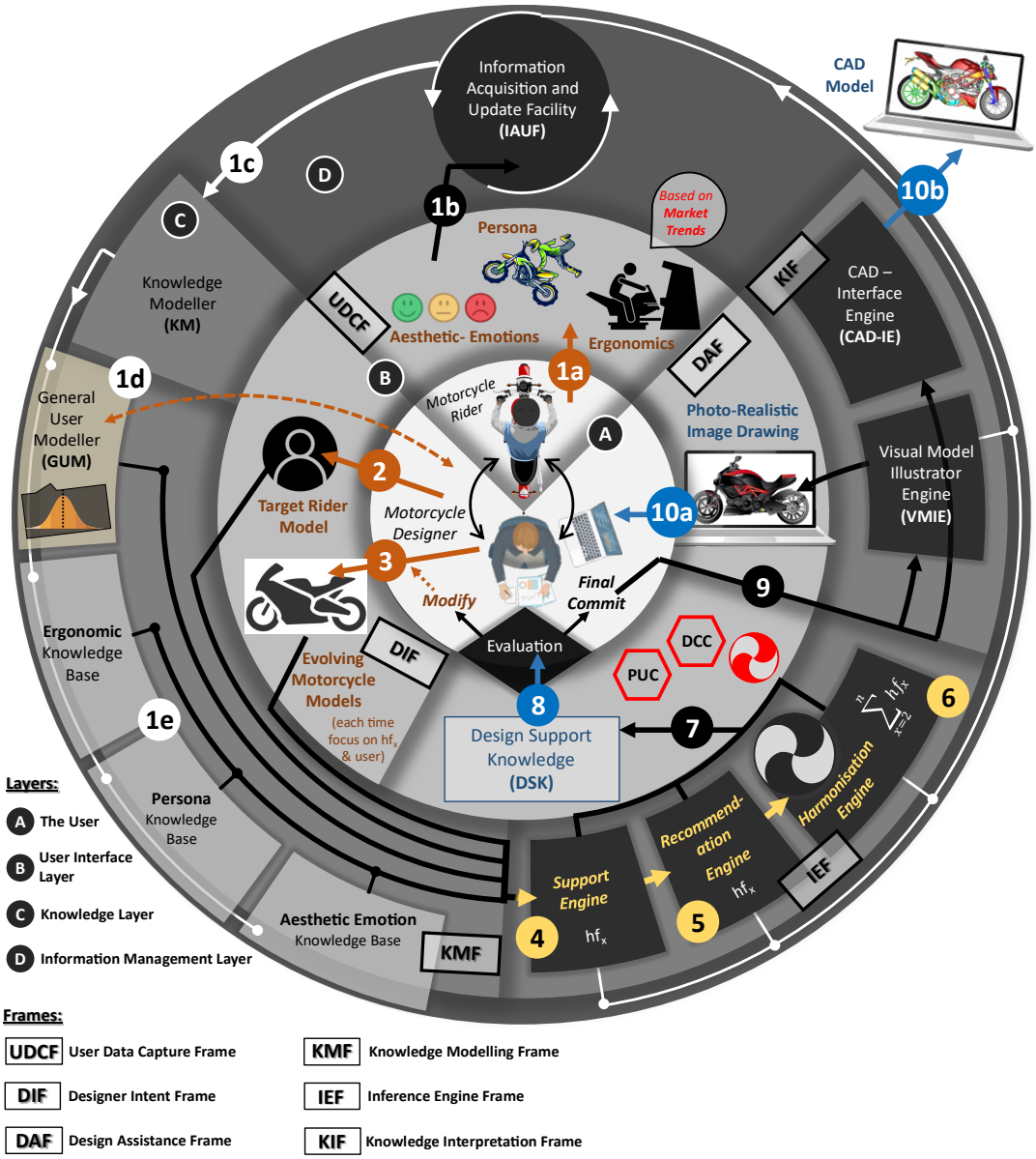


Figure 8.2 – DESMO archetype framework

STEP 1

Capture of $hf_{E\text{-}AE\text{-}P}$ data

In the first step (*STEP 1a*), the *DESMO* framework captures factual human factors information on motorcycle riders (potential customers). This information is based on the three aspects:

(i) Ergonomics (hf_E) – This includes riders' anthropometric data, posture, and discomfort levels in relation to a given motorcycle's physical configuration, as seen from Section 2.4.1.

(ii) Aesthetic-derived emotions (hf_{AE}) – The emotions elicited in riders, as detailed in Section 2.4.2, which stem from the visual aesthetics of different motorcycle types and styles.

(iii) Persona (hf_P) – This aspect covers riders' persona attributes, according to Section 2.4.3, including demographics, personality, behaviour, and the context in which motorcycles are used.

No restriction on data collection instrument

As argued in Section 8.2.2, a variety of methods can be employed to gather data on these three human factors and their sub-aspects. The choice of methods is at the discretion of the motorcycle company/designers, and *DESMO* does not impose restrictions on the methodologies utilised. For instance, for the discomfort levels one might use a motion capture system to assess the posture, or alternatively conduct experiments and gather feedback on riders' discomfort levels.

$hf_{E\text{-}AE\text{-}P}$-based on latest market trends

Given that emotions derived from aesthetics and the persona-related human factors are inherently subjective and, as argued in Section 2.1, prone to change over time, the framework recommends having these aspects based on the current or latest market trends. For example, if a matt black colour variant in the colour-scheme PDE is considered outdated in the market, the designer possesses the ability to exclude this variant from the data collection. Nonetheless, this remains the prerogative of the company/designer, and the framework does not mandate the exclusive collection of information pertaining to the most recent market trends.

Update with each new/edited record

With each observation of each rider in *STEP 1a* the IAUF gets updated (*STEP 1b*), resulting in the creation of a new record. Through the continuous repetition of this procedure, a database comprising

collections of $hf_{E\text{-}AE\text{-}P}$ for various riders is established. With the addition of each new record to the database the IAUF automatically initiates an update of the KM (*STEP 1c*) to refresh the knowledge base, given that the new information has an influence on the knowledge generated.

GUM based on central tendency characteristics

Analogous to the KM, the General User Modeller (GUM) systematically recalculates (*STEP 1d*) the representation of the *general rider* (GR) with each incremental observation. These calculations entail in the average anthropometric dimensions (such as height or weight) of the sampled population, salient personality traits (such as the frequency of motorcycle utilisation), as well as the motorcycles and associated PDEVs that elicit the most favourable emotional responses within the motorcycle-riding demographic under study. Continuing with the hypothetical example, subsequent to the update of the GUM, Table 8.1 summarises the general rider (that is, the central tendency characteristics of all the riders collected through the IAUF so far) and represented as follows:

Ergonomic preference of GR

- Anthropometrically the general rider is of medium height, which results in the optimal handlebar position being identified at level 5. Positions 4 and 6, whilst still offering a degree of comfort, are considered inferior to level 5 in terms of ergonomic suitability. Consequently, the ergonomic human factor pertinent to the general rider can be mathematically represented as $\mathrm{hf}_{\mathrm{E(GR)}}[\mathrm{P}_{\mathrm{HB.v\text{-}S}}] = \rightarrow[5]\leftarrow$.

  The expression: $\rightarrow[5]\leftarrow$ indicates that the best ergonomic position is level 5. The subsequent preferable positions are 4 and 6, followed by 3 and 7, and so forth, with position 10 being the worst ergonomic position.

Aesthetic-derived emotions preference of GR

- From an aesthetic standpoint, a handlebar alignment positioned at level 7 elicits the most favourable emotional response in the general rider. Thus, the aesthetic human factor

associated with the general rider is expressed as $hf_{AE(GR)}[P_{HB.v\text{-}S}] = \rightarrow[7]\leftarrow$.

Persona preference of GR

- Within the context of usage, the general riders predominantly utilise their motorcycle for recreational purposes, followed by the requirement for long-distance travel. Consequently, from a persona perspective, the general rider places a higher emphasis on the motorcycle's role in hobby-related activities over its utility for travel, thus prioritising aesthetic considerations above comfort. Accordingly, the persona-based human factor for the general rider is represented as $hf_{P(GR)}[P_{HB.v\text{-}S}] = \rightarrow[7]\leftarrow$.

Table 8.1 – General rider characteristics for the handlebar PDE

Human Factor	General Rider Characteristic	GR preference for $[P_{HB.v\text{-}S}]$
hf_E	Medium height	→[5]←
hf_{AE}	Aesthetically likes medium-to-tall handlebar	→[7]←
hf_P	Primarily for leisure pursuits and occasionally for extended distance journeys (thus, aesthetic considerations predominate)	→[7]←

Information to knowledge

Through *STEP 1e*, the KM also models the knowledge discovered from data (illustrated in Figure 8.3), in a form of patterns (explained in Chapter 9), which are stored in the respective human factor KB. Within the archetype framework of *DESMO*, the following distinct KBs are established: hf_EKB; hf_{AE}KB and hf_PKB.

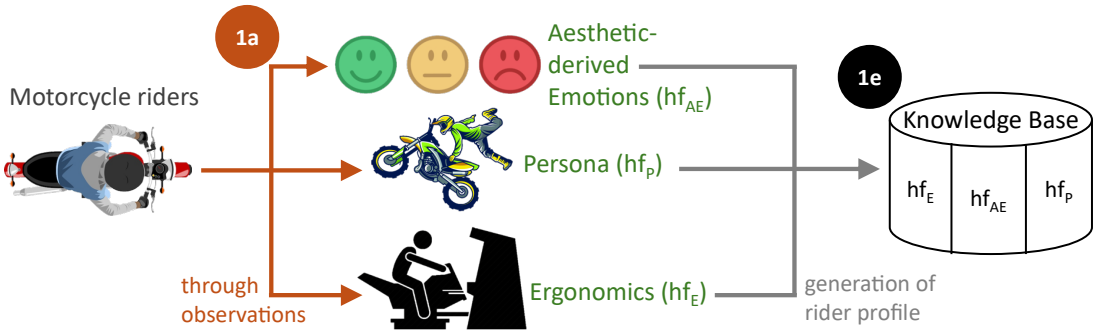


Figure 8.3 – Knowledge discovered from data

Knowledge base representation

The patterns stored can be thought of semantic networks, for example in hf_EKB the rules extrapolated from the data might be articulated as follows:

IF *(A_H = Medium)* AND *($P_{HB.v\text{-}S}$ = 5)* THEN ***ED = 0***

ELSEIF *(A_H = Medium)* AND *($P_{HB.v\text{-}S}$ = 3)* THEN ***ED = 2***

ELSEIF *(A_H = Medium)* AND *($P_{HB.v\text{-}S}$ = 1)* THEN ***ED = 6***

Where:

- ED *(Ergonomic Discomfort)* – Denotes the degree of discomfort experienced by an individual, measured on a scale from 0 to 10, with *0 symbolising 'no pain'* and *10 denoting 'unbearable pain'*.
- A_H – Refers to the anthropometric height category of an individual.

STEP 2

Modelling of TR

In the second step (*STEP 2*), the designer delineates the target rider (TR) for whom the motorcycle is intended. The designer can directly model the intended TR from the target user specifications established during the task clarification design stage. Similar to the (GR) model, the modelling of the TR encompasses: the anthropometric; aesthetic-derived emotions; and persona characteristics. In a manner analogous to the approach taken for the GR, the specified characteristics of the intended TR for this hypothetical example are given in Table 8.2.

Table 8.2 – Intended target rider characteristics for the handlebar PDE

Human Factor	Intended Target Rider Characteristic	TR preference for $[P_{HB.v\text{-}S}]$
hf_E	Short height	→[2]←
hf_{AE}	Exhibits a pronounced preference for tall handlebar positioning	→[10]
hf_P	Primarily for extended distance journeys and occasionally for leisure pursuits (thus, ergonomic considerations predominate)	→[4]←

STEP 3

Modelling of the evolving motorcycle model

STEP 3 is concerned with the design synthesis of the motorcycle model. This involves in selecting PDEVs from a reusable library to construct the envisaged motorcycle model. From an ergonomic standpoint, the

designer decides on setting the motorcycle's ergonomic dimensions. This includes, for example, specifying the rise and pullback of the handlebar, the height of the seat, among other measurements that contribute to the formation of the rider triangle. Furthermore, the designer selects motorcycle's PDEVs (from a pre-populated library) that are intended to evoke specific aesthetic emotions, with the TR as the central focus. This step primarily concentrates on aesthetic-derived emotions and persona related motorcycle design elements. Considerations encompass a variety of fuel tanks, handlebars, seats, stylistic and positional elements, as well as the motorcycle type, its power output, and the preferred colour scheme.

Designer provisionally commitment

In the context of the hypothetical example, it is posited that the designer provisionally commits to a handlebar height setting of 3, denoted as $[\mathrm{d}]\mathrm{P}_{\mathrm{HB.v\text{-}S}}\{3\}$.

STEPS 4 and 5

Application knowledge fed to IEF

Once the designer provisionally commits to the synthesised decisions, *DESMO* provides $\mathrm{hf}_{\mathrm{E-AE-P}}$ consequences in *STEP 4*, employing the SE, and subsequently facilitates the exploration of alternative avenues in *STEP 5* via the RE. As illustrated in Figure 8.4 the support and recommendations are generated by utilising the following:

i. Intended target rider model
ii. General rider model
iii. Three human factor knowledge bases ($\mathrm{hf_EKB}$, $\mathrm{hf_{AE}KB}$ and $\mathrm{hf_PKB}$)
iv. Provisionally committed motorcycle PDEVs

Ergonomic discomforts, rider's liking level and probability of accident scenario

In *STEP 4*, the SE evaluates the motorcycle decision commitments made by the designer during *STEP 3* and evaluates their effects on the provisional motorcycle solution model. Such use-phase and PUC *support* include the posture of both TR and GR on the evolving motorcycle model, the total ergonomic discomforts, as well as the

motorcycle induced emotions and the rider's (dis)liking levels towards the evolving motorcycle model. From a persona perspective, the support provided pertains to the probability of the TR or GR being involved in an accident. DCC knowledge is inferred in a form of interactions between two or more distinct human factors within a particular PDE. An exemplar of such a PDE could be the vertical height of the handlebar or footpegs, influencing the rider's ergonomics, aesthetic-derived emotions, and the use-context (persona).

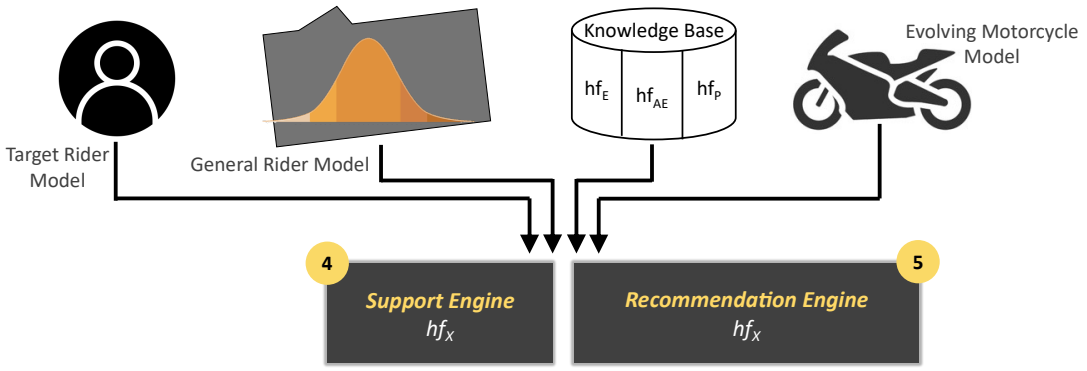


Figure 8.4 – Inputs to the SE and RE

PUC and DCC representation in the hypothetical example

Proceeding with the simplified hypothetical scenario, here it is posited that, for the purpose of illustration, the consequences are articulated as deviations from the committed handlebar height with respect to each human factor and rider specification. For each human factor, a hypothetical support for PUC and DCC is illustrated in Table 8.3.

Table 8.3 – Representation of PUC and DCC for the hypothetical case of $[d]P_{HB.v\text{-}S}$ {3}

Human Factor	$[d]P_{HB.v\text{-}S}$	TR Spec.	TR PUC	GR Spec.	GR PUC	PUC
hf_E	{3}	→[2]←	< 1 >	→[5]←	< 4 >	< 5 >
hf_{AE}		→[10]	< 7 >	→[7]←	< 8 >	< 15 >
hf_P		→[4]←	< 1 >	→[7]←	< 8 >	< 9 >
		TR DCC ⇒	< 9 >	GR DCC ⇒	< 20 >	
					RC = PUC + DCC ⇒	< 29 >

PUC as a deviation function

The PUC consequence (represented as a deviation function), for each human factor (i) and type of rider (x), is formalised as follows:

(Eq. 8.1)

$$\mathrm{PUC}_{xR_hf_i} = \left|[\mathrm{d}]P_{HB.v-S} - \mathrm{Spec}_{xR_hf_i}\right| \times W_{xR}$$

$$\text{for } i = 1 \text{ to } 3 \quad \& \quad x = 1 \text{ to } 2$$

Type of rider priority weight

Where:

- W_{xR} denotes a rider priority weight. In this example, $W_{TR} = 1$, while $W_{GR} = 2$. This allocation reflects the premise that failing to cater to the general rider (GR) incurs greater penalties (consequences) in comparison to the target rider (TR), attributable to the greater population size of the GR relative to that of the TR.

Severity of PUC consequences

For illustrative purposes within this example, an array of values can be established for signifying the severity of consequences, such as:

$\text{PUC}_{xR_hf_i} = 0$	Consequences which are not negative
$0 < \text{PUC}_{xR_hf_i} \leq 2$	Slightly negative consequences
$2 < \text{PUC}_{xR_hf_i} \leq 6$	Negative consequences
$6 < \text{PUC}_{xR_hf_i} \leq 9$	Very negative consequences

DCC as a deviation function

The DCC consequence (represented as a deviation function) between each human factor (i) and for the two types of riders (x) is expressed as follows:

(Eq. 8.2)

$$\text{DCC}_{xR} = \sum_{i=1}^{3} \text{PUC}_{xR_hf_i} \times W_{hf_i}$$

$$\text{for } i = 1 \text{ to } 3 \quad \& \quad x = 1 \text{ to } 2$$

Human factor priority weight

Where:

- W_{hf_i} signifies the priority weight attributed to each human factor. In this example, all human factors are deemed of equal importance, hence $W_{hf_E} = W_{hf_{AE}} = W_{hf_P} = 1$.

Severity of DCC consequences

Analogous to the approach taken with the PUC, an array of values can be similarly established to signify the severity of DCC consequences, such as:

$0 \leq \mathrm{DCC}_{xR} \leq 2$	Consequences which are not negative
$2 < \mathrm{DCC}_{xR} \leq 6$	Slightly negative consequences
$6 < \mathrm{DCC}_{xR} \leq 18$	Negative consequences
$18 < \mathrm{DCC}_{xR} \leq 30$	Very negative consequences

Real Consequences (RC)

As highlighted in Section 7.4.2, PUC and DCC will in turn have an effect on each other, giving rise to further consequences, untimely affect the level of a myriad of human factors during the (potential) utilisation of the product. These were denoted as Real Consequences (RC) and within the context of the hypothetical example (refer to Table 8.3), this cumulative impact is quantified by the sum of deviations:

(Eq. 8.3)

$$RC = PUC + DCC = 29$$

Alternatives, but which is the best?

In *STEP 5*, the RE is then utilised to guide the motorcycle designer in exploring other routes to avoid or minimise the negative $\mathrm{hf}_{\mathrm{E-AE-P}}$ PUC and DCC consequences. To enhance the motorcycle's compatibility with both the TR and GR from ergonomic standpoint, the RE recommends motorcycle configurations that yield the minimal ergonomic discomfort. For instance, for the ergonomic aspect of the target rider $\mathrm{RE}_{TR_hf_E}$, the RE recommends a handlebar setting of $[\mathrm{d}]P_{HB.v-s}\{2\}$, which is associated with the lowest level of ergonomic discomfort for the target rider. Furthermore, the RE proposes adjustments to elements and placements that would foster a more emotionally resonant motorcycle model to each rider model. As an illustration, for the aesthetic-derived emotion aspect of the general rider $\mathrm{RE}_{GR_hf_{AE}}$, the RE suggests a handlebar setting of $[\mathrm{d}]P_{HB.v-s}\{7\}$, deemed the most emotionally engaging position for the general rider. It should be noted, as illustrated by Table 8.3 and the examples

provided, that each human factor knowledge base delivers support and recommendations specific to its domain.

STEP 6

Minimise ergonomic discomforts and maximise positive aesthetic-derived emotions

The Harmonisation Engine (HE) is subsequently employed to integrate potential design recommendations (*STEP 6*), with the aim of formulating a provisional harmonised solution. This process involves collating information from the design solutions proposed by the designer thus far, pertaining to each aspect of human factors and rider category. To achieve this balance, the HE sets out an objective to minimise the total ergonomic discomfort experienced by both TR and GR, whilst simultaneously enhancing the aesthetic emotional responses of both rider groups. The outcome of this engine is a harmonised motorcycle solution model, constituting of PDEs that, in unison, reduces ergonomic discomfort (ED) and increases the appeal for both the target and general riders.

Multiple harmonised solutions

Continuing with the hypothetical example, the same analytical methodology employed in *STEP 4* for the construction of Table 8.3 is applied to calculate the RC of each committed handlebar position. The HE subsequently communicates the results to the designer, specifically those denoted in green within Table 8.4, indicative of being closely aligned with the optimised harmonised solutions, while other outcomes, which are not close to the optimised harmonised solutions, are omitted from display.

Table 8.4 – Representation of PUC + DCC for the hypothetical case of $[d]P_{HB.v\text{-}S}$ {1 to 10}

$[d]P_{HB.v\text{-}S}$	{1}	{2}	{3}	{4}	{5}	{6}	{7}	{8}	{9}	{10}
(RC) PUC + DCC	<45>	<36>	<29>	<22>	<17>	<16>	<15>	<22>	<29>	<36>

Multiple harmonised solutions with the minimum problematic RC

Given that *DESMO* is a support-oriented framework, it facilitates the provision of multiple harmonised solutions to better suit the ergonomics, aesthetic-derived emotions and persona of TR and GR. The decision as to which solution possesses the most suitable attributes

rests with the designer. In this instance, the optimal solution, as determined through the harmonisation process, is identified with a handlebar position of $[\mathrm{d}]P_{HB.v-S}\{7\}$, which results in the least adverse consequences when combining PUC and DCC, that is, *PUC + DCC = 15*. Nonetheless, the HE also presents additional solutions that are close to the ideal one, including handlebar positions $[\mathrm{d}]P_{HB.v-S}\{6\}$ and $[\mathrm{d}]P_{HB.v-S}\{5\}$ as viable alternatives. Therefore, the designer is free to choose or modify any proposed harmonised solution.

Furthermore, the HE leverages the capabilities of both the SE and RE. As demonstrated in *STEP 4*, the SE evaluates the PUC and DCC associated with the harmonised provisional motorcycle model, whereas the RE provides recommendations (if possible) to potentially refine the harmonised provisional motorcycle solution further. Within the context of the hypothetical example, the PUC and DCC for the selected harmonised solution are illustrated in Table 8.5.

Compromising to achieve a minimum RC score

Comparing Table 8.3 with Table 8.5, it is observed that by compromising $\mathrm{PUC}_{TR_hf_E}$ (from <1> to <5>), $\mathrm{PUC}_{TR_hf_P}$ (from <1> to <3>) and slightly DCC_{TR} (from <9> to <11>) the other human factor negative consequences are diminished. Furthermore, the DCC_{GR} is minimised as well as the interactive effects between PUC and DCC (i.e. RC).

Table 8.5 – Representation of PUC and DCC for the harmonised hypothetical case of $[d]P_{HB.v\text{-}S}\{7\}$

Human Factor	$[d]P_{HB.v\text{-}S}$	TR Spec.	TR PUC	GR Spec.	GR PUC	PUC
hf_E	{7}	→[2]←	< 5 >	→[5]←	< 4 >	< 9 >
hf_{AE}		→[10]	< 3 >	→[7]←	< 0 >	< 3 >
hf_P		→[4]←	< 3 >	→[7]←	< 0 >	< 3 >
		TR DCC ⇒	< 11 >	GR DCC ⇒	< 4 >	
					RC = PUC + DCC ⇒	< 15 >

This hypothetical example demonstrates a preference for improving aesthetic-derived emotions, persona considerations, and the general

rider's human factors. Consequently, the motorcycle designer is proactively informed about the evolving motorcycle's design direction.

STEPS 7 and 8

Design support knowledge

As illustrated in Figure 8.2 and Figure 8.5, throughout any stage of the design process, provisional support (*STEP 4*), recommendations (*STEP 5*), and harmonisation (*STEP 6*) for the evolving motorcycle model are presented to the designer in *STEP 7*. Within the context of the hypothetical example, the designer might opt for a handlebar position of $[\mathrm{d}]P_{HB.v-S}\{2\}$ over $[\mathrm{d}]P_{HB.v-S}\{7\}$, although this leads to more severe negative consequences, potentially rendering the motorcycle less successful.

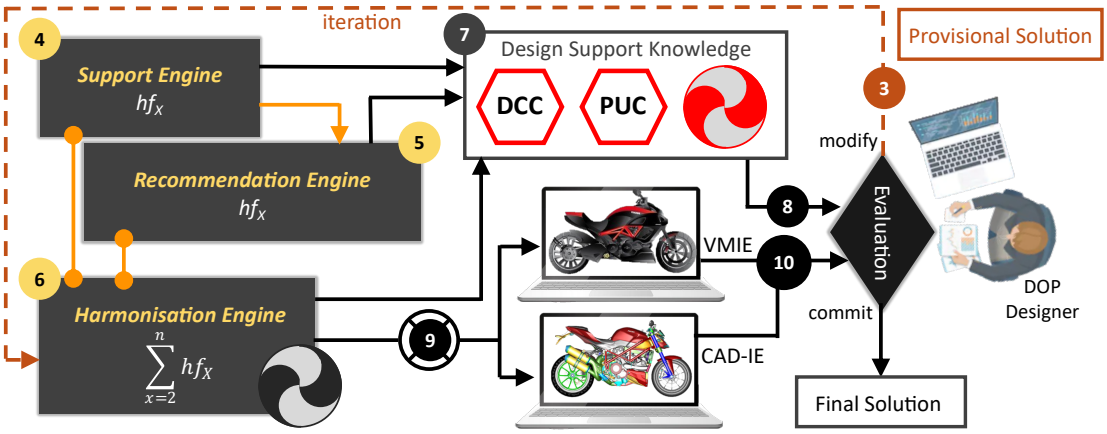


Figure 8.5 – Designer support through the evaluation approach

Evaluation by designer

Therefore, in *STEP 8* it is up to the designer to evaluate the inferences given by the three engines (SE, RE and HE). The designer may either modify the provisional solution based on the support given or commit to the provisional solution. Opting for the modification, the designer is encouraged to commit to new PDEVs for the motorcycle, reverting to *STEP 3* via the DIF. This initiates an iterative process (encompassing *STEPS 3 to 8*) of generating provisional solutions, until the designer is satisfied with the last one, that is, the final committed motorcycle model.

STEPS 9 and 10

Outcomes of DESMO

By the final commitment action (*STEP 8*), the final committed solution is forwarded for visual rendering (*STEP 9*). At this point, the designer can choose the VMIE, for it to generate a two-dimensional *photo-realistic drawing* (*STEP 10a*). Else, opting for the CAD-IE, which is able to construct a 3D CAD geometric model (*STEP 10b*). Both options use the committed ergonomic geometry and PDEVs to generate a 2D or 3D representation of the final motorcycle solution. This involves the translation of the motorcycle design elements' geometry and aesthetic attributes into either a 2D realistic image, or a 3D model within a CAD framework. As such, the outputs of *DESMO* encompass:

(i) *Design support knowledge*, or PUC and DCC deriving from the committed motorcycle design solution.

(ii) A visual representation, either through a 2D realistic-drawing or a 3D geometric model, of the final committed motorcycle design solution.

Hypothetical example limitations

It should be noted that the hypothetical example of the handlebar discussed here is, in reality, applied to a broader array of motorcycle PDEs and human factor sub-aspects, making the actual process considerably more complex than the simplified scenario presented in this section. More detailed examples will be provided in Chapters 9 and 10.

8.4 Preliminary Validation of the *DESMO* Framework

Preliminary validation

The *DESMO* archetype framework is the combined result of research conducted in this doctoral work. The focus now shifts to the preliminary validation of the *DESMO* framework. This study gives an indication whether the framework adequately supports DOP designers in-line with the identified requirements (disclosed in Chapter 4) that have been articulated and structured in such a way to form a knowledge structure, in this chapter.

8.4.1 Preliminary Validation Objective

Overall aim of the preliminary validation

The primary objective of this investigation is to conduct a preliminary evaluation of the *DESMO* framework with DOP designers. The term 'preliminary' in this context refers to the validation of *DESMO* in its current form, as a design framework. This evaluation seeks to ascertain the framework's effectiveness in providing the expected support and knowledge to the designers before being implemented in a prototype tool. This step is important to ensure that if designers find the framework inadequate or envisage that it may not sufficiently support them, there is an opportunity for its enhancement or refinement.

The following are the specific objectives of this investigation:

Preliminary validation objective 1 (POV1)

The first objective (PVO1) is to ascertain whether DOP designers currently employ any approach or tool similar to what *DESMO* offers, and if so, to determine whether *DESMO* fills an existing gap in the industry.

Preliminary validation objective 2 (POV2)

The second preliminary validation objective (PVO2) focuses on establishing whether the developed approach holds value and importance within the DOP industry, while ensuring that it adequately addresses the DOP industry's needs.

Preliminary validation objective 3 (POV3)

The last preliminary validation objective (PVO3) focuses on identifying any potential shortcomings of the approach framework thus far.

8.4.2 Study Procedure and Participants

Why DESMO for preliminary validation?

Section 8.2 presented the *HARMONIOUS* framework in theoretical an abstract manner. This level of abstraction poses challenges in conveying the framework's functionality and its support mechanism for designers. As noted by Zwart (2022) and Feldhusen & Lemburg (2007), such an abstract body of knowledge can also be challenging for common practitioners to comprehend. Here is where *DESMO*, an exemplified version of the approach framework, would land itself well

to this challenge. For this reason, it was decided to preliminary validate the *HARMONIOUS* design framework through the *DESMO* archetype framework for motorcycles.

Participants

The validation process represents an extension of the procedure outlined in Section 4.2. For this preliminary validation, the *same eight European motorcycle designers, as mentioned in Section 4.2.4, were engaged.* These designers possess a varied range of work experience, spanning from 2 to 30 years (with a mean of 17 years), and have all collaborated with prominent motorcycle brands.

Procedure

The preliminary validation involved an initial presentation of the underlying framework and its functionalities, followed by a practical demonstration using the *exploration-based use case scenario* of the *DESMO* framework, illustrated in Section 8.3. Subsequent to this demonstration, brief interviews were conducted with the participants. During these interviews, open-ended questions were posed, allowing participants to provide detailed feedback on specific aspects of the *DESMO* framework.

The interview questions were divided into three main categories, supporting the specific objectives of this study. The first set of questions aimed to determine whether motorcycle designers had previously encountered similar approaches in their field. The second set focused on assessing whether the approach framework offers the required support. The third focused on any shortcomings of the approach framework. The open-ended preliminary validation interview questions, documented in Appendix D, received formal approval from the Ethics Committee of the University of Malta (Application ENG 669/2019, part 1b), and informed consent was secured from each participant prior to the initiation of the study.

Pilot test and reliability analysis

Reflecting the methodology employed in the studies described in Section 4.2.1, a pilot test was carried out prior to the actual study with designers. This step was crucial to ensure the elimination of any biases

and leading questions. For the qualitative and study reliability method similar to the one outlined in Section 4.2.3 was utilised. The *Cohen Kappa's index* for this study was calculated to be 0.77, indicating a good level of agreement between the two raters and thereby confirming the qualitative reliability (IRR) of the study.

Limitations of study

Considering the similarities between the studies, the same limitations that were discussed in Section 4.7 are also applicable to this preliminary validation investigation. In addition to those previously mentioned limitations, the method utilised to demonstrate the framework is somewhat abstract. As referenced in Pedersen et al. (2000), validating a theoretical framework poses challenges due to its inherently abstract nature and the subjective interpretations of theoretical concepts by motorcycle designers. The complexity and difficulty to comprehend the concepts of such frameworks often elude straightforward pragmatic testing, thereby complicating validation efforts.

Consequently, and as argued in Section 8.4.1, this constitutes only a *partial validation* aimed at ensuring the research is progressing correctly. *A more comprehensive, practical validation will be conducted once the approach framework is implemented in a computer-based tool.*

8.4.3 Qualitative Results and Discussion

Identification of three themes

The subsequent section presents the qualitative outcomes derived from the interviews conducted with motorcycle designers as part of the preliminary validation study. These results are categorised into three themes. These themes align with the objectives established for this study, as outlined in Section 8.4.1. Details of the thematic analysis are presented below.

Gap in the motorcycle industry

Lack in the industry

The interviewed designers were asked regarding any prior utilisation of a design support approach or tool analogous to the *DESMO* framework. The uniform feedback from the interviewed designers highlighted an absence of such a support framework in the industry, particularly one that focuses on designing motorcycles from a human factors perspective. Statistically, this suggests a 95% confidence level that more than 74% of all motorcycle designers have never utilised an approach similar to *DESMO* in their design practices. Participant D8 remarked that: *"I do not use, and in my 20 years of experience, I have never used such a design approach to motorcycle design."*

Need for a support in the motorcycle industry

Necessity and importance of what DESMO framework

Among the eight participants, seven acknowledged the necessity and importance of what *DESMO* framework offers. Statistically, this suggests a 95% confidence level that more than 58% of all motorcycle designers would be interested in integrating a framework like *DESMO* into their workflow. This statistic underscores the value of having such a design framework to assist designers. For instance, D1 commented: *"It is a good idea to have a design approach like DESMO because there are sometimes occasions where you design a super cool, super nice motorcycle but in the end, it might not be comfortable for our clients, or vice versa. There is a need for an approach that guides us towards a harmonised motorcycle solution. The concept of an approach that facilitates constant communication between aesthetics and ergonomics is very interesting."* The statement from D1 encapsulates the views of many motorcycle designers who participated in this study.

Value seen in user-centred approach

During the interviews, there were ten separate instances (*10 refs.*) where participants expressed a need or appreciation for the proposed motorcycle design approach, especially for the UCD approach embodied by *DESMO*. D5 remarked: *"You need to have an approach*

like this, especially the fact that you directly collect and use information from your potential customers. You are getting the source of truth and requests directly from the ones who would eventually purchase your motorcycle. This will significantly reduce our reliance on assumptions." This sentiment highlights the perceived value of integrating direct customer feedback into the design process.

Other benefits

The participants identified several potential benefits of utilising this approach, including the ability to explore different design solutions in the early phase (*3 refs.*) and reducing design lead times (*5 refs.*). This is attributed to the approach's focus on the early stages of motorcycle design, which also contributes to minimising costs and design change implementations. D4 personified this advantage by stating that: "*This design approach can help artistic designers and mechanical engineers develop the motorcycle in parallel. From one side based on mechanical and technical engineering systems like ergonomics, and aesthetical features on the other side. This way, the design process moves faster as all the departments move in parallel along the project, trying different solutions and analysing their consequences upon use."* This perspective highlights how the approach facilitates a more integrated and accelerated design process.

Overall appreciation

The qualitative analysis yielded, twelve instances where the need or importance of *DESMO* was highlighted, while three instances reflected scepticism regarding the use of the proposed framework. This outcome indicates that 80% of the participants recognise and appreciate the benefits of this approach from a qualitative standpoint.

Concerns with *DESMO*

Reservations for KIF

One participant, D2, expressed concern about the complexity of developing *DESMO*, given the need to account for a wide range of factors for each motorcycle. Another participant, D6, acknowledged the usefulness of the design approach but expressed reservations about developing the Knowledge Interpretation Frame (KIF). D6 noted

that: *"The design approach is interesting, especially when converging ergonomic aspects with aesthetical ones. However, I am more dubious about implementing the KIF frame. Creating a photo-realistic image from the selected motorcycle components seems very challenging, and it would require significant efforts. Just displaying the consequences of decision commitments and providing alternatives would be adequate for us."*

8.5 Chapter Conclusions

Design approach framework

This chapter proposed *HARMONIOUS*, a DOP design approach framework that leverages the requirements identified by both designers (RPUs) and DOP users (RTUs), along with the understanding of population majority privation and design-stage conflict phenomena. The approach framework is based on a workflow carried out during the conceptual design stage to support the synthesis activity, while enhancing the communication between designers and DOP users. This proposed approach is intended to support DOP designers by making them aware of PUCs and DCCs that arise from synthesis decision commitments. This approach not only makes designers conscious of these consequences but also guides them towards a harmonised product design solution. *HARMONIOUS* also support designers to consider alternative synthesis commitments to mitigate or alleviate these consequences during both the design and use phases.

Exemplification through DESMO

The *HARMONIOUS* approach framework has been developed to be applicable for various dual ontological products. To demonstrate this versatility, *HARMONIOUS* was exemplified through the creation of a motorcycle-specific archetype framework. This archetype, *DESMO*, not only assists in providing a more pragmatic explanation of the framework but has also undergone preliminary validation with motorcycle designers.

Preliminary validation

The preliminary validation of the *HARMONIOUS* approach framework, as exemplified by the *DESMO* archetype, yielded promising results.

80% of the participants recognised the benefits of this design approach. Additionally, all participants confirmed that they had not previously encountered a framework similar to *DESMO*, preliminary indicating that it addresses both theoretical and industrial gaps in the field. The review of this work in Agius et al.'s (2020) at the *ASME's IDETC-CIE* conference further underscores the framework's validation in the design research community.

How to model harmonistic knowledge?

Consequently, the *DESMO* archetype framework will serve as the foundation for developing a computer-based tool. This tool will enable a thorough validation of the framework with motorcycle designers in their professional context. The resulting design approach framework collectively describes how to model and use harmonistic knowledge. However, this chapter does not delve into the specific concepts and structuring techniques required for modelling harmonistic knowledge for DOP during synthesis design activity. These aspects will be addressed in the forthcoming chapter.

9 Formalism of a Harmonistic Knowledge Model

Chapter 8 provided the concept of harmonistic knowledge. This chapter aims to explain the reason why a knowledge intensive approach is being proposed by this doctoral research. As such, this chapter presents a formalisation of the human factors and harmonisation knowledge models for supporting design of DOPs. Before presenting the knowledge models it is essential to first comprehend the nature of knowledge. This, along with the concept of the harmonistic knowledge representation are explained and discussed in Section 9.1. How domain tacit knowledge is rendered explicit via the data capture process is presented in Section 9.2, focusing on knowledge discovery from data (KDD). Section 9.3 provides the core functionality of the knowledge-based system (KBS) and encapsulates the relevant business logic, where knowledge is translated into a human-recognisable format. Chapter conclusions are then delineated in Section 9.4.

What is Knowledge?

The question *"What is knowledge?"* can have a variety of answers, even in the context of engineering design (Chandrasegaran et al., 2013). For Sainter et al. (2000), knowledge is an internal ontology, that is a collective of experiences, concepts, values, and beliefs which humans can communicate, understand or interpret. Sunnersjö (2010) emphasises its role in understanding design information, including both the rules and the underlying principles. Others (Zins, 2007) define knowledge as being external such as engineering drawing which can be recorded, managed, and structured. The *classification of knowledge* in design encompasses numerous dimensions and types, a topic that has been extensively explored by various scholars such as Chandrasegaran et al. (2013), Wang & Duffy (2007) and Rodgers & Clarkson (1998).

Knowledge in this doctoral research

These diverse perspectives collectively underscore knowledge as a dynamic and context-dependent construct. While all the above definitions are valid, knowledge is viewed as an asset used for problem-solving in knowledge-based design approaches (Sriram, 1997). Within the approach of *HARMONIOUS*, knowledge is conceptualised as

evolving from information, which in turn is derived from DOP-related human factors data capture. This conceptualisation aligns with the *Data-Information-Knowledge-Wisdom* (DIKW) hierarchy (Müller & Maasdorp, 2011; Bernstein, 2011). This involves associating data to produce information, with knowledge subsequently being formed through the identification of patterns within this information (Chandrasegaran et al., 2013).

Data, information and knowledge

In accordance with the definitions proposed by Bernstein (2011) and Chandrasegaran et al. (2013), the concepts of Data, Information, and Knowledge are delineated as follows:

- *Data:* Raw, unprocessed facts or figures without context. Within the scope of this doctoral research, data pertains to anthropometric measurements (e.g., arm length), motorcycle dimensions (e.g., handlebar height), rider posture (e.g., wrist flexion), and ergonomic discomfort scores.
- *Information:* Processed or organised data that provides meaning or context. In the context of this research, information involves structuring the collected data, for example, "Rider with a height of 170 cm is comfortable at a handlebar height of 75 cm."
- *Knowledge:* Represents the insights or understanding gained from information, which facilitate informed decision-making. In this doctoral research, knowledge is exemplified by "A handlebar height of 75 cm minimises wrist discomfort for riders with a height of 170 cm. Discomfort begins to manifest at a handlebar height below 70 cm, while the optimal ergonomic position for minimal discomfort is identified at 77.5 cm."

Knowledge discovery

To construct a computer model of the approach framework, it is imperative that the knowledge utilised is systematically structured, as suggested by Gembarski et al. (2016). This essentially means that design knowledge must be transformed into a formalised format,

according to Wang & Duffy (2007). This chapter explores the process of *knowledge discovery from data* (KDD), employing a specific learning methodology capable of identifying patterns, trends, and relationships within data (Han et al., 2011; Fayyad et al., 1996) and in accordance to the DIKW hierarchy. This process often uncovers insights that might not be immediately apparent to human observers (Witten et al., 2017).

Explainable knowledge

As outlined by Tomiyama et al. (1996), *codified knowledge* refers to knowledge expressed in a form recognisable by humans. As such, this chapters delves also into the aspect of *knowledge explainability*, which is crucial for understanding and interpreting the decisions, predictions, or outputs generated by models (Samek et al., 2017). This is particularly important in scenarios where this knowledge is used for decision-making approaches (Díaz-Rodríguez et al., 2023), case in point *HARMONIOUS*, necessitating a clear trust and understanding of *how* and *why* a particular decision was reached. Wang & Duffy (2007) emphasise that for a design support system to effectively assist design at the knowledge level, it should be founded on a valid knowledge model that offers a suitable framework for knowledge. Design knowledge is then organised within this established framework.

9.1 Harmonistic Knowledge Representation

This section offers an overview of the nature of knowledge, including its classification and representation. The information presented here will lay the groundwork for characterising harmonistic knowledge within the scope of the approach framework.

9.1.1 The Application and Generation of Harmonistic Knowledge during Synthesis Decision-Making

Exploration-based model of synthesis

The model illustrated in Figure 9.1 explains that the design synthesis process for a DOP, not only necessitates the *application of knowledge*, but also contributes to the *generation of new knowledge*, as discussed by Smithers & Troxell (1990) and Schreiber et al. (2001).

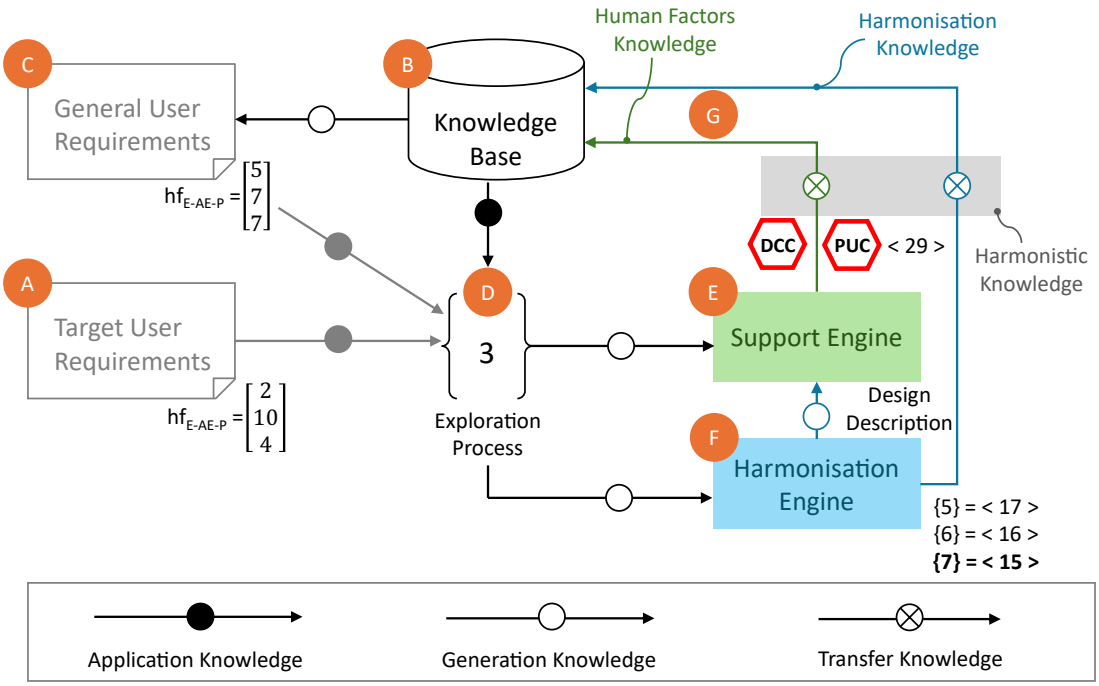


Figure 9.1 – An exploration-based model of synthesis, adopted from Smithers & Troxel (1990)

Knowledge cycle

Figure 9.1 highlights the *knowledge cycle*, a process that involves the acquisition, representation, evaluation, refinement, and utilisation of knowledge (Russell & Norvig, 2021). The knowledge cycle is a continuous process, as new data is constantly being generated (application knowledge), the system can learn and adapt based on this new information (generation knowledge) (Russell & Norvig, 2021).

With reference to Figure 9.1, the design process is initiated with the recognition of a need. In the example illustrated, the need is to design a DOP for an intended target user (TU) but also for the design to be successful in the market. Drawing from the hypothetical example in Section 8.3, the task is to determine an appropriate vertical handlebar height ($P_{HB.v\text{-}S}$) for both the intended target rider (TR) and the general rider (GR). The GR's requirements are derived directly from the knowledge base, as outlined in Section 8.2.2. The designer utilises both the existing knowledge from the knowledge base *(B)* in Figure 9.1, and the newly acquired GR knowledge *(C)* to explore potential handlebar heights and make a commitment to a specific height *(D)*. As seen in Figure 9.1, new knowledge is generated during the design process through the awareness of PUCs and DCCs. For example, a motorcycle

designer becomes aware that a certain handlebar height ($[d]P_{HB.v\text{-}S}\{3\}$), leads to ergonomic discomfort or reduced product attachment, hypothetically represented as RC = PUC + DCC = <29>. Additionally, the harmonisation process generates new knowledge, where the designer is made aware of potential harmonised solutions which collectively lead to the minimum PUCs and DCCs. This newly generated knowledge is represented by the design description, given by *(E*) and *(F)*. The knowledge of human factor consequences and harmonisation are employed to update *(G)* the knowledge base *(B)* for subsequent exploration of alternative handlebar settings.

Types of knowledge in design

Zhang (1999) categorises design knowledge into two distinct components: *current working knowledge* and *domain knowledge*, as illustrated in Figure 9.2.

Domain knowledge

Domain knowledge serves to define the space of possible solutions to be explored (Smithers & Troxel, 1990; Wang & Duffy, 2007). For example, the design of a motorcycle requires the application of human factors domain knowledge such as knowledge about the handlebar styles and vertical positions.

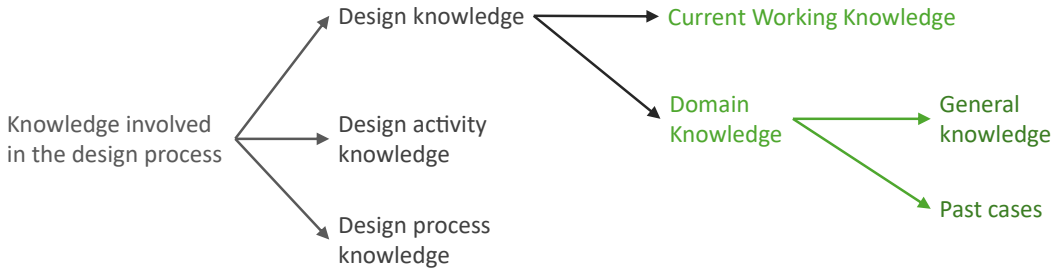


Figure 9.2 – Design knowledge, adopted from Zhang (1999)

Current working knowledge (CWK)

Current working knowledge (CWK) consists of descriptions of DOP elements which are concurrently defined during synthesis decision-making. The dual ontological design phenomena model discussed in Section 7.4, disclose that PUC and DUC knowledge is implicitly generated during DOP design synthesis. Furthermore, as discussed in Section 7.4, current working knowledge of both the TR and GR requirements together with DOP solution, are necessary to explicitly

reveal PUCs and DCCs resulting from DOP decision synthesis commitments.

9.1.2 Utilisation of Harmonistic Knowledge

Knowledge classification

Classification into three dimensions

The *classification of knowledge* in the field of engineering design can be categorised into *three dimensions* (Chandrasegaran et al., 2013).

Formal vs. tacit knowledge

The first include the distinction between *formal and tacit knowledge*. Formal knowledge in product design is embedded in explicit materials like product documents, repositories, problem-solving routines, and computer algorithms. Tacit knowledge, in contrast, is tied to the experiences, intuitions, unarticulated models, and implicit rules of thumb of individuals or design teams. It is often subjective, gained through long periods of learning and experience, and is difficult to express.

Declarative vs. procedural knowledge

Knowledge can be viewed as either *declarative or procedural*. Declarative knowledge, often termed as *'know what'* knowledge (Wang & Duffy, 2007), encompasses the ability to describe objects, events, or methods. An example of this type of knowledge could be describing the colour of a motorcycle's fuel tank. Procedural knowledge, conversely, is referred to as *'know how'* knowledge. It pertains to the understanding of how to execute specific tasks, such as the process involved in designing a DOP. As explained by Wang & Duffy (2007), viewing knowledge as declarative or procedural is subjective, since judgement depends on the human being's expectation, and DOPs can be viewed both in terms of declarative and procedural knowledge.

Product vs. process knowledge

Chandrasegaran et al. (2013) also classify *knowledge as being product or process related*, where these can be connotated to declarative or procedural knowledge. Product knowledge encompasses information associated with a product's evolution throughout its life-cycle, including requirements, relationships between parts, geometry,

functions, behaviours, constraints, and design rationale. This knowledge can be expressed in a declarative form, such as facts, rules, or propositions. It is often represented using logic-based representations such as knowledge graphs or ontologies. Process knowledge, on the other hand, is divided into design process knowledge, manufacturing process knowledge, and business process knowledge. This knowledge is used to perform specific tasks or actions and is often represented using flowcharts (Balasubramanian et al., 1999). It is responsible for knowing how to do something.

Compiled vs. dynamic

Knowledge can also be defined as *compiled or dynamic* (Chandrasegaran et al., 2013). Compiled knowledge consists of experience-based rules, plans, scripts, and cases of previously solved problems with explicit solutions. Dynamic knowledge, however, is used to generate new knowledge structures that are not covered by compiled knowledge, with solutions being implicit. It includes both qualitative knowledge (like common sense reasoning and causal models of processes) and quantitative knowledge (such as physical laws, numerical techniques, and closed-form equations).

Knowledge representation

Classification of knowledge representation

Knowledge representation is a fundamental concept that involves creating models and structures to represent information and knowledge. The goal of knowledge representation is to enable machines to reason about the world like humans, by capturing and encoding knowledge in a format that can be easily processed and utilised by systems. Like knowledge, knowledge representation can be classified as well. Horvath (2002) classified knowledge representations into five categories: pictorial, symbolic, linguistic, virtual, and algorithmic. Table 9.1 shows some of the various representation forms with respect to product design for both product and process knowledges. From Table 9.1, there are various representations that can fit under more than one category. For example, flow charts can fall

under both symbolic, but also a computer algorithmic representation (Chandrasegaran et al., 2013).

Table 9.1 – Classification of knowledge representations in product design, adopted from Horvath (2002)

Pictorial	Symbolic	Linguistic	Virtual	Algorithmic
- Sketches - Detailed drawings - Charts - Photographs - CAD model views	- Decision tables - Production rules - Flow charts - Assembly tree - Fishbone diagrams - Ontologies	- Customer Requirements - Design Rules, constraints - Analogies - Customer feedback - Verbal communication	- CAD Models - CAE Simulations - Virtual Reality simulations - Virtual prototypes - Animations - Multimedia	- Mathemeatical Equations - Parametrisations - Constraint Solvers - Computer Algorithms - Design/operation procedures

Knowledge representation techniques

How knowledge can be represented or codified so that a computer can make sense of it? This prompts a discussion on exploring the diverse techniques and methods available for knowledge representation:

Logical representation

The most fundamental method of conveying knowledge to machines involves the use of a well-defined syntax governed by clear rules. This syntax must be unambiguous in its meaning and capable of handling prepositions. As such, this *logical form* of presentation serves as a set of communication rules, making it particularly effective for representing facts to a machine (Brachman & Levesque, 2004).

Semantic networks

In this form, a graphical representation conveys how the objects are connected and are often used with a data network. The relationships found in the *semantic networks* can be of two types: *IS-A* and instance (*KIND-OF*). This form of representation is more natural than logical (Sowa, 1992).

Production rules

At its most basic level, this approach can be perceived as a simple if-else rule-based system. For each input, the system evaluates conditions against a set of *production rules*. Upon identifying a rule that matches the conditions, an action is executed (Ceri, 1990).

Frame representation

To grasp the *frame representation* at a basic level, one might envision a table with column names and corresponding values in rows, with information being transmitted within this structure. More accurately, though, it represents a collection of attributes, each linked to specific values. This particular data structure employs 'slots' and 'fillers', where the fillers (or slot values) can vary in data type and structure. Notably, this concept bears resemblance to the manner in which information is stored in a standard Database (Brachman & Levesque, 2004).

Approaches to knowledge representation

According to Russell & Norvig (2021) and Gupta et al. (2011) there are four primary approaches to knowledge representation: *simple relational knowledge, inheritable knowledge, inferential knowledge, and procedural knowledge.* Each of these approaches correlates with a specific method of knowledge representation as previously discussed. This correspondence and example of each approach is illustrated by Figure 9.3.

Knowledge Representation techniques and Classification intersection

Figure 9.3 demonstrates how traditional knowledge techniques intersect with the classification system proposed by Chandrasegaran et al., (2013). It is observed that pictorial and virtual knowledge representations do not align with traditional knowledge representation categories (Brachman & Levesque, 2004). In contrast, symbolic and linguistic knowledge representations intersect with all traditional categories. These broad categories encompass various methods for structuring information and knowledge in a symbolic, linguistic format. Algorithmic knowledge, due to its structured, rule-based nature, can be partially represented using logical representations and production rules (Jackson, 1999).

Simple relational knowledge limitations

Chacón (2018) suggests that *simple relational knowledge*, especially for big data, is very challenging for humans to interpret in its bare form. As such, this knowledge representation necessitates additional processing or analytical techniques to render it into a *human-recognisable form*. For example, *statistical analysis* or *machine learning techniques*, known for their capability to extract knowledge from data (Brandt, 2014), can

be employed in this context. Once a machine learning technique is applied to simple relational knowledge, a model is created that can be represented in various forms such as *mathematical equations, graphs, or classification trees*, revealing the patterns hidden in the data to a format comprehensible to humans (Russell & Norvig, 2021).

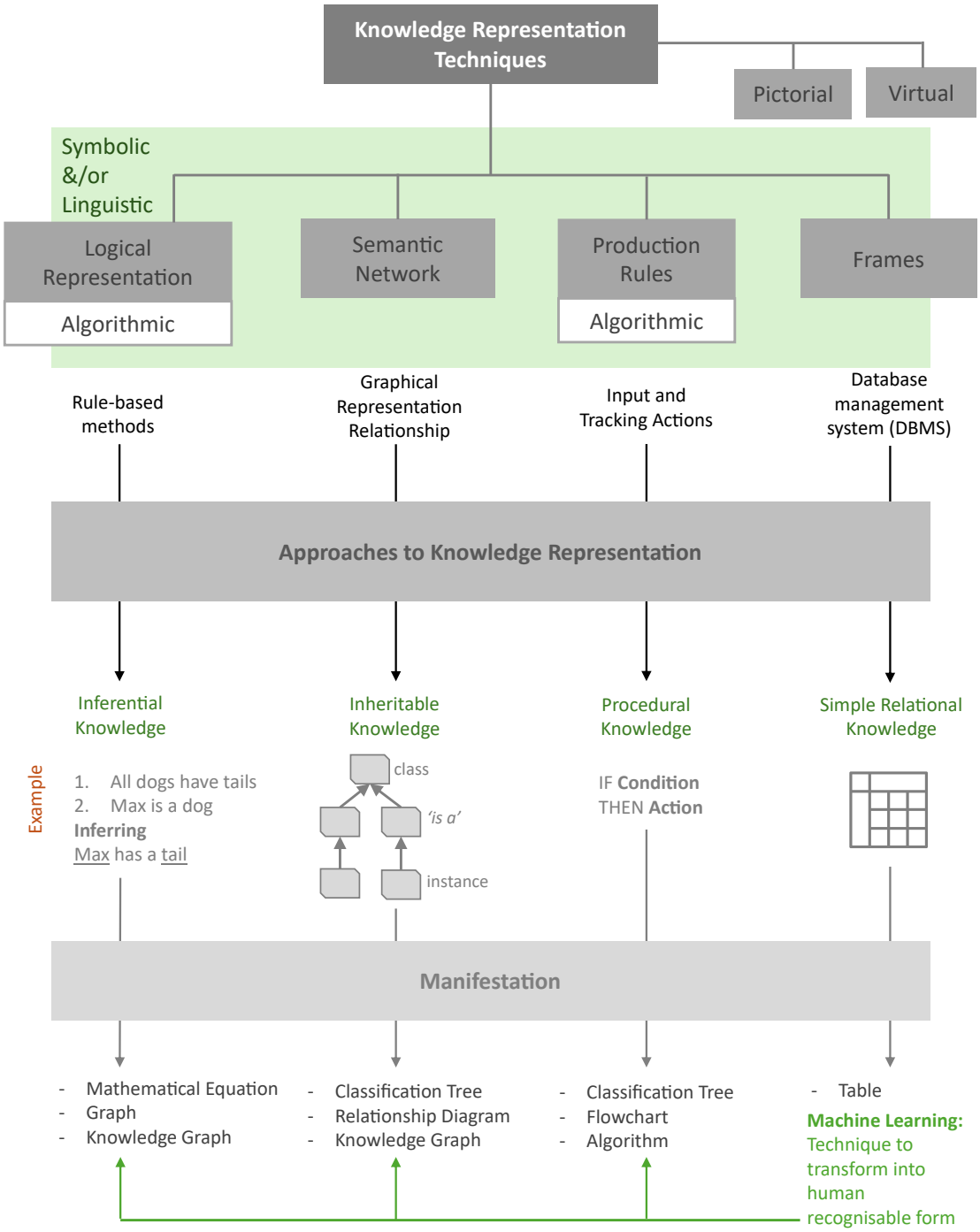


Figure 9.3 – Correspondence of knowledge representation techniques, approaches and classification

9.1.3 Harmonistic Knowledge Management

This section is dedicated to examining the architecture of the approach framework. Understanding this architecture is crucial, as it provides insight into how the framework manages and models harmonistic knowledge.

Knowledge-based architecture

Knowledge-based system

To address approach framework requirement 2 – FR2 (provided in Section 8.1) and as depicted in Figure 8.1 the approach framework is modelled on a *knowledge-based system* (KBS) architecture (Tripathi, 2011). The KBS aims to capture knowledge to support decision-making (Kusiak & Salustri, 2007). The KBS is layered on the *logical layered design* as presented in *Microsoft's application architecture guide* (Microsoft, 2009). The logic layer architecture constitutes the *data, business,* and *presentation* layers. A high-level view of the KBS logic layered architecture is illustrated in Figure 9.4.

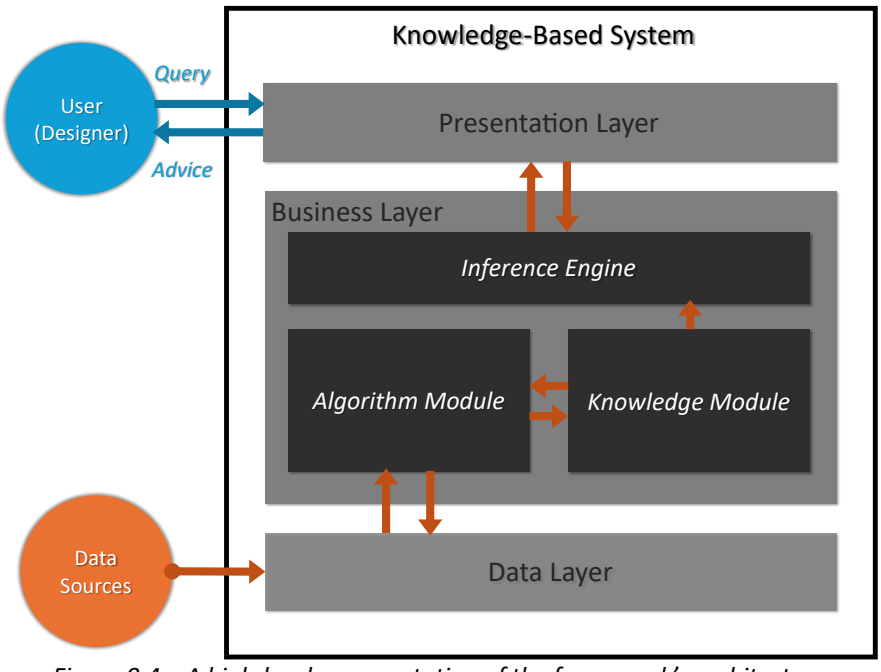


Figure 9.4 – A high-level representation of the framework's architecture

Logic layered architecture

The data layer provides access to data hosted within the boundaries of the system, collected from various sources. The data layer also prepares and warehouses information which the modules in the business layer can consume. The business layer implements the core

functionality of the system and encapsulates the relevant business logic. The business layer is composed of the *algorithm module, knowledge module,* and *inference engine*. The presentation layer contains the user-oriented functionality responsible for managing user interaction with the system and consists of components that provide a common bridge into the core business logic encapsulated in the business layer.

A machine learning approach

Reasoning systems

KBS can encode knowledge as rules and draw logical conclusions based on these programmed rules. These are referred to as *reasoning systems* (Kusiak & Salustri, 2007). Reasoning systems are programmed to follow a logical process and map conditions to actions, where the knowledge is captured by an *expert* (Hvam et al., 2008). Reasoning systems employ inferential, inheritable and procedural knowledge approach representation (Brachman & Levesque, 2004) to codify the knowledge captured by the *expert*.

Drawbacks of reasoning systems

As explained in Chapter 2, users and potential customers of DOP are diverse from human factors perspective. For instance, riders vary in anthropometry, physical properties, persona, and elicited emotions towards different motorcycle designs. Due to these complexities, here it is being argued that it is difficult to capture this knowledge from an *expert* and represent it as logical rules. Traditionally, the flow of data and information in design and manufacturing systems has been essentially unidirectional.

Learning systems

The developments in *data-driven* approaches, such as *learning systems* have contributed to the emergence of the closed-loop system, where the data collected from users during the product's use phase can be translated into declarative or procedural knowledge during the design phase to assist designers (Kusiak & Smith, 2007). This can be seen in Figure 9.5.

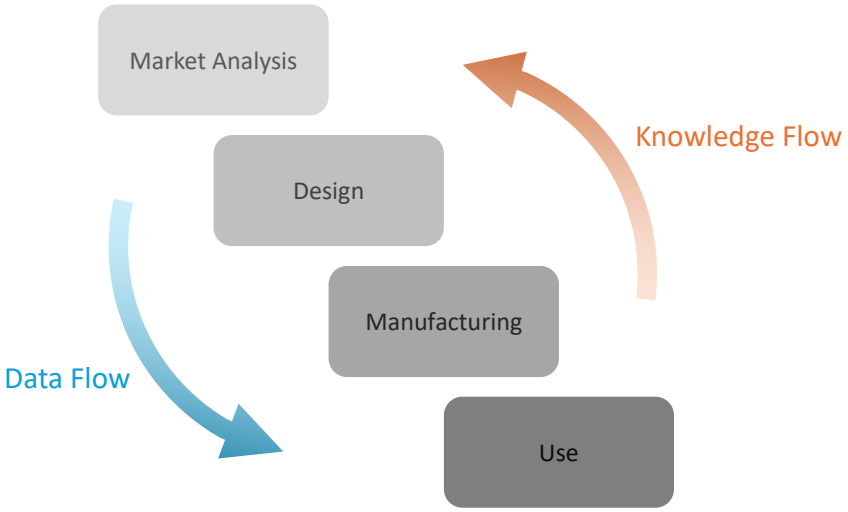


Figure 9.5 – Data and knowledge flow in a modern product life-cycle system, adopted from Kusiak & Smith (2007)

Machine learning a type of learning system

Machine learning (ML) is a subfield of artificial intelligence and gives computers the ability to learn without explicitly being programmed. In some cases, making available explicit knowledge to computers, by codifying tacit human factors knowledge, is impossible due to diversity. Furthermore, the UCD approach, highlighted by FR4 in Section 8.1, requires the collection of (potential) customers' data on $hf_{E\text{-}AE\text{-}P}$.

Advantages of machine learning

With ML, complex, inexpressible knowledge can be generated from the data (Ogidan, 2018). Another positive aspect of ML techniques (a subset of learning systems) is that no rule change is needed to update the knowledge base (KB). By updating the dataset, the knowledge stored within the data is automatically updated as new patterns are formed through the training process. ML techniques have the possibility to re-train the model every time new data is inserted, optimising, and refining predictive capacity over time.

Update support and recommend-ations with every added record

The support and recommendations brought forward to the designer are based on the interaction between the use phase DOP evolved model and different users with various anthropometries, persona, and elicited emotions. As these interactions change in time, so will the support and recommendations given.

Machine Learning Knowledge-

Based on the aforementioned reasons, a machine learning approach is employed to construct the *HARMONIOUS* approach framework's

Base System (ML-KBS)

knowledge base, yielding *a Machine Learning Knowledge-Based System (ML-KBS)* (Ratner & Ré, 2018).

Knowledge discovery from data (KDD)

How is knowledge discovered from data?

In ML-KBS, data-driven approaches are essential for constructing its knowledge base (Dinh et al., 2016). As argued in section 9.1.2, contrary to inferential, inheritable and procedural knowledge, simple relational knowledge requires a dedicated architecture necessary to extract information from data sources and populate the KB (Krzywicki et al., 2016), as seen in Figure 9.6. The ML-KBS architecture also portrays how knowledge discovery from data (KDD) is achieved. KDD forms part of the knowledge cycle outlined in Section 9.1.1, and is the whole process consisting of data pre-processing, storing the information in a database, model generation from ML techniques, and storing ML-based models in the KB (Krzywicki et al. 2016).

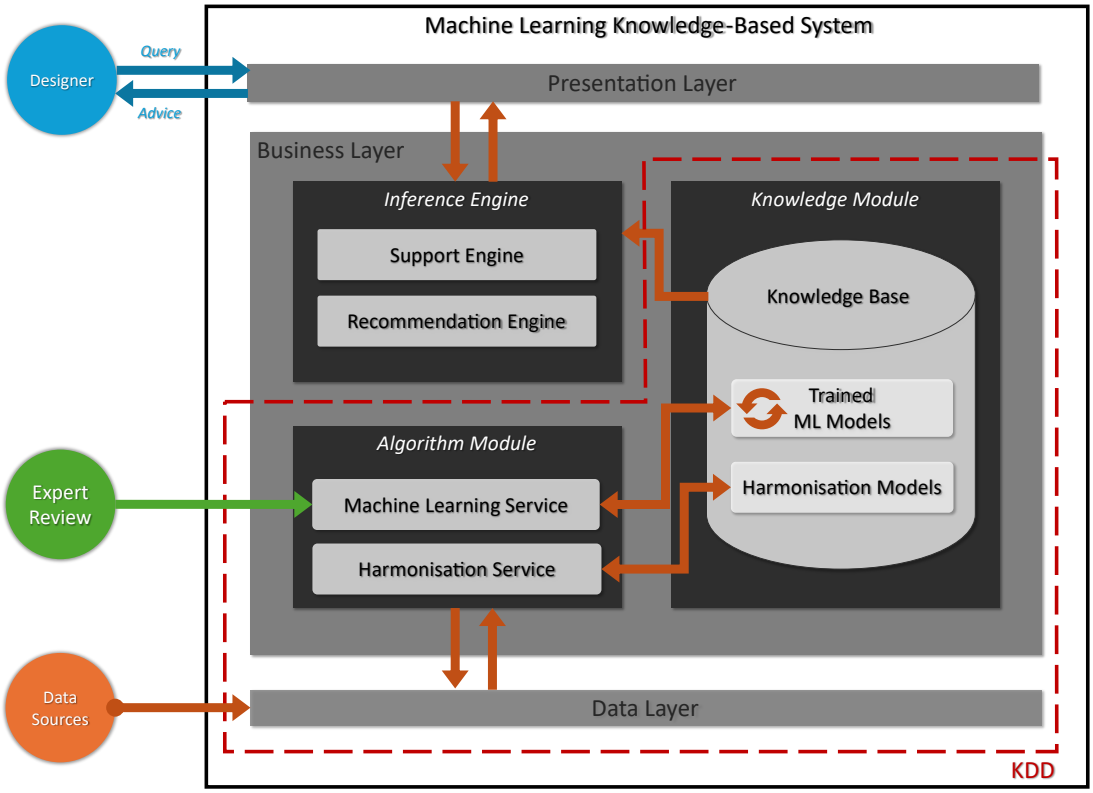


Figure 9.6 – Knowledge discovery from data in a ML-KBS

Process of KDD in this doctoral research

The following sections provide a more detailed explanation, focusing on the investigation of KDD within the *DESMO* framework. Additionally,

these sections will reveal the specific procedures regarding *what* data to collect and *how* to collect it, encompassing both declarative and procedural knowledge for designers.

9.2 The Data Layer and Data Sources

First step in KDD

The data layer is the first step in a ML-KBS KDD is composed of the *Data Collection* (extracting data from data sources), *data engineering* and the *database*. The data layer is illustrated in Figure 9.7.

9.2.1 Data Collection and Data Engineering

Data collection

The component responsible for collecting the data required by *DESMO* is the Data Collection. This relies on the integration of various data capturing methods and tools, developed specifically to derive the necessary knowledge. The data collected is categorised into two segments: (i) *ergonomic and persona-related aspects* and (ii) *aesthetic-derived emotions and persona related aspects.*

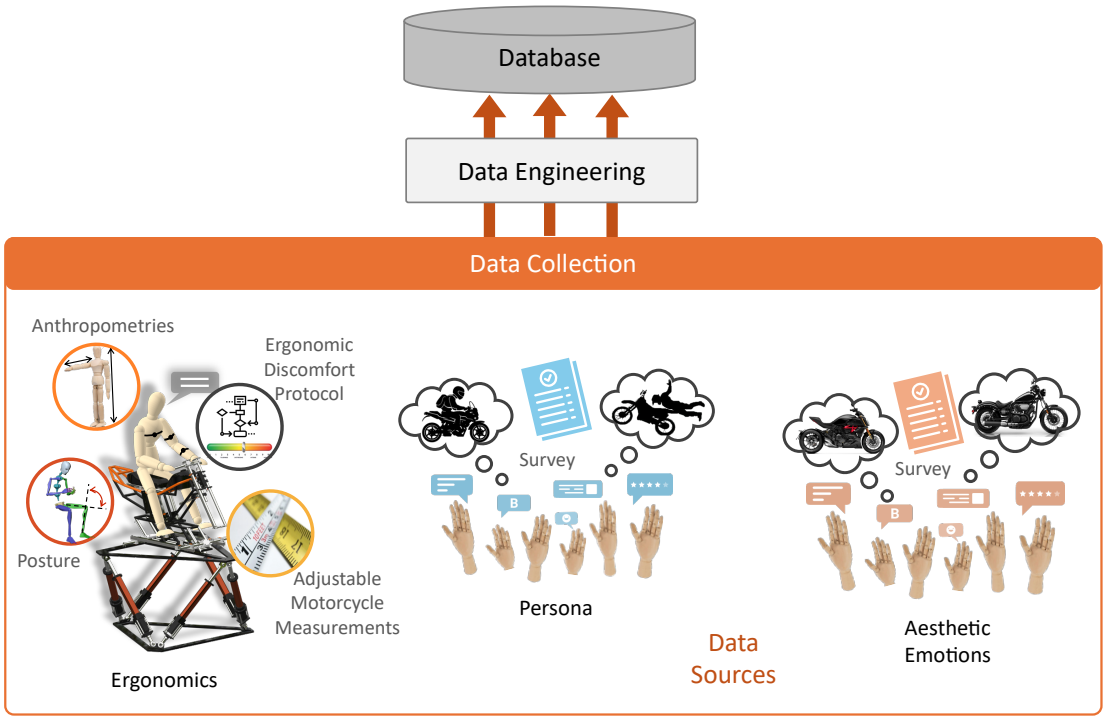


Figure 9.7 – The data layer and sources

Data Engineering

The major challenge in a data-driven approach is that raw data cannot be directly used for processing by a ML model in its native state, but

requires further processing, transformation, integration and encoded in a way that the ML model understands (Dinh et al., 2016).

Collecting ergonomic-persona related data

What ergonomic data to collect

Arunachalam et al. (2019) posits that in order to comprehend and characterise the comfortable and/or optimal posture for motorcycle riding, it is essential to be informed about the varied postures undertaken by riders on different types of motorcycles. This includes databases detailing motorcyclists' anthropometry (human body dimensions) and body joint angles in conditions of perceived comfort or discomfort, as well as means to record postural discomfort encountered during motorcycle riding.

ADAMS: A Simulator to capture actual ergonomic information

Ergonomic capturing hardware tool

To satisfy requirement FR4a and FR4c (Section 8.1) and as part of the *RIDE+SAFE* project[8] an *ADjustAble Motorcycle Simulator (ADAMS)* was designed, constructed (Farrugia, 2021), patented (see Appendix E) and validated (Farrugia, 2022a) to capture actual riders' posture whilst riding in a simulative environment. This ergonomic capturing hardware tool is illustrated in Figure 9.8.

ADAMS is composed of two main elements:

1. The adjustable jig
2. The hexapod motion-system

Adjustability

The adjustable jig element of the simulator focuses on all of the features involving a physical motorcycle. The main characteristic of this jig is that it can resemble various motorcycle ergonomic configurations, achieved through its adjustability elements. The frame geometry and the adjustability mechanisms of the jig have been engineered to represent an extensive array of motorcycle geometries. Consequently, the jig can simulate a spectrum of motorcycle styles, ranging from a

[8] A project funded by the Malta Council for Science & Technology (MCST), through the FUSION Technology Development Programme (R&I-2017-003-T).

small scooter to a large *cruiser*, as illustrated in Figure 9.9. Furthermore, this wide variety of adjustment help to capture edge cases.

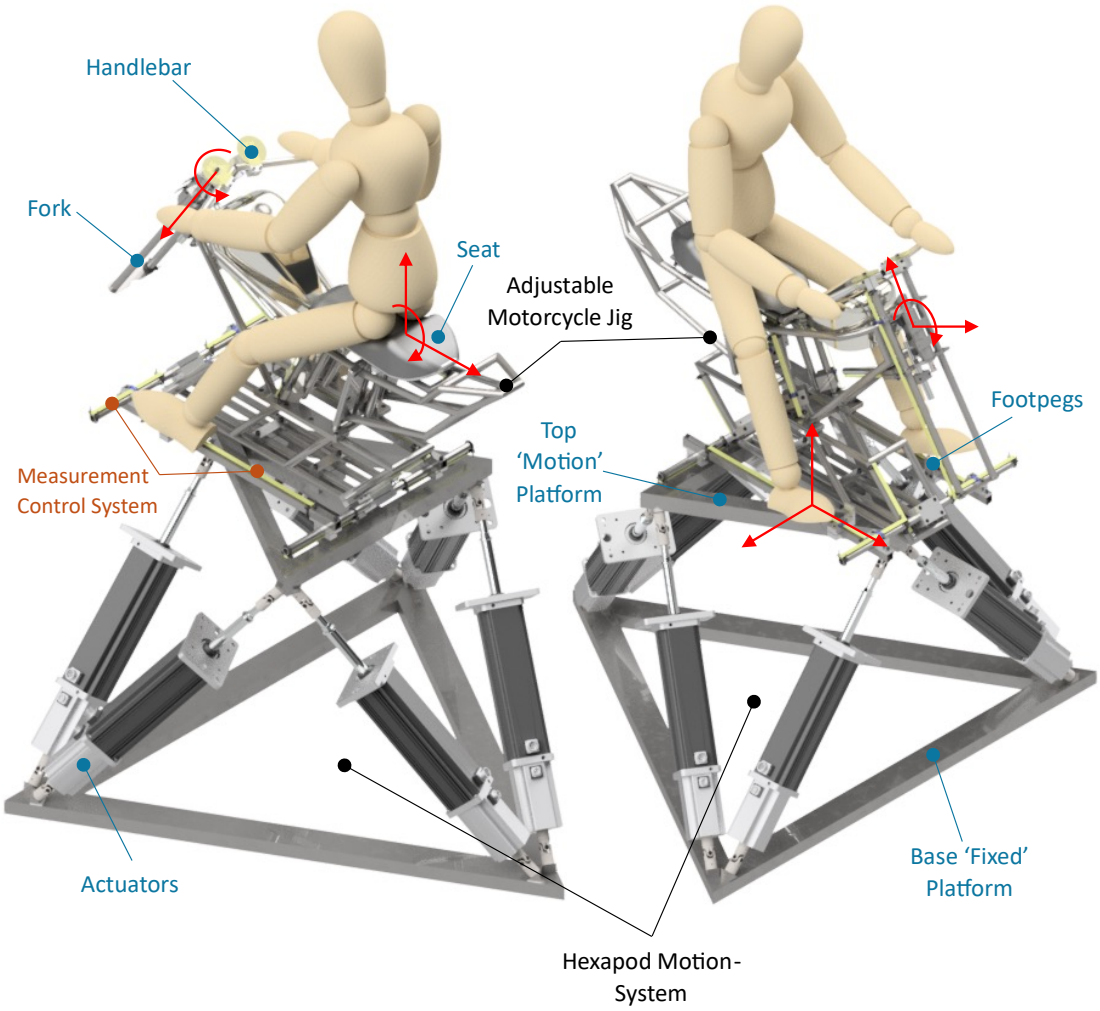


Figure 9.8 – Front and back isometric projection of the adjustable simulator

Adjustment of the most influential PDEs on the rider's ergonomics

To satisfy FR3 (Section 8.1) the seat, footpegs and handlebar can be moved in the desired location. The red linear and angular arrows in Figure 9.8 show all the adjustable *degrees of freedom*. The three red points in Figure 9.9 indicate the contact points of the rider with the motorcycle, already specified in Chapter 3 as the rider triangle, composed of the handlebar, seat and footpegs. The fork (which connects the handlebar to the front tyre) is also adjusted to resemble the same angle of the actual motorcycle. The fork tilt angle affects the steering behaviour of the motorcycle and as such has a considerable influence on the rider's ergonomics. To facilitate the adjustment of

these features, the jig is equipped with measuring tapes for linear dimensions and protractors for gauging angles.

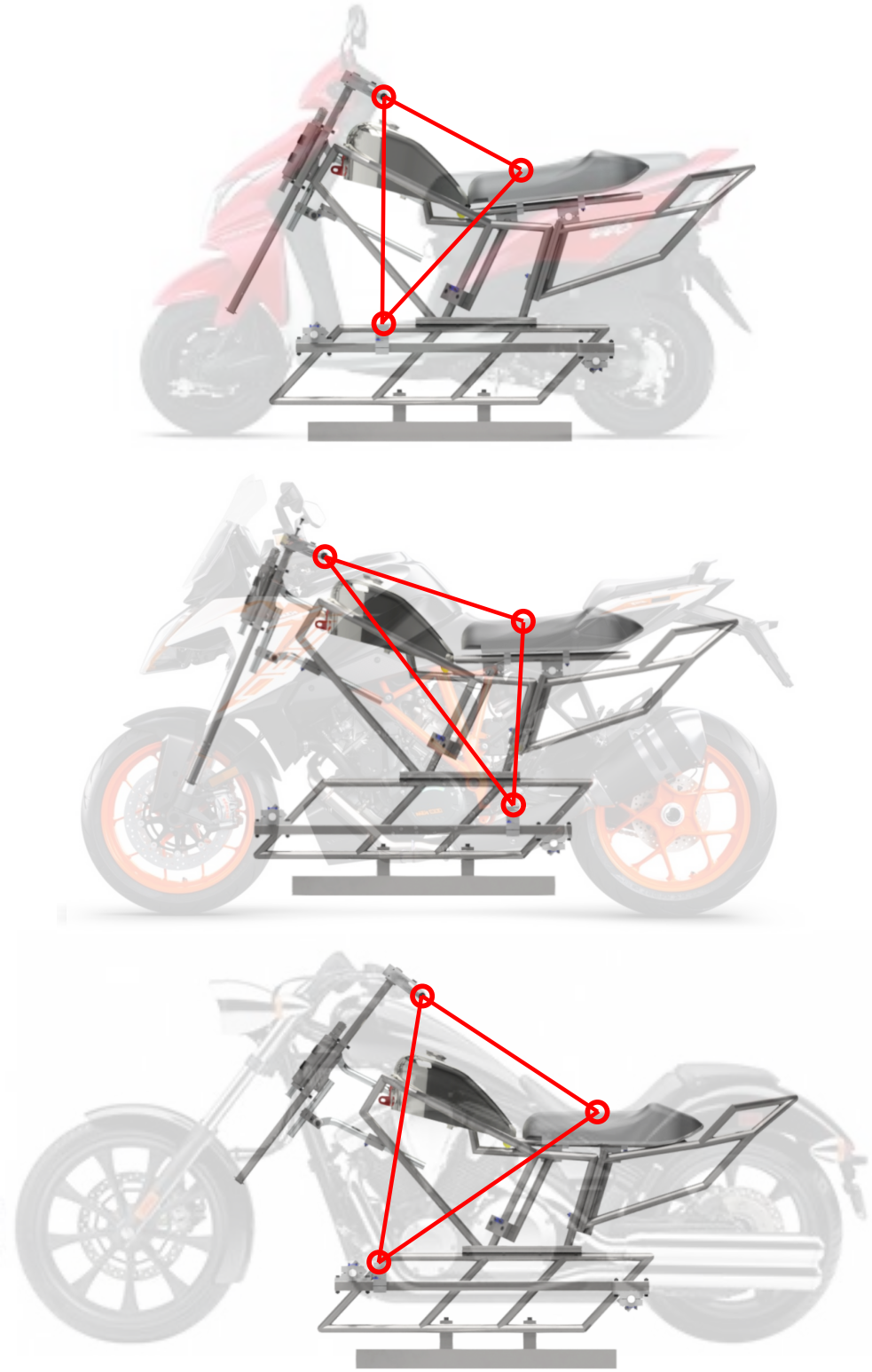


Figure 9.9 – ADAMS adapted to represent different motorcycle styles/types

Simulation software

The jig serves as an interface to the simulation software, which is a commercially available off-the-shelf product purchased from *IPG*

Automotive[9]. This software is capable of computing the physics and dynamics associated with the motorcycle, thereby enabling it to simulate the motorcycle's behaviour within a virtual environment, in a manner that replicates real-world phenomena. The simulation software also generates the visual environment, such as streets and surroundings, constantly updating the visuals with the movement of the motorcycle.

The hexapod

The hexapod element in the simulator focuses on the features involved with the motion-system of the simulator. The hexapod serves as an output system which transforms the movement generated from the simulation software to actual movements that the jig is required to perform.

Mirroring virtual to physical motorcycle adjustment

Physical adjustments applied to the *ADAMS* are mirrored by the corresponding virtual adjustments within the simulation software. For instance, should the seat on the physical motorcycle jig be positioned at a height of 100cm from the ground, the seat of the virtual motorcycle within the simulation software will similarly be established at 100cm from the virtual ground. Such parameters alter the dynamics of the virtual motorcycle, which subsequently affects the movements generated by the hexapod. These adjustments significantly influence the motorcycle's driving dynamics, including handling, control, and cornering capabilities, in addition to the road-feedback experienced by the rider.

Capturing real data

As discussed in Section 8.3, *DESMO* does not limit the type of instrument used to capture data. For instance, 3D CAD human manakins can be used to extract this information. However, here it is argued that through the use of the adjustable simulator coupled with actual riders, a more accurate and real feedback can be gathered. The knowledge gained through physical experiments can be superior compared to a 3D CAD human manakin simulation approach (Högberg

[9] https://www.ipg-automotive.com/en/

et al. 2019). With these manakins, there is a limit of what can be captured. Such examples include a particular person's age, medical conditions, specific attire, and variable use contexts.

Set-up of ADAMS and procedure to collect information

Ergonomic experiment lab layout

To collect the necessary ergonomic data, an ergonomic experimental laboratory was set-up. This lab includes *ADAMS* along with additional simulation elements. The layout of the lab is illustrated in Figure 9.10.

Ergonomic setup elements

The setup is comprised of the following elements:

- The adjustable motorcycle simulator, *ADAMS*.
- Commercially available *off-the-shelf simulation software* (SS1).
- Anthropometric measurement system, designed to measure the body dimensions of the rider.
- The *NOTCH - Motion Capture System*[10], which captures and records the rider's posture on the motorcycle.

A *software script* (SS2) that facilitates the mapping of adjustments made to the physical motorcycle jig onto the actual motorcycle, and vice-versa.

Ergonomic procedure

ErgoSim-Study

A onetime study was conducted utilising the aforementioned setup and tools to collect ergonomic-related data, eventually to be used for the computer-based tool (as it will be seen in the next chapter). What follows is an explanation of the *ErgoSim-Study* procedure, employed to collect ergonomic data from participants. Furthermore, this procedure serves as procedural knowledge for designers, demonstrating the process of how to collect such data.

[10] https://animation.wearnotch.com

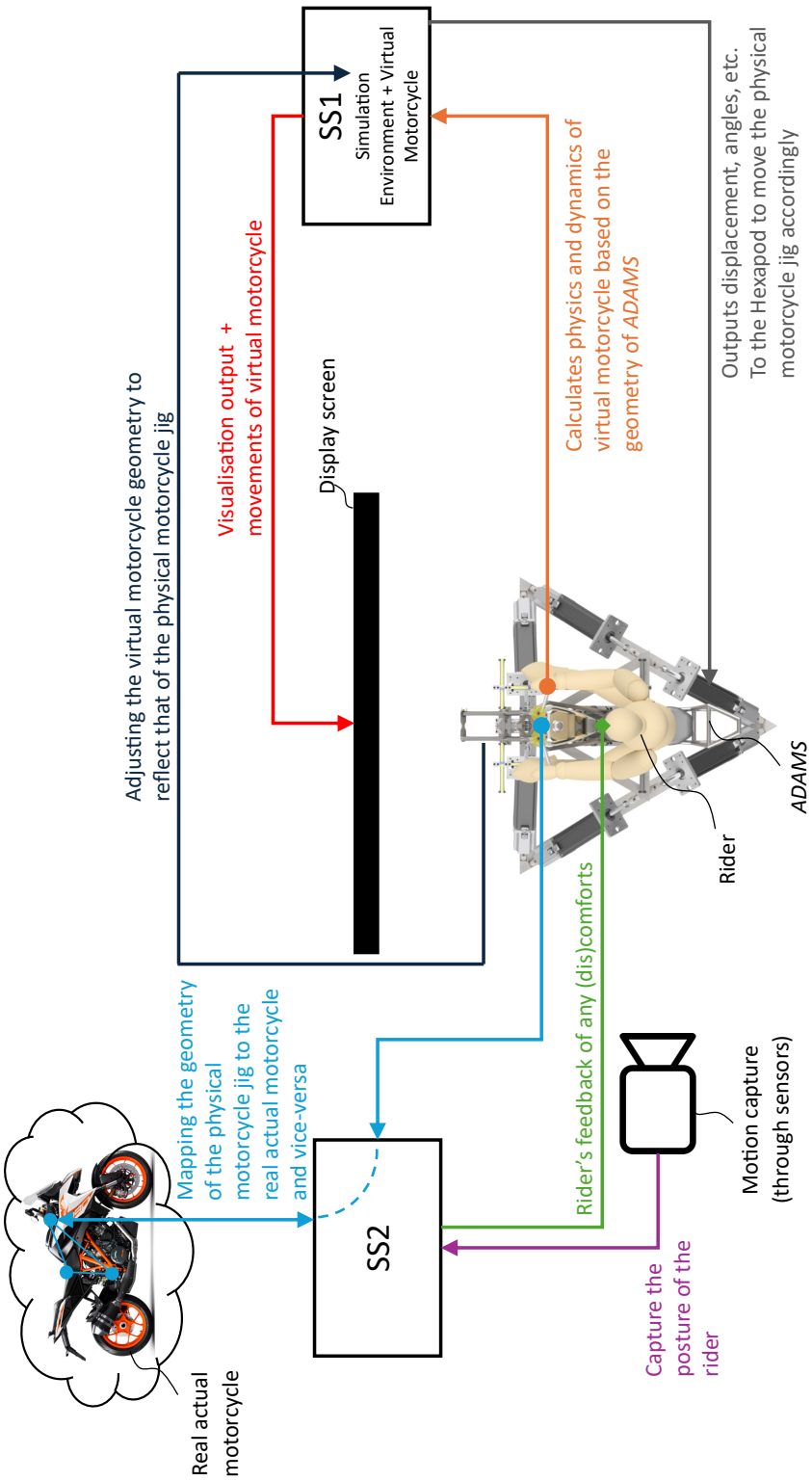


Figure 9.10 – Schematic representation of the ergonomic experimental lab

Limitation of ML-based systems

Accuracy is a paramount concern within ML-based systems (Russell & Norvig, 2021). Low model accuracy leads to suboptimal predictions, compromising the system's reliability and potentially obstructing rather than facilitating the designer's work. This issue becomes particularly pronounced in scenarios characterised by a low sample size

to the number of variables ratio, where the risk of underfitting increases (Hastie et al., 2009). To mitigate such circumstances, the study focused on observations of a specific category of motorcycle, specifically the *cruiser* type (given by the lower most motorcycle in Figure 9.9). Concentrating on this singular motorcycle type helps to restrict excessive variability in the measurements of motorcycles, thereby enhancing the predictive accuracy and reliability of the ML-based system.

Span diversity in anthropometry

A convenience sampling was utilised to recruit participants for the *ErgoSim-Study*. A total of 40 individuals were recruited through established connections within the motorcycle industry, developed as part of the *RIDE+SAFE* project. The selection of participants for the simulation run was guided by the following inclusion criteria and as depicted in Figure 9.11:

- *Experience with cruiser motorcycles:* Participants were required to have prior or current experience riding a cruiser motorcycle.
- *Anthropometric diversity:* The participant group was designed to encompass a wide range of body dimensions, ensuring representation across the full spectrum of the normal distribution for height.

These criteria underscore the importance of a diverse sample population in refining the accuracy and generalisability of ML-based systems and contributes to enhancing the precision of the machine learning (ML) model, which is to be developed subsequently.

ErgoSim-Study part 1

The actual study to capture ergonomic data is divided in two parts. The first is prior the simulation, as delineated in Figure 9.12, during which both *ADAMS* and the virtual motorcycle configuration are set-up. Furthermore, in this part of the study, anthropometric measurements of the rider are also recorded (refer to Figure 9.13 for the specific body measurements recorded), accompanied by the strategic placement

and subsequent calibration of motion capture sensors upon the rider (illustrated in Figure 9.13 for sensor positioning).

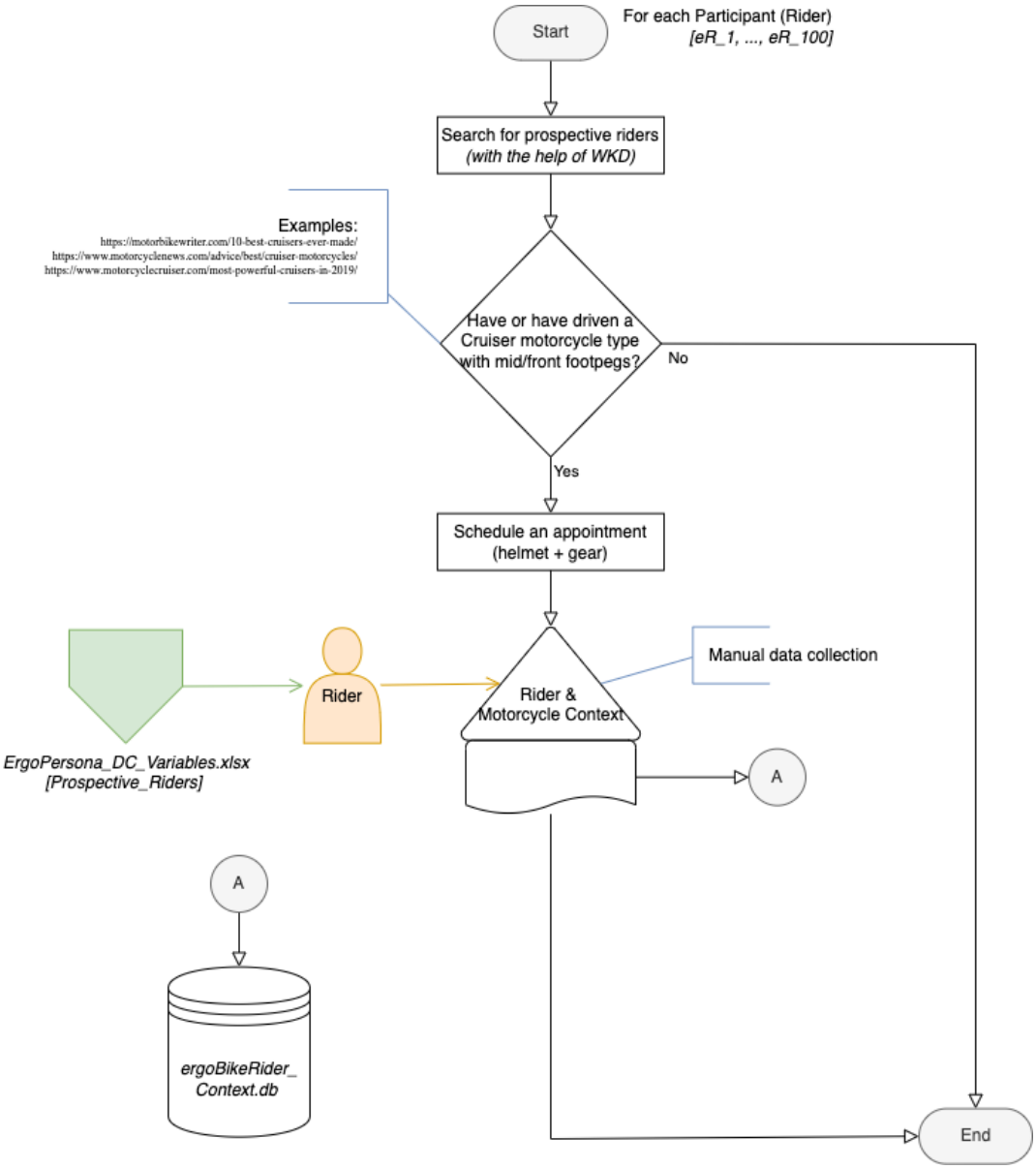


Figure 9.11 – Prospective riders for the ErgoSim-Study

ErgoSim-Study part 2

The second part of *ErgoSim-Study* involved in the actual simulation run of riders on *ADAMS*. Riders' postures are monitored via a motion capture system, while their ergonomic discomfort (for instance, pain or numbness levels and the origin of pain) is gathered through a structured questionnaire. For instance, to simulate a *cruiser* motorcycle type the handlebars are adjusted to an elevated vertical position. After ten minutes participants are requested to evaluate the ergonomic discomfort experienced in various body regions. A series of simulation runs, not exceeding the two-hour mark, are carried out. With each

iteration a different riding posture is undertaken, attributable to the variable adjustments made to *ADAMS*, as delineated in Figure 9.14.

The detailed data collection instrument (DCI) used in this study is documented in Appendix F.1. This was reviewed and approved by the Ethics Committee of the University of Malta (Application ENG 669/2019, part 4), and informed consent was secured from each participant. Mirroring the approach taken in other studies, a pilot test was conducted with riders prior to the commencement of the main study to ensure the validity and reliability of the experimental procedures.

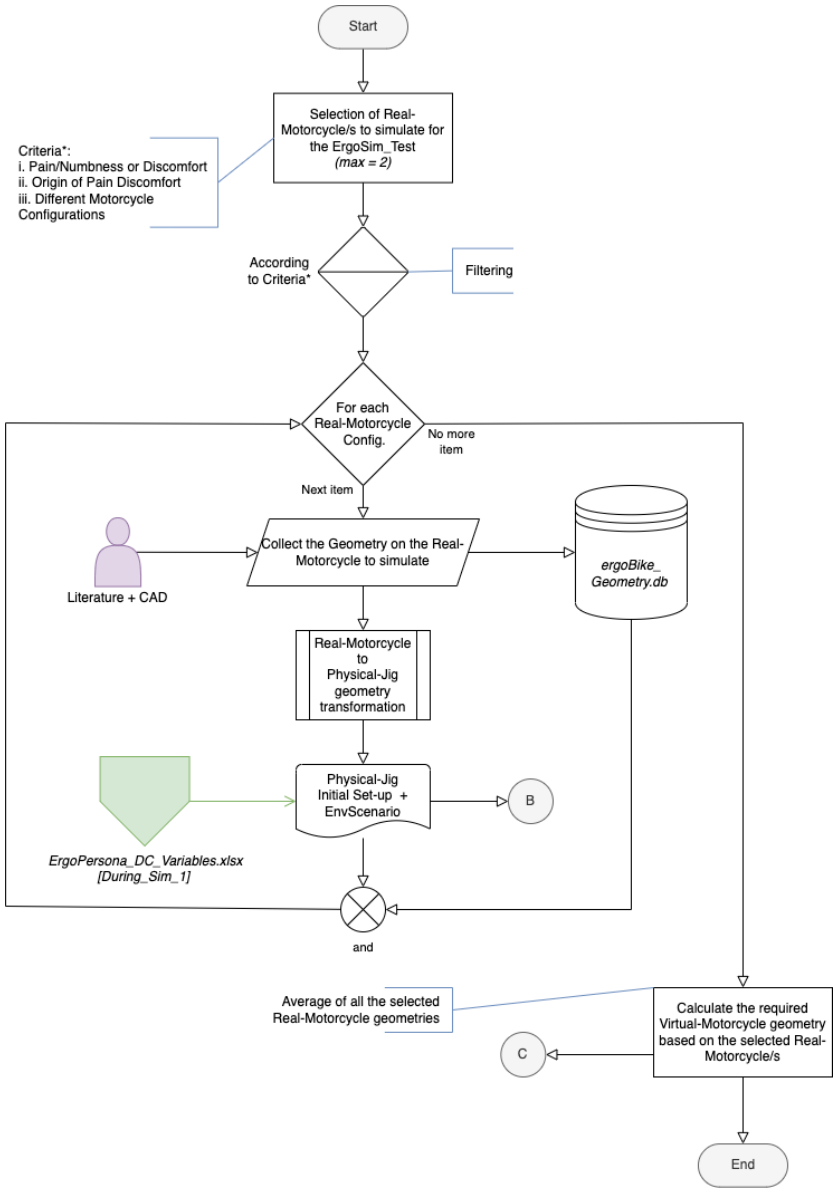


Figure 9.12 – Data preparation for ErgoSim-Study

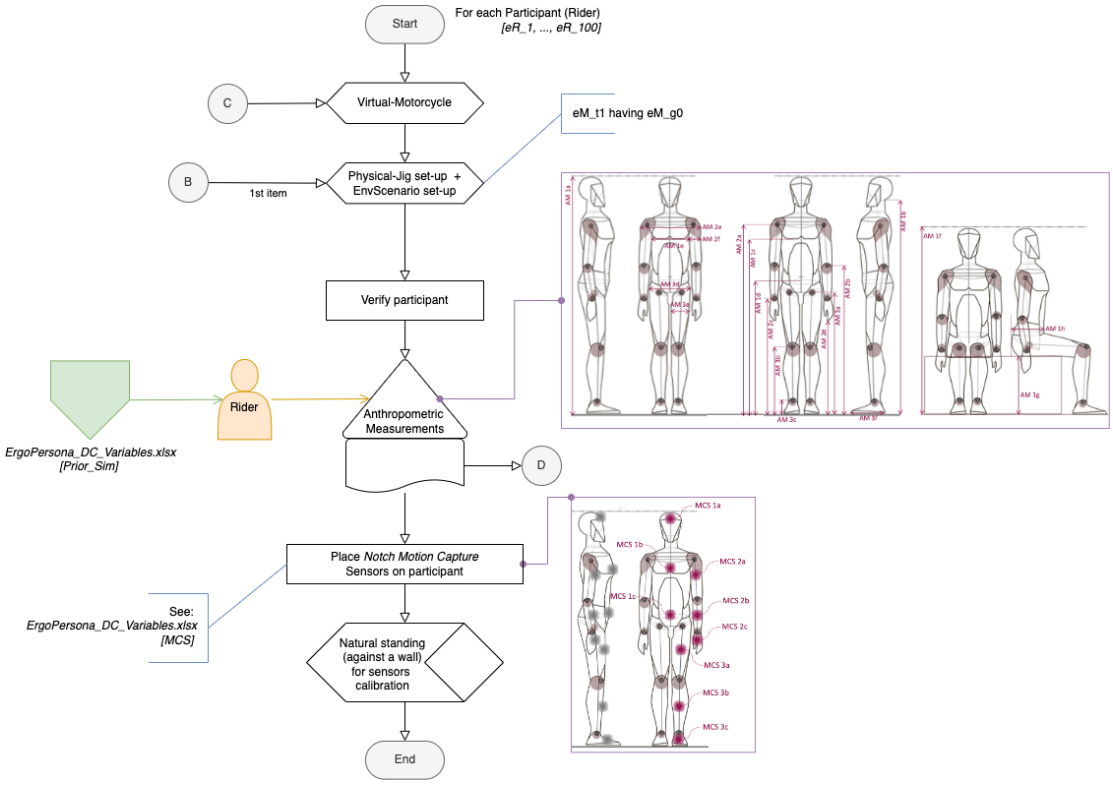


Figure 9.13 – ErgoSim-Study part 1: Prior simulation on ADAMS

Ergonomic data engineering

When ergonomic-related data is captured, the methodology adopted was designed to both facilitate and optimise the data acquisition process, rendering it intuitive for the data collector. For instance, to ensure precision in measurements, the standing height and neck height were recorded relative to a baseline (see Figure 9.13). Subsequently, the actual neck length was derived by subtracting one measurement from the other during the data engineering process. Other ergonomic-related data engineering processes are given in Figure 9.15.

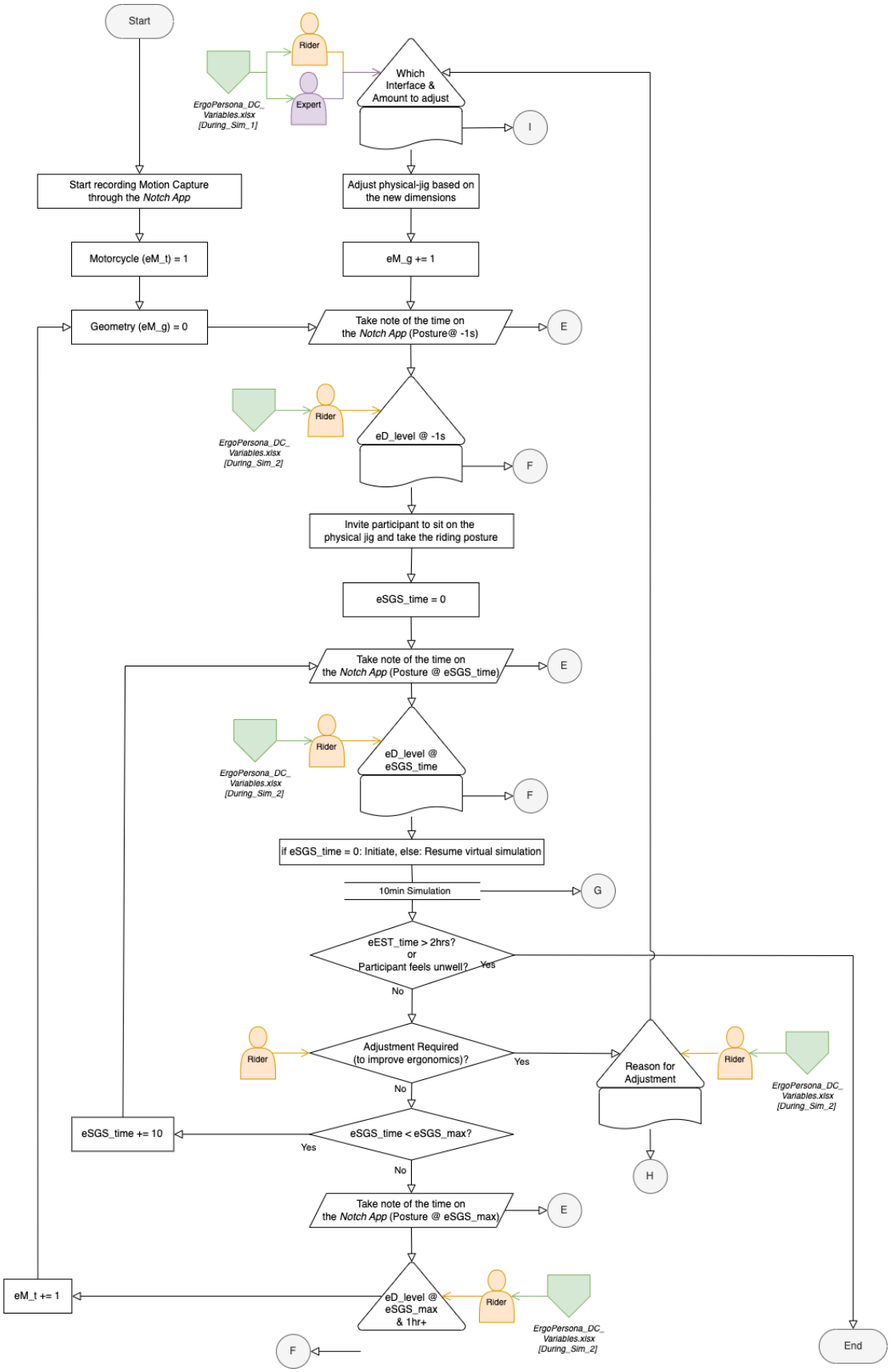


Figure 9.14 – ErgoSim_Study part 2: During simulation on ADAMS

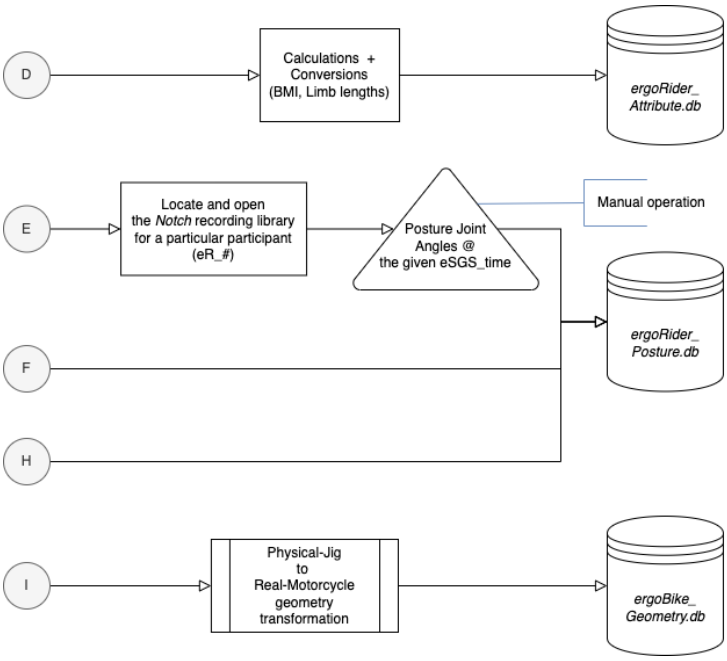


Figure 9.15 – Ergonomic data gathering post simulation

Collecting emotion-persona related data

Representing emotions

Various methods of emotion representations

Vitters et al. (2005), Mamo (2018) and Chandra (2018) have conducted an examination of diverse models aimed at accurately mapping and quantifying emotions, together with evaluations (advantages and limitations) of these models. Here, it is reiterated that as long as FR3 (PDEs which take precedence over others, due to the dual nature) and FR4 (provide a UCD approach during the DOP design process) are adhered to, any methodology capable of capturing (potential) customers' emotions and aesthetic preferences — which reflect market trends and work on the three emotion levels (Norman, 2004), is deemed valid within the context of the proposed approach framework.

The concept of emotion profiles

Nonetheless, as pointed out by Singh (2013) most of the terminology employed to describe emotions, such as 'amused', 'satisfied', 'awaiting', 'bored', and 'irritated', fails to encapsulate the emotive essence or character inherent to a motorcycle (DOP). For instance, it is

uncommon to refer to the *Kawasaki Ninja H2R*[11] using descriptors like an 'amused bike' or a 'satisfied bike'. Rather, it is widely recognised and described as an 'aggressive' motorcycle, which more accurately conveys the distinct personality and emotive appeal.

Moreover, Chandra (2018) posits that a comprehensive understanding of emotions necessitates a neurological, psychological, and socially oriented perspective, provided by concepts such as the Rasas (Chandra, 2018) and Russel's (Nogueira et al., 2015) emotion wheel, illustrated in Figure 9.16. This model for representing emotions is based on two dimensions: *valence* and *activation*. Valence pertains to the degree of pleasure (or its absence), while activation relates to the level of excitement (or its absence) elicited by an artifact. Figure 9.16 employs polar coordinates to delineate the *type of emotion* via angle 'θ' and the *intensity of emotion* through the radius '*r*'. In this model, '*r*' is defined on an arbitrary scale ranging from 0 to 3, where 0 signifies the complete absence of emotion, and 3 represents the utmost extreme of emotion intensity.

According to Chandra (2018) the emotion generated 'θ' by an artefact can be classified into four distinct categories each represented by a particular angle (see Figure 9.16). Henceforth, this model of emotion representation will be referred to as the *Emotion profile* (EP), comprising the following four dimensions:

- *S – Sober (Serious or Sensible)*
- *G – Glamour (Elegant)*
- *D – Dynamic (Lively)*
- *I – Intimidating (Scary)*

[11] https://www.kawasaki.com/en-us/motorcycle/ninja/hypersport/ninja-h2r

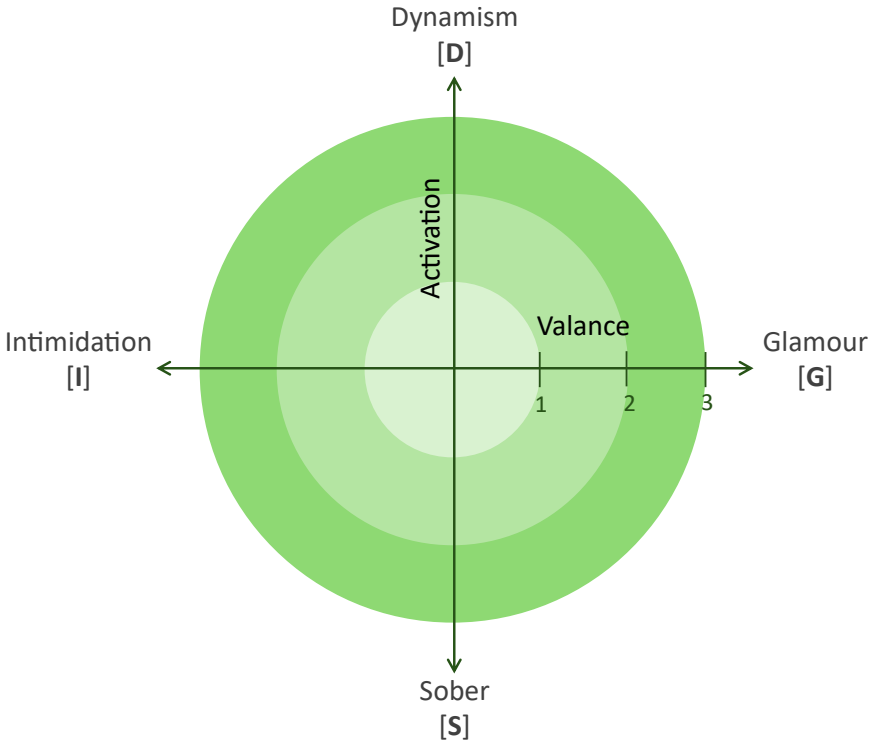


Figure 9.16 – Representation of the emotion profile, adopted from Chandra (2018)

Aesthetic value of the motorcycle

Having established the basis for quantification of emotions through emotion profiles, another challenge remains, to relate the emotion profile of riders to that evoked by the DOP, in this case the motorcycle. Chandra (2018) argues that the *aesthetic value* of an artefact is a function of the intensity of various emotions generated by it. This is mathematically denoted as:

(Eq. 9.1)

$$V_{aesthetic} = f(r, \theta)$$
$$= f[r]_{S,G,D,I}$$

REP and IMEP

Human emotions are not standalone phenomena (Norman, 2004); they are invariably elicited by interactions with entities or individuals. The manifestation of human emotions are a function of two entities: the human and the artefact. In this doctoral research these are identified as the *Rider Emotion Profile* (REP) and *Induced Motorcycle Emotion Profile* (IMEP), respectively. REP is intrinsic to the rider, and as seen in Chapter 2 is moulded by a multitude of factors, while IMEP is the emotions that the motorcycle induces to the rider. Bearing in mind Equation 9.1, this relation can be mathematically formulated as:

(Eq. 9.2)

$$V_{aesthetic} = \left\{1 - \left(\frac{[\sum \delta r]_{S,G,D,I}}{[\sum r_{max}]_{S,G,D,I}}\right)\right\} \times 100$$

Where:

(Eq. 9.3)

$$\delta r = REP - IMEP$$

$$\delta r = [|r_R - r_{IM}|]_{S,G,D,I}$$

$$\delta r = [|r_R - r_{IM}|]_S + \cdots + [|r_R - r_{IM}|]_I$$

And:

(Eq. 9.4)

$$\left[\sum r_{max}\right]_{S,G,D,I} = 3 + 3 + 3 + 3 = 12$$

Is the maximum deviation of the emotion intensity, which cannot be more than 3.

Two opposite scenarios, further explaining REP and IMEP

To illustrate the concept of REP and IMEP consider two opposite hypothetical scenarios, as presented in Figure 9.17. *Scenario (A)* depicts a situation where the IMEP diverges entirely from the REP, whereas *scenario (B)* describes a condition in which the IMEP aligns precisely with the REP.

Substituting the values of these scenarios from Figure 9.17 into Equation 9.2 yields the following outcomes:

- In *scenario (A)*, the aesthetic value, $V_{aestheic} = 0\%$
- While in *scenario (B)*, the aesthetic value, $V_{aesthetic} = 100\%$

These findings, in conjunction with Figure 9.17, elucidate that the aesthetic value of an artefact is nullified when it fails to elicit any emotional response. Conversely, the aesthetic value is 100% when the artifact succeeds in evoking emotions that precisely match those desired by the (potential) customer, that is, when the REP and IMEP are congruent.

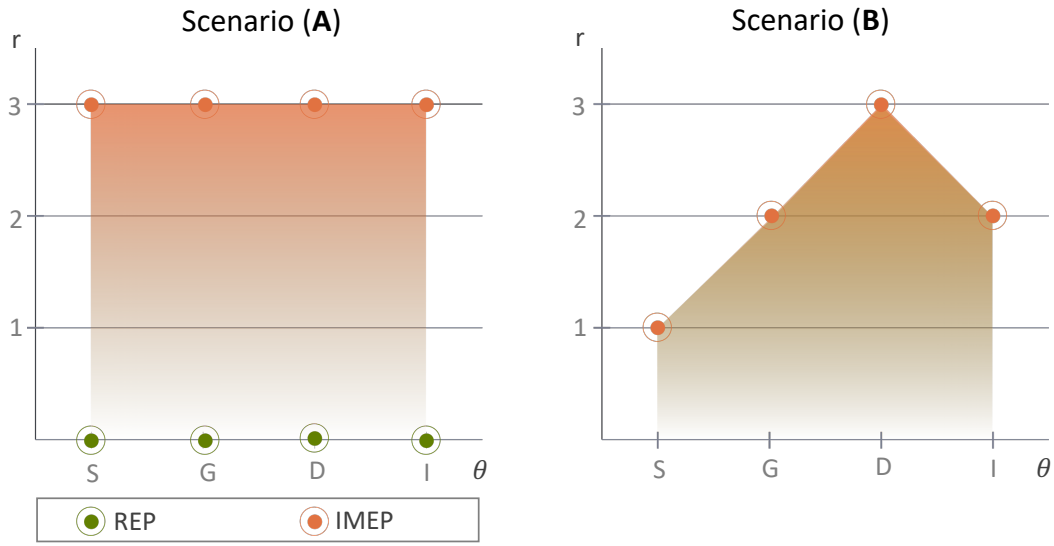


Figure 9.17 – Two scenarios explaining REP and IMEP

Deconstructing emotions

How to obtain IMEP from committed PDEs?

Given framework requirement 2 – FR2 (specified in Section 8.1), and considering that during the design synthesis activity, designers select PDEs from a reusable library (referenced in Section 7.3), the ensuing question is: how can one deconstruct the Induced Motorcycle Emotion Profile (IMEP) and construct it by utilising motorcycle PDEs?

Kansei Engineering

Nagamachi (2002) has conducted research in this area through the study known as *Kansei Engineering*. *Kansei Engineering* is a methodological approach for translating the emotional requirements of an artefact into engineering attributes (Nagamachi & Lokman, 2016). Figure 9.18 demonstrates this concept, outlining the process of emotion deconstruction. The outcome of this methodology is the identification of specific PDEVs required to evoke a particular emotion, as discussed by Schütte (2002) and Chandra (2018). For instance, if the objective is to instil a motorcycle with a certain level of *glamour* and *intimidation*, this approach guides the determination of which body construction, colour scheme, or other PDEVs should be synthesised during the design activity. This process is depicted as the backward translation in Figure 9.18.

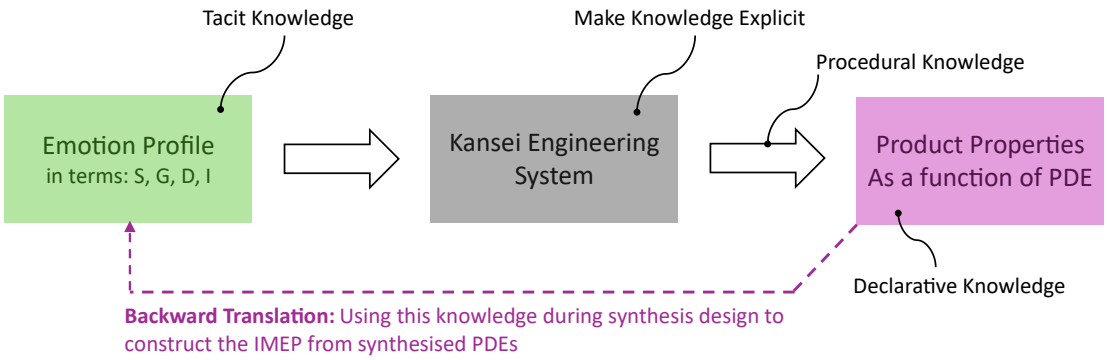


Figure 9.18 – Kansei Engineering framework for product design, adopted from Chandra (2018)

Design factors and PDEs

Design Factors (DFs)

In Section 2.2.1 the product compositional model was explained, illustrating that the motorcycle is constructed from product design elements (PDEs). During synthesis the designer needs to commit to a specific variant for each PDE in order to model the motorcycle. Additionally, Section 2.2.3 explored two inherent product structure philosophies: Structuralist and Gestalt. Chandra (2018) argued that in reality a product is perceived both as the summation of PDEs as well as a cohesive whole. Chandra (2018) categorised the PDEs into distinct groupings, referred to as *design factors* (DFs), which encompass *form*, contribution to *ride-experience*, *colour and texture, unity,* and *dynamism*.

Design factors and PDEs used in this research

Insights from the literature by Chandra (2018), supplemented by information from local motorcycle experts, were utilised to identify PDEs (categorised under the five mentioned DFs). The proof-of-concept presented in Chapter 10, incorporated a non-exhaustive 56 stylistic and positional PDEs, with a selection of these being illustrated in Figure 9.19. An extensive table provided in Appendix G.1 catalogues these PDEs, delineating the design factor to which each PDE is attributed, as well as the emotional processing level, as defined by Norman (2004), that the PDEs influence. To provide a clearer understanding, an exploration of these DFs is given below:



Figure 9.19 – Motorcycle Design Factors and PDEs

Form

According to Hannah (2013) *form* is defined by the relationship between surfaces and significantly influences the emotions elicited by a design. The visible PDEs of a motorcycle are categorised into two distinct groups: elements that contribute to the motorcycle's style and

those that serve a functional purpose. Stylistic PDEs *include fenders, wheels, footpegs, handlebars, front fascia, exhaust systems, side fairings, seats,* and *fuel tanks,* each playing a crucial role in shaping the motorcycle's aesthetic and emotive appeal.

Ride-experience

The contribution to *ride-experience* on a motorcycle encapsulates an array of feelings and sensations encountered by a rider during the operation of the motorcycle (Mehrotra et al., 2016). Various PDEs influence this aspect, including *engine* type, *tyre* thickness, *seat* positioning, and *rake angle*, among others Cocco (2013). For instance, sport motorcycles typically feature elevated horsepower and sharper rake angles to enhance agility and speed. Conversely, touring motorcycles prioritise comfort, incorporating superior seat cushioning and PDEVs aimed at improving rider's stability.

Colour and texture

According to Mikellides (2012) colour affects emotions, where a single hue can manifest in countless of variations. The introduction of a second colour exponentially increases the potential variations. In the area of the automotive industry, surface textures can be broadly categorised into *plain, rough,* and *glossy* types (Chandra, 2018). Although this classification is rudimentary, delving into more detailed categorisations would exceed the boundaries of this doctoral dissertation and necessitate a dedicated investigation.

Unity

Unity is the harmonious relationship between individual PDEs and the overall composition, emphasising coherence towards a unified artefact (Hannah, 2013). In motorcycle design, unity is manifested through five primary factors: *unity of form, continuity of parts, character lines* and *feature lines*. Unity of form relates to the complementary nature of object shapes, while continuity suggests a seamless visual extension between components, exemplified by the coherent flow from the fuel tank to the rear fender. Feature lines denote the visible boundaries of parts, and character lines are defined by the intersection of two surfaces, collectively contributing to a cohesive and integrated design.

Dynamism

According to Chandra (2018) visually dynamism can be defined as the anticipation of change within a visual representation of a static artefact. Dynamism (see Figure 9.19) is distinguished by three key attributes: the alignment and divergence of lines, creating a sense of movement; the visual impression of the centre of gravity, where a higher height-to-length ratio heightens the sense of potential instability; and visual imbalance, which, unlike the stability conveyed by balanced compositions, introduces a feeling of instability, thereby generating *visual tension*. Together, these elements contribute to the dynamic quality of a visual composition, enhancing its perceived liveliness and movement.

Mathematical modelling of emotion profiles

IMEP mathematical formulation

The development of a relationship between emotions and PDEs necessitates the systematic gathering, collation, and analysis of data concerning the elicitation of emotions in response to PDEs, as noted by Chandra (2018). According to Chandra (2018) this correlation can be mathematically articulated through Equation 9.5, providing a quantitative framework to understand how PDEs influence emotional responses.

(Eq. 9.5)

$$IMEP = [r]_{S,G,D,I} = \left[\sum w_x r_x\right]_{S,G,D,I}$$

Utilising Equation 9.5 enables the quantification of emotion intensities, denoted as '*r*', which constitutes the weighted sum of various design factors. Here, 'w_x' signifies the weighting assigned to different DFs. *Design Factor Emotion Profile* (DFEP), symbolised as 'r_x' for a specific design factor, is similarly derived as the weighted sum of different sub-factors or PDEs. This is mathematically expressed as:

(Eq. 9.6)

$$DFEP = [r_x]_{S,G,D,I} = \left[\sum w_a r_{xa}\right]_{S,G,D,I}$$

where '*a*' represents various PDEs.

IMEP construction table

For the purposes of this discussion, it is assumed that each motorcycle PDE, has a specific emotion profile which is already specified. For instance, a fuel tank designed with sharp corners might have an emotion profile leaning towards *intimidating* and *dynamic* characteristics, in contrast to one with soft, rounded edges, which may align more closely with *glamour* or *sobriety*. Bearing this concept in mind, Equations 9.5 and 9.6 facilitate the construction of the IMEP table, as depicted in Figure 9.20. This figure demonstrates how the PDE-specific emotion profile (r_{xa} or *PDEVEP*) for each PDE is aggregated into a DFEP incorporating the respective weightings (w_a) for each PDE. In turn these are aggregated into the IMEP after considering the weightings for the DFs (w_x). The data presented in Figure 9.20 serves as an illustration, while the weightings w_a and w_x will be discussed in Chapter 10.

			$[d]_E\{O\}$			
		weight	S	G	D	I
DF	**Colour-Texture**					
PDE	Colour	0.50	1.02	1.42	1.33	0.65
PDE	Texture	0.50	0.98	2.43	2.00	2.15
	Weighted mean		1.00	1.93	1.67	1.40
DF	**Form**					
PDE	Fuel Tank	0.31	1.31	0.95	0.58	0.21
PDE	Handlebar	0.34	1.12	1.04	0.87	0.04
PDE	Seat	0.31	0.47	1.66	1.28	1.09
PDE	Footpegs	0.04	0.59	0.83	2.26	0.83
	Weighted mean		0.96	1.20	0.96	0.45
DF	**Ride Experience**					
PDE	Construction	0.75	0.86	0.57	0.52	0.59
PDE	Engine	0.25	0.92	0.68	1.99	0.44
	Weighted mean		0.87	0.60	0.89	0.55
DF	**Unity**					
PDE	Character Lines	0.54	0.14	0.74	2.87	1.39
PDE	Feature Lines	0.23	0.27	1.86	1.25	0.30
PDE	Engine Bay	0.23	0.20	1.90	0.93	0.24
	Weighted mean		0.18	1.26	2.05	0.87
DF	**Dynamism**		0.64	1.36	2.25	1.88
	Overall					
DF	Colour-Texture	0.12	1.00	1.93	1.67	1.40
DF	Form	0.18	0.96	1.20	0.96	0.45
DF	Ride Experience	0.15	0.87	0.60	0.89	0.55
DF	Unity	0.25	0.18	1.26	2.05	0.87
DF	Dynamism	0.30	0.64	1.36	2.25	1.88
	Weighted Mean		0.66	1.26	1.69	1.11

Legend
r_{xa} - PDEVEP
w_a - PDE weight (Contribution to DFEP)
r_x - DFEP
w_x - Design Factor weight (Contribution to IMEP)
r - IMEP

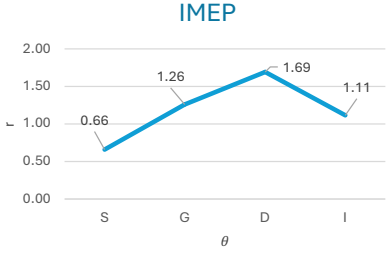


Figure 9.20 – IMEP construction table

EmoPersona-Study

Data collection required to construct IMEP

In the previous section, the concepts of REP and IMEP (decelerative knowledge), alongside with the methodology for constructing the IMEP (procedural knowledge) were explored. While construction of the IMEP is to be undertaken by a dedicated algorithm, the acquisition of raw data or inputs necessary for feeding this algorithm is essential. Such data is collected from experts in the field, and actual motorcycle riders. Consequently, this section explains what, how and tools employed for data collection. To optimise data collection from motorcycle riders while avoiding the deterrent of lengthy surveys, the *EmoPersona-Study* was sub-divided into two parts. This approach aimed to maximise the breadth of information collected, ensuring participant engagement and response efficacy.

EmoPersona-Study part 1 – Identifying PDEV emotion profile and whole motorcycle emotion profile by experts

EmoPersona-Study part 1: Number of experts

In theory, conducting this study with a single expert is feasible, yet such an approach would likely result in highly biased ratings. Therefore, it was deemed sufficient to employ six industry related individuals (identified as experts). The participants were conveniently recruited through established connections within the motorcycle industry. Participants included motorcycle dealers, marketing personnel, and riders. This selection is based on the premise that a smaller number of participants would fail to encompass diverse perspectives, while a larger group could render the study impractical (van Dijk, 1995). Furthermore, no specific inclusion criteria were applied in the selection process, as the study did not necessitate any specialised skills or abilities from the participants.

EmoPersona-Study part 1: Data collection procedure

The method employed was an online questionnaire-based DCI. To mitigate any potential influence among the experts, responses were collected independently. Moreover, a fifteen-minute call was

conducted with each expert to clarify the objectives and procedures of the task, ensuring a comprehensive understanding of their role in the study.

Deriving of PDEV emotion profiles

The first section of *EmoPersona-Study part 1* involved in rating over 400 motorcycle PDEVs by experts, who were tasked with identifying the emotion predominantly evoked upon viewing various PDEVs. The emotions to be identified included: Sobriety (serious/sensible); Glamor (elegant); Dynamism (liveliness); and Intimidation (scare).

Experts were also required to rate the intensity of the elicited emotion using a Likert-scale ranging from 1 to 3. An example is given in Figure 9.21, showcasing four different variants (or PDEVs) for the rim style product design element (PDE).

Deriving of whole motorcycle emotion profiles

Similarly, in the second section of *EmoPersona-Study part 1* the six experts had to identify the emotion type and intensity of entire motorcycles. For this exercise, 50 motorcycles, all of which were *cruiser* motorcycle type but with different styles, were selected. This approach aims to minimise variability, thereby enhancing the accuracy of the machine learning model later on. Moreover, both the PDEVs and motorcycles chosen for this investigation are of a relatively modern design, in alignment with the requirement to adhere to current market trends, as specified in FR4d.

Documentation of the questionnaire DCI

The detailed structured questionnaire DCI used in *EmoPersona-Study part 1* is documented in Appendix G.2. This was reviewed and approved by the Ethics Committee of the University of Malta (Application ENG 669/2019, part 4), and informed consent was secured from each participant.

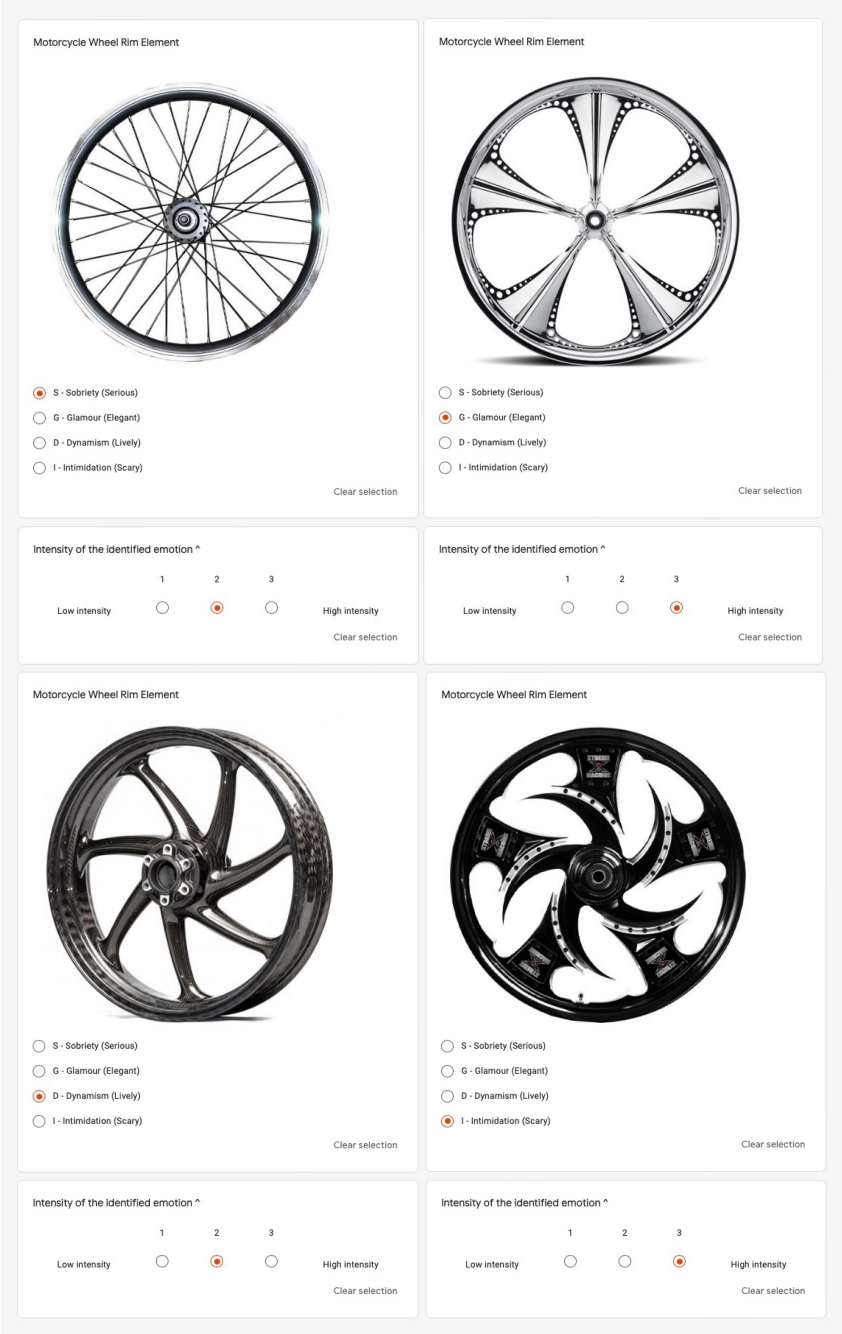


Figure 9.21 – Emotion and intensity of four PDEVs of the Rim PDE

EmoPersona-Study part 1: Data engineering

Following this exercise, the data collection resulted in 6 x 400 PDEV and 6 x 50 motorcycle emotion profiles, reflecting the six experts' ratings. These profiles necessitate consolidation into a singular emotion profile, that is, 1 x 400 PDEV and 1 x 50 motorcycle emotion profiles. This consolidation was achieved through the use of Equation 9.7, as given below:

(Eq. 9.7)

$$[X]_{S,G,D,I} = \frac{\frac{[a]_{S,G,D,I}}{n} \times 3}{\left(\frac{[a]_{S,G,D,I}}{n}\right)_{max}}$$

Where:

- $[a]_{S,G,D,I}$ = aggregate score of the 6 experts for each emotion dimension [S,G,D,I].
- n = number of experts = 6.
- $\left(\frac{[a]_{S,G,D,I}}{n}\right)_{max}$ = is the maximum mean score from the 400 PDEV and from the 50 motorcycles.

PDEVs emotion profile consolidation

The outcome of the PDEV consolidation process, facilitated through Equation 9.7, is a singular PDEV emotion profile (r_{xa}) for the 400 variants under consideration, with a selection thereof illustrated in Figure 9.20.

Whole motorcycles emotion profile consolidation

On the other hand, the derivation of the motorcycle emotion profile, utilising Equation 9.7, is delineated in Table 9.2. (Note that only 3 of the 50 motorcycles are shown for illustrative purposes).

Table 9.2 – Motorcycle emotion profile calculation method

Number of respondents: (n=6)

Motorcycle	Aggregate score (a)				Mean score (x = a/n)				Weighted score ($X = x*3/x_{max}$)			
	S	G	D	I	S	G	D	I	S	G	D	I
M1	14	11	3	10	2.8	2.2	0.6	2.0	3.00	2.36	0.64	2.14
M2	7	12	7	13	1.4	2.4	1.4	2.6	1.50	2.57	1.50	2.79
M3	3	4	12	14	0.6	0.8	2.4	2.8	0.64	0.86	2.57	3.00

EmoPersona-Study part 2: Study carried out to collect (potential) motorcycle customers' emotion and persona related information

EmoPersona-Study part 2: Objective

The objective of *EmoPersona-Study part 2* was to gather data relevant to (potential) motorcycle customers' persona and aesthetic-derived emotions. This data will subsequently facilitate (during data engineering) the construction of profiles encompassing personality,

behaviour, and the Rider Emotion Profile (REP) of different individuals who may constitute potential customers.

EmoPersona-Study part 2: Data collection

To gather the required information, a questionnaire-based DCI was employed, targeting 200 local motorcycle riders. The survey was disseminated online through various local motorcycling Facebook groups using a convenience sampling approach. To encourage participation in the *EmoPersona-Study part 2*, respondents were offered the opportunity to enter a draw to win a voucher provided by *RIDE+SAFE*'s industrial partner. The survey remained open for a duration of one week, during which 200 valid responses were received. The survey is structured into three principal sections: the first section aims to collect data on riders' attributes, including age, experience, frequency of motorcycle use, and personality; the second section encompasses questions related to behaviour; and the third section is about questions to determine riders' aesthetic-derived emotions or REP. The structured questionnaire employed as the data-collection instrument for this investigation is detailed in Appendix G.3. This was reviewed and approved by the Ethics Committee of the University of Malta (Application ENG 669/2019, part 4), and informed consent was secured from each participant. Similar to *EmoPersona-Study part 1, part 2* was conducted on an individual basis to ensure that no participant could exert influence or introduce bias among others.

International Personality Item Pool (IPIP)

In the second part of the *EmoPersona-Study part 2*, to measure and assess the personality a version of the *International Personality Item Pool* (IPIP) personality construct was chosen to help identify broad personality characteristics of the riders. The items in the IPIP are designed to assess various personality traits and characteristics based on different psychological theories and models. The validated IPIP-Neo method (Stidham et al., 2018) makes use of 50 questions consisting of 10 items for each of the *big-five personality factors: Extraversion (E), Agreeableness (A), Conscientiousness (C), Emotional Stability (ES)* and *Intellect (I)* (Romero et al., 2019). Participants were requested to read

each of the 50 questions like *"I am always prepared"* (Conscientiousness), *"I feel comfortable around people"* (Extraversion), or *"I have a vivid imagination"* (Intellect) and then rate how well they believed it described them on a 5-point Likert-scale (very inaccurate to very accurate).

Dula Dangerous Driving Index (DDDI)

The *Dula Dangerous Driving Index* (DDDI) is a validated psychological assessment tool designed to measure various aspects of dangerous driving behaviour (Dula & Ballard, 2003) and was employed to collect participants' tendencies of engaging in dangerous driving behaviours. Similar to the IPIP-Neo, the DDDI consists of 28 questions to which individuals respond, indicating the degree to which they engage in certain driving behaviours or agree with certain attitudes towards driving. These items cover a range of topics, including aggressive driving, risky behaviours, and violations of traffic laws (McGowin et al., 2015).

Within the third part of *EmoPersona-Study part 2*, or the aesthetic-derived emotions section of the questionnaire, riders were requested to rate, via a 5-point Likert-scale, their level of aesthetic-appreciation towards each of the 50 motorcycles (previously identified in *EmoPersona-Study part 1* and as illustrated in Appendix G.2). The rating criteria used is as follows:

0. Do not like it – *I do not like the motorcycle.*
1. Somewhat like it – *It is a nice motorcycle, but I do not want it for me.*
2. Moderate – *I have a mixed feeling if I buy the motorcycle or not.*
3. Like it – *I buy it, but if I am between two or motorcycles, I likely would not buy it.*
4. Like it very much – *If I am between two or more motorcycles, I definitely will buy it.*

Aesthetic-derived

Data engineering is required to extract the participants' emotion profile (REP) for the second section of *EmoPersona-Study part 1* and

emotions data engineering

EmoPersona-Study part 2. Equation 9.8 is used to compute the REP for each survey rider respondent, and is given by:

(Eq. 9.8)

$$REP = [\theta_{rider}]_{S,G,D,I} = \frac{\sum W_{rider_{Mx}} \times [Mx]_{S,G,D,I}}{\sum_{i=1}^{n=50} W_{rider}}$$

Where:

- θ_{rider} is the REP represented in the 4 dimensions of emotion.
- $W_{rider_{Mx}}$ the weight (rating of the 5-pointed Likert-scale) provided by the participant for a particular motorcycle.
- $[Mx]_{S,G,D,I}$ the motorcycle emotion profile derived from experts (in *EmoPersona-Study part 1* section 2) computed through Equation 9.7 and illustrated in Table 9.2.

To aid with the interpretation and result of Equation 9.8, Figure 9.22 presents the calculations in a tabular representation of a hypothetical case using just three motorcycles (derived from Table 9.2), for one particular rider participant. The preferences articulated by participants towards various motorcycles are reinterpreted and articulated across four dimensions: S (Sober), G (Glamorous), D (Dynamic), and I (Intimidating), leading to Rider Emotion Profile (Chandra 2018). In the context of this research, the REP is a characteristic inherent to the rider, encapsulating their motorcycle-related emotion profile, centred on their preferences for specific motorcycles and design elements.

Emotion processing levels

The REP captures both *visceral* (*form* DF) and *behavioural* emotion processing levels (contribution to *ride-experience* DF). The *reflective* emotion level (Norman, 2004) is identified by correlating the REP with the persona.

Motorcycle	S	G	D	I
M1	3	2.36	0.64	2.14
M2	1.5	2.57	1.5	2.79
M3	0.64	0.86	2.57	3

Respondent 1 (W_{rider})	S	G	D	I	
5	15	11.8	3.2	10.7	
2	3	5.14	3	5.58	
0	0	0	0	0	
7	18	16.94	6.2	16.28	
REP	**2.57**	**2.42**	**0.89**	**2.33**	*Weighted average sum*

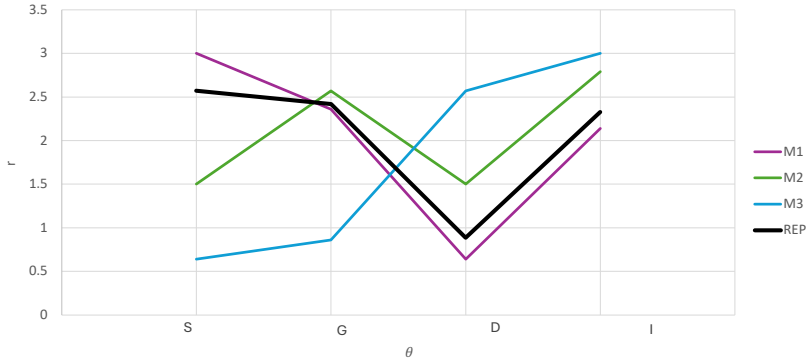


Figure 9.22 – Calculation and derivation of participants' REP

Persona data engineering

When capturing participant personas through the questionnaire, questions are formatted in a way that participants can understand. The answers to these questions are then translated into quotients that the computer can process. For the personality construct, collected through the IPIP and DDDI DCIs, the results are transformed using the algorithm provided by McGowin et al. (2015) and Dula & Ballard (2003), respectively to build the persona and behaviour of each rider participant. The persona and behaviour profile constructs are delineated in Figure 9.23, and utilising the specified algorithm, it becomes feasible to ascertain, for instance, whether a respondent exhibits *sociable* or *introverted* tendencies within the *Extraversion* personality dimension.

No collection of personally identifiable information

It is imperative to underscore that no personally identifiable information of participants was collected in both the ergonomic-persona and emotion-persona studies. This precludes any potential association between the participant's identity and their anthropometry or personality profile.

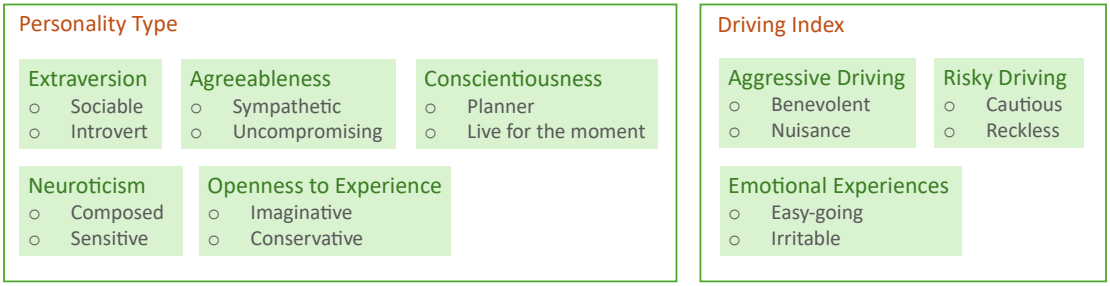


Figure 9.23 – Persona and driving behaviour profile

9.2.2 Database

Collection of databases

This organised collection of data, gathered from the data capture process in Section 9.2.1 and transformed by the data engineering, is stored within the database in the form of structured tables. These tables consisting of the rider ergonomics, aesthetic-derived emotions and persona related data are thus ready to be accessed by the a*lgorithm module*.

Ergo-Persona dataset

The *ErgoSim-Study* was conducted with a cohort of 40 participants, each subjected to 10 variations of motorcycle adjustments, yielding a total of 400 unique data points. This dataset, referred to as the *Ergo-Persona Table*, encompasses a variety of collected variables and their respective categories, detailed in Appendix F.2, including:

- *Rider attributes* (ATT), capturing age and riding scenarios such as intermittent, traffic, static, or long-distance simulations.
- *Anthropometric measurements* (AM), detailing riders' anthropometric characteristics, such as standing height, forearm length, thigh length, and weight, among others.
- *Motorcycle adjustments* (MA), encompassing adjustments within the rider triangle, for example, the horizontal distance from the handlebar to the seat.
- *Posture or Joint angles* (JA), illustrating the ergonomic posture assumed by a rider on a specific motorcycle setup, such as hand flexion or extension.

- *Ergonomic discomfort* (ED), a numerical scale ranging from 0 to 10 that quantifies discomfort, where 0 indicates no discomfort and 10 signifies extreme or unbearable discomfort.

Emo-Persona dataset

The *EmoPersona Study* was conducted with a total of 200 rider participants. This dataset, referred to as the *Emo-Persona Table*. Detailed information on the collected variables, along with their respective categories, is provided in Appendix G.4 and encompasses the following components:

- *Rider attributes*, which include details such as age, riding experience, frequency of motorcycle use, involvement in motorcycle accidents, and the severity of those accidents.
- *Personality traits*, as assessed by the International Personality Item Pool (IPIP).
- *Driving behaviour*, evaluated using the Dula Dangerous Driving Index (DDDI).
- *Visceral ratings*, level of aesthetic appreciation towards the 50 motorcycles, which later are transformed to the participants' *Rider Emotion Profile* (REP), categorised into four dimensions: *Sobriety (S), Glamour (G), Dynamism (D)* and *Intimidation (I).*

Acquiring simple relational knowledge

This section has provided an overview of how domain tacit knowledge is rendered explicit via the data capture process outlined herein. The intricate and previously uncodified relationships between diverse riders and motorcycles (or motorcycle design elements) have been explained and catalogued in a structured table format, representing a form of simple relational knowledge. This constitutes both domain and declarative knowledge, encapsulating the *'know-what'* aspects. Subsequently, the discussion will transition to examining how computers, employing machine learning (ML) techniques, process this simple relational knowledge and translate it into a format recognisable by humans and current working knowledge.

9.3 The Business Layer – Transforming Information to Knowledge

The business layer, illustrated in Figure 9.6, implements the core functionality of the system and encapsulates the relevant business logic.

9.3.1 Algorithm Module

Algorithms used to transform implicit knowledge

The *algorithm module* (see Figure 9.6) contains all the algorithms (procedural and mathematical constructs) which are used by the knowledge module and inference engine to assist the designer during the decision-making. The algorithm module is further split into two: (i) *Machine Learning Service* (MLS), and (ii) *multiple objective optimisation* (MOO)–a mathematical-based algorithm used for the harmonisation. This module is an enabler to transform the simple relational knowledge found in the database (Section 9.2.2) to models where inference can be used to support and provide recommendations to the designer.

Mathematical expressions are a form of knowledge

As illustrated in Table 9.1, according to Horvath (2002) mathematical expressions are a form of knowledge. The reason is that they encapsulate complex ideas and relationships in a universally understandable and precise language, serving as the cornerstone for various scientific theories (Horsten, 2022).

Machine Learning Service (MLS)

Machine learning mathematical basic rapresentation

The MLS covers several ML algorithms which are used to build models from the data stored inside the database, in order to, later on, make predictions or decisions. The generation of these models is specified as a mathematical relationship between one or more dependent variables and other independent variables (contained in the data). This is in the form of:

(Eq. 9.9)

$$Y = \alpha X_1 + \beta X_2 + \ldots + \zeta$$

Where:

Y is the output/prediction/dependent variable.

α, β, ζ are non-dependent coefficients (representing the relationship between the dependent and independent variables). These coefficients are obtained during the training phase of the ML algorithm.

X_1 and X_2 are the different input/dependent variables.

For instance, in simple terms, to predict the ergonomic discomfort of a particular rider Equation 9.9 can be expressed as follows:

(Eq. 9.10)

$$ED = \alpha ATT + \beta AM + \chi MA + \delta JA + \zeta$$

Where: ATT, AM, MA, JA and ED are ergonomic categories highlighted in Section 9.2.2.

Supervised machine learning

The main learning method used is *supervised learning*. In this method, data inputs are presented together with their desired outputs, given by a *'teacher'*. The goal is to generate a model which maps inputs to outputs, that is, finding the value of the α, β, …, ζ coefficients in Equation 9.9 (Romeo et al., 2020). Table 9.3 provides a list of algorithms which are used in the ML engine for model creation.

Table 9.3 – Machine Learning Algorithms used

Algorithm	Learning Method	Technique	Predictor	Used for
Support Vector Machine (SVM)	Supervised Learning	Statistical Pattern-finding Technique	Regressor	Predicting continuous data type (e.g., handlebar vertical dimensions)
			Classifier	Predicting categorical data type (e.g., the severity of an accident and likelihood of occurrence)

Support Vector Machines

Support Vector Machine (SVM) is a type of machine learning algorithm that is particularly useful for classification and regression tasks. SVM is conceptualised as a technique for delineating the optimal line or hyperplane that distinctly segregates varying categories of data points (Christmann & Steinwart, 2008). For classification tasks, this means, identifying the line that best divides, for example, *Category A* from

Category B. The SVM finds the line that not only separates the two classes but does so in a way that maximises the distance (or margin) between the nearest points of each class to the line, which are known as the support vectors. This approach helps in achieving better classification accuracy. In regression tasks, SVM works similarly, but instead focuses on finding the best fit line or curve that can predict a continuous output based on the input variables. The efficacy of SVM lies in its flexibility to handle various types of data and its effectiveness in situations where the relationship between the data points is not straightforward or linear (Christmann & Steinwart, 2008).

Use of SVM

SVM-based algorithms (classifiers and regressors) are used to predict population use-phase and design-stage conflict consequences (PUC and DCC) of the evolving motorcycle model. The MLS contains different algorithms of the SVM technique with different inputs to predict different outputs. This will give rise to different models. Consider as an example, that the ergonomic discomfort of a rider's wrist needs to be predicted. An expert suggests the dependent variables, i.e. those variables that lead to the ergonomic discomfort (ED) in the wrists. For instance, the rider's feet anthropometric characteristic or the motorcycle's footpegs do not affect the ED of the rider's wrists. On the other hand, the seat, handlebar position affect, amongst others have an impact. This dependency can be represented as follows:

(Eq. 9.11)

$$ED(wrist) = \alpha ATT + \beta_1 StH + \ldots + \beta_7 HWL + \chi_1 HBX + \ldots + \chi_6 S\phi + \delta_1 HEfe + \ldots + \delta_{12} Wfe + \zeta$$

Where:

- $\beta_1 StH + \ldots + \beta_7 HWL$ are the anthropometric measurements which directly affect the ergonomic discomforts of the wrists, for example hand-to-wrist length (HWL);
- $\chi_1 HBX + \ldots + \chi_6 S\phi$ are the motorcycle adjustments which directly affect the ergonomic discomforts of the wrists, for example the handlebar horizontal setting (HBX);

- δ_1HEfe + … + δ_{12}Wfe are the joint angles which directly affect the ergonomic discomforts of the wrists, for example the wrist flexion/extension angles (Wfe).

Different SVM models

The application of the SVM extends beyond predicting wrist ergonomic discomfort. It is employed to predict various outcomes, including limb-specific posture, limb-specific discomforts, support for emotion profiles, occurrence and severity of accidents, and the bases to formulate recommendations. Consequently, this approach gives rise to an array of distinct machine learning models. For instance, ergonomic discomfort in the wrist, denoted as ED(wrist), is estimated using *model 1* with the SVM technique, as per Equation 9.11, whereas ED(ankle) is derived from *model 'n'* employing the same technique. The latter model adheres to the structure of Equation 9.11, albeit with differing variables or dependencies. For instance, while the measurement from handlebar to seat might not influence ankle ergonomic discomfort, the vertical distance from foot-peg to seat does. The responsibility of the Inference Engine encompasses determining which trained ML model from the Knowledge Base is to be activated for a given prediction.

Knowledge interpretation (Explainability)

Implicit and explicit representations in ML

In ML, an explicit function is one that is defined explicitly by an equation or algorithm. For example, a linear regression model (like Equations 9.9 to 9.11) is an explicit function because it has a specific equation that describes the relationship between the input and output variables. On the other hand, an implicit function is one that is defined implicitly by data. For example, the tables presented in Appendix F.2 and G.4 are implicit because they do not have a specific equation that describes the relationship between the input and output variables. Explicit functions are generally easier to understand and are represented in a human-recognisable format, but they can be limited in their ability to model complex relationships. Implicit functions, on the other hand, can model

complex relationships but they can be more difficult to understand and interpret (Berry, 1987).

Distinction between Support given to designer and Knowledge explainability

It is imperative here, to *distinguish knowledge explainability from the support offered by the design framework* through the Support Engine (SE). The concept of knowledge explainability pertains primarily to the inherent processes of machine learning and the formulation of intrinsic rules, as opposed to the PUC and DCC support provided to designers.

Transforming implicit to explicit knowledge through XAI

The process of transforming implicit to explicit knowledge is through a technique called *explainable AI* (XAI) (Kamath & Liu, 2021). This refers to methods and techniques in the field of AI and ML that make the output of these models understandable to humans. It involves making the decision-making process of AI and ML models transparent, interpretable, and comprehensible (Kamath & Liu, 2021).

XAI techniques

Techniques for machine learning explainability include *feature importance scores* or *mathematical expressions* (for example, as seen by Equation 9.11), *partial dependence plots* (PDPs), and *decision trees* (Murdoch et al., 2019). The choice of the technique often depends on the complexity of the model and the specific requirements of the application (Murdoch et al., 2019). These techniques will be presented below, employing actual data obtained from riders. However, due to the complexity of the data, the discussion will concentrate specifically on the ergonomic discomfort in the wrist (ED_{wrist}).

Explainable AI techniques

Feature importance scores

Within the framework of XAI, a feature importance analysis will be conducted using the *Random Forest* ML algorithm to ascertain the most critical factors (Liaw & Wiener, 2002) in predicting ergonomic discomforts in the wrist. This analytical approach enables the identification of key anthropometric measurements and other relevant factors that significantly influence wrist discomfort. The most

influential five features identified by the Random Forest model in predicting wrist discomfort are as follows:

1. *Hand Radial/Ulnar Deviation (degrees)*: This metric, reflecting the angle of hand deviation, emerges as the paramount predictor of wrist discomfort, accounting for more than 52% of the importance score.
2. *Age*: The influence of various age groups is substantial, with an importance score of approximately 12%, underscoring age as a significant determinant of wrist discomfort.
3. *Hand Flexion/Extension (degrees)*: This factor, indicating the degree of hand flexion or extension, holds a score of 5.75%.
4. *Scenario (Intermittent, Repeated, Static)*: The usage context of the motorcycle plays a significant role in wrist discomfort, evidenced by a 5.05% importance score.
5. *Arm Flexion/Extension (degrees)*: The degree of arm flexion or extension also plays a role in predicting wrist discomfort, with a 1.42% importance score.

This analysis explains the intricacies involved in predicting ergonomic discomfort in the wrist, highlighting the critical influence of hand positioning (both radial/ulnar deviation and flexion/extension) and the age of the rider. Additionally, the specific usage scenario of the motorcycle is identified as playing a crucial role.

Partial dependence plots (PDPs)

Partial Dependence Plots (PDPs) provide insights into the relationship between a feature (or variable) and the target outcome in a ML model, while averaging out the effects of all other features (Molnar, 2023).

Figure 9.24 illustrates PDPs for the top predictors of ergonomic discomforts in the wrist identified earlier through the *feature importance score*. Each plot delineates the marginal impact of a given feature on the level of predicted ergonomic discomfort, offering the following insights:

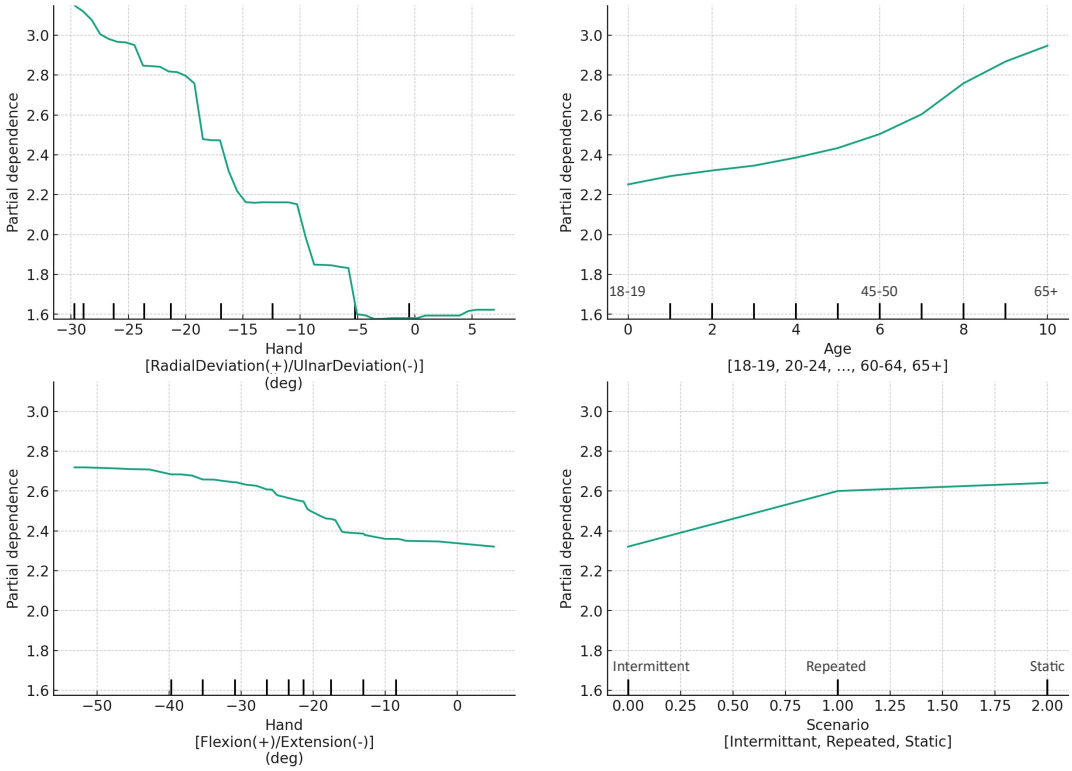


Figure 9.24 – The combined PDPs for the top variables affecting ED_{wrist}

1. *Hand Radial/Ulnar Deviation (degrees)*: The plot shows how changes in hand radial/ulnar deviation degrees affect wrist discomfort, indicating a specific trend or pattern. Typically, one might expect to see that extreme deviations (either positive or negative) could lead to increased discomfort.
2. *Age*: The effect of age on wrist discomfort reveal that certain age groups are more susceptible to discomfort than others, possibly due to factors like decreased flexibility or strength.
3. *Hand Flexion/Extension (degrees)*: This plot shows how wrist discomfort changes as the hand flexes or extends. It could indicate, for instance, that certain positions are more ergonomically comfortable and lead to less discomfort, particularly values higher than -15 degrees.
4. *Scenario*: This plot shows the marginal effect of different riding scenarios on ergonomic discomfort in the wrist. In Figure 9.24, 0 signifies *intermittent*, 1 signifies *repeated* and 2 means *static*. The difference between the scenarios indicate how each uniquely contribute to the level of discomfort, with the

intermittent scenario providing the least ergonomic discomfort while *static* contributes to the highest ergonomic discomforts.

These visual representations facilitate in understanding the influence of individual features on the model's predictions. For instance, if '*Hand Radial/Ulnar Deviation (degrees)'* shows a clear increase in discomfort at certain angles, designers and riders could aim for handlebar and control layouts that minimise such deviations.

IF-THEN rules and Decision Trees

The employment of IF-THEN rules and *Decision Trees* constitutes an efficacious approach for the development of models that are inherently interpretable (Kamath & Liu, 2021). Decision Trees are inherently interpretable because they split data into branches based on feature values, leading to a decision or prediction. The path from the root to any leaf can be expressed as a series of IF-THEN rules (Molnar, 2023).

A Decision Tree model will be utilised to forecast ergonomic discomforts in the wrist. As illustrated in Figure 9.25, the Decision Tree model explains the structural logic underpinning how the four previously identified variables impact the prediction of ergonomic discomforts in the wrist.

The tree structure, shown in Figure 9.25, allows IF-THEN rules to be extrapolated and formalised as follows:

IF *Hand Radial/Ulnar Deviation (degrees)* ≤ -18.85 THEN

- IF *Age* ≤ 40 THEN
    - IF *Hand Flexion/Extension (degrees)* ≤ -19.65 THEN ED_{wrist} = 2.99
    - ELSE ED_{wrist} = 2.56
- ELSE IF *Age* > 40 THEN
    - IF *Scenario* is not *'Intermittent'* THEN ED_{wrist} = 3.59
    - ELSE ED_{wrist} = 3.05

IF *Hand Radial/Ulnar Deviation (degrees)* > -18.85 THEN

- IF *Hand Radial/Ulnar Deviation (degrees)* ≤ -8.95 THEN
  - IF *Age* ≤ 60 THEN ED_{wrist} = 2.09
  - ELSE ED_{wrist} = 2.73
- ELSE IF *Hand Radial/Ulnar Deviation (degrees)* > -8.95 THEN
  - IF *Age* ≤ 60 THEN ED_{wrist} = 1.42
  - ELSE ED_{wrist} = 2.06

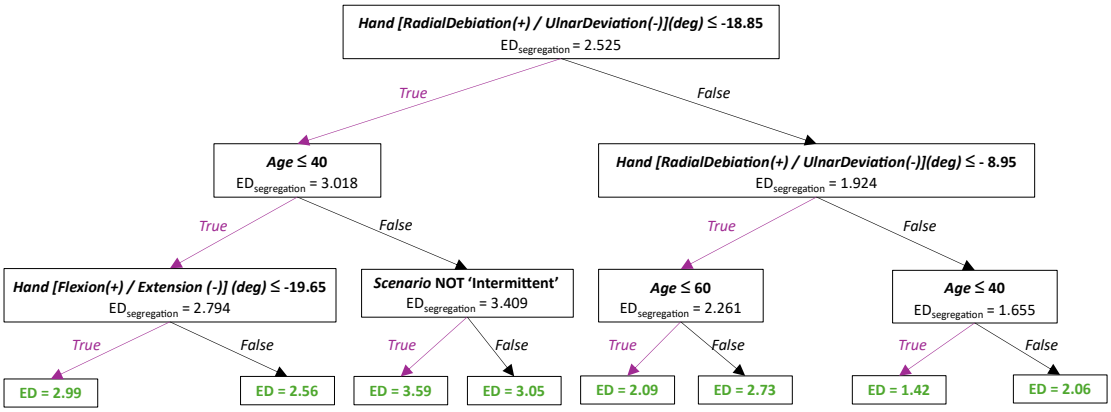


Figure 9.25 – Decision Tree model for ergonomic discomforts in the wrist

The decision tree highlights the significant impact of *'Hand Radial/Ulnar Deviation'* on wrist ergonomic discomfort, with specific threshold angles identified for increasing or decreasing discomfort levels. *'Age'* acts as a secondary split within the branches, while *'Hand Flexion/Extension'* and *'Scenario'* further refine the predictions.

Harmonisation Service

Non-Dominated Sorting Genetic Algorithm (NSGA-II) - MOO

To attain a harmonised motorcycle design solution the *Non-Dominated Sorting Genetic Algorithm* (NSGA-II), a multiple objective optimisation (MOO) technique, is used. This algorithm solves mathematical optimisation problems involving more than one objective function. Specifically, where optimal decisions need to be taken in the presence of trade-offs (in the form of ergonomic motorcycle measurements and aesthetic motorcycle design factors) between two or more objectives that may be in conflict. The harmonising algorithm balances between four main conflicting objectives functions:

Optimising 4 objectives

f1. Minimising the *total Ergonomic Discomforts* of *Target Riders*

f2. Minimising the *total Ergonomic Discomforts* of *General Riders*

f3. Maximising the *total Positive Elicited Aesthetic-derived Emotions* of *Target Riders*

f4. Maximising the *total Positive Elicited Aesthetic-derived Emotions* of *General Riders*

Minimising deviation between IMEP REP

As discussed in Section 9.1, *objective functions (3)* and *(4)*, are represented as follows: Minimising the *divergence of the Induced Motorcycle Emotion Profile (IMEP)* from the *Target Rider/General Rider Emotion Profile (TREP)/(GREP)*.

Objective space

The above objective functions are constructed from a feasible set of decision vectors, defined by some constraint functions. One example of the feasible set is the ergonomic discomfort of each limb for a particular rider and for a given motorcycle adjustment. Note that the ergonomic discomforts would have already been predicted through the MLS for a given rider's attributes and anthropometries subject to a certain motorcycle adjustment. Therefore, the harmonisation service is used to harmonise the aforementioned *objective functions (1-4)*, which as indicated through Equation 9.12 one of the functions, f_1, denotes the total ergonomic discomfort of the rider, that is, the summation of each limb's ergonomic discomfort (represented by the neck, back, feet, etc.) Each limb's ergonomic discomfort, for example ED in Neck, is predicted from a particular machine learning model, as was seen in section 9.3.1– Machine Learning Service. For the most comfortable position f_1 needs to be at the minimum value possible. The first objective function given above can be represented as follows:

(Eq. 9.12)

Minimise f_1 where:

$$f_1 = (W_1 * \text{ED in Neck}_{\text{TR-ATT_AM_MA}}) + (W_2 * \text{ED in Back}_{\text{TR-ATT_AM_MA}}) + \ldots + (W_n * \text{ED in Feet}_{\text{TR-ATT_AM_MA}})$$

- W, represent priority weights. The priority is based on a particular designer's or a company's philosophy and will be discussed further in Chapter 10.

- $_{TR\text{-}ATT_AM_MA}$, represents target rider's attributes and anthropometries subject to a particular motorcycle adjustment. This means that objective function f_1 can have multiple variations of that same objective function, as motorcycle adjustments are varied for the same target user characteristics (ATT and AM).

Concept of non-dominance

For a nontrivial MOO problem, no single solution exists that simultaneously optimises each objective. In that case, the objective functions are said to be conflicting (Kusiak et al., 2011). A solution is called *nondominated* or *Pareto optimal*, if none of the objective functions can be improved in value without degrading some of the other objective values (Kusiak et al., 2011).

Representation of dominance

Dominance is represented as follows: a given solution, S_A, *dominates* S_B or (S_B is *dominated* by), if:

- Solution S_A is no worse than S_B in all objectives.
- Solution S_A is strictly better than S_B in at least one objective.

This definition can be illustrated in Figure 9.26. It is evident that if one compares:

- Solution S_A with solution S_B → S_B *dominates* S_A
- Solution S_A with solution S_C → S_C *dominates* S_A
- Solution S_B with solution S_C → *neither solution dominates*, as S_B is better in the f_2 space while S_C is better in the f_1 space

Pareto-optimal front

The boundary defined by the set of all points mapped is called the *Pareto-optimal front*. Solutions lying on Pareto optimal front are all considered equally good as none is dominated (case in point S_B and S_C in Figure 9.26). The solutions which lie on the optimal Pareto front are passed to the motorcycle designer as the harmonised solutions, where the designer has to decide which solution is the best out of the harmonised potential solutions.

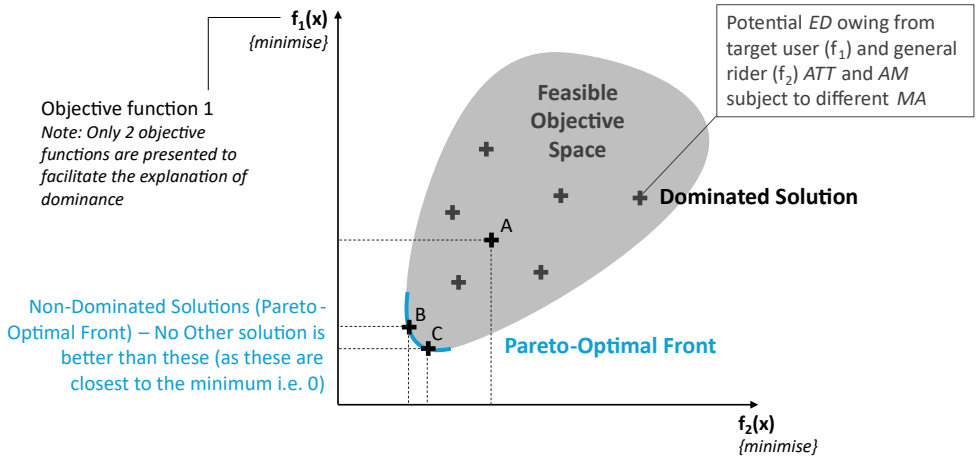


Figure 9.26 – The concept of non-dominance in the objective space

9.3.2 Knowledge Base

ML model stored in knowledge base

As it was seen in Sections 9.3, the training of ML, and generation of harmonisation models are specified as mathematical relationships. As such, the created models are *'a formal representation of knowledge'* (Adèr, 2008). The ML trained models generated from the MLS are then stored in the Knowledge Base (KB), which can later be accessed by the Inference Engine (Ratner & Ré, 2018).

9.3.3 Knowledge Inference

Functions of the Inference Engine

Once the data has been represented by a model, the knowledge-based system (KBS) can use this current working knowledge to make decisions. The model can draw inferences based on the patterns it has learned from the training data and then make predictions or decisions about new data, thus generating new knowledge. The Inference Engine (IE) component has multiple tasks. The ML-based and harmonisation models are made available and can be accessed by the IE, to predict patterns and give advice in case a user (designer) makes a query. As previously discussed, several models are created through the MLS. As such the first task of the IE is to handle which trained ML model will be executed from the KB. Secondly, the IE gets queries from designers. The IE uses these inputs to predict a new solution by fitting the inputs to the selected model. To arrive at a recommendation solution, this

component may also use a series of trained ML models, where a model's result is used as input to another different model. Also, the IE contains other instructions to reason with the computed predictions. After this computation the IE will put forward the solution in the form of advice to the designer (or research primary user – RPU) through the user interface. The inference engine will provide both support and recommendations to the designer.

9.4 Chapter Conclusions

Harmonistic Knowledge modelling concepts

The objective of this chapter was to explain the concepts of knowledge modelling, encompassing the identification of the knowledge to be modelled, the selection of tools employed in the modelling process, and the methodologies adopted for modelling. Consequently, the principles of harmonistic knowledge modelling are articulated across this chapter, facilitated by an exploration of the *knowledge cycle* within *Machine Learning Knowledge-Based Systems* (ML-KBS). Fundamental features of the knowledge model incorporate the knowledge discovery from data approach, coupled with machine learning techniques to convert tacit knowledge into explicit knowledge, and the NSGA-II algorithm to achieve a harmonised solution.

Part domain specific relationships

This harmonistic knowledge modelling concept was then applied to the motorcycle part domain, and established examples of the domain specific relationships were presented in Section 9.3.1.

Computer-based model

Chapters 8 and 9 were respectively concerned with disclosing how and what to model as harmonistic knowledge. As has been argued, due to human mental processing limitations and as per the framework requirement 2 – FR2 (see Section 8.1), the *DESMO* archetype framework necessitates implementation into a computer-based design tool in order to provide the required support. The next chapter therefore presents how harmonistic knowledge is codified into a proof-of-concept computational form.

10 *DESMO* Framework Prototype Tool Implementation

This chapter discloses how HARMONIOUS through the DESMO archetype framework is implemented as a prototype computer-based support tool. The requirements for this tool are detailed in Section 10.1, followed by a discussion on the challenges encountered during the prototype's development in Section 10.2. The software's implementation, mode of operation and DESMO-APP's activity diagram are presented in Section 10.3. An extensive explanation of how DESMO-APP's modules are applied and exemplified through a hypothetical case are provided in Section 10.4. Part C conclusions are then presented in Section 10.5.

Computational means

The constraints faced by DOP designers in terms of storing and processing harmonistic knowledge, as elaborated in Chapters 8 and 9, would hinder the effective utilisation of the *HARMONIOUS* design approach framework. Furthermore, as previously elucidated, addressing the intricacies of the DOP design process through manual methodologies, would result in a support tool that is not only time-intensive and complicated, but also challenging to implement and utilise. Hence, to address framework requirement 2 (FR2), the adoption of a computer-based design tool for the implementation of this approach, is particularly suited.

Automating DOP design

As delineated in Section 4.6.1 and by MacCallum (1990), design support systems can be categorised into two distinct types, each embodying a different strategy for offering support. The first approach attempts to mimic human cognitive processes within artificial intelligence (AI) frameworks to automate design tasks. Goodwin (2011) and Merati et al. (2021) argue that there are numerous drawbacks for fully automated design systems.

Computational support

The second approach, as defined by MacCulum (1990) and (National Research Council, 2001), a support design approach offers active guidance, can learn from past design experiences, can carry out semi-automated tasks, whilst explaining its reasoning and acting as a

colleague to the designer. MacCulum (1990) and Nourian et al. (2023) articulate that the underlying philosophy of a computer-based design support tool is to augment the designer's abilities, while simultaneously ensuring that the designer retains ultimate authority over decision-making, control, and responsibility. Moreover, as highlighted in Section 4.6.1, designers specifically required computational support (FR2). The interviewed designers indicated that the employment of computer-based support tool would enable human designers to control the design process, while technical means offer support to decision makers by making them aware of consequences associated with design commitments.

DESMO-APP

Based on the above argumentation, a solution is to therefore realise *the* approach framework in computational form as a support design tool. Therefore, *DESMO* an archetype of the approach framework, has been developed and implemented into a computer-based prototype tool – ***APP****lication* for ***D****esigning harmonis****E****d motorcycle****S*** *for hu****M****an fact****O****rs (DESMO-APP).*

Objectives of DESMO-APP

The objective behind the development of this tool was to exemplify the application of the foundational principles of the approach framework through a concrete solution. The prototype computer-based design tool is intended to function as an intelligent design assistant, offering proactive support during the motorcycle design process. A secondary objective of *DESMO-APP* within this research is to have a means for the validation of *HARMONIOUS* through the *DESMO* framework, as documented in Chapter 11.

10.1 Tool Requirements

Blessing & Chakrabarti (2009) discuss how the actual functionality of the prototype tool compares with the intended functionality of the total intended support, as illustrated in Figure 10.1. They argue that the prototype should capture the research's core contribution and should

include the necessary features to allow the approach framework to be evaluated in a descriptive study of the envisaged reality.

In light of this, this section discloses, with explanations, the fundamental requirements of a computer-based proactive tool for supporting design of motorcycles, a case of DOP. These requirements are derived from the description of the frames constituting the *DESMO* archetype framework, as presented in Chapter 8, in conjunction with the concepts of harmonistic knowledge modelling and structuring described in Chapter 9.

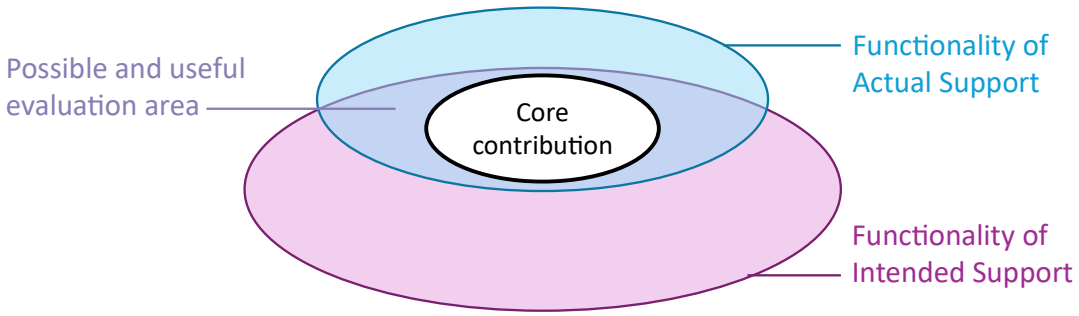


Figure 10.1 – The functionality of a prototype, adopted from Blessing & Chakrabarti (2009)

10.1.1 Data Capture Functionality

Computer-based tool requirement 1 (CTR1): Capture of user data

It is a requisite for the computer-based tool to incorporate pre-populated tables within the *DESMO-APP*'s database. Factors contributing to this include the user-centred design (UCD) approach (FR4), the User Data Capture Frame (UDCF) delineated in Section 8.2.2, the knowledge discovery from data (KDD) approach outlined in Section 9.1.3, and the extraction of the general rider's (GR's) characteristics. These tables serve as repositories of domain-specific information concerning (potential) customers.

Furthermore, given that the assistance provided is derived from the human factor-related data, through the KDD approach. This data needs to be precise to enable the *DESMO-APP* to offer accurate support. Therefore, designers should be guided on how to collect and populate this database. This guidance is crucial for the effective construction and expansion of their customer base.

CTR2: Library of reusable synthesis PDEs

Due to the Designer Intent Frame's (DIF's) reuse principle (Section 8.2.2), the computer-based tool should provide designers with a domain library of reusable synthesis product design elements (PDEs). According to the requirements stipulated by the design approach framework, this library should encompass stream-specific reusable elements, including:

- The most current marketing trends, as mandated by FR4d, to facilitate the support that resonate with current trends.
- Motorcycle reusable PDEs that impact the three human factors ($hf_{E\text{-}AE\text{-}P}$), according to FR3.
- The PDEs provided need to be in line with the five design factors (DFs), identified in Section 9.2.1, encompassing both stylistic and positional categories.
- These PDEs should be accompanied by their induced emotion profile, as established in Section 9.2.1, referred to as the PDEV Emotion Profile (PDEVEP).

CTR3: Update mechanism

Providing designers with the methodology for gathering additional information, without facilitating the capability to update the Knowledge Bases (KBs) (following any *record*'s addition, modification, or deletion), would render the support inaccurate. Therefore, it is imperative that the computer-based tool possesses the functionality to refresh its KBs, subsequent to any update made to the records.

CTR4: Provide access to modify

The facility for motorcycle designers to access, modify, or update the motorcycle PDE reusable library (in the context of CTR2) as well as information concerning (potential) customers (related to CTR1 and CTR3), is essential for the diversification and scalability of the computer-based tool. This necessity arises from several factors:

- Customisation of products to cater to specific user groups or market segments.
- Evolution of current trends.

- Additional motorcycle categories that incorporate different PDEs.
- Need for supplementary PDEVs to refine the support.

To accommodate these requirements, a specialised *user interface* (UI), designated as the *editor*, is needed. This interface enables designers to efficiently update both PDE and customer-related data, thereby ensuring the tool remains adaptive and relevant to ongoing changes and developments within the domain. Furthermore, this will allow the tool to provide company specific harmonistic knowledge to designers (company specific knowledge re-use).

10.1.2 Modelling Functionality

CTR5: Modelling of TR and GR

As explained in Section 7.4.1, the phenomenon of population majority privation necessities designs that cater to the broad spectrum of the GR requirements. Concurrently, as highlighted in Section 4.4.3, the targeted rider (TR) demographic, which represents a specific segment of the market, also demands consideration during the design process. The approach framework discussed in Chapter 8 acknowledges the significance of both general and targeted rider groups, positioning them as foundational pillars within the design paradigm. Consequently, it is imperative that the computer-based tool incorporates modelling capabilities to adequately address the needs and preferences of both these pivotal audiences, ensuring the successful development of motorcycles that appeal to a diverse clientele.

CTR6: Modelling of $hf_{E\text{-}AE\text{-}P}$

From the outset, as delineated in Chapter 2, this doctoral dissertation has centred on three pivotal human factors: ergonomics, aesthetic-derived emotions, and persona ($hf_{E\text{-}AE\text{-}P}$). Additionally, both the approach and archetype frameworks have been developed with $hf_{E\text{-}AE\text{-}P}$ as their foundation. Consequently, it is imperative that the tool enables designers to accurately model user characteristics based on the aforementioned human factors. Furthermore, the selected PDEs,

contained within the reusable library, need to have impact on riders' $hf_{E\text{-}AE\text{-}P}$.

CTR7: Provide hf-Multi X assistance

The computer-based tool should facilitate the concurrent consideration of multi human factors (hf-Multi X). Achieving this involves advancing certain critical PDEs and parametrisation, which are typically addressed in later stages, to the earlier design synthesis activity. The tool needs to facilitate this in its environment, where designers can concurrently design for hf-Multi X, TR and GR.

CTR8: Modification of user model and commitments through project

The tool should enable the modification of TR and GR, as well as the committed motorcycle PDEs models throughout the project's life-cycle. Providing users with the capability to adjust parameters affords them significant control over their software environment. Additionally, this feature enables research primary users (RPU) to rectify mistakes or fine-tune the software's functionality without the necessity of initiating a new project, offering a considerable advantage from a user experience perspective.

10.1.3 Harmonistic Knowledge Functionality

CTR9 and CTR10: Provide pro-active PUC and DCC support

Inferring motorcycle solution interactions from hf-Multi X' perspective presents considerable challenges. This is attributed to limitations in human cognitive processing as well as requirements set forth by designers (in Chapter 4). Therefore, the computer-based design tool needs to take an active role in supporting the design of motorcycles from human factors perspective. The tool should therefore provide explanation of the revealed PUCs and DCCs, and guide designers to those commitments which avoid or relax the problems of population majority privation and design-stage conflict.

CTR11: Assists and directs towards a harmonised design solution

As explained throughout this doctoral dissertation, the harmonisation constitutes the core of the approach framework. Therefore, the computer-based tool should assist designers and provide awareness of harmonised motorcycle design solutions which balances population

majority privation and conflicts between $hf_{E\text{-}AE\text{-}P}$. Yet, the role of the tool extends beyond this. The framework explicitly guides designers towards the attainment of a harmonised design solution. Given the critical nature of this process, the tool must also provide clear guidance to designers on navigating towards a harmonised solution, underscoring its significance in the design process.

CTR12: Support and recommendation

In addition to tool requirements CTR9, CTR10 and CTR11, support and recommendations should be provided for the harmonised singular solution model in terms of PUCs and DCCs.

CTR13: Timely awareness

The tool should provide timely awareness of unintended population use-phase and design-stage conflict consequences (PUCs and DCCs) influencing (potential) customers' human factors, as well as harmonistic support and recommendations.

CTR14: Decision commitments remain under the designer's discretion

The computer-based tool should provide non-intrusive support. As seen in Section 4.6.1 interviewed designers required autonomy and control over their design process rather than being forced to interact with the tool at inconvenient times or constraints imposed by the computer-based tool. As such, by exploiting the captured harmonistic knowledge, the tool should operate in the background, independently from the designer's cognitive abilities, to model a harmonised solution and were necessary infer harmonistic knowledge. Furthermore, design elements prioritisation and final decision commitments remain under the discretion of the designer.

CTR15: Design history

The tool is required to autonomously preserve a record of the design history input by the designer throughout a session, ensuring that no information is lost upon the designer revisiting a prior stage or module of the tool. It is equally crucial to retain records of support, recommendations, and synthesis decision commitments, whether they are enacted or withdrawn. This is relevant for a number of reasons, including allowing designers to review the solution alternatives

explored and utilised as a suitable means for communicating design intent, as explained by Henderson et al. (2022).

CTR16: Generated knowledge reuse

In Section 9.1.1, it was explained that knowledge can be categorised into three types: application, generation, and transfer. Throughout the design process, new knowledge is generated through the awareness of PUCs, DCCs and harmonisation process. This newly generated knowledge is subsequently integrated into the KB to facilitate the exploration of alternative solutions. Consequently, the computer-based design tool should reuse the generated knowledge of past cases/projects to new projects.

10.1.4 Interpretation Functionality

CTR17: Provide knowledge explainability and access to knowledge management

As discussed in Section 9.3.1, knowledge explainability entails rendering the processes of machine learning (ML) more transparent and interpretable, by ensuring the outputs of these models are comprehensible to humans. Incorporating knowledge explanation capabilities within the computer-based tool is pivotal for augmenting designers' confidence in the predictions furnished by the ML algorithms.

Furthermore, the computer-based tool should provide knowledge management and maintenance facilities. This functionality would allow users with the required access to update and/or tailor captured harmonistic knowledge.

CTR18: Implementation of the model illustrator

As delineated in Section 8.2.2, the Knowledge Interpretation Frame (KIF) aims to translate the finalised harmonised DOP model into a tangible 2D visual representation or integrate it with a CAD software for rendering in a 3D geometry format. Having a computer-based tool with this capability will enhance the designer's understanding of intricate designs. These representations can convey the nuances of a motorcycle's design in a way that words or numbers alone cannot (Leake & Goldstein, 2022). These visual representations also serve as

the foundations for ensuing activities and stages in the design process. For example, the 2D representation provides a starting point for designers to commence the motorcycle sketching activity. Additionally, according to Chisnell & Rubin (2008), visual representations are acknowledged for their efficacy in engaging evaluators during the evaluation process of the tool.

10.1.5 Other Functionality

CTR19: A user interface for the computer-based tool

As outlined in Chapter 8 within the *DESMO* framework, upon receipt of the design brief, the designer engages with the graphical user interface (GUI) of the computer-based tool. This GUI, a form of user interface featuring graphical icons, also referred to as the tool's *front-end*, is essential for enabling users to utilise the tool's functionalities. The GUI is designed to facilitate the following actions by design engineers:

- View and edit (potential) customer human factors-related information as well as the reusable PDEs library.
- View and edit design element priority weights.
- View, define/manipulate (harmonised) motorcycle solution models at the required level of synthesis decision commitment.
- Specify and view the results of queries made to the reusable synthesis.
- View relevant harmonistic knowledge and information, providing explanations about PUC and DCCs detected.
- View the design session history.

10.2 Tool Implementation Boundary

Implementation limitations

The identified requirements were used to realise *DEMO-APP*. Within the scope and time limitations of this doctoral research, a number of requirements had to be prioritised in order to implement the essential aspects that would well represent the capabilities of the *HARMONIOUS* design approach framework, and requirements that were deemed necessary to support the evaluation of *HARMONIOUS* through *DESMO*

were implemented within *DESMO-APP*. The requirements for this prototype tool are outlined in Table 10.1.

Table 10.1 – DESMO-APP system requirements and level of implementation

	CTR	***DESMO-APP* Requirements**	**Level of Implementation**
Data Capture	1	Provide designers with prefilled (potential) customers' database and guide them on how to collect and populate these databases	✓✓✓
	2	Provide a library with the latest market trends PDEs used in the motorcycle industry	✓
	3	Incorporate an update mechanism, wherein the knowledge base is refreshed after the addition, modification, or deletion of any record	✓✓✓
	4	Provide the user interface and ability for designers to access, edit, or change motorcycle PDE library and (potential) customers' data	✓✓
Modelling	5	Empower designers to model both General and Target Riders.	✓✓
	6	Support modelling of the three human factors	✓✓
	7	Provide design for multi human factors (*hf-Multi X*) assistance	✓✓✓
	8	Enables the modification of GR, TR, and the committed motorcycle PDEs throughout the project	✓✓
Harmonistic Knowledge	9	Guidance in the form of support and recommendations to avoid or minimise the effects of DCCs	✓✓✓
	10	Guidance in the form of support and recommendations to avoid or minimise the effects of PUCs	✓✓✓
	11	Assists and directs the designer towards achieving a harmonised motorcycle design solution	✓✓✓
	12	Support and recommendations for the harmonised motorcycle design solution	✓✓
	13	Timely awareness of harmonistic support and recommendations	✓✓
	14	A supportive approach, where design prioritisation and final decision commitments remain under the discretion of the designer	✓✓✓
	15	Automatically maintains decision commitment library, ability to load past projects and save work in progress decisions	✓✓✓
	16	Reuse the generated knowledge of past cases/projects to new projects	✓
Interpretation	17	Provide knowledge explainability and access to the knowledge library/management	**X**
	18	Implementation of the Visual Model Illustration Engine (VMIE) or Computer Aided Design Interface Engine (CAD-IA)	**X**
Other	19	Provides a suitable user interface of the computer-based tool to motorcycle designers	✓✓✓

✓✓✓ = Fully implemented ✓✓ = Partially implemented ✓ = Limited implementation **X** = Not implemented

The requirements that were deemed essential to demonstrate the underlying principles and evaluation of the *HARMONIOUS* design approach framework are fully supported by *DESMO-APP*.

Requirements which were considered to be less essential, and which could be safely omitted have also been identified.

Limited implementation tool requirements

While the *DESMO-APP* incorporates a library of 400 motorcycle PDEVs to fulfil tool requirement CTR2, its implementation encounters certain constraints. A primary limitation stems from the fact that, despite the existence of numerous PDEVs, only a small fraction is included in *DESMO-APP*. This is largely constrained by time, as all PDEVs required extraction and editing, as illustrated in Figure 9.21 of Section 9.2.1.

In relation to CTR16, the reuse of knowledge generated from previous cases or projects encountered a limited implementation. Specifically, the transfer of generated knowledge to the KB is not automated. However, since the designer has the capability to manually store all the commitments made, as well as support and recommendations provided by the tool, this knowledge can be accessed by reviewing the support and recommendation files from past projects. This approach was adopted with the understanding that the evaluation period was time constrained, rendering it impractical to assess the tool's efficacy through secondary case scenarios.

Tool requirements which are not implemented

As discussed in Section 9.3.1, knowledge explainability (CTR17) is not the same PUC and DCC support offered through the Support Engine (SE). Instead, it explains the intrinsic formulation of rules processes by the ML algorithm, primarily from a ML-model transparency rather than directly supporting designers for their synthesis design decisions. Given this reason and time constraints, the decision was made to exclude this functionality from the *DESMO-APP*.

While exploratory literature research was conducted on how to fulfil CTR18, it was recognised that the implementation of at least one of the two proposed methods of visual representation would require substantial effort. The incorporation of this feature warrants comprehensive research in its own right. Considering that this aspect is not central to the core contribution of this doctoral investigation, it was

decided not to implement the Visual Model Illustration Engine (VMIE). This decision is also congruent with the feedback voiced by participant D6 during the preliminary validation study in Section 8.4.3.

10.3 Software Implementation

Stand-alone application

As it has been discussed in Section 10.1, designers have to interact with the prototype tool in order to support customer data capture, user modelling, and motorcycle synthesis. Consequently, in order to meet the specifications of *DESMO-APP*, the development of a *stand-alone* application was deemed necessary. Considering the deployment of ML algorithms, which demand significant computational resources, stand-alone applications are capable of providing more rapid response times and enhanced performance in contrast to web-based applications, which are dependent on internet connectivity and server response times.

System architecture

To meet this requirement the *DESMO-APP* utilises the Machine Learning Knowledge-based System (ML-KBS) architecture, already illustrated in Figure 9.6 as presented in Section 9.1.3.

DESMO-APP mode of operation

As depicted in Figure 10.2, users interact with the system via the GUI. Knowledge about the decision commitment is communicated to the *back-end* for processing. The project management function, referred to as '*data admin*', manages and directs these decision commitments and inputs into the inference engine. *DESMO-APP* oversees the Inference Engine, which utilises the human factors knowledge, discovered from data and translated through the ML algorithms. This process facilitates the prediction and inference of several evolving models focused on ergonomics, aesthetic-derived emotions, and persona. Subsequently, harmonisation knowledge is applied to harmonise these multiple evolving solutions into a unified harmonised DOP solution. This harmonistic knowledge (encompassing both harmonisation and human

factors knowledge) is then conveyed back to the GUI where the design support and recommendations are provided to users in real-time.

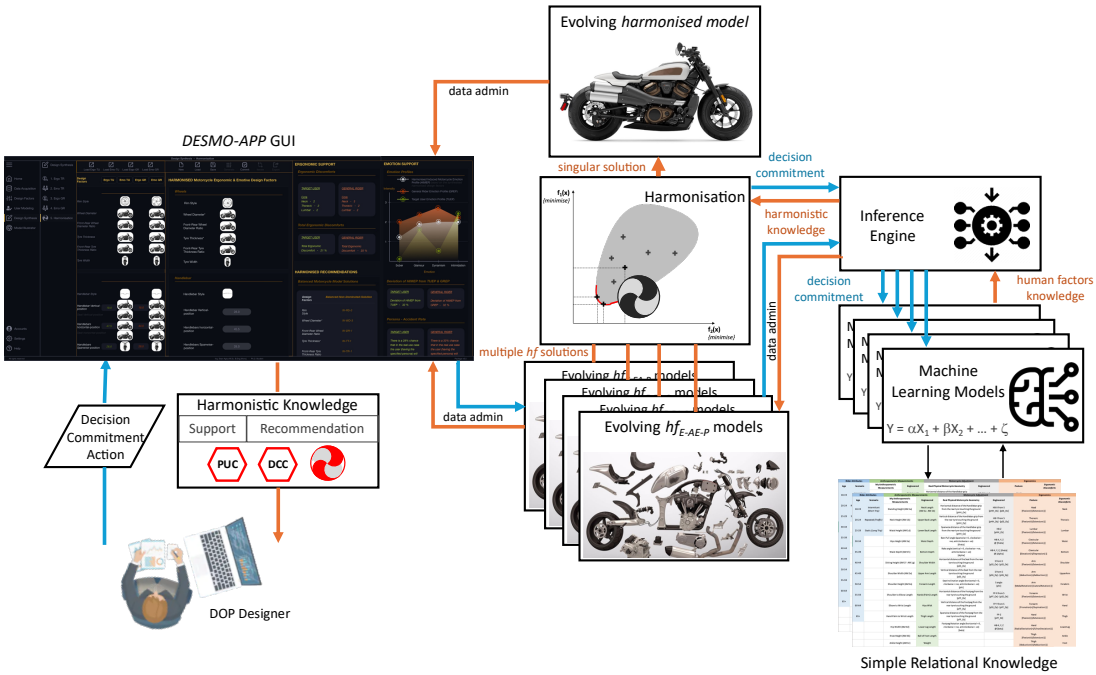


Figure 10.2 – DESMO-APP mode of operation

10.3.1 Development Hardware and Software

Hardware

Stand-alone applications are capable of operating across a variety of computing devices, including laptops, which offer portability, or can be distributed in an *executable* format. This flexibility renders them particularly suitable for the evaluation phase of a project.

Presentation layer

The *presentation layer* contains the user-oriented functionality responsible for managing user interaction with the system and consists of components that provide a common bridge into the core business logic. The user interface was implemented using *Qt Designer*, a cross-platform software development kit that uses *Qt Modelling Language* (QML), a declarative UI markup language for designing UIs. A *Python* library - *PyQt5* (Fitzpatrick, 2020) was used to facilitate the communication between the front-end and back-end of *DESMO-APP*.

Business layer

For the *business* and *data layers* (back-end) the *Python*[12] objective-oriented programming language was used. Public domain *Python*

[12] https://www.python.org

libraries, *Scikit-learn*[13] and *Pymoo*[14], were used to implement the ML and harmonisation algorithms. *Python* has become the dominant language for ML and data science (Géron, 2019). Its advantages over other programming languages stem from a combination of ease of use, extensive library support, community engagement, and versatility (Géron, 2019).

Data layer

Given the KDD approach and therefore the necessity for designers to access, amend, or append data, it was crucial for the database and data management system of *DESMO-APP* to be user-friendly. To this end, the system was designed with a foundation of structured CSV tables, managed through *Pandas*[15], an open-source *Database Management System* (DBMS) library, ensuring ease of use, flexibility, and scalability.

Use of Python programming language

The decision to develop the tool utilising Python, as opposed to adopting *CLIPS, PCPACK*, or *PROTÉGÉ* as recommended by Milton (2008), was primarily influenced by *Python*'s functionalities. These include extensive ecosystem of libraries and frameworks, strong community support, versatility, and compatibility with other technologies, which render this programming language an exemplary platform for executing machine learning tasks (Géron, 2019). Additionally, *Python* facilitates the use of contemporary *graphical control elements* (GCE), enhancing the presentation of essential data and visual elements to users.

10.3.2 User Interface Layer Composition

Different users of the prototype tool utilise different interfaces in order to interact with the system. The users interact with the system through a GUI illustrated in Figure 10.3. A retractable pane on the left-hand side of the GUI, referred to as the *Main Menu (Area A)* displays the core

[13] https://scikit-learn.org/stable/
[14] https://pymoo.org
[15] https://pandas.pydata.org

modules and is the main navigation of *DESMO-APP*. This allows the user to select which interface they want to access. This consist of:

- *Module 1 – Data Acquisition* handled by the R&D (research and design) team
- *Module 2 – Design Factors and PDEs* handled by the product planner or designer
- *Module 3 – User Modelling* handled by the product planner or strategist
- *Module 4 – Design Synthesis* handled by the product designer

Modules 1 and 2 concern with populating *DESMO-APP*'s database and where DFs and PDEs, refer to Section 9.2.1 and 9.3.1, are prioritised from others. Module 3 is for product planning and where the TR (for which the new motorcycle is intended) and the GR are identified and modelled. Module 4 concerns the actual design synthesis of the evolving DOP (motorcycle) model. It is the area where the designer makes the design decisions and where *DESMO-APP* provides the support and recommendations.

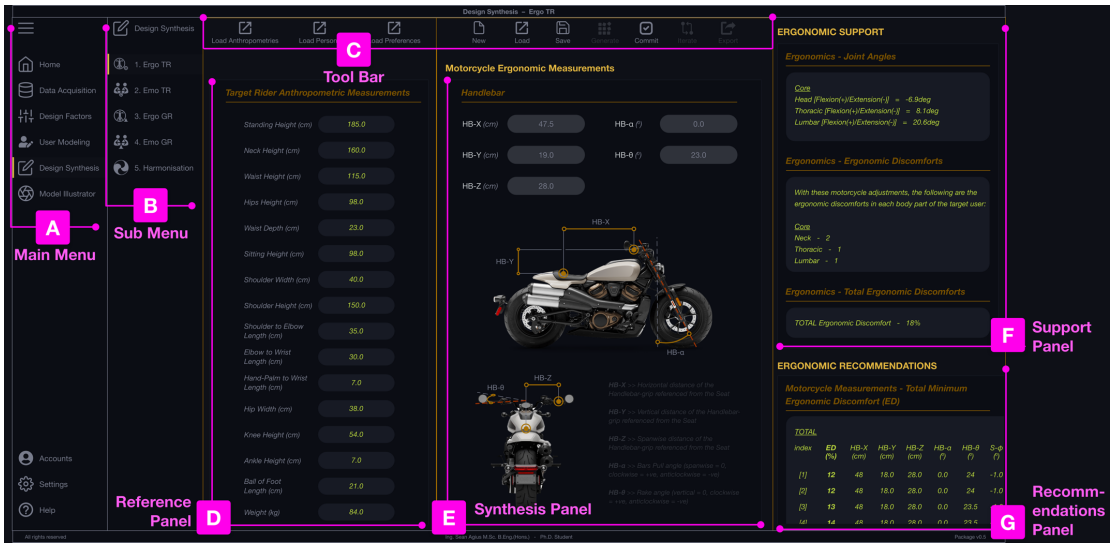


Figure 10.3 – Graphical user interface composition of DESMO-APP

The main modules are further split up into sub-modules. In the case of the design synthesis module, the *Sub Menu (Area B)* highlights the synthesis stages (sub-modules) required for the designer to arrive to a harmonised solution. The *Tool Bar (Area C)* is a graphical control

element which allows users for quick access to functions depending on the operation which they want to carry out. Such elements consist of *loading, saving, generating* and *committing* to design decisions. The *Reference Panel (Area D)* is an area where the software is pre-populated with relevant information. For example, if the designer is setting the ergonomic geometry of a motorcycle for a particular rider, the reference panel will be populated by the anthropometric properties of that user. In the *Synthesis Panel (Area E)* the designer takes the motorcycle design decisions. For example, setting a handlebar vertical height or choosing a fuel tank from a list of elements and add it to the evolving motorcycle model. Once the designer commits to those decisions, the *Support Panel (Area F)* presents the support in the form of use-phase consequences, while the recommendations for design improvement are presented in the *Recommendations Panel (Area G)* by the computational tool.

10.3.3 Designing a Motorcycle Case Study

Demonstrating DESMO-APP

To describe and exemplify the proof-of-concept, this section introduces a hypothetical use case. The use case enables to illustrate the functionalities of *DESMO-APP,* as well as to showcase the inherent strengths and limitations of the underlying design approach framework. The use case also serves to demonstrate the comprehensive features of the tool, adhering to the steps of the harmonistic design approach presented in Section 8.3. The case study encompasses the demonstration of the following activities:

- Data Acquisition
- Design Factors / PDEs priority and Elements Editor
- Target Rider and General Rider Modelling and
- Motorcycle Design Synthesis and Harmonisation

Activity diagram

The activity diagram depicted in

Figure 10.4 outlines permissible actions within *DESMO-APP*, delineating the functions that have been integrated.

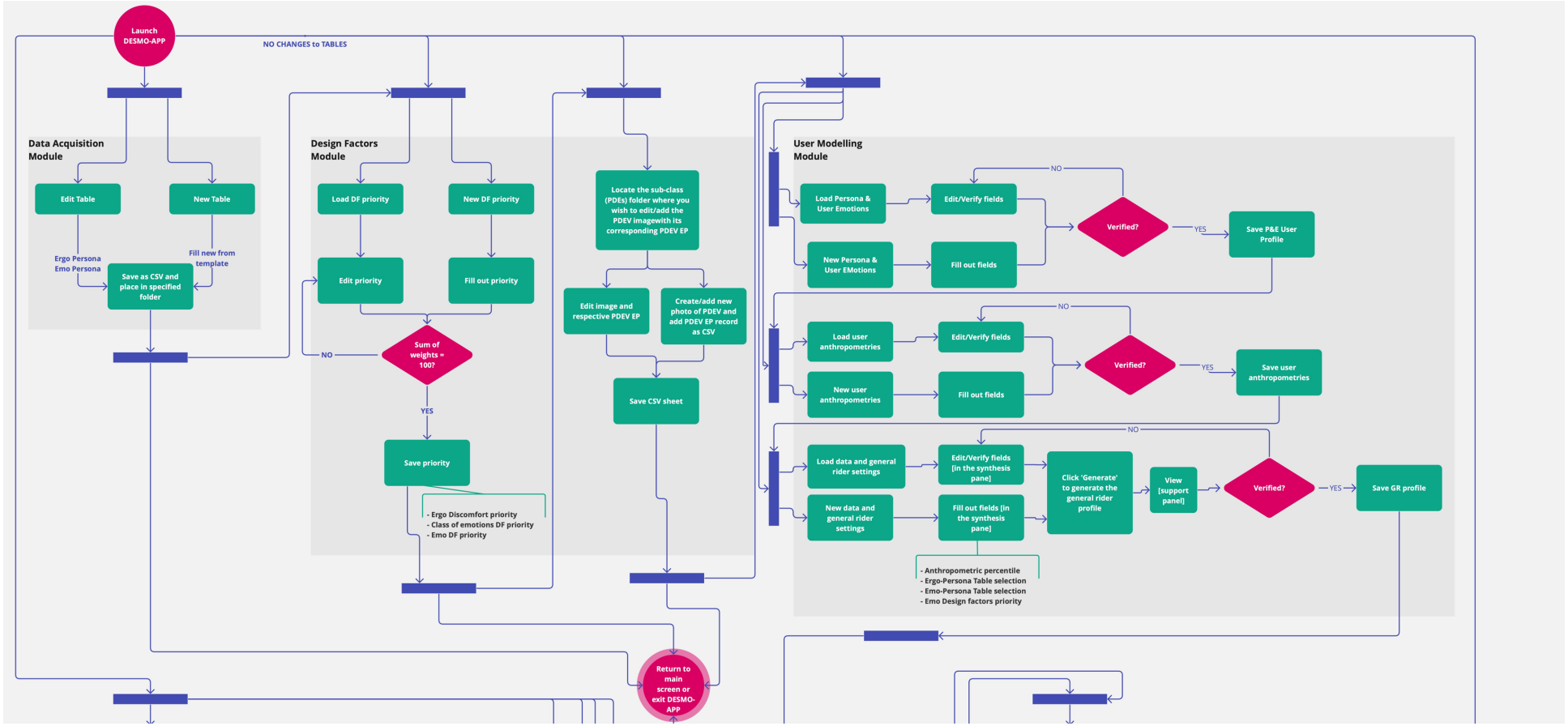


Figure 10.4a – DESMO-APP activity diagram part 1

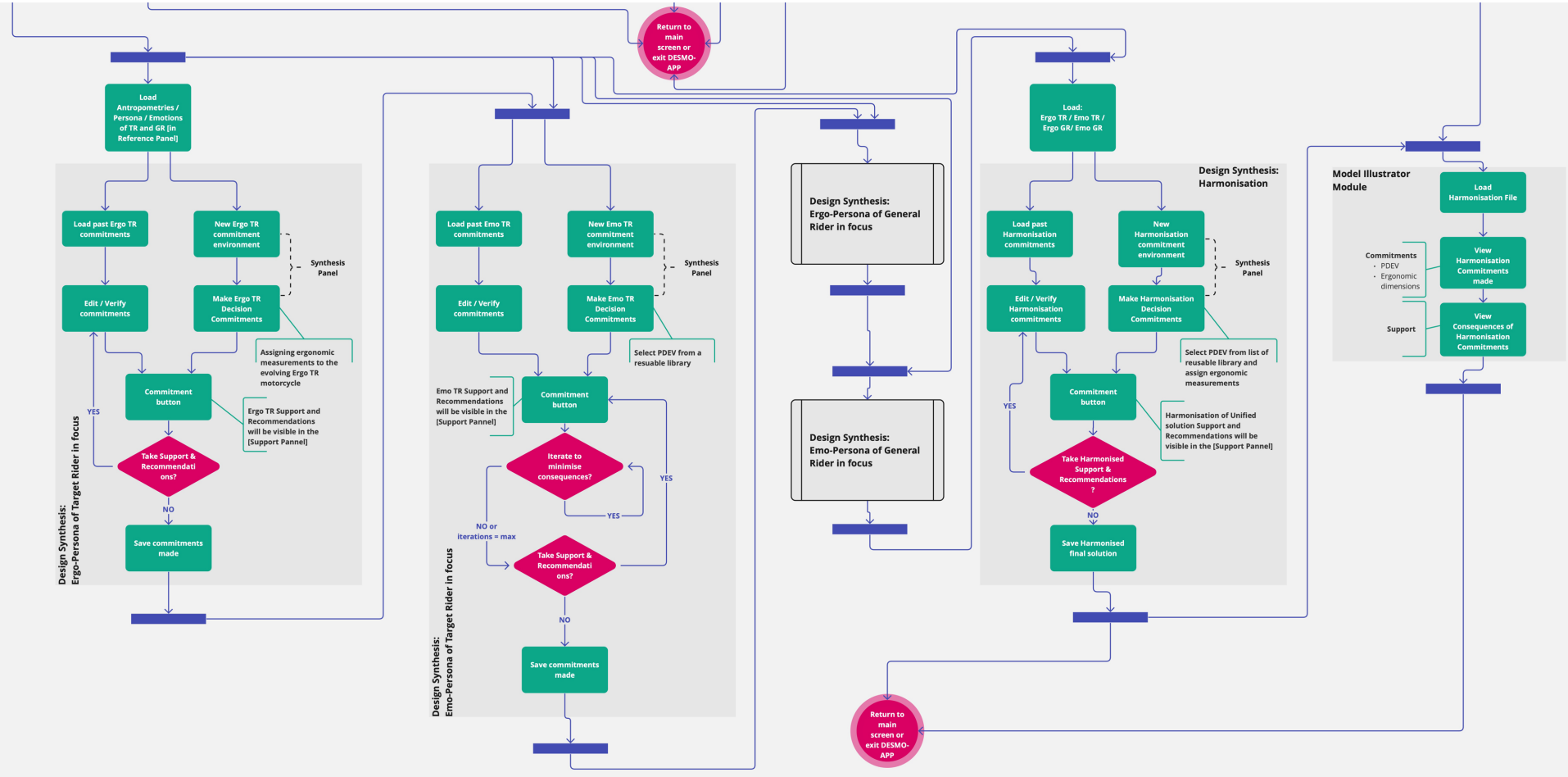


Figure 10.4b – DESMO-APP activity diagram part 2

This diagram places emphasis on the designer, the RPU of *DESMO-APP*, by illustrating the anticipated sequence of design activities facilitated by the computer-based tool. It also provides information on what is required at a particular instance to generate PUC, DCC and harmonisation support and recommendations. Consequently, activity diagrams are instrumental in enabling developers to anticipate the interactions between the user (in this case the designer) and the prototype tool (Rumbaugh et al., 2004).

As shown in

Figure 10.4, upon accessing the main user interface of *DESMO-APP*, the designer is presented with a few possible actions, namely, access to edit or create new:

- Simple relational knowledge, through the Data Acquisition module
- DF and PDE human factor priorities
- Motorcycle library PDEVs, through the Design Factors module
- User anthropometries, Rider Emotion Profiles (REP) and Persona through the User Modelling module
- Synthesis decision commitments for the four human factor scenarios, through the Design Synthesis module
- Harmonised solution, through the Design Synthesis module.

DESMO-APP's modularity

These activities are facilitated by an *open project activity*. The design approach framework endorses a flexible synthesis sequence. As such, *DESMO-APP* is compartmentalised into various modules, allowing designers to engage with or exit from any specific segment as needed, thus, precluding the necessity for a fixed order of operations. The procedural sequence outlined in the hypothetical use case serves only for illustrative purposes and is not prescriptive. For instance, should data already be present within *DESMO-APP*'s database, the designer may bypass initial steps and proceed directly to the design synthesis activities. However, absent rider data prevents further steps, as *DESMO-APP* requires data from each module for operation. The system

accommodates multiple saved files, granting designers the liberty to select the most relevant file for their current project, thereby enhancing flexibility and enabling simultaneous progression on diverse projects. This setup also facilitates the generation of multiple solutions for a single user model.

Decision points

Decision points represent the choices that the designer needs to make when using the tool. For instance, *DESMO-APP* will provide with support and recommendations, and it is up to the designer to take onboard those recommendations or sticks with his/her decision commitments.

Hypothetical use case

The subject of the use case is a company, whose business is the development and prototyping of *cruiser* type motorcycles. The company is responsible for the design of new motorcycles. It then produces three to five prototypes, which are forwarded to another entity for large-scale production.

Use case problem background

This scenario begins when the company is commissioned to design a new type of *cruiser* motorcycle and begins a product development project. The company has been supplied with a target rider (TR) profile for this motorcycle. The agreement stipulates the production of five prototypes, which are then to be sent to another entity (as blueprints) for large-scale production. Furthermore, the contract includes a clause for a percentage of sales revenue, and considering the company's current challenging economic situation, a motorcycle that attracts a wider customer reach would be beneficial in improving the company's financials. Furthermore, this hypothetical use case involves conflicts between motorcycle aesthetics and ergonomics.

Demonstrating the design approach framework

The first part of the case study, presented in Section 10.4.1 and 10.4.2, pertains to *STEP 1* of the *DESMO* framework. It illustrates the process of data acquisition, storage, as well as the prioritisation of DFs and PDEs. Section 10.4.3 proceeds to detail the conversion of project requirements during the task clarification stage into a user model (*STEP*

2 in the framework), using the *DESMO-APP* tool. The latter part of the case study, delineated in Section 10.4.4, showcases the harmonistic knowledge support provided by the computer-based design tool throughout the motorcycle design process, in accordance with *STEPS 3* to *9* of the *DESMO* archetype framework.

10.4 Implementation of *DESMO-APP*'s Modules

Implementation

The development of the proof-of-concept was intended to showcase the foundational principles of the harmonistic design approach framework. The next sections describe how *DESMO*'s frames were implemented in the *DESMO-APP* prototype tool by presenting a walkthrough of the UI layer with use case examples to demonstrate the functionality.

10.4.1 Data Acquisition (Module 1)

In *Module 1*, Data Acquisition, the R&D team populate *DESMO-APP* with the necessary information. The information collected is mainly composed of two:

What information is to be collected

1) Information related to the ergonomics and persona of (potential) customers, illustrated in Appendix F.2, and
2) Information related to the aesthetic-derived emotions and persona of (potential) customers, given in Appendix G.4.

Ergonomics-Persona

Under the *Ergonomic-Persona* sub-menu, the R&D team using *DESMO-APP* are guided on how to create, edit and save these database files. To recapitulate and as seen on Figure 10.5, this Ergo-Persona database is populated with the rider's persona attributes, anthropometric measurements, motorcycle dimensions, rider's joint angles whilst sitting on the motorcycle, and ergonomic discomforts.

The capturing method to populate these database files is in the hands of the R&D team and the procedure illustrated in Section 9.2.1 can be

employed, together with the necessary set-up and procedure to collect real and robust data.



Instructions on How to Create, Edit, and Save Database Files for Ergonomics and Persona

Under Application Folder, **DataBase > External > Data_Acquisition** populate the **ErgoPersona_Table_Template.xlsx** excel table. The first row indicates the name and units of the variables.
- **Curved Brackets (..):** Indicate that the variable is continuous
- **Squared Brackets [..]:** Indicate that the variable is categorical

Once the table is filled, save it as **.CSV** file under the **Data_Acquisition** folder.

The below is an empty version of the ErgoPersona_Table_Template.xlsx excel table:

Class	Variable	Units
Anthropometric Measurements	Age	[18-19, 20-24, ..., 60-64, 65+]
	Scenario	[Intermittent, Repeated, Static]
	Standing Height	(cm)
	Neck Height	(cm)
	Waist Height	(cm)
	Hips Height	(cm)
	Waist Depth	(cm)
	Sitting Height	(cm)
	Shoulder Width	(cm)
	Shoulder Height	(cm)
	Shoulder to Elbow Length	(cm)
	Elbow to Wrist Length	(cm)
	Hand-Palm to Wrist Length	(cm)
	Hip Width	(cm)
	Knee Height	(cm)
	Ankle Height	(cm)
	Ball of Foot Length	(cm)
	Weight	(kg)

Class	Variable	Units
Motorcycle Adjustment	Horizontal distance of the Handlebar-grip referenced from the Seat [HBX]	(cm)
	Vertical distance of the Handlebar-grip referenced from the Seat [HBY]	(cm)
	Spanwise distance of the Handlebar-grip referenced from the Seat [HBZ]	(cm)
	Bars Pull angle (spanwise = 0, clockwise = +ve, anticlockwise = -ve) [HBB]	(deg)
	Rake angle (vertical = 0, clockwise = +ve, anticlockwise = -ve) [HBx]	(deg)
	Horizontal distance of the Seat referenced from the Seat [SX]	(cm)
	Vertical distance of the Seat referenced from the Seat [SY]	(cm)
	Seat Inclination angle (horizontal = 0, clockwise = +ve, anticlockwise = -ve) [Sb]	(deg)
	Horizontal distance of the Footpeg referenced from the Seat [FPX]	(cm)
	Vertical distance of the Footpeg referenced from the Seat [FPY]	(cm)
	Spanwise distance of the	

Class	Variable	Units
Posture	Head (Flexion(+)/Extension(-))	(deg)
	Thoracic (Flexion(+)/Extension(-))	(deg)
	Lumbar (Flexion(+)/Extension(-))	(deg)
	Clavicular (Flexion(+)/Extension(-))	(deg)
	Clavicular (Elevation(+)/Depression(-))	(deg)
	Arm (Flexion(+)/Extension(-))	(deg)
	Arm (Abduction(+)/Adduction(-))	(deg)
	Arm (MedialRotation(+)/LateralRotation(-))	(deg)
	Forearm (Flexion(+)/Extension(-))	(deg)
	Forearm (Pronation(+)/Supination(-))	(deg)
	Hand (Flexion(+)/Extension(-))	(deg)
	Hand (RadialDeviation(+)/UlnarDeviation(-))	(deg)
	Thigh (Flexion(+)/Extension(-))	(deg)
	Thigh (Abduction(+)/Adduction(-))	(deg)
	Thigh (MedialRotation(+)/LateralRotation(-))	(deg)
	Leg (Flexion(+)/Extension(-))	(deg)
	Leg (MedialRotation(+)/LateralRotation(-))	(deg)
	Foot (DorsiflexionPlantarFlexion(	(deg)

Class	Variable	Units
Ergonomic Discomfort [0 - 10] {min. - max.}	Neck	[0 - 10]
	Thoracic	[0 - 10]
	Lumbar	[0 - 10]
	Waist	[0 - 10]
	Bottom	[0 - 10]
	Shoulder	[0 - 10]
	UpperArm	[0 - 10]
	ForeArm	[0 - 10]
	Wrist	[0 - 10]
	Hand	[0 - 10]
	Thigh	[0 - 10]
	LowerLeg	[0 - 10]
	Ankle	[0 - 10]
	Foot	[0 - 10]

Figure 10.5 – Data Acquisition (Ergonomics and Persona)

Emo-Persona

Similarly, the information to populate the *Emo-Persona* database files (seen in Figure 10.6) necessitates the R&D team to collect and input the rider's persona attributes, personality constructs, dangerous driving index, and the likeability of the rider to different motorcycles, as illustrated in Section 9.2.1.



Figure 10.6 – Data Acquisition (Emotions and Persona)

Different tables can be constructed to represent various riders. For example, a particular R&D team may opt to have two pair of tables, where one pair would be based on a European rider population while the second pair will reflect Asian population. Another approach is to have a third pair of tables, where European and Asian population are merged together. This gives a higher degree of flexibility to represent the market inside *DESMO-APP*. Furthermore, the computer-based tool comes packaged with the Ergo-Persona and Emo-Persona database files populated from several studies conducted in Malta.

10.4.2 Design Factors Priority and Element Editor (Module 2)

Setting priority weights

In the first part of *Module 2*, that is, in the Ergonomic Discomfort Priority and Emotions Design Factors and Element Priority the product planner or designer prioritise DFs and PDEs from others by assigning weights. These are given respectively in Figure 10.7 (for ergonomics) and Figure 10.8 (for aesthetic-derived emotions).

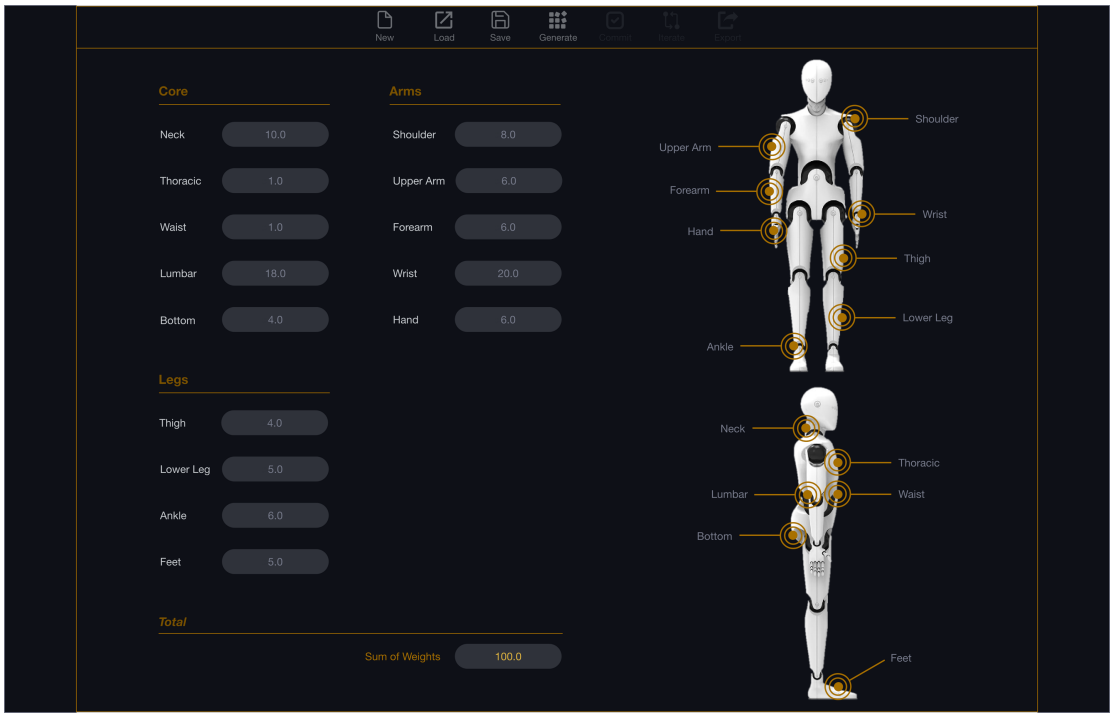


Figure 10.7 – Ergonomic Discomfort Priority

These priority weights are based on a particular designer's or a company's philosophy. For example, from a local study (Farrugia, 2022b) it was found out that pains/numbness in wrists and in the lumbar region followed by the neck, affect most the rider's controls to manoeuvre the motorcycle thus, these can be given higher weights. If the motorcycle planner or designer do not feel that they are inclined towards certain DFs or PDEs, they can equally distribute the weighting among DFs and PDEs. As explained in Section 9.2.1 (through Equation 9.5) and Section 9.3.1 (through Equation 9.12), these priority weights are required to compute the Induced Motorcycle Emotion Profile (IMEP) evoked by the evolving motorcycle and the total ergonomic discomfort, respectively.

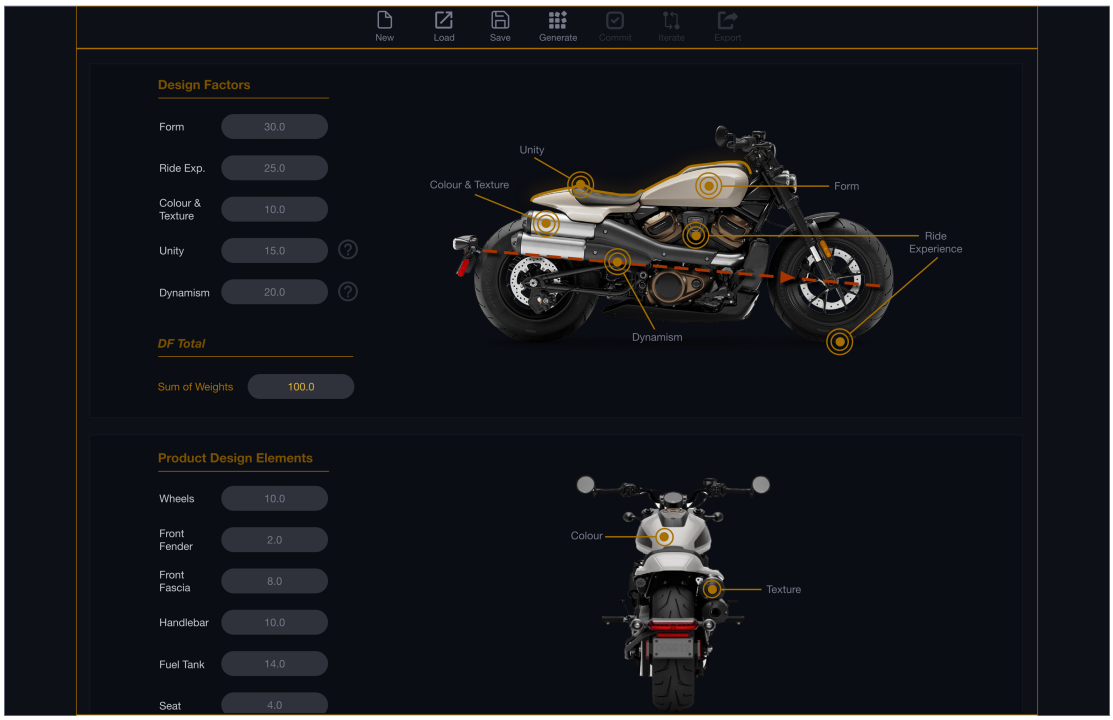


Figure 10.8 – Emotions Related DFs and PDEs priority

Updating the PDE library

The software comes packaged with more than 400 different PDEs (collected from experts as highlighted in Section 9.2.1 – *EmoPersona-Study part 1*). This constitutes in images of the element variant together with the product design element variant's emotion profile (PDEVEP). This is illustrated in Figure 10.9. To change the form of the motorcycle, each PDE can take various style and positional PDEVs. This is based on what the motorcycle designer wants to portray. For example, one variant for the fuel tank design factor might be a tear-drop shaped tank. Other options might be, ovel or squarish fuel-tanks, placed either near or far relative to the rider.

The product planner and/or designer are encouraged to add the latest motorcycle aesthetic trends to better maximise the saleability of the motorcycle once it is in its use phase (highlighted by FR4d). The PDEVEP, which comes packaged with *DESMO-APP*, were collected by surveying local riders, as seen in Section 9.2.1.

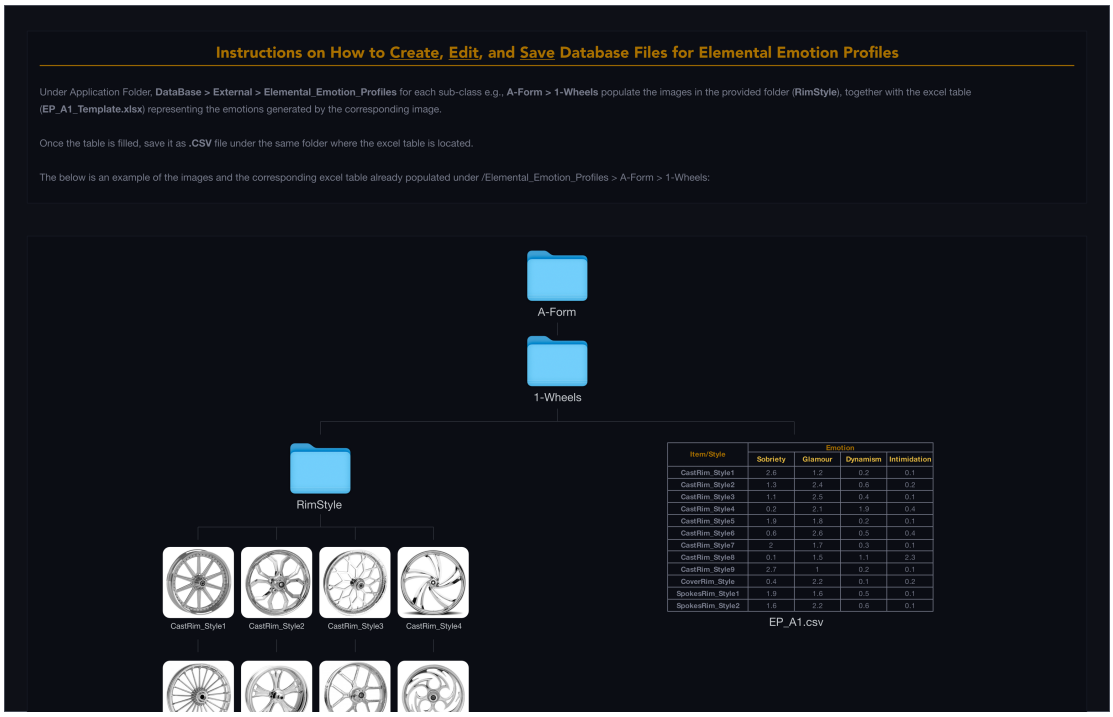


Figure 10.9 – Design Factors (PDEV Emotion Profile)

10.4.3 User Modelling (Module 3)

In the User Modelling module, the product planner or strategist identifies and models the target rider (TR) for which the new motorcycle is intended. Here, the planner or strategist models the persona, aesthetic-derived emotions (see Figure 10.10) and anthropometric measurements (see Figure 10.11) of the intended target rider, specifically:

User modelling features

- Rider attributes
- Personality type
- Driving index
- TREP, by setting the level of each of the four-emotion dimension
- Human 16-limb dimensions.

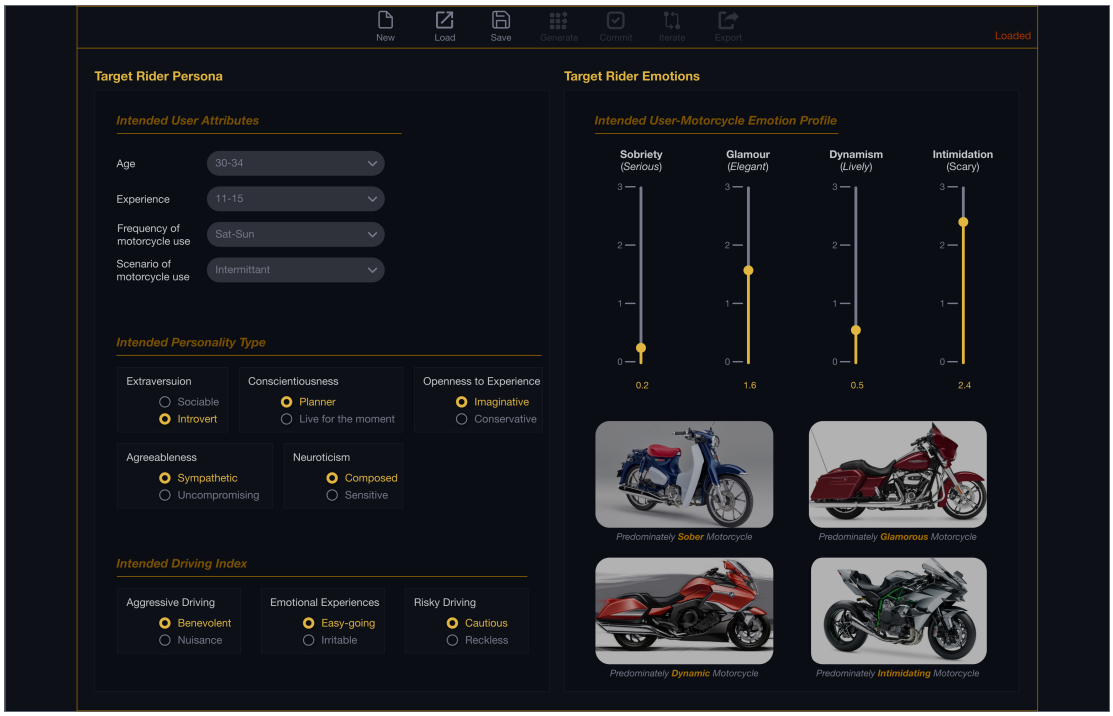


Figure 10.10 – User Modelling: Persona and Emotions

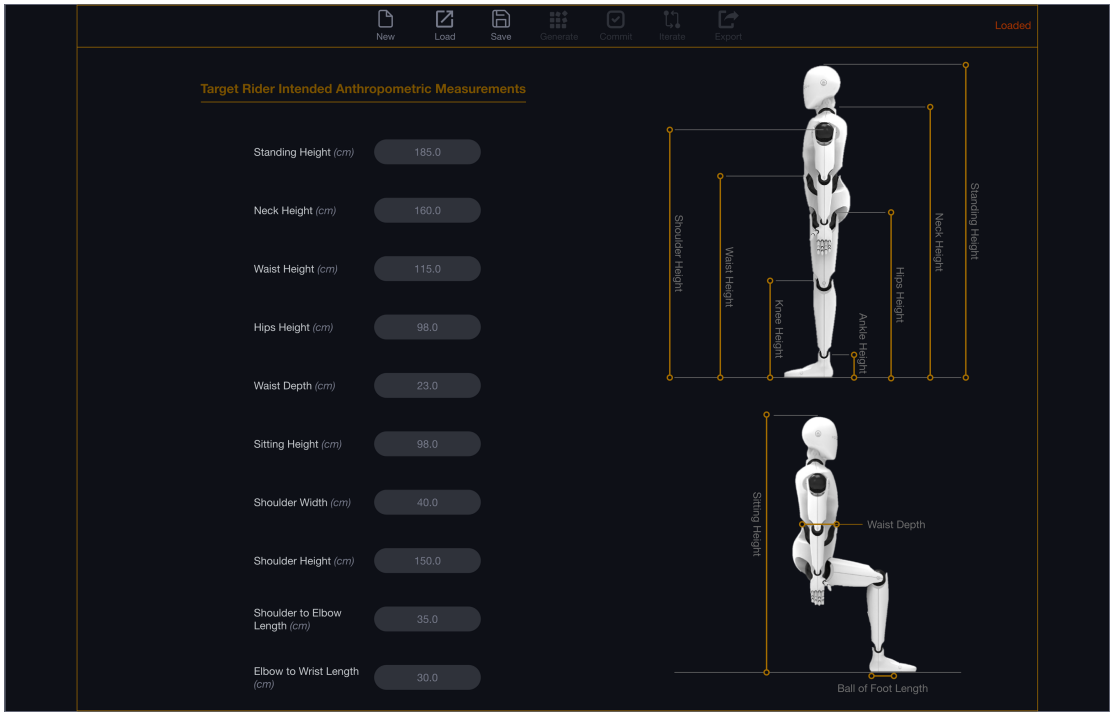


Figure 10.11 – User Modelling: Anthropometries

Defining the general rider

The *Data and General Rider Setting* tab is used to model the general rider (GR). In this sub-module, *DESMO-APP* will automatically create the GR model by calculating the average height of the population sample, the notable persona characteristics, and their aesthetic emotion profile (GREP).

10.4.4 Design Synthesis (Module 4)

Five stages in the design synthesis module

Module 4, Design Synthesis, is the kernel of *DESMO-APP*. This session will be carried by the product designer, and this module is further split into the following five stages:

S1) Synthesising the motorcycle's ergonomics with the TR in focus.
S2) Synthesising the motorcycle's PDEs to portray certain aesthetic-derived emotions with TR in focus.
S3) Synthesising the motorcycle's ergonomics, this time with the GR in focus.
S4) Synthesising the motorcycle's PDEs to portray certain aesthetic-derived emotions with GR in focus.
S5) Harmonising together the previous four stages (S1 – S4) to achieve a harmonised design solution.

<u>*Stage 1* – Ergonomic-Persona and Target Rider in focus</u>

Taking ergonomic design decisions

In the synthesis workspace (see Figure 10.12), the motorcycle designer makes the design decisions. In this case, the designer sets the evolving motorcycle model's ergonomic measurements. For example, setting the handlebar to seat horizontal distance. This is achieved by writing the value of the distance in the text field provided.

Provisionally commitments

Once all the text fields in the synthesis workspace are populated, the designer provisionally commits, and *DESMO-APP* offers its support for the ergonomic design decisions. As illustrated in Figure 10.12, the support panel is categorised into two parts. The first part displays the consequences, where *DESMO-APP* displays the following:

Ergonomic consequences of commitments made

- Joint angles of each body part (e.g. wrist angle, neck angle, etc.).
- Ergonomic discomforts of each body part. The discomforts are scaled from 0 to 10 (10 implies maximum discomfort, 0 means no discomfort). The maximum discomfort resulting in unbearable pain/numbness.

- Total ergonomic discomfort. That is, the summation of each body part ergonomic discomfort multiplied by its corresponding weight (assigned in *Module 2*). An ergonomic discomfort of 100% means that the rider will be subjected to unbearable pain in all the body parts.



Figure 10.12 – Synthesising ergonomic measurements for the target rider

Ergonomic recommend-ations

The second part, *Ergonomic Recommendations*, assists the designer in finding other routes of ergonomic measurements to minimise the highlighted target use-phase consequences. This information constitutes in motorcycle measurements which lead to the minimum total ergonomic discomforts. For example, to have a total ergonomic discomfort of 12% (see Figure 10.12), the handlebar horizontal distance ($P_{HB.h\text{-}S}$) must be set to 48cm from the current 47.5cm, the handlebar vertical distance ($P_{HB.v\text{-}S}$) from 19cm to 18cm and so on. *DESMO-APP* provides the designer with the optimal ten motorcycle ergonomic measurements for the TR. After analysing the consequences and recommendations the designer may or may not take the advice of *DESMO-APP* to improve the TR's ergonomics. The designer has two options, either (i) taking all or partly the advice given by *DESMO-APP*, or else (ii) sticks with his/her original decisions. If the designer wishes

to take the advice of *DESMO-APP*, it is required to go back to the synthesis workspace and change the measurements based on *DESMO-APP*'s support. Finally, the designer can save the motorcycle geometry commitments, where these will be stored in *DESMO-APP*'s database and can be accessed later.

<u>*Stage 2* – Emotion-Persona and Target Rider in focus</u>

Taking emotions and persona design decisions

In the synthesis aesthetic-derived emotions for the TR's workspace (Figure 10.13), the designer selects a variant of each PDE from the library populated in *Module 2*. For example, for the first PDE *'Rim Style'*, under the *'Wheels'* section, the designer is prompted with a list of available rim styles in *DESMO-APP* and their corresponding PDEVEP. PDEs are mainly categorised into two groups: *positional factors* and *styling factors*. The latter group encompasses handlebar, fuel tank, colour scheme, etc. For example, elements of handlebar styling factor can take the form of *ape-hangers, T-shaped, straight rod*, etc. Positional factors concern the position of those components making up the motorcycle. For example, a handlebar can have various vertical positions. It can be set to a high-vertical position (like *cruiser*) or low-vertical position (like *café racer* motorcycles). Like styling factors, positional factors have an impact on the motorcycle's aesthetics and ergonomics. Once the designer provisionally commits, *DESMO-APP* displays the emotion-persona support and recommendations. For the support *DESMO-APP* display the following:

Emotions and persona consequences of commitments made

- A superimposition of two emotion profiles – the green highlighted graph in Figure 10.13 displays the TREP, constructed in *Module 3,* and the white one displays the IMEP computed for the synthesised motorcycle. As explained in Section 9.2.1, in order for the TR to be fully attached to the motorcycle, during the purchasing phase, the white graph needs to have the same exact profile as the green one. This means that the evolving motorcycle emotion profile matches that of the target rider.

- The discrepancy in percentage between the two graphs. As it can be seen from Figure 10.13, there is a discrepancy of 42% between the two graphs. A 0% discrepancy means that the two graphs are aligned perfectly.
- The likeliness that the intended target rider will be involved in an accident and the severity of the accident. The less this percentage is, the better and safer the motorcycle would be. For example, to make the motorcycle safer, *DESMO-APP* suggests reducing the engine size or making the motorcycle less intimidating.

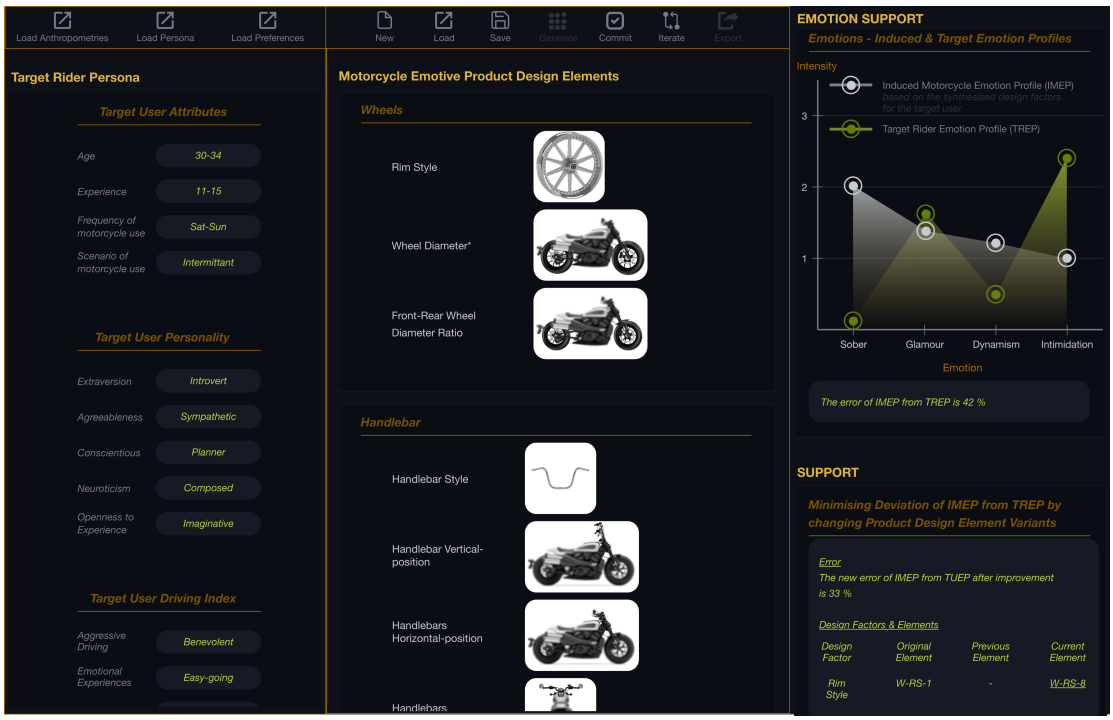


Figure 10.13 – Synthesising emotions related PDEs for the target rider

Emotions and persona recommend-ations

In the Emotion Recommendations, *DESMO-APP* will propose what PDEVs needs to be changed to create a better emotively connected motorcycle model with the TR. This is intended to minimise negative target use-phase consequences, in this case, the error between the two graphs and the likeliness of an accident. This information constitutes in which element to change. For example, as seen in Figure 10.13, if the designer had to change the *'Rim Style' W-RS-1* to the *W-RS-8* element the discrepancy between the two graphs is reduced by 9%, from 42% to 33%. The new IMEP graph is displayed to reflect the change. It is

important to note that *DESMO-APP* only changes one variant at a time. *DESMO-APP* suggests modifications predicated on the identification of which PDE alteration results in the most significant diminution of the disparity between IMEP and TREP. This approach is adopted to ensure minimal deviation from the aesthetic vision the designer intends for the evolving motorcycle model. Such modifications are facilitated through the use of an iteration button. *DESMO-APP* continues to propose changes until either all PDEs have been adjusted, the discrepancy between IMEP and TREP is nullified, or the designer deems it appropriate to finish alterations.

At the designer's discretion

After analysing the consequences and recommendations the designer may or may not take the advice of *DESMO-APP* to improve the evolving motorcycle induced emotions. In this stage, the designer has one of the following three options:

i) Sticks with his/her original decisions
ii) Implement the advice given by *DESMO-APP*
iii) Click the *'iterate'* button to further minimise the discrepancy.

To take the advice of *DESMO-APP*, the designer needs to go back to the synthesis workspace and change the elements based on *DESMO-APP*'s support.

***Stage 3* – Ergonomic-Persona and General Rider in focus**

In this stage, a similar procedure to the first stage (*S1*) is used, but in this stage the designer must synthesis the motorcycle measurements for GR, which has a different characteristic compared to TR.

***Stage 4* – Emotion-Persona and General Rider in focus**

In this stage, a procedure similar to the second stage (*S2*) is employed. However, the designer must synthesize motorcycle aesthetic PDEs tailored for GR, who possesses different characteristics compared to the TR.

Also, in both *S3* and *S4*, *DESMO-APP* proposes support and recommendations in order for the designer to minimise negative general rider use-phase consequences or the Population Use-phase Consequences (PUCs).

***Stage 5* – Harmonisation**

The last and key stage of the Design Synthesis module is *Stage 5*, *Harmonisation*. In this stage the aim is to provide the designer with Design-stage Conflict Consequences (DCCs) support as well as integrating the four previously synthesised motorcycle models (*S1 to S4*) into a singular harmonised solution.

Displaying the commitments taken in the previous four stages

In the reference panel (see Figure 10.14), the designer is prompted to enter the four motorcycle models which were committed in the previous four stages. The DCCs are portrayed as a mismatch between human factors in the reference panel. For example, in Figure 10.14 a conflict occurs between *short* handlebar vertical position (19cm) aimed to satisfy hf_E of the TR and the *tall* handlebar vertical position aimed to satisfy hf_{AE} of TR.

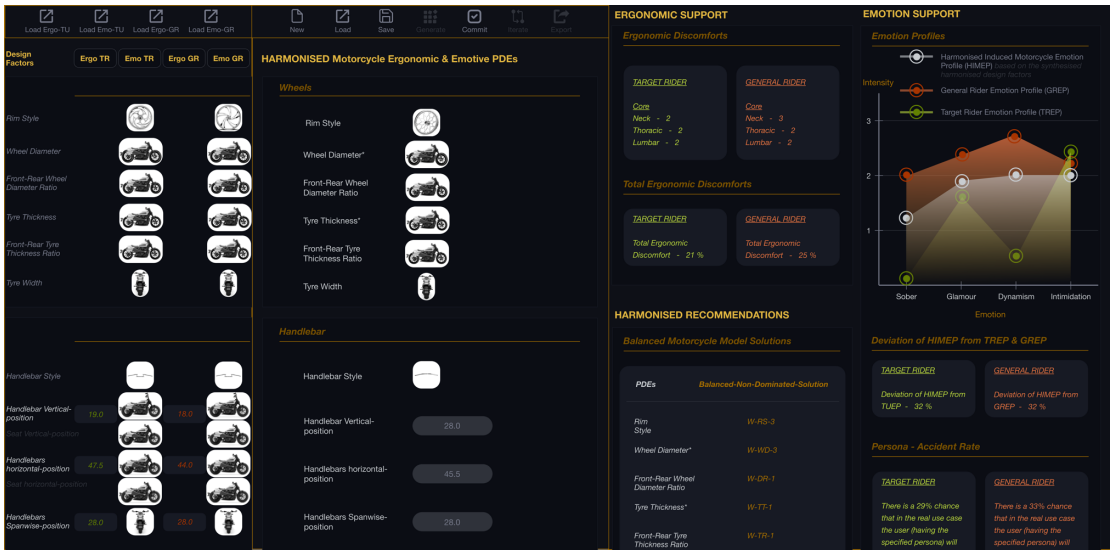


Figure 10.14 – Harmonising ergonomic measurements and emotions related PDEs for the target rider and general rider in DESMO-APP

Harmonisation support and recommend-ations

After analysing the conflict, the goal of the designer is to commit to one measurement or PDEV, from the potential four. This is carried out in the synthesis workspace, under the harmonisation column. Once the

designer provisionally commits to the harmonised motorcycle model, the PUCs and recommendations appear in the support panel. In the consequence area there are both the ergonomic and emotive consequences. For the emotion support, a graph displaying three curves is shown, as illustrated in Figure 10.14. The white curve is the *Harmonised Induced Motorcycle Emotion Profile* (HIMEP), the green and orange curves are for the TR and GR respectively. This graph is accompanied by deviation of the HIMEP from the TREP, given by 64% and the deviation of HIMEP from GREP, which is 26%. The latter one is used to portray the severity of PUC.

How harmonisation support is achieved

Through the procedure presented in Section 9.3.1 – Harmonisation Service, *DESMO-APP* computes a harmonised solution. Information is gathered directly from the four potential design solutions committed by the designer in each stage. To achieve this harmonisation, *DESMO-APP* sets out an objective to minimise the total ergonomic discomforts for TR and GR as well as finding the right elements to enhance aesthetic-derived emotions of both TR and GR. This is composed of elements/positions and measurements to better suit the emotions and ergonomics of the target and general riders. The designer may or may not take the advice of the support system, and the final harmonised decision commitment rests in the designer's discretion.

In this hypothetical example, *DESMO-APP* managed to reduce the total ergonomic discomforts by 6% for the general rider and by 2% for the target rider. *DEMO-APP* also managed to reduce the deviation of the HIMEP from the GREP by 32% but increased slightly the deviation from HIMEP to TREP by 4%. This outcome exemplifies the essence of harmonising, which endeavours to identify a solution that optimally accommodates the four aspects by collectively reducing discrepancies.

10.5 *Part C* Conclusions

Computer-based design tool

This chapter has presented a computer-based design tool, which represents the computational realisation of the *HARMONIOUS* approach framework. This computer-based tool allows designers to generate a harmonised motorcycle design solution from a set of (potential) customer-related data.

Part C Conclusions

Part C has introduced the doctoral research solution, centred around the *HARMONIOUS* design approach, utilising the *DESMO* archetype frameworks outlined in Chapter 8. It is concluded that the design approach framework exploits the dual ontological design decision commitments phenomena models presented in Chapter 7. Formalised harmonistic knowledge models, which explain what and how knowledge needs to be modelled, were established in Chapter 9.

Implemented within the computer-based design tool showcased in Chapter 10, the *HARMONIOUS* design approach framework addresses the research challenges outlined in *Part B* of this dissertation. It is concluded that this tool equips dual ontological product (DOP) designers with proactive harmonistic knowledge during the development of DOP solutions. Such knowledge makes designers explicitly aware of population use-phase and design-stage conflict consequences (PUCs and DCCs) resulting from the DOP synthesis decisions being made. Furthermore, it is concluded that this knowledge provides recommendations to minimise the effects of these negative consequences whilst achieving a harmonised unified DOP solution.

To validate the effectiveness of this solution, *Part D* begins with a formal evaluation of *DESMO-APP* with actual motorcycle designers. The evaluation will be carried out utilising the computer-based design tool and used as a basis to validate the hypothesis postulated in this research.

Part D:
Solution Evaluation and Discussion

11 Solution Evaluation

This chapter presents the evaluation methodology, utilised to evaluate DESMO-APP in supporting the DOP design process, together with the evaluation results. This serves as the foundation for determining the efficacy of the harmonistic knowledge-based DOP design approach framework introduced in Chapter 8. The evaluation of the research solution was conducted through several formal demonstrations using the DESMO-APP prototype tool, as detailed in Chapter 10. Section 11.1 explains the evaluation objectives, including the evaluation criteria. The evaluation methodology is presented in Section 11.2, while the evaluation results, including strengths and limitations of the framework and its implementation are listed in Section 11.3. Difficulties encountered during the evaluation study are given in Section 11.4 and key conclusions, drawn from the formal evaluation of the proposed design support, are presented in Section 11.5.

11.1 Evaluation Objectives

Why the use of a prototype tool to evaluate the framework

Blessing & Chakrabarti (2009) argued that validating a theoretical framework directly might pose challenges due to the inherent abstract nature of the theory, suggesting that a prototype should be employed to clarify the theory in a manner accessible to industrial designers. The prototype tool was deliberately developed based on the principles and structure of the knowledge-based design approach framework. As demonstrated in Chapter 10, Table 10.1 outlines the core functionalities implemented to effectively represent the capabilities of the *HARMONIOUS* design approach framework. This integration ensures that any assessment of the tool's efficacy inherently serves as an evaluation of the validity and effectiveness of the underlying framework.

Why the use of DESMO for evaluation

To assess the research hypothesis with respect to the reality situation, experimentation was deemed necessary. This was conducted using *DESMO-APP*, a computational realisation of the *HARMONIOUS* design approach framework, through *DESMO*, a more tangible demonstration

of the approach framework's application. Prototypes or actual tools aid participants in grasping the conceptual aspects of the frameworks (Blessing & Chakrabarti, 2009), particularly as *HARMONIOUS* represents a high-level abstraction of *DESMO*. By evaluating the proposed solution against a set of criteria, the level of validity of the hypothesis posited in this doctoral research can be determined.

Evaluation aim

As such, the main aim delineated for the evaluation of *DESMO-APP* is to obtain a degree of evidence that that designers who develop dual ontological products (DOPs), benefit from an approach which makes them aware of human factor ($hf_{E\text{-}AE\text{-}P}$) design and use-phase consequences (DCC and PUC) whilst supports them in handling harmonisation.

Evaluation objectives

Transpiring from the main aim, the evaluation objectives (EOs) were therefore to obtain:

Evaluation objective 1 (EO1)

An understanding, from appropriate DOP designers, of the underlying design approach framework, which supports concurrent consideration of multi human factors (hf-Multi X) and guides towards a harmonised DOP solution.

Evaluation objective 2 (EO2)

A degree of evidence that that DOP designers benefit from receiving DOP solution specific harmonistic knowledge. This includes awareness of population use-phase and design-stage conflict consequences (PUC and DCC), along with decision guidance knowledge, facilitated by a computer-based support tool.

Evaluation objective 3 (EO3)

Feedback on the functionality and practical acceptance of the computer-based design prototype tool, while assessing its strengths and limitations.

Feedback from motorcycle designers

Aligned with the established evaluation aim and objectives, this *second descriptive study* (Blessing & Chakrabarti, 2009) involved gathering qualitative and quantitative feedback from motorcycle designers on the efficacy of the *DESMO* archetype framework, and its

implementation (*DESMO-APP*), through the application of a motorcycle design case scenario.

11.1.1 Evaluation Criteria

Criteria

As described in Section 1.7, the final objective of this doctoral research was to evaluate the main outcomes of this doctoral research. Stemming from the research problem articulated in Chapter 6, and with the intention of fulfilling the objectives of evaluation, the following set of key evaluation criteria (EC) were postulated, more specifically to investigate to what extent the design approach framework:

Evaluation criterion 1 (EC1)

Integrates within the workflow of the DOP designer during the activity of conceptual synthesis design.

Evaluation criterion 2 (EC2)

Makes DOP designers aware of multiple life-phase view consequences (PUCs and DCCs) arising from the interaction between the three human factors ($hf_{E\text{-}AE\text{-}P}$).

Evaluation criterion 3 (EC3)

Support designers, in concurrent consideration of hf-Multi X, and in handling harmonisation.

Evaluation criterion 4 (EC4)

Encourages designers in minimising PUCs and DCCs, as well as in exploring different commitments and harmonised motorcycle solutions.

Evaluation criterion 5 (EC5)

Through *DESMO*, representation of motorcycles is well demonstrated and in line with the motorcycle industry.

Evaluation criterion 6 (EC6)

Is beneficial and useful in practice, whilst addressing a real and practical problem in DOPs.

11.2 Evaluation Methodology

Evaluation using a hypothetical case study

The evaluative methodology employed was centred upon a hypothetical case study, detailed in Sections 10.3.3 and 10.4, which served to demonstrate the various aspects and capabilities of the

DESMO-APP and the underlying framework. This methodology was primarily concerned with assessing the evaluators' perceived efficacy of the framework in making the evaluators aware of PUCs and DCCs, as well as in motivating them in exploring diverse motorcycle solutions, underpinned by the support and recommendations offered. The adoption of this methodology further facilitated the examination of whether the provision of harmonistic knowledge could guide motorcycle designers in considering hf-Multi X, thereby leading to the realisation of a harmonised, unified motorcycle solution. In light of these considerations, the evaluation of *DESMO-APP* through a hypothetical case study was posited to confirm the hypothesis proposed by this doctoral research endeavour.

11.2.1 Evaluation Procedure

Three-staged evaluation session

Each evaluation session was held in-person and spanned on average ninety minutes with each participant. The session was divided into three distinct stages, as illustrated in Figure 11.1.

Stage 1: Background information

The first stage, lasting approximately fifteen minutes, commenced with a short presentation to introduce the research to the participants who accepted to take part in the study. This presentation provided the evaluators with a foundational understanding of the doctoral research, encompassing an overview of the problem background and an overview of the *DESMO* framework. Such an overview acted as a guide, enabling designers to have a holistic understanding of *DESMO*. The presentation also included definitions of specific terminology, such as ‘human factors’, ‘PUCs’, ‘DCCs’, and ‘harmonisation’, which were to be employed throughout the demonstration. Establishing these definitions beforehand ensured that participants were acquainted with the concepts essential for explaining the demonstration and *DESMO-APP*.

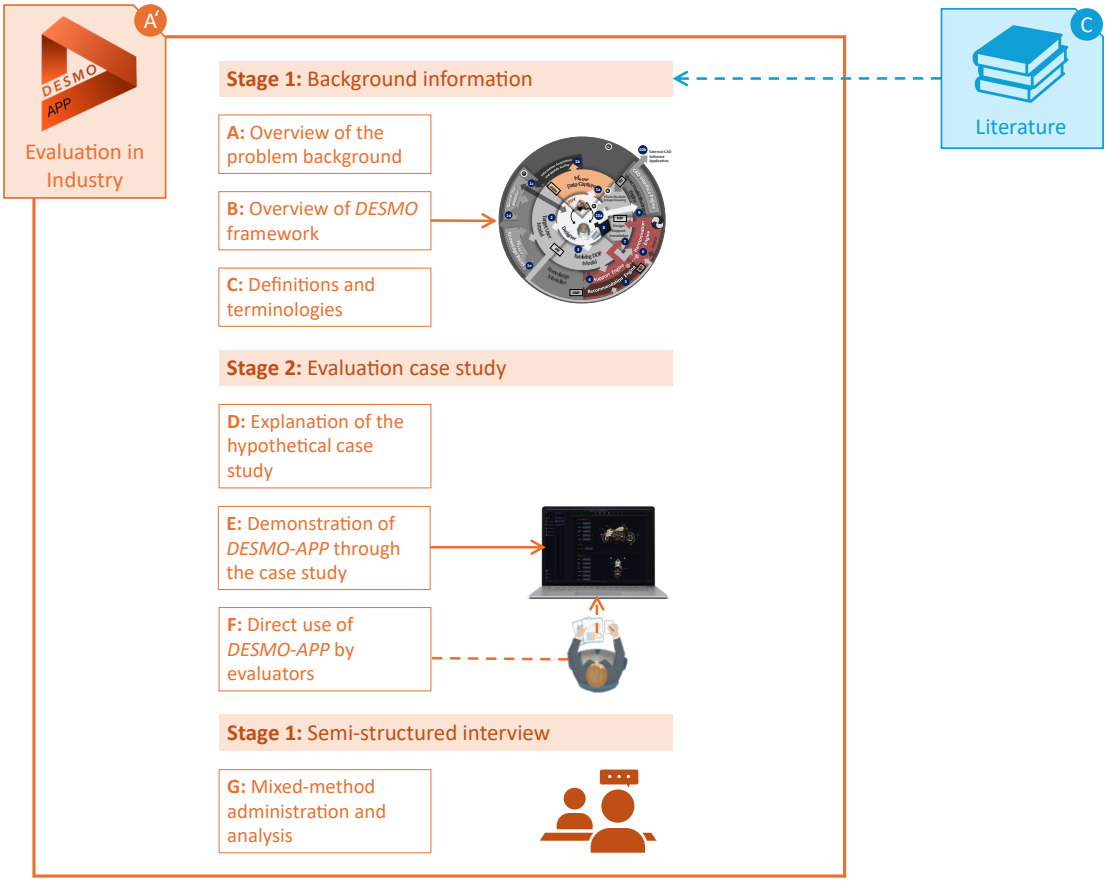


Figure 11.1 – Structure of the in-person Evaluation study with each participant

Stage 2: Evaluation case study

In the second stage, the hypothetical case study (as explained in Section 10.3.3) was used in order to showcase the functionality and capabilities of *DESMO-APP* and the underlying harmonistic framework. This entailed in the design conceptualisation of an entirely new motorcycle for a specific user demographic, but with the intent to reach a broader spectrum of riders, and where conflicts between motorcycle ergonomics and aesthetics occurred. The demonstration, averaging forty-five minutes in duration, entailed a comprehensive walkthrough of each module and stage of *DESMO-APP*, as detailed in Section 10.4, where ultimately a harmonised motorcycle design solution was achieved. During this step the researcher navigated the prototype and explained step by step the capabilities of the computer-based tool. Furthermore, to enhance understanding of the proof-of-concept and its functionalities, the evaluators were given a fifteen minute opportunity to engage directly with *DESMO-APP*.

Stage 3: Semi-structured interview

Following the demonstration for the whole group of participants, a semi-structured interview was carried out with evaluators, in the third stage of evaluation. A quantitative and qualitative methodology was employed to administer and analyse the interview, combining a structure format based on pre-planned questions and open-ended feedback to leave the opportunity for the evaluators to elaborate on specific aspects of *DESMO-APP*.

11.2.2 Demographics of Evaluation Participants

Motorcycle designers as evaluators

Based on the above considerations a number of formal demonstrations using *DESMO-APP* were carried out abroad with twenty-eight international experts in the motorcycle industry with expertise in motorcycles design. The majority of participants came from Europe, with others have worked in the American and Asian markets. The designers' work experience varied between 6 and 40 years (mean = 18.4 years). During their experience, participants worked with top brands such as *Honda, Yamaha, Suzuki, Triumph, Ducati, Harley Davidson and Indian*. Most of the participants have a bachelor's degree (82.1%) in mechanical (automotive) engineering (46.4%) and industrial design (35.7%). Participants came from different roles: chief engineers (15.7%); (senior) designers (30%); and design/mechanical engineers (47.9%). Evaluators were recruited following relationships formed during the design problem phase of this doctoral research (refer to Chapter 4), as well as through connections established through the *RIDE+SAFE*[16] project. The sessions were held in a cluster of automotive industrial companies in Bologna, Italy.

[16] A project funded by the Malta Council for Science & Technology (MCST), through the FUSION Technology Development Programme (R&I-2017-003-T).

11.2.3 Evaluation Questionnaire

Data collection instrument (DCI)

Evaluators were subjected to a series of inquiries during a semi-structured interview, with the data collection instrument (DCI) utilised being detailed in Appendix H.

Quantitative scores

To quantitatively gauge the attitudes of participants, a 5-point Likert-scale response was utilised, where the highest rate in the scale (5) denoted a signified positive attitude, whilst a rating of (1) signified a pronounced negative attitude. This way characteristics of the approach the designers have found useful and necessary can be assessed.

Qualitative responses

Acknowledging the limitations of quantitative scores in conveying comprehensive insights into participants' feedback and experiences, particularly in studies with limited sample sizes, qualitative analysis was leveraged to bridge these gaps. It provided detailed explanations for the feedback given. The semi-structured nature of the interview enabled evaluators to express their level of agreement to each question whilst being encouraged to explain the reason and share their experience. The final two questions posed to the evaluators were deliberately open-ended, fostering a dialogue-based engagement.

Pilot study

A pilot study was carried out with two local experts in motorcycle customisation, prior to the actual evaluations. This led to the inclusion of the definitions and terminologies in the actual study, a better explanation of how *DESMO* maps to *DESMO-APP* in the evaluation's first stage, and the modification of a number of questions within the questionnaire.

Ethics approval

This study was reviewed and received approval from the Ethics Committee of the University of Malta (Application ENG 669/2019, part 5), and informed consent was secured from each participant prior to the initiation of the study's activities.

11.2.4 Qualitative and Quantitative Analysis

Quantitative analysis

As explained in the preceding section, the evaluation questionnaire employed Likert-type questions to ascertain the evaluators' disposition towards a series of questions. Becker (2020) recommends an approach to present the findings from each Likert-type item through the use of bar charts and suggests the analysis of data via the calculation of the mean ($\boldsymbol{\mu}$) and standard deviation ($\boldsymbol{\sigma}$) to quantify the scores.

Qualitative analysis

As previously mentioned, the application of statistical analysis does not invariably yield profound insights into the feedback and experiences of participants. For this reason, qualitative analysis is employed to bridge these informational gaps by elucidating the rationale behind the feedback provided. Additionally, through the application of thematic analysis, patterns within the data can be discerned, facilitating a deeper comprehension of the investigation. Consequently, the qualitative method approach delineated by Chwo et al. (2018) was adopted, where the evaluators' feedback was organised into themes. All interviews were recorded and later transcribed for qualitative analysis. The evaluators' feedback was read multiple times and coded in an iterative process, aimed at diminishing subjective bias, refining the emergent themes, and adequately addressing the evaluation criteria pertinent to the framework. The inter-rater reliability (IRR) test was employed in this research to gauge the reproducibility and consistency of the qualitative analysis undertaken. A *Kappa's index* of 0.75 for the IRR was recorded, indicating a good agreement among the two raters and thereby attesting to the qualitative reliability of the study.

Identified themes

The feedback collected from the evaluators throughout the interview sessions were affined into five main themes, as shown in Figure 11.2, and is subsequently discussed in the following sub-sections.

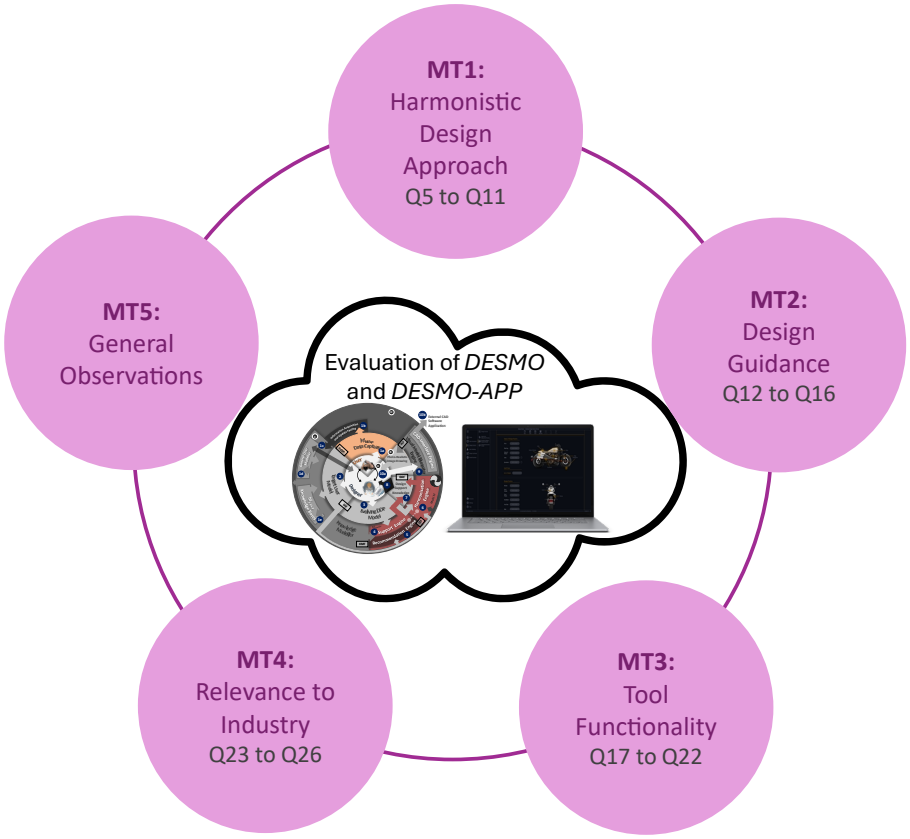


Figure 11.2 – Identified themes during the evaluation study

11.3 Evaluation Results

Visual interpretation of results

A stacked horizontal bar chart was utilised to plot the results of Likert-type questions. Results for questions 5 to 26, each categorised within their respective thematic area, are illustrated on horizontal bar charts, presented by Figure 11.3 to Figure 11.6. In these figures, the questions posed to the evaluators are plotted with their respective responses. Responses are expressed as percentages, indicating the proportion of participants who either agreed or disagreed with the posed questions. In the charts showcased in Figure 11.3 to Figure 11.6, participants, exhibiting negative responses or disagreeing to questions, were plotted on the negative scale (highlighted in orange). Positive or agreeable responses were positioned on the positive spectrum (highlighted in blue). The intensity of agreement or disagreement is reflected in the saturation of the bar's colour. Uncertain or neutral responses have their origin at 0. Given that indecisiveness is a non-indicative nature of either agreement or disagreement, indecisive responses were omitted

from Figure 11.3 to Figure 11.6. Additionally, in this analysis, responses categorised as 'strongly agree' and 'agree' were aggregated under a 'positive' sentiment towards the harmonistic approach frameworkor the *DESMO-APP* tool, whereas the 'strongly disagree' and 'disagree' responses were interpreted as negative sentiment and an opportunity for potential enhancements of the approach framework or tool.

Excluding Q25, the remaining twenty-two questions were depicted on a line-plot chart, as illustrated in Figure 11.7. The solid line within this plot represents the mean ($\boldsymbol{\mu}$) rating score for each question, where a score of 1 signifies 'strongly disagree', 3 denotes 'uncertain', and 5 signifies 'strongly agree'. A mean score exceeding 3 indicates that the obtained score surpasses the threshold of acceptability (set at 50%). The faintly shaded region around the line illustrates the standard deviation ($\boldsymbol{\sigma}$) surrounding the mean rating for each question, encapsulating the variability's upper and lower bounds. In Figure 11.7, the higher the solid line is, the favourable the responses from the evaluators are. Moreover, a narrow standard deviation region around a specific question implies a consensus among participants regarding their response. The division of the analysis into four categories, as detailed in Section 11.2.4, is visually demarcated by grey vertical grid lines.

11.3.1 Harmonistic Design Approach (Main Theme 1)

As explained in Section 11.1, one of the objectives was to evaluate the harmonistic design approach and the design guidance provided by *DESMO-APP*. These are highlighted respectively in this section and the successive section (11.3.2).

Q5: Demonstrates a rider-centred approach?

In question 5 (Q5), evaluators were asked if the approach adopted demonstrates a (user) rider-centred approach and if it provided awareness on potential customers' requirements. As shown in Figure 11.3, the responses to Q5 were predominantly positive (85.7%), with 53.6% of participants strongly concurring with the assertion ($\boldsymbol{\mu}$ = 4.4

out of 5 and $\boldsymbol{\sigma}$ = 0.8, seen in Figure 11.7). Evaluator E8 highlighted that: *"Here everything revolves round the rider, which is a positive thing to see. It gave me a new perspective on how to consider what you called the 'general rider' during design. That alone is already an eye opener for the company I work for."*

Q6: Awareness of multiple life-phase views?

Mirroring the findings of Q5, the outcomes of Q6, as presented in Figure 11.3, also shows a positive sentiment of 85.7%, albeit with the majority of responses falling into the 'agree' category at 53.6% ($\boldsymbol{\mu}$=4.2 and $\boldsymbol{\sigma}$=0.7). Throughout the discussion, numerous evaluators acknowledged that the approach made them aware of negative consequences occurring during a later design stage or during the DOP's use phase, as a result of early routine design decision commitments. Evaluator E10 articulated: *"This approach gave a new perspective on the ability to foresee how the motorcycle will interact when it is being used by users. In practice it is more complex than that as thousands of factors come into play, but in theory it is possible."*

Conversely, Evaluator E13 remarked that even though "*The framework encapsulates an abundance of information*" he initially did not grasp the concept of multi life-phase awareness. It was during the hands-on step in the evaluation stage 2 that the evaluator E13 actually comprehended this awareness.

Q7: Supports concurrent consideration of multi human factors?

Through the use of *DESMO*, motorcycle designers concurrently adopt a multi human factors ($hf_{E\text{-}AE\text{-}P}$) mindset. As illustrated in Figure 11.3 (Q7), this statement was the third most important according to the participants' evaluations, with a mean score of 4.6 and a standard deviation of 0.6, where 71.4% strongly agreed and 21.4% agreed with the statement. Evaluator E22 remarked: *"The concurrent design for aspects such as ergonomics and aesthetics is important as these usually tend to oppose each other. In reality this is very challenging, but the software simplified it and made it intuitive."* Building upon this point, Evaluator E3 added that: *"Concurrent design is very challenging and effective team communication is required. I am seeing this approach as*

a means of effective communication. Different teams can meet around a table, have this software in front of them, and start planning the motorcycle together."

Q8: Supports and guides towards a harmonised solution?

As shown in Figure 11.3 (Q8), all the evaluators (N = 28 or 100%) affirmed that they were guided and supported to find a harmonised solution, perceiving this as a particularly strong aspect of *DESMO* ($\boldsymbol{\mu}$=4.8 and $\boldsymbol{\sigma}$=0.4, which is the highest score recorded across all questions). Some evaluators disclosed that they were previously unfamiliar with the term 'harmonisation', habitually using 'balance' instead. In response, the researcher explained the distinction between the two terms, as elaborated in Section 4.5.4, leading to a consensus that 'harmonisation' was indeed the more apt terminology. Evaluators E2, E14, and E19 uniformly expressed that: *"One of the huge headaches of designers whilst designing these types of products, is finding a balance between several aspects. So, the harmonisation emerges as one of the most noteworthy aspects characterising this approach."* Moreover, evaluator E9 commented that: *"I agree that the harmonisation philosophy is an important factor during motorcycle design. In my opinion it is also important to harmonise teams, as every aspect seen in this demonstration falls under the responsibility of distinct team. For example, in our company we have ergonomists who look into the comfort of the motorcycle while designers who come up with the form. Harmonising the teams means a well-balanced motorcycle which is good for the many."*

Q9: Provide the right knowledge to make decisions?

As delineated in Chapter 4, DOP designers encounter difficulties during the early routine design activities, attributable to the right knowledge necessary to make informed design decisions. When asked to what extent does *DESMO* provide the right knowledge to make motorcycle design decisions, 46.4% of evaluators strongly agreed, 39.3% agreed ($\boldsymbol{\mu}$=4.3, $\boldsymbol{\sigma}$=0.7) with the statement, as illustrated in Figure 11.3.

Q10: Proactively assists in the design process?

Evaluators stated ($\boldsymbol{\mu}$=4.4 and $\boldsymbol{\sigma}$=0.7) with 85.7% positive sentiment, that the tool adopts a proactive approach (Q10), and knowledge is given at the right time. Evaluator E1 commented on the simplicity and intuitiveness of the support provided, which aids in identifying potential issues at an early routine design activity, thereby reducing the necessity for later design modifications. This evaluator also positively remarked that the approach is not a fully automated system, noting that: *"A fully automated system could otherwise lead towards the motorcycle designers not engaging in actual thinking, and relying too heavily on the system."* Similarly, another evaluator (E11) observed that the provision of this knowledge during the motorcycle exploratory design activity encourages designers to pause and consider alternative solutions immediately. Supporting this view, evaluator E27 highlighted that the assistance offered prompts designers to pose pertinent questions at opportune moments, thereby averting possible mistakes.

Q11: Fits with the design workflow?

Participants were requested to express their level of agreement regarding whether the approach would facilitate their role and align with their workflow during the conceptual synthesis activity. Among the participants, 46.4% strongly agreed and 39.3% agreed, whilst the remaining 14.3% provided neutral feedback ($\boldsymbol{\mu}$=4.3, $\boldsymbol{\sigma}$=0.7). Those who exhibited a positive attitude towards the approach explained that the way the approach supports the conceptual synthesis activity is particularly beneficial for ideation in the initial design process and for generating motorcycle design concepts within the solution exploration space. They described the approach as *"Clear and reflective of how the designer should work"* (ES5) and *"Very supportive and contains all the elements to consider in the early stages of the design process, especially when we need to start ideating"* (ES6), among other feedback.

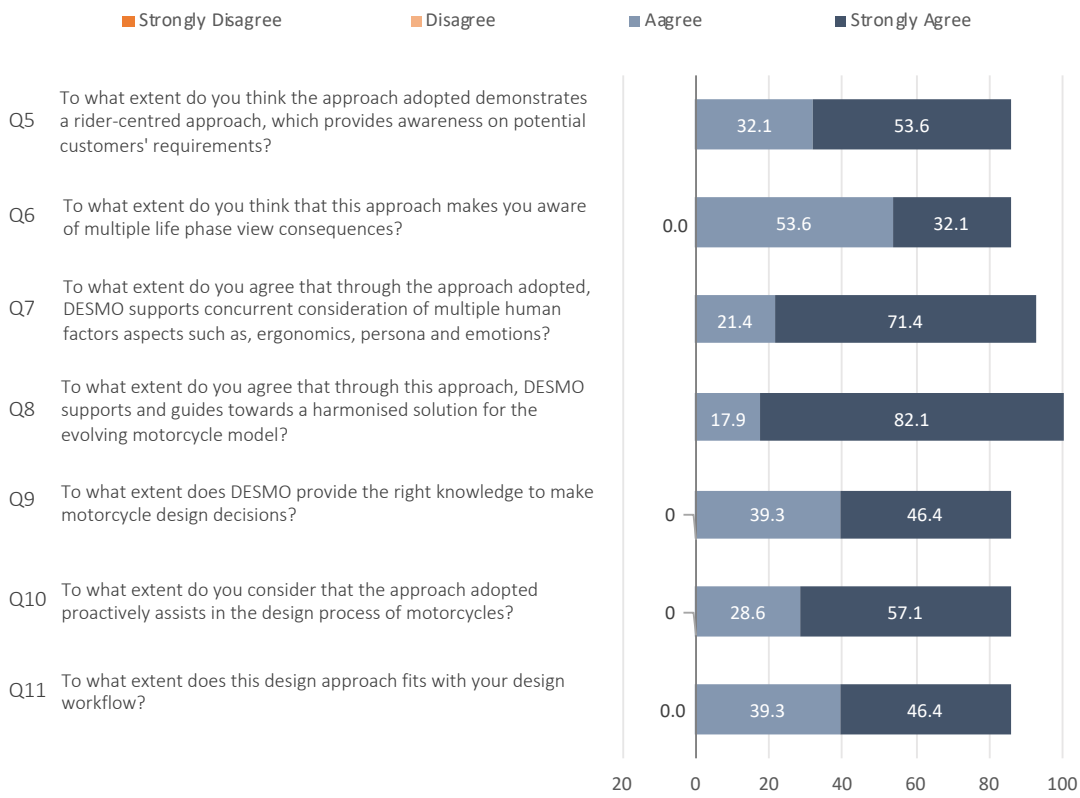


Figure 11.3 – Harmonistic design approach (main theme 1): Questions and responses

11.3.2 Design Guidance (Main Theme 2)

Q12a: Awareness of population use-phase consequences (PUCs)?

In question 12a, evaluators were questioned regarding the extent to which the approach framework provides awareness on population use-phase consequences (PCCs) during the evolving motorcycle model. As illustrated in Figure 11.4, the responses were predominantly (89.3%) of positive sentiment, 7.1% neutral or undecided and 3.6% negative ($\boldsymbol{\mu}$=4.2, $\boldsymbol{\sigma}$=0.7). Numerous evaluators highly valued this aspect, asserting that designing to accommodate a broader spectrum of riders is a critical objective that companies aim to achieve to increase their profit margins. Evaluator E20 remarked: *"I was immediately made aware of how I could improve the motorcycle in order to satisfy the requirements of the many. In reality using this (guidance) would allow me to see the consequences on the large population, not solely focusing on the target rider."*

Q12b: Awareness of conflicts between the

The relatively less positive reaction (ranking as the second lowest scored question) pertain to question 12b ($\boldsymbol{\mu}$=3.6, $\boldsymbol{\sigma}$=1.1), with 60.7%

target and general rider?

positive, 25% neutral, and 14.3% negative sentiment of which 3.6% expressing strong disagreement. From the feedback on question 6, it is apparent that evaluators recognise the approach framework's capacity to make them aware of use-phase consequences of both target user and general riders. However, some evaluators feel the interaction between the target and general riders is not adequately emphasised well in the proof-of-concept, as E12 noted: *"When you [the researcher] explained the approach framework, I could understand that there is an interaction between the target rider and general rider, and this makes sense as they are two different profiles. But during the illustration of DESMO-APP I could not see it, or it needs to be highlighted more. It would be nice if this was transmitted visually."*

Q12c: Awareness of design-stage conflict consequences (DCCs)?

The results of Q12c, as illustrated in Figure 11.4, reveal that the majority (46.4%) of evaluators agreed that the approach framework adopted made them aware of the DCCs arising during the motorcycle solution synthesis, with 25% of the evaluators strongly agreeing and 46% agreeing with this statement, 21.4% natural and 7.1% disagreeing ($\boldsymbol{\mu}$=3.9, $\boldsymbol{\sigma}$=0.9). Upon enquiry into the rationale behind the opposing perspectives, mirroring the feedback to question 12b, Evaluator E24 commented that: *"From your explanation I understood that there is a conflict occurring between the ergonomics and aesthetics for example. But it would be nice if this was transmitted visually. For example, having red boxed around conflicting elements. Because there are other interactions which complement each other and are not conflicting. Having this visual differentiator helps a lot."*

Q13: Knowledge to avoid or mitigate human factor consequences (PUC and DCC)?

In response to Q13, the majority of evaluators agreed ($\boldsymbol{\mu}$=4.5 and $\boldsymbol{\sigma}$=0.8, with 60.7% strongly agreeing and 28.6% agreeing) that the approach framework provided proactively guides and offers support knowledge to avoid or minimise $hf_{E\text{-}AE\text{-}P}$ unintended consequences (PUCs and DCCs). Evaluator E8 remarked: *"I see this as a strong point of DESMO, because you are not giving me the problems but also the solution, and above that you are not constraining me with what*

solution to use." Evaluator E18 acknowledged a potential drawback of this approach framework but rationalised it considering its status as a proof-of-concept and a research endeavour, *"Recommendations are nice. Although in real life there are much more consequences and recommendations to think of, but for a proof-of-concept they are good and serve their purpose."*

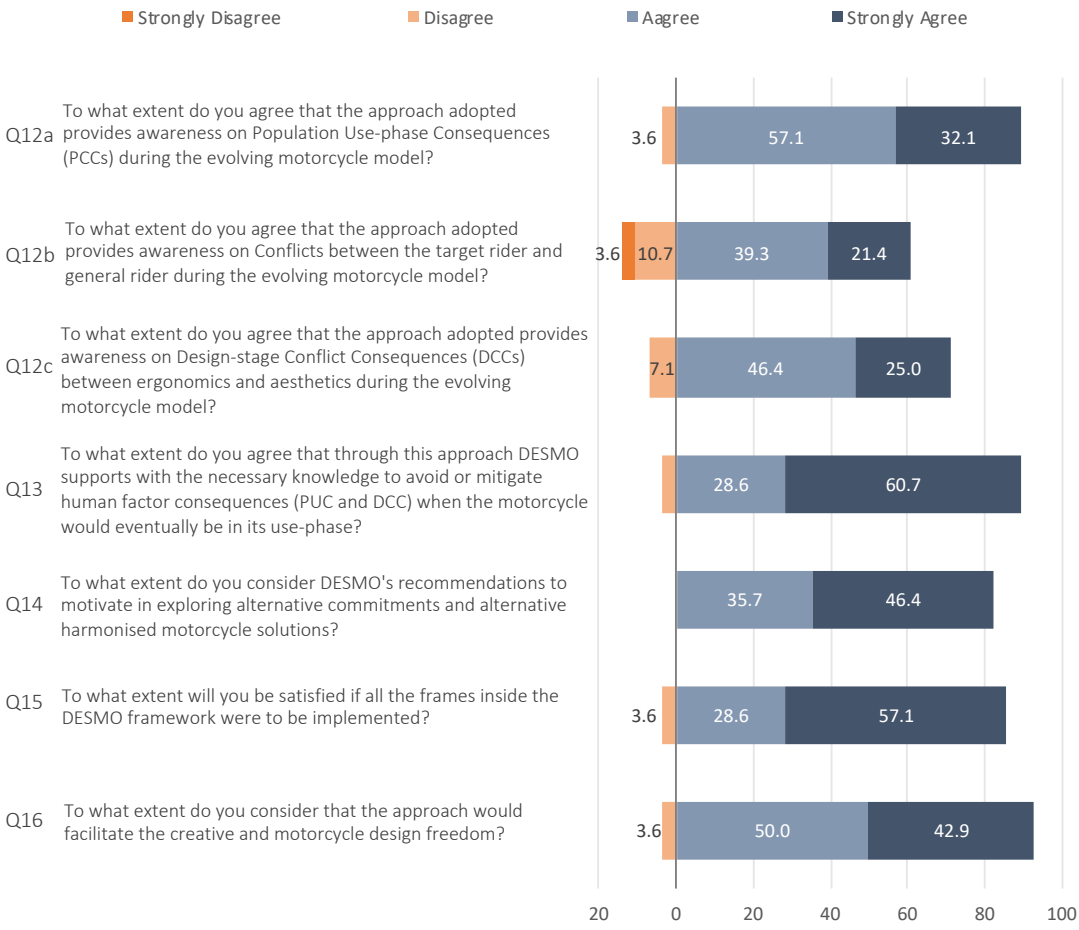


Figure 11.4 – Design guidance (main theme 2): Questions and responses

Q14: Exploring alternative commitments and alternative harmonised motorcycle solutions?

As illustrated in Figure 11.4, a substantial consensus among evaluators was observed in response to Question 14, with 46.4% strongly agreeing, 35.7% agreeing, and 17.9% remaining undecided. Collectively these results indicate that awareness of PUCs and DCCs, evolving with their solution, together with the decision guidance knowledge, motivated them to explore different solutions. Notably, evaluators noted that they would explore different solutions both in terms of product design elements (PDEs) and geometric commitments, but also in terms of harmonised motorcycle solutions that could be adopted to

better guide DOP designers on how products may evolve. In this context, Evaluator E22 remarked: *"The recommendation section inspired me to explore more creative solutions. In itself it can be seen or used as an idea generator."*

Q15: All frames were to be implemented?

Evaluators were asked to express their level of satisfaction should all the frames outlined in the *DESMO* framework, specifically the Knowledge Interpretation Frame (KIF), was to be implemented. 85.7% of the evaluators would be 'very satisfied' while only one evaluator (3.6%) was sceptical on the implementation of the KIF ($\boldsymbol{\mu}$=4.4, $\boldsymbol{\sigma}$=0.8). This particular evaluator, E7, whose scepticism echoed sentiments voiced during the preliminary evaluation of *DESMO* (refer to Section 8.4.3), stated that: *"You need a lot of resources and expertise to implement the part where the harmonised solution is transformed into a 2D photorealistic drawing. I think this project needs to be backed up by a company with the necessary resources."* Conversely, another evaluator (E14) suggested that: "*DESMO-APP would be significantly enhanced if it could include further interfaces which could be developed in order to transfer the knowledge generated by the tool to different sources within a company, such as interface to CAD applications."*

Q16: Facilitate creativity and design freedom?

With a mean rating of 4.3 and standard deviation of 0.7, 92.9% of the evaluators strongly agreed or agreed that the approach framework and the tool would not interfere with creativity and design freedom, since the approach framework did not constrain the user to select a particular option. This sentiment was aptly summarised by evaluator E13: *"Freedom is not hindered at all. If I want to stop at the ergonomics for target riders I can and if I want a balanced solution I can go to the end. Also, the software does not force its recommendations."* Meanwhile, a single participant (3.6%) expressed disagreement, positing that: *"Adding more tools to your toolkits will invariably constrains the creative aspect by nudging you towards a set process."* Contrarily, evaluator E20 countered this viewpoint, asserting: *"Tools*

will give you a fresh perspective that you have never imagined there was. This alone will enhance creativity."

11.3.3 Tool Functionality (Main Theme 3)

As delineated in Section 11.1, the evaluation's aim was also to obtain feedback on the functionality of the *DESMO-APP* tool. A number of questions were formulated with the intention to ascertain the practical utility of *DESMO-APP*. The results of these questions are highlighted in this section (11.3.3) and the subsequent one (11.3.4).

Q17: Demonstrates how information content can be manually changed?

As shown in Figure 11.5 in response to Q17 – concerning whether *DESMO-APP* demonstrates how new elements and knowledge content can be manually changed during the use of the system – 46.4% of participants strongly agreed and 32.1% agreed. Meanwhile, 17.9% were undecided and one (3.6%) disagreed with Q17 (μ=4.2, σ=0.9). Two evaluators remarked on its potential as a research tool, noting: *"This could serve as an invaluable tool for the R&D team, who may dedicate hours to researching trends and user characteristics."* Evaluator E3 highlighted that: *"One of the most powerful features of DESMO-APP in my opinion is that it actually allows us to populate its database. This affords us greater control and liberty."* Conversely, E18 critiqued the effort required to construct and maintain a dynamic database, especially considering the substantial volume of surveys a company must conduct to build knowledge from the gathered data.

Q18a: Demonstrates user ergonomic model?

As depicted in Figure 11.5, pertaining to Q18a, when asked if *DESMO-APP* demonstrates how a user model can be defined using ergonomic properties, 89.3% of the evaluators, either strongly agreed or agreed, while three participants (10.7%) offered a neutral stance on this assertion (mean of 4.2 and standard deviation of 0.6).

Q18b: Demonstrates user aesthetic-derived emotion model?

When evaluators were posed question Q18b, regarding whether the prototype tool demonstrates how a user model can be defined using aesthetic-derived emotions, 35.7% of evaluators strongly agreed, 50%

agreed, 10.7% were undecided and 3.7% disagreed with this assertion, as shown in Figure 11.5 (μ=4.2, σ=0.8). The evaluator who disagreed remarked: *"Although I understood the notion of emotion profile, this is the first time I am hearing about how we can model the emotions of a user."* In contrast, Evaluator E19 pointed out: *"As engineers, our focus tends to gravitate towards numerical data. I liked the fact that DESMO-APP can detect and quantify users' emotions and more importantly aligning those evoked by the motorcycle with them."*

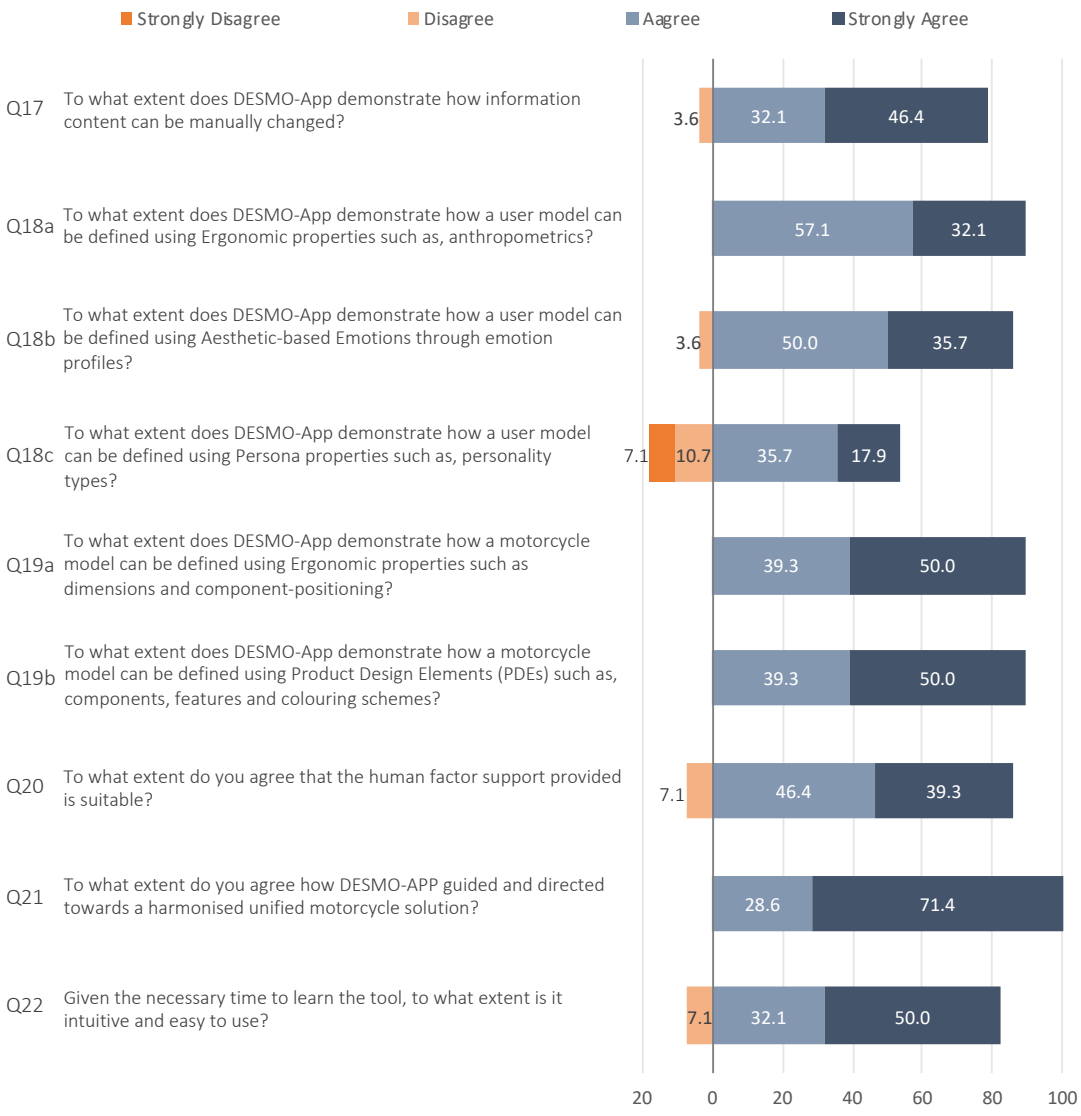


Figure 11.5 – Tool functionality (main theme 3): Questions and responses

Q18c: Demonstrates user persona model?

Upon being queried regarding whether *DESMO-APP* demonstrates how a user model can be defined using persona properties such as personality types, 53.6% of evaluators showed a positive sentiment,

17.9% showed a negative sentiment and the rest were undecided (**μ**=3.5, ***σ***=1.1). Evaluator E10, who harboured negative sentiments towards this question, remarked: *"This is something new that I am seeing being considered during motorcycle design. Personality is not explicitly included during the design process for mass produced motorcycles."* Although this was a requirement outlined in the problem definition, the industry has yet to fully adopt a shift towards a total user-centred design (UCD). Evaluator E14, among the undecided, clarified that: *"We don't specifically ask riders whether they are 'sociable' or 'introvert' or whether they are 'cautious' or 'reckless' when driving. However, I imagine the persona factor to encapsulate aspects like the frequency of use, the context of use, age as you rightly outlined and also other parameters such as what type of motorcycles does a rider have, etc."*

Q19: Demonstrates motorcycle model from a) ergonomics and b) aesthetic-derived emotions perspective?

The motorcycle ergonomic dimensions and product design elements (PDEs) used to define the motorcycle model (Q19a and b) according to 89.3% (**μ**=4.4, ***σ***=0.7) of the evaluators resemble those elements and properties used in the motorcycle industry. Having a tool which speaks the language of motorcycle designers is crucial for it to be effective. In fact, E25 asserted that: *"I loved the fact that this tool speaks our language, and the way emotions are simulated through mathematical constructs. Stylist cognitively do this without explicitly being aware."*

Q20: Human factor support provided is suitable?

In Q20, the evaluators were asked if *DESMO-APP* provided suitable human factors design-stage and use-phase support. As illustrated in Figure 11.5, 85.7% of the evaluators showed a positive sentiment while 7.1% exhibited a negative reaction, with the rest being undecided (**μ**=4.2, ***σ***=0.9). The majority of the evaluators were satisfied with the support provided, particularly highlighting: *"Ergonomics, through posture and ergonomic discomforts and aesthetic-derived emotions, through the graphs portraying emotion of rider and that induced by the motorcycle"* (E13). On the other hand, several evaluators suggested the inclusion of additional support features, such as technical

specifications of the motorcycle like engine capacity, torque, transmission, suspension type, and other considerations including the cost of manufacturing the motorcycle. Evaluator E23 notably proposed that *DESMO-APP* should offer users the flexibility to customise and select which types of support to monitor.

Q21: Guided and directed towards a harmonised unified motorcycle solution?

In relation to Q8, question 21 further queried evaluators on the implementation of harmonisation in the prototype tool. A significant majority highlighted the positive impact of the harmonistic knowledge aspect and how *DESMO-APP* directs its users towards a harmonised solution, after making them aware of multiple human factor consequences. With 71.4% strongly in agreement and 28.6% in agreement, this question achieved the second highest mean score of 4.7, alongside a standard deviation of 0.5. Evaluator E14 remarked: *"The aspect I like the most about DESMO-APP is its harmonisation module. I like how it does not limit you to go for only one solution but gives a number of harmonised solutions which from different lenses can be all great solutions."* Echoing this sentiment, Evaluator E9 observed: *"I think the journey building towards harmonisation is also well thought."*

Q22: DESMO-APP intuitive and easy to use?

When queried on whether *DESMO-APP* was intuitive and user-friendly, 50% of evaluators strongly concurred and 32.1% agreed with the assertion. The remainder either disagreed (7.1%) or were undecided (10.7%) ($\boldsymbol{\mu}$=4.3, $\boldsymbol{\sigma}$=0.9). Numerous evaluators remarked on the logical structure and user-friendliness of the modules. Evaluator E4 mentioned, that: *"Given the time limitation I thought it was easy to use, and the fact that I was able to get my hands dirty with it further reinforced this thought."* On the other hand, one of the creative designers (E26) observed that: *"Motorcycles are about style. As a stylist I want to see curves, shapes and images. Interface is more on numbers, text and graphs. It is more suited for engineers in my opinion … Integrating the model illustrator, you [the researcher] mentioned earlier, would have improved the score."*

11.3.4 Relevance to Industry (Main Theme 4)

Q23 Beneficial for a) bespoke / custom or b) mass produced motorcycles?

In Q23 evaluators were asked whether they consider *DESMO-APP* suitable for a) designers who develop bespoke/custom motorcycles and b) designers who develop motorcycles for mass production. As discernible from Figure 11.6, Q23a elicited a 71.4% positive response and a 10.7% negative response ($\boldsymbol{\mu}$=3.8, $\boldsymbol{\sigma}$=1), while Q23b received a 96.4% positive response with no negative feedback ($\boldsymbol{\mu}$=4.2, $\boldsymbol{\sigma}$=0.5). These findings suggest that evaluators perceive the tool as particularly advantageous for the development of mass-produced motorcycles. Evaluator E3 noted: *"The software is suited for different business models as it is very flexible. Although you can design a bespoke motorcycle with this tool, but the general rider model is essential for mass produced motorcycles as we are designing for a broad spectrum of motorcyclists."* Extending this perspective, another evaluator pointed out: *"For bespoke [motorcycle design] you can directly ask the questions to the rider who will purchase the motorcycle and build the motorcycle around him/her satisfying all his/her requirements."*

Q24: Help designers to design ergonomically safe and at the same time aesthetically pleasing motorcycles?

The evaluators agreed ($\boldsymbol{\mu}$=4.5, $\boldsymbol{\sigma}$=0.6, and 96.4% positive reactions) that the harmonistic approach would help designers, to design ergonomically safe and at the same time aesthetically pleasing motorcycles (Q24). *"I appreciate the innovation behind DESMO-APP and for sure it will help the company design better motorcycles, given its ergonomic discomfort, accident and emotion awareness"* (E10).

Q25: Any tools which are similar to DESMO-APP?

As indicated from Figure 11.6 (Q25), all the evaluators (N = 28) stated that they have never came across a tool like *DESMO-APP*, which takes into account $hf_{E\text{-}AE\text{-}P}$ and harmonises design solutions during their experience in designing motorcycles. This emphasises that *DESMO-APP* is a novel tool which can assist designers, as can be highlighted by the response given by E1: *"I have never seen a similar tool during my thirty year experience in this industry. This can actually fill a gap in the motorcycle design industry."*

Q26: Proposed design approach is useful and beneficial in practice?

The majority of the evaluators (92.9%) stated that they see the relevance of *DESMO-APP* in the motorcycle industry (Figure 11.6, Q26), (mean of 4.4 and standard deviation of 0.7). This reflects a positive sentiment and only one (3.6%) expressing a negative sentiment, the tool is very helpful in practice and would *"Recommend this tool mainly because of its powerful support and harmonisation features as well as because it is compatible with our design workflow."* While the evaluator, E19, who disagreed that it would be beneficial highlighted that: *"Due to the complexity of the software it is difficult to evaluate through a forty-five minute presentation and a fifteen minute use of the tool. More time is needed to get acquainted."*

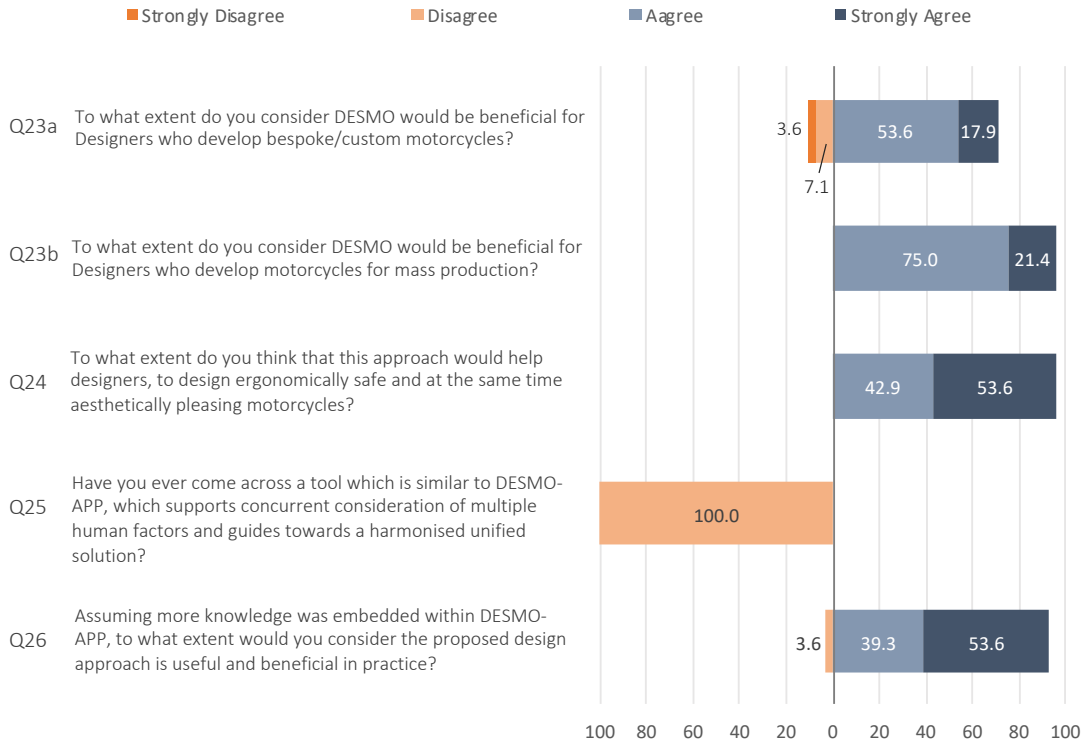


Figure 11.6 – Relevance to industry (main theme 4): Questions and responses

11.3.5 General Observations of DESMO (Main Theme 5)

Q27: Demonstration highlights any other issues?

Given the detailed demonstration provided on *DESMO-APP*, participants were inquired if there was any additional information needed within the demonstration to enhance their understating of the approach or tool. The unanimity among participants was that the

demonstration was *"exceptionally thorough"* and *"all aspects were clearly conveyed."*

As highlighted in Section 11.2.2, among the participants, thirteen (46.4%) were engineers with expertise in the automotive sector, and it emerged during discussions that six of these individuals had experience within car design teams. In relation to this question, evaluators were probed regarding the potential applicability of the approach and tool across different domains, specifically within the car industry. The purpose of this question was to ascertain whether, based on the demonstration provided, participants could envisage the utility of the *HARMONIOUS* design approach framework in contexts beyond the motorcycle domain. Five out of the six participants (83%) indicated that despite the change in domain, the harmonistic knowledge remains applicable. These five participants elaborated on how the tool might be employed within the car industry. Evaluator E17 observed: *"This approach can be used, for instance, in determining the optimal placement of the steering wheel and the accessibility of controls, whilst also considering their aesthetics with the complimentary of the car's interior."* Evaluator E22 added: *"It could also be instrumental in achieving a balance between the aesthetics of the dashboard, lights, etc., and the dashboard's readability, which represents another important sub-factor in ergonomics."*

Q28: Other recommend-ations to improve DESMO-App or the approach framework?

Upon questioning evaluators on potential enhancements to the approach framework or *DESMO-APP*:

- Two evaluators suggested that *DESMO-APP* could extend the human factor considerations beyond ergonomic, aesthetic-derived emotions, and persona, including aspects such as cognition – referring to the mental effort required to perform tasks – or other characteristics like users' budget: *"This ensures that the motorcycle design is acceptable to the same type of users with the same type of requirements and motorcycles in the same market."*

- Four evaluators recommended integrating mechanical or functional aspects of the motorcycle into the tool, including engine configurations and specifications, transmission, damping systems, and braking mechanisms. They observed that: *"There are companies who give high priority to aesthetics. On the other hand, there others which give high priority to the functionality of the motorcycle and aim for performance."*
- Four evaluators proposed the addition of manufacturing considerations to the tool, alongside the three human factors. Evaluator E3 remarked that: *"We do industrial design and not artistic design and so we need to think about the whole engineering design cycle and more importantly the production phase of the motorcycle. So, from my experience you have to use your inner art, but you have to match this with production."*
- Finally, five evaluators emphasised the need to include financial considerations in conjunction with $hf_{E\text{-}AE\text{-}P}$, with two specifically mentioning the integration of manufacturing, financial, and human factors. *"We had some cases where companies wanted to invest money for short envelop so, we had to use commercial headlamps (mass produced headlamps). I couldn't design the headlamps as I wanted as manufacturing and financial aspects are very important factors … Therefore, understanding the negative consequences of different solutions and finding a balance between human factors, manufacturing and financial aspects would further enhance the tool."*

11.3.6 Summary of Evaluation Results

The aim of the evaluation was to ascertain a degree of evidence that DOP designers benefit from being provided with solution specific harmonistic knowledge. The forthcoming arguments shed light on the degree of validity of the research hypothesis formulated in Chapter 1.

Validity of results

From Figure 11.7 it is possible to observe which questions achieved the highest and relatively lowest mean rating scores, as well as those broadly agreed upon by a majority of designers or questions that exhibited a high standard deviation. It is imperative to acknowledge that all questions attained a mean rating score exceeding 3 (equivalent to a 50% threshold of acceptability), with an average rating score of 4.20, indicating that the majority of designers were in agreement or satisfied, thereby validating to the utility and effectiveness of the tool for DOP designers. These findings are observed also in Table 11.1, which further details the mean rating score and standard deviation for each of the four main themes.

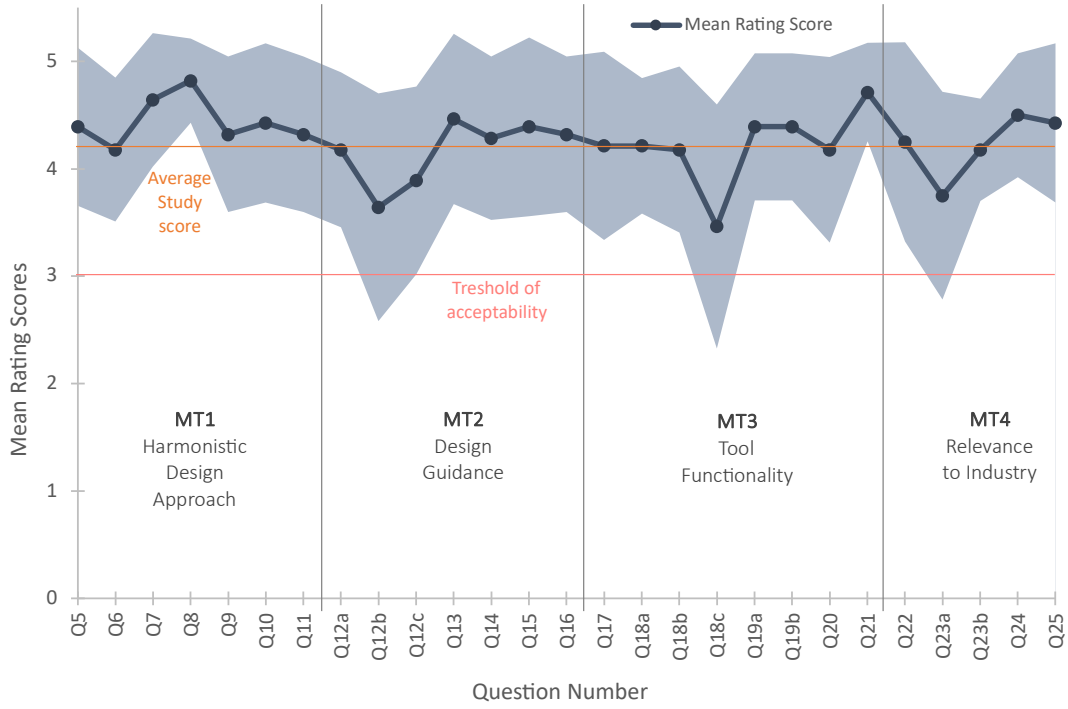


Figure 11.7 – Mean rating score of each question

From the results presented in Section 11.3.1 to 11.3.5, with the aid of Figure 11.7 and Table 11.1, the below conclusions can be drawn:

Harmonistic design approach (Main theme 1)

The harmonistic design approach main theme represents the combined results of questions Q5 to Q11, shows that the response from the questionnaire evaluators can be considered as highly positive (μ=4.44, positive sentiment=88.8%). This outcome therefore confirms the research hypothesis, that is, the proposed UCD approach

proactively supports designers in concurrent consideration of multiple human factors, providing awareness of multiple life-phase view consequences and guides towards a harmonised unified solution thanks to the harmonistic knowledge.

Design guidance (Main theme 2)

The design guidance main theme encompasses the combined results of questions Q12 to Q16, shows that the response from the questionnaire evaluators can be considered as positive (**μ**=4.17, positive sentiment = 83.7%). This confirms the research hypothesis that the harmonistic approach framework provides awareness and supports in mitigating population use-phase and design-stage conflict consequences (PUCs and DCCs) and motivate designers to explore alternative harmonised motorcycle solutions.

Relevance in industry (Main theme 4)

The relevance in industry main theme represents the combined results of questions Q23 to Q26, and shows that the response from the participants can be considered as distinctively positive (**μ**=4.21, Positive Sentiment = 92.9%). This confirms that there is no tool which is similar to *DESMO-APP* in the design industry which helps designers to design ergonomically safe and at the same time aesthetically pleasing motorcycle, fits within the conceptual synthesis activity workflow and that is useful and beneficial in practice.

Table 11.1 – Average theme rating scores and standard deviations

	Harmonistic Design Approach (Q5 – Q11)	**Design Guidance** (Q12 – Q16)	**Tool Functionality** (Q17 – Q21)	**Relevance to Industry** (Q22 – Q25)	***All*** *(Q5 – Q25)*
Mean Theme Rating Score	4.44	4.17	4.22	4.21	*4.20*
Standard Deviation	0.66	0.82	0.78	0.69	*0.77*

11.3.7 Strengths and Weaknesses

Strengths

With the aid of Figure 11.7 and based on the evaluation of *DESMO-APP*, it has been established that the underlying harmonistic design approach framework:

i. Guided and directed designers to handle not only by exploring different $hf_{E\text{-}AE\text{-}P}$ and harmonised solutions, but also by providing the product development team with feedback and exploring different product evolution decisions.
ii. Supported designers in concurrent consideration of hf-Multi X during the synthesis decision commitments.
iii. Provided the designers with knowledge and support to guide them in mitigating human factor consequences (PUCs and DCCs).
iv. Proactively assist in the conceptual synthesis design activity through a UCD approach, which provides awareness on potential customers' requirements.

Weaknesses

Conversely, the evaluation illuminated certain limitations within *DESMO-APP* and the underlying design approach framework, thereby presenting avenues for enhancement:

i. Personality is not explicitly included during the design process Although this was a requirement outlined in the problem definition, the industry has yet to fully adopt a shift towards a total UCD. Moreover, to provide greater clarity for designers, the persona factor can encompass additional sub-aspects like the types of DOPs that users possess.
ii. Although the harmonistic approach framework makes designers aware of conflicts between a) target and general, and b) human factors considered at different stages, they feel the interaction between these conflicts is not highlighted well or transmitted visually in the proof-of-concept.

iii. Although the approach can be utilised to develop bespoke/custom motorcycles, this would be a trivial case since a designer can synthesis the motorcycle around the rider who will directly purchase the motorcycle.

11.4 Evaluation Difficulties

Difficulties

As delineated by Duffy & O'Donnell (1998), a principal challenge in conducting a rigorous evaluation lies in sufficiently define the evaluation datum, the criteria measures, and the selection of suitable methodologies for the evaluation. Other difficulties encountered during the evaluation include:

Sample size and time constraints

i. The niche domain of motorcycle design poses a significant challenge in recruiting a considerable number of participants with the requisite expertise. The scarcity of local participants, coupled with the requirement for them to volunteer their personal time without direct benefit, intensified this difficulty.

ii. Owing to the necessity for evaluators to allocate their personal time, the duration allocated for the demonstration and interview was confined to ninety minutes. Furthermore, the tool was utilised by the evaluators for only fifteen minutes. Consequently, the results are based on the evaluators' perceptions and their brief period of usage.

iii. Arising from the aforementioned constraints, twenty-eight participants consented to participate in the study. As Morse (2000) suggests, a narrow-focused study nature allows for a smaller sample size. Moreover, van Dijk (1995) posits that six evaluators are generally enough to obtain all possible comments during an initial evaluation and reach saturation.

Limited knowledge

iv. As explained in Section 10.2, the proof-of-concept tool incorporates a limited amount of knowledge and library elements. While this permits evaluators to gauge the strengths

and weaknesses of the design approach, it restrains the ability to support a comprehensive exploratory activity that encompasses an extensive array of options.

Limited functionality

v. The prototype tool did not fully incorporate all the tool requirements and the approach framework, as noted in Section 10.2. Nonetheless, the rationale behind the tool and framework missing aspects were explained to the evaluators and subsequently evaluated as can be seen from Q15.

Type of evaluation

These challenges in executing an effective evaluation of *DESMO-APP* align with the issues outlined by Blessing & Chakrabarti (2009) and Duffy & O'Donnell (1998). For this reason, the overall purpose of the evaluation was to understand the usefulness of the tool, focusing on its strengths and limitations in facilitating the design of DOP.

11.5 Chapter Conclusions

Evaluation procedure

This chapter commenced by detailing the methodology employed in leveraging *DESMO-APP* to assess the efficacy of the harmonistic design approach framework among a group of industrial DOP designers, as discussed in Section 11.2.

Evaluation overview

The evaluation case study, in conjunction with the demonstration of *DESMO-APP*, explained how the design support facilitated by the harmonistic knowledge-based approach assisted and guided DOP designers to design for $hf_{E\text{-}AE\text{-}P}$ at the synthesis design activity. Moreover, it is concluded that the validation results showed that the design computational-based tool and the harmonistic design approach framework on which it is based meet their goals, are beneficial and are required in the DOP industry.

Validity of results

The evaluation used metrics that align closely with the framework's objectives, such as awareness of Population Use-phase Consequences (PUCs) and Design-stage Conflict Consequences (DCCs). Positive

outcomes in these areas directly validate the framework's theoretical underpinnings.

Despite the encountered limitations in executing the evaluation exercises, it is concluded that the results obtained collectively support, with evidence, the hypothesis of this doctoral research as delineated in Section 1.5.2, namely:

- A degree of evidence that the underlying design approach framework supports concurrent consideration of hf-Multi X and guides towards a harmonised DOP solution as affirmed by 88.8% of the evaluators.
- A degree of evidence that that DOP designers benefit from receiving DOP solution specific harmonistic knowledge. This includes awareness of population use-phase and design-stage conflict consequences (PUC and DCC), along with decision guidance knowledge as identified by 83.7% of the evaluators.
- A degree of evidence demonstrating the practical utility and benefit of the harmonistic design approach, as recognised by 92.9% of the evaluators.

The next chapter will engage in a discussion of these evaluation results in the context of the doctoral research hypothesis, culminating in the conclusions and future work of this dissertation.

12 Discussion and Conclusions

This chapter discusses the significant contribution to knowledge stemming from this doctoral research. The process through which this contribution and its spin-offs have been realised, in accordance with the established research objectives, is discussed in Section 12.1. Following from the results obtained, directions for subsequent research endeavours are proposed in Section 12.2. The doctoral research contribution is then discussed in Section 12.3. This chapter concludes with final remarks on the research, presented in Section 12.4.

12.1 Research Results Achieved

Research results

The contributions arising from this doctoral research will be presented in a sequence that facilitates their understanding and in line with the objectives set out in Chapter 1.

12.1.1 Research Problem: Supporting DOP design activity

DOP and the influence on $hf_{E\text{-}AE\text{-}P}$

The dualistic nature of certain products, encompassing both physical and subjective-emotional dimensions, highlights their role as extensions of the user. This underscores the critical relevance of human factors, particularly ergonomics, aesthetic-driven emotions, and persona ($hf_{E\text{-}AE\text{-}P}$), in this doctoral research.

DOP users' needs and human factor consequences

The characterisation of dual ontological products (DOPs) emphasised the critical interactions of $hf_{E\text{-}AE\text{-}P}$ with such products, revealing challenges and requirements from both user and human factors perspectives. These findings highlight potential negative implications during the use phase if design processes inadequately address these factors.

Approach framework requirements

The inherent design challenges of dualistic products underscore the necessity of a $hf_{E\text{-}AE\text{-}P}$ solution to effectively address the realities and expectations of DOP designers and users, guided by the framework

requirements. These requirements underscore the design problem inherent in products of dualistic nature:

- Support the conceptual synthesis routine design activity
- Be implemented as a design computer-based support tool
- Precedence of certain product design elements
- Provide a user-centred design approach
- Provide multiple life (design and use) phase awareness
- Design for Multi human factors (hf-Multi X)
- Provide harmonisation awareness

Inadequate means of supporting $hf_{E\text{-}AE\text{-}P}$ and harmonisation

A critical review of current *means* (Chapter 5) concluded that whilst reviewed *means* further prove the need for supporting DOP design, and they cover a wide range of support, collectively they do not proactively support designers in becoming aware of human factor consequences (PUC and DCC), not guided to concurrently design for the three human factor aspects coupled with human diversity, and providing harmonisation knowledge to arrive to a harmonised product unified solution.

Answering the five research questions

The five research questions posed in Chapter 6 have been addressed through the research conducted, and their conclusions are explored in the following sub-sections.

12.1.2 Dual Ontological Design Phenomena Model

RQ1: How are PUCs and DCCs Generated from design decisions for products of dualistic nature?

This doctoral research has successfully addressed research question 1 (RQ1) by explicitly identifying and explaining two key consequence mechanisms, Population Use-phase Consequences (PUCs) and Design-stage Conflict Consequences (DCCs). The developed phenomena model illustrates how these mechanisms are generated and their implications in DOP design. By integrating human factors into the understanding of DOP evolution, this research highlights the critical need for balancing competing design priorities and addressing unintended consequences to enhance the product's success in the market. The phenomena

provides a valuable model upon which a framework could be built to mitigate the phenomena's impacts.

12.1.3 Harmonistic knowledge-based design approach for supporting DOP

RQ2: How to develop a design approach that supports designers with harmonistic knowledge

This doctoral research has successfully addressed research question 2 (RQ2) by providing a novel harmonistic knowledge-based design approach framework to support DOP designers. The framework proactively addresses the requirements and DOP phenomena by harmonising $hf_{E\text{-}AE\text{-}P}$ while mitigating the adverse effects of PUCs and DCCs.

The framework's conclusions are outlined as follows:

Knowledge derived from DOP users

- By employing a knowledge discovery from data (KDD) approach, the framework places users at its core, extracting insights on $hf_{E\text{-}AE\text{-}P}$ directly from potential DOP (potential) customers to inform design decisions.

General user model

- The creation of the general user (GU) model encapsulate human factors qualities indicative of central tendencies.

hf-Multi X early support

- It assists designers in exploring and refining hf-Multi X solutions early in the design process, encouraging the concurrent consideration of $hf_{E\text{-}AE\text{-}P}$.

Support element

- The framework evaluates the impact of design commitments on provisional solutions, enabling early identification of PUCs and DCCs.

Recommend-ation element

- Through its recommendation element, the framework motivates designers to explore alternative decisions, avoiding or mitigating adverse consequences.

Multi-aspect harmonisation

- It directs designers toward a unified synthesis solution that harmonises conflicting human factors ($hf_{E\text{-}AE\text{-}P}$) while addressing the needs of both target users (TU) and the general user (GU) population.

12.1.4 Harmonistic Knowledge Model

RQ3: How can DOP users be understood by DOP designers? And how can it be transformed into meaningful knowledge?

This doctoral research concludes that bridging the gap between DOP users and designers requires a systematic integration of data-driven methodologies. By developing procedural knowledge and adopting a knowledge discovery from data (KDD) approach, this research demonstrates how user requirements can be transformed into actionable harmonistic knowledge. This transformation empowers designers to proactively address PUCs and DCCs, ensuring harmonised solutions that balance human factors effectively. Through these advancements, this research establishes a vital link between user-centric insights and design practices, contributing to the creation of inclusive and harmonised DOPs.

12.1.5 Framework Prototype Tool Implementation

RQ4: How can this harmonistic knowledge be modelled in a computer-based tool?

The developed system architecture utilises a machine learning knowledge-based system (ML-KBS) back-end system to enable the transformation of user-derived data into harmonistic knowledge through a KDD approach. By integrating machine learning, harmonisation modelling, and knowledge management into a back-end system, the framework ensures robust support for designers. This research demonstrates the potential of computer-based tools to operationalise the harmonistic design approach framework, offering a pathway for further refinement and broader applications in computer assisted design.

12.1.6 Validation of Research Results

RQ5: To what extent are designers willing to use such an approach in their practice? and why?

The evaluation of the approach framework and prototype tool focused on addressing the fifth research question. It is argued that the findings presented in Chapter 11 clearly show that DOP designers would adopt the proposed harmonistic approach to design DOPs. The findings provide a degree of evidence for accepting the research hypothesis

articulated in Section 1.5.2. This assertion is underpinned by the following observations:

- A significant majority, 92.9%, of DOP evaluators found the tool useful, beneficial and are willing to use it in their conceptual synthesis activity workflow. Furthermore, none of the evaluators reported prior exposure to or usage of a similar tool within the industry.
- A substantial proportion of the evaluators, 83.7%, attested that the harmonistic approach framework provides awareness and supports in mitigating population use-phase and design-stage conflict consequences (PUCs and DCCs), as well as motivate designers to explore alternative harmonised DOP solutions.
- A substantial majority, 88.8%, of the evaluators, agree that this user-centred design (UCD) approach proactively supports them in concurrent consideration of hf-Multi X, providing awareness of multiple life-phase view consequences and guides towards a harmonised unified solution via the harmonistic knowledge.

Evidence for the research hypothesis

By evaluating the results collected from the research evaluation and the aforementioned results, it is argued that the research hypothesis has been validated. There is significant evidence to suggest that the developed harmonistic design approach framework provides designers adequate support during the conceptual synthesis of DOP design activities.

Data privacy and security

It is worth noting that during all the studies, from the exploratory phase through to data collection for the tool and proof-of-concept evaluation, data privacy and security were prioritised. Every participant remained anonymous, and no personally identifiable information was collected. Furthermore, every data collection instruments used in this research, was reviewed and approved by the University Research Ethics Committee (UREC) to ensure that data privacy was not compromised.

12.2 Future Improvements and Research Directions

Work required to develop the results further

In the preceding section (Section 12.1.6), the dissertation presented favourable evaluation outcomes. Nonetheless, there exists future research avenues for additional research endeavours. These are warranted to address the supplementary observations made by DOP evaluators, as delineated in Section 11.3.5, and to confront the identified limitations inherent within both the harmonistic knowledge-based DOP design approach framework and the computer-based tool.

12.2.1 Approach Framework Improvements

Expanding (sub) human factors

Currently the approach framework utilises human factors knowledge modelling of three aspects: ergonomics, persona and aesthetic sub-aspect under emotions. To enhance the integration of human factors further, this approach could be expanded to include additional aspects or sub-aspects of human factors, such as cognitive aspects, or to incorporate other elements beyond aesthetics that influence emotions, such as symbolism.

Other DFXs + human factors

The knowledge models constructed throughout this research have been centred on human factors. There exists a requisite for future investigations to explore how this approach can be further evolved to explicitly make designers aware of additional considerations in product development, that is design for other *Xs* (DFXs), in conjunction with human factors.

Product development considerations may encompass:

- The mechanical design or functional aspects of the DOP. In case of motorcycle artefact, this includes engine configuration and specifications, transmission, damping systems, and braking systems.
- Financial aspects of the DOP throughout its development phase, covering costs associated with design, manufacturing,

assembly, and the procurement of standard parts, among others.

Other product life-cycle views

This research has provided insights into knowledge pertaining to multiple life-phase views. More specifically this research presented DCC and PUC knowledge, representing different phases within the product life-cycle, specifically design and use phases. There is a necessity for further research to identify and elaborate on other life-cycle phases beyond the ones mentioned herein, such as the manufacturing life-cycle view.

Accordingly, subsequent investigations should also aim to revisit and refine the harmonistic knowledge. This entails making designers aware and harmonising conflicts between human factors and aspects considered during the manufacturing phase. Another direction is to consider the needs of both target and general users, and other 'design for X' considerations, which may encompass a multitude of aspects such as financial aspects or design for manufacturing within the context of DOPs.

12.2.2 Prototype Tool Improvements

Other support types

The participants have indicated that the prototype tool could be enhanced by including additional support types. As such, future enhancements to the computer-based tool could involve in expansion of a broader array of library elements and consequences. For instance, this could entail in DOP technical specifications related consequences. Specifically, in the context of motorcycles, this enhancement could address not only the consequences pertaining to human factors but also the potential adverse effects on motorcycle handling, reliability, mechanical engineering system, as well as other considerations such as cost of development. Moreover, the current approach to human factors, such as ergonomic support, relies predominantly on the rider's

triangle. This approach overlooks aspects such as seat cushioning, which, in practical terms, significantly impacts ergonomics.

Other user attributes other than personality or behaviour

Evaluators have noted that users' personalities are not explicitly included during the design process, despite such requirement was stipulated in the problem definition. This observation suggests that the industry may not have fully adopted a shift towards a total UCD. Nonetheless, future work necessitates to focus more on user attributes, such as context of use, frequency of use, etc., as opposed to emphasise on the users' personality and behaviour with the product during its use phase.

Highlight interaction between target and general user

As transpired from the evaluation detailed in Chapter 11, while the harmonistic approach framework makes designers aware of conflicts between a) target and general users, and b) human factors considered at different stages, there is a need for improvements to the computer-based tool. Such improvements are essential to portray the interaction happening between the target user and the general user. The feedback has indicated a necessity for these interactions to be visually more prominent within the graphical user interface of the computer-based tool.

Implementation of KIF

As transpired from Chapter 10, the Knowledge Interpretation Frame (KIF) was not implemented as preliminary framework evaluations suggested that it was not a core frame of the approach framework. However, during the actual evaluation, there were two evaluators who highlighted the significance of incorporating this frame, not as a fundamental component but as an enhanced method for presenting the harmonised solution product model to designers. Thus, future work shall explore the development of this frame, potentially employing cutting-edge algorithms from *generative artificial intelligence* (GEN-AI), such as *generative adversarial networks* (GANs).

Furthermore, future work could also investigate the implementation of the CAD Interface Engine (CAD-IE). This would facilitate the creation of

an interface with existing computer-aided design (CAD) tools. Such an endeavour would necessitate further development of the computer-based tool system architecture to enable interfaces with other CAD/simulation systems.

12.3 Doctoral Research Contributions

12.3.1 Primary Contribution to Knowledge

Main contribution

As a result of the research work carried out, the main original and significant contribution to knowledge arising from this doctoral research is:

> *A user-centred design framework that prescribes a human factor ($hf_{E\text{-}AE\text{-}P}$) and harmonisation knowledge-based design approach to proactively support the dual ontological product synthesis design activity.*

Main contribution manifestation

The main contribution to knowledge highlighted above manifests itself in the generalised harmonistic approach design framework for dual ontological products – *HARMONIOUS*.

Looking beyond the specific case study

In this research work the archetype framework for the motorcycle case study – *DESMO* was also explored as an exemplar of the *HARMONIOUS* framework. *DESMO* was in turn employed as a bases to develop the computer-based prototype tool – *DESMO-APP*. This approach was intended to offer tangible examples that could help explain abstract principles of DOPs, without necessarily restricting the scope of the research to solely the motorcycle artefact. It is thus argued that the relevance and potential applicability of *HARMONIOUS* may extend beyond the specific case study (*DESMO*) used for demonstration. While it remains challenging to establish this with certainty, several arguments could be advanced to suggest its generalisability beyond the motorcycling domain:

- The literature review carried out in Chapter 5 reviewed *means* beyond motorcycles. In fact, similar work has been identified,

such as the work by Kaljun & Dolsak (2011), which harmonises ergonomics and aesthetics for hand tool products, amongst others. The knowledge gap that *HARMONIOUS* addresses, as defined in Section 5.10, is not confined to a singular domain but is applicable to a broad range of DOP products.

- Blessing & Chakrabarti (2009) argued that validating a theoretical framework directly might pose challenges due to the inherent abstract nature of the theory, suggesting that a prototype should be employed to clarify the theory in a manner accessible to industrial designers. Consequently, the *DESMO* case study is a proof-of-concept that demonstrates the practical applicability and effectiveness of the *HARMONIOUS* framework for motorcycles. Although the evaluation primarily concentrated on motorcycles, by analogy, *DESMO* served as a tangible example of the framework's validity and potential applicability across various domains.
- Five from six evaluators who worked in another domain besides that of the motorcycle, foresaw that the *HARMONIOUS* framework could be employed in other fields. Additionally, they provided specific automotive examples (as detailed in Section 11.3.5) on how *HARMONIOUS* could be adopted and applied to a variety of dual ontological products beyond motorcycles. Though preliminary, these observations by five DOP designers highlight the potential of *HARMONIOUS* to be utilised across different domains.

12.3.2 Comparison with the State-of-the-Art

In order to demonstrate how the *HARMONIOUS* approach framework makes a contribution to current knowledge, Table 12.1 compares the harmonistic design approach framework with the state-of-the-art support *means*.

Table 12.1 – Comparison of harmonistic design approach framework with the sate-of-the-art

Review Criteria	**State-of-the-Art Support *Means***	***HARMONIOUS* Design Approach Framework for DOP**
Timing and Activity	Providing support *late* in the design process or not in the conceptual synthesis activity	Providence of pro-active support *early* in the design DOP process, specifically in the conceptual synthesis design activity
Multiple Life-Phase View	No multiple life-phase awareness. View only to one life-phase	Multiple life consequence awareness of: i. Human factors considered at a later design stage and activity (DCCs) ii. DOP's use-phase for both intended and non-intended users (PUCs)
Guidance Type	Consideration of *either*, ergonomics *or* aesthetic-derived emotions *or* persona, but not the three human factors at the same time	Concurrent consideration of the three human factors *($hf_{E\text{-}AE\text{-}P}$)*
Harmonisation Awareness	No or limited harmonisation. Full harmonisation only between two human factor aspects	Harmonisation of $hf_{E\text{-}AE\text{-}P}$: i. Ergonomics ii. Aesthetic-derived emotions iii. Persona—Target User iv. Persona—General User

Timing and activity

In contrast to state-of-the-art support *means*, it is argued that the proposed harmonistic approach framework proactively supports DOP designers in the early routine design process. Hence, DOP designers can immediately address PUCs, DCCs and harmonisation at the conceptual synthesis design activity, when the artefact solution model is still evolving and easier to implement changes to the DOP solution before major expenses.

Multiple life-phase view

The *HARMONIOUS* framework provides multiple life-phase views knowledge, and therefore assists in foreseeing the design-stage conflict consequences (DCCs) arising between $hf_{E\text{-}AE\text{-}P}$ considered at the early routine design process with those considered at a later process. Furthermore, it is argued that this knowledge assists in making aware DOP designers of population use-phase consequences (PUCs) for both intended (target) and non-intended (general) but potential customers. Revealed PUC and DCC knowledge allows designers to explore alternative decision commitments in order to avoid or minimise these consequences. This human factor knowledge is derived from a UCD approach, where the framework captures (potential) user-related human factor characteristics. Such an approach enables to foresee consequences that arise when these human factor characteristics interact with the evolving DOP model.

Guidance type

In comparison to the *means* reviewed, it is argued that the developed *HARMONIOUS* design approach framework motivates and supports multi human factors (hf-Multi X), by concurrently considering ergonomics, aesthetic-derived emotions and persona aspects ($hf_{E\text{-}AE\text{-}P}$).

Harmonisation awareness

The evaluators agreed that the harmonistic design approach framework guides and directed them towards a harmonised synthesis DOP solution, utilising harmonisation knowledge to harmonise the three human factors:

i. Ergonomics
ii. Aesthetic-derived emotions
iii. Persona through the Target User
iv. Persona through the General User

Addressed Research Gap

The research gap presented in Section 5.10 and summarised through Table 12.1, illustrates that none of the means reviewed, with respect to the established four review criteria, contributes directly towards supporting DOP designers with harmonistic knowledge during the dual ontological product design process. The evaluation results can

therefore lead to the assertion that the original approach to design DOP developed during this doctoral research, addresses the research gap identified in the state-of-the-art.

12.3.3 Secondary Contributions

Other secondary contributions

The research work that led to the development and implementation of the *HARMONIOUS* approach framework required an understanding of; how design and use-phase consequences emerge from interactions between human factors and DOP synthesis decision commitments; and how to model this knowledge. Hence, other secondary original contributions have also been made:

1. *Characterisation of the DOP user-centred design problem leading to a phenomena model that explains how dual ontological product evolution occurs during population majority privation and design stage conflict.*
2. *A machine learning and harmonistic knowledge-based system architecture that defines the conceptual structure on which computer-based tools for supporting the design of DOP can be developed.*

12.3.4 Significance of Research Work

This doctoral research has contributed towards both the DOP design research community and industry.

<u>Significance on DOP design research community</u>

Dual ontological products paradigm

Throughout this dissertation the doctoral research has expanded on the paradigm of dual ontological products by further adding to the body of literature DOP characteristics (Chapters 2 and 3), requirements of DOP users (Chapter 3) and the challenges encountered during the design process of such products (Chapter 4). These insights were directly observed from individuals who use and design DOPs. Considering that products of dualistic nature are classified under the

overarching category of 'products', this research has endeavoured to apply principles defined in *'Design Theory'* specifically to the conceptual design of dual ontological products. The applied concepts encompass the life-cycle of DOPs and DOP life-cycle consequences, DOP activity-based design (Chapters 3 and 4), synthesis decision-making in DOP design (Chapter 7) and the DOP solution model (Chapter 9).

PUCs and DCCs phenomena

This research has given further proof of population majority privation and design-stage conflict exist in industrial reality and consequently developed a phenomena model that provides an understanding how this privation and conflicts can occur from two different conditions: PUCs and DCCs. This model was directly informed by experiences of actual designers in the field and further substantiated by the literature. This dissertation argues that knowledge of dual ontological product synthesis decision consequences is not always known. This explains why supporting designers in explicitly becoming knowledgeable of PUCs and DCCs resulting from synthesis decision commitments, assists them in handling of population majority privation and design-stage conflicts. The explanations provided by the phenomena model and the harmonistic knowledge model provide a basis for developing solutions that help DOP designers being aware of PUCs and DCCs, whilst providing recommendations in order to minimise the negative consequences.

Harmonistic approach

According to Ulrich et al. (2020) and Hassenzahl (2010), it is imperative for designers to harmonise aspects related to the human factor in order to create products that are both effective and successful in the market. The harmonisation between these human factor aspects is often an area of difficulty for the designer (Hu et al., 2020) and has been identified by the product design research community as a pivotal area necessitating further investigation (Zhou et al., 2023). As explained in Chapters 8, 9 and 10 this doctoral research has enriched the understanding of how to guide DOP designers towards achieving a

harmonised DOP solution model. In doing so, this doctoral research has made a significant contribution to the development of a harmonistic design approach that supports the DOP synthesis decision-making activity by providing human factor knowledge to foresee population use-phase and design-stage conflict consequences (PUCs and DCCs) as well as by providing harmonisation guidance knowledge.

KDD as a user-centred approach

This doctoral research has also concluded that the design of DOPs, with regards to human factors, necessitates intricate and complex to accurately model the interactions between $hf_{E\text{-}AE\text{-}P}$ and DOPs. Moreover, due to the population majority privation phenomenon it was deemed essential to model the general user. Consequently, as posited in Chapter 9, traditional computational techniques have been found to be inadequate for addressing these complexities. Therefore, this doctoral research has brought forward the notion of knowledge discovery from data (KDD) to the design research community, offering an approach framework which defines *what* and *how* to model user-centred harmonistic knowledge in order to develop computer-based design tools that can address the aforementioned problem.

Support means bridging the research gap

The examination of the state-of-the-art presented in Chapter 5 identified a research gap where, collectively none of the reviewed means—according to the specified criteria specified, provide a pro-active support early in the design process of DOPs that concurrently consider $hf_{E\text{-}AE\text{-}P}$, make the DOP designer aware of human factors consequences considered at a later design stage and activity (DCCs) and DOP's use-phase consequences for both intended and non-intended users (PUCs), whilst guiding towards a harmonised design solution. In light of this, the developed harmonistic design approach framework has made a contribution to the design research community by bridging this knowledge gap.

Significance on DOP design practice

UCD philosophy

The research methodology employed in this doctoral dissertation was founded on a UCD research philosophy. This entailed the direct engagement of DOP designers to understand their DOP design reality by understanding their challenges and requirements for improving their reality situation, through the validation of the developed solution (presented in the form of a computer-based tool). These are reported in the two descriptive studies of this dissertation, presented respectively in Chapters 4 and 11.

Computational means for solving DOP designer's challenges and requirements

The evidence presented in Chapter 4 demonstrated that DOP designers necessitated to be:

- Supported in the conceptual synthesis design activity
- Assisted through a design computer-based support tool
- Provided with a user-centred design approach
- Made aware of multiple life-phases (design and use)
- Provided with concurrent design for hf-Multi X
- Guided towards a harmonised solution.

The evaluation results, as detailed in Chapter 11 showed that these requirements were effectively incorporated within the computer-based tool. As such, this substantiates that DOP designers' requirements were satisfied, since their challenges have been addressed through the validation of the computer-based design tool.

As reflected in the evaluation via the *DESMO-APP* computer-based tool, the framework offers a *means* through which the theories of DOPs, human factors, and harmonisation are leveraged for the development of computer-based design tools. The system architecture upon which the *DESMO-APP* was developed has contributed to a conceptual model for developing computer-based design tools that actively offer guidance on DOP design, emphasising harmonistic knowledge. The significance of appropriate knowledge structuring,

modelling, and capturing was underscored during the evaluation. This is reflected in the fact that the evaluators strongly expressed their wish to have and utilise harmonistic knowledge-based tools in industrial practice.

Further to the development of the computer-based tool to make DOP designers' aware of population use-phase and design-stage conflict consequences (PUC and DCC) along with decision guidance knowledge, it is argued that this doctoral research has also contributed to DOP designers with procedural knowledge. This knowledge specifically pertains to the process of how to gather information related to human factors ($hf_{E\text{-}AE\text{-}P}$) from (potential) customers of DOPs.

Closing the industrial gap

When evaluators were inquired if they had previously encountered or utilised a tool similar to the computer-based tool in question, all evaluators have stated that they have never came across a tool enabling them to design ergonomically safe and at the same time aesthetically pleasing DOPs. As such this underscores the tool's contribution to addressing an industrial gap in the design of DOPs.

Useful and beneficial in the industry

Evaluators acknowledged the applicability of the computer-based tool within the DOP industry and perceive its utility extending to other domains, such as the automotive industry, provided that the proper knowledge is used. The findings also demonstrate that the computer-based tool is very helpful and highly beneficial in practice, and would recommend this tool mainly because of its prevailing support and harmonisation capabilities. Additionally, there was a desire among evaluators for the adoption and utilisation of harmonistic knowledge-based tools in the industrial practice, highlighting the tool's compatibility with their design workflow.

12.4 Doctoral Research Concluding Remarks

Reality exploration discovered industrial designers' challenges, and expectations from an approach framework, when designing dual

ontological products from the three human factors perspective ($hf_{E\text{-}AE\text{-}P}$). Furthermore, the current *means* that support the DOP design process provide support late in the design process or not in the conceptual synthesis activity. It is concluded that none of the means reviewed contributes directly towards supporting DOP designers with harmonistic knowledge during the DOP process. To address these industrial and literature gap, it is concluded that this doctoral research contributes a novel human factor ($hf_{E\text{-}AE\text{-}P}$) and harmonisation knowledge-based DOP design approach framework. Through the establishment of a harmonistic knowledge model and the identification of (i) a set of general computer-based tool requirements (ii) user derived declarative knowledge (iii) a machine learning type knowledge discovery from data based architecture and (iv) harmonisation modelling, the prototype computer-based design tool was realised.

The validation results, derived from the evaluation of the computer-based tool by industrial designers, lead to the conclusion that the harmonistic knowledge-based dual ontological product development approach demonstrates the practical utility and benefit in the industry. Furthermore, the encouraging results obtained from the evaluation collectively reflect the relevance to design practice of providing a machine learning and harmonistic knowledge-based system architecture computer-based design tools.

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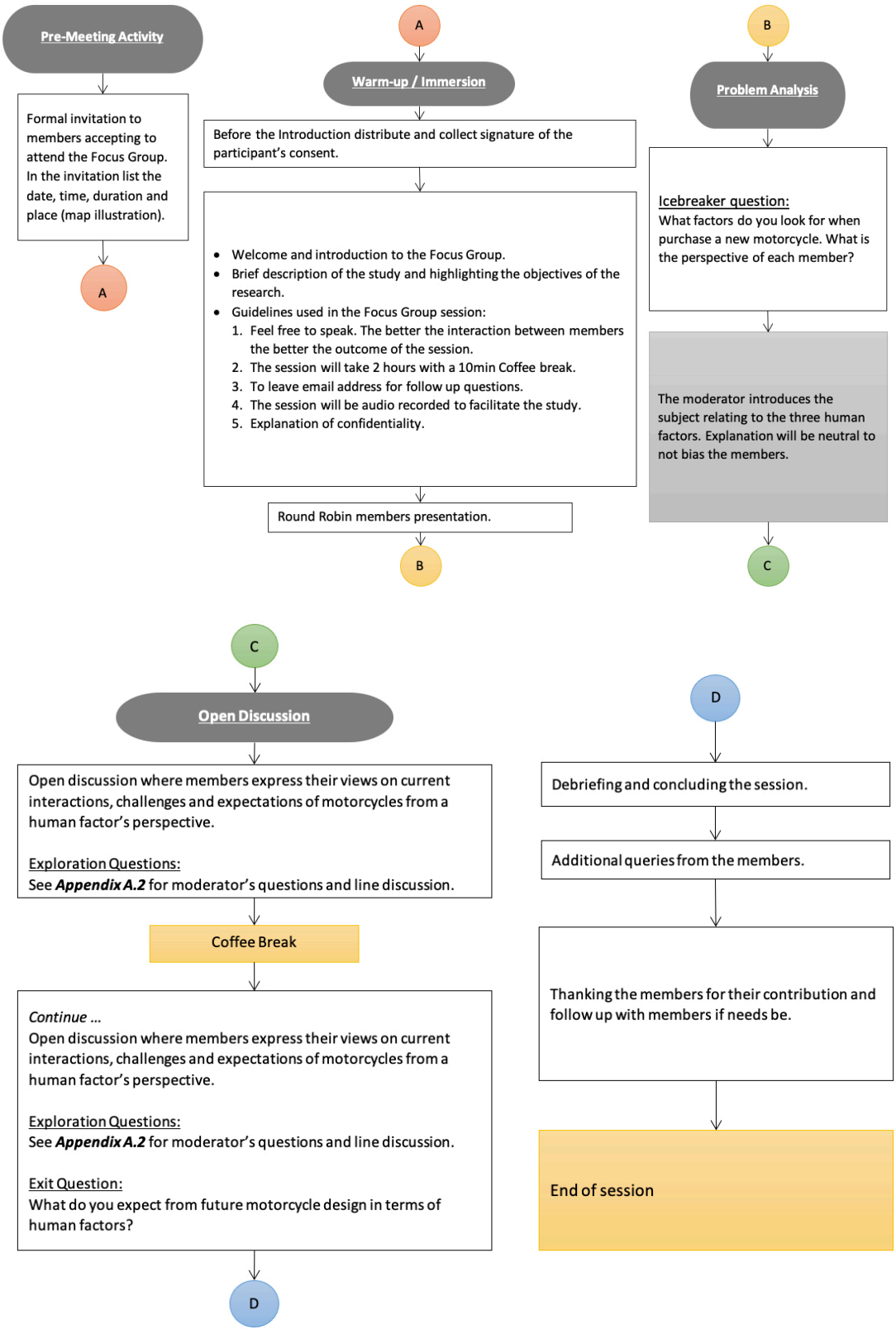
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Appendix A: Focus Group (*Study A*)

A.1 Focus Group Study Procedure



A.2 Focus Group Questions

Question 1

What challenges related to motorcycle design are you currently facing regarding:

- Ergonomics
- Aesthetics
- Rider behavior with the motorcycle

How do these factors impact accidents, safety, and riding pleasure? What new features would you like to see in future motorcycles?

Question 2

How do you interact with your motorcycle or new motorcycles in terms of:

- Ergonomics
- Aesthetics
- Rider behavior with the motorcycle

For instance, what features would you like new motorcycles to have to improve sales? What aesthetic aspects make a motorcycle more appealing?

Question 3

Regarding ergonomics, what would make a motorcycle more marketable? Additionally, how can we reduce accidents?

Based on your experience in motorcycle design and accessories:

- What problems do riders face during long-distance travel?
- What causes a rider to lose control of a motorcycle?
- What features should a simulator have to address these issues?

Question 4

Do you believe there is a connection between a rider's personality or riding behavior and accidents? Or with the context of use? Why? How about the impact of motorcycle riding groups?

Question 5

Which aspects of the motorcycle do you prioritize in terms of:

- Ergonomics
- Aesthetics
- Rider behavior with the motorcycle

Why?

Question 6

Which of the following human factors do you prioritize:

- Ergonomics
- Aesthetics
- Rider behavior with the motorcycle

Consider the entire experience, from seeing the motorcycle for the first time in a showroom to its long-term use. Why?

Question 7

Do you have any specific requirements or expectations for developing future motorcycles that best fit your needs and consider the three human factors discussed earlier?

Question 8

Are there any other thoughts or suggestions on this topic that we haven't mentioned?

Appendix B: Survey to Local Riders (*Study B*)



L-Università ta' Malta
Faculty of Engineering

Department of Industrial & Manufacturing Engineering

Information Letter to Participants

Dear Sir/Madam,

I am a researcher at the University of Malta and I am currently reading for a Ph.D. which is being supervised by Dr Ing. Philip Farrugia and co-supervised by Dr Ing. Emmanuel Francalanza. The purpose of this Ph.D. research is to develop a computer-based tool which proactively supports design engineers to develop rider-centred, safer (through improved comfort/ergonomics) motorcycle designs, while at the same time enhance the aesthetic emotional values of such artefacts. This questionnaire will highlight current problems, which hinder safety and cause ergonomic issues as seen from your perspective, as a motorcycle user.

This Ph.D. work is related to the research project, "RIDE+SAFE" (reference no. R&I-2017-003-T), funded by the Malta Council for Science and Technology (MCST).

As the study is bound by strict deadlines, we would really appreciate if you can send us the questionnaire response by not later than one week.

For further information, or any questions regarding this research study, please do not hesitate to contact me.

Sincerely,

Ing. Sean Agius
Mob: (+356) 79300688
Email: sean.agius@um.edu.mt

Consent Form

This is to certify that, I, give consent to my participation in the above-mentioned research project carried out by Sean Agius, supervised by Dr Ing. Philip Farrugia and co-supervised by

Dr Ing. Emmanuel Francalanza. In this questionnaire, questions will not be personal and will not be linked to my personal identity. Questions will reflect motorcycle problems which hinder safety and cause ergonomic issues.

The questionnaires will be kept safe and strictly private and confidential, used only by Sean Agius for the scope of the research only.

By giving consent, I am:

- Allowing Sean Agius to lead the activities and allow this questionnaire exercise to be used in the study.
- Aware that I retain the right to withdraw from this study at any time, without giving any reason whatsoever.

Participant's Signature / Initials

Date

Questionnaire to Investigate Motorcycle Safety and Comfort

*** Required**

Enter your responses in the provided light-red highlighted cells.

Background Information

Q1. Age: *

Q2. Nationality: *

Q3. Gender: *

Mark with "**X**" only one.

Male

	Female
	Other

Q4a. Do you have a valid and confirmed motorcycle license? *

If the answer is Yes, continue to questions Q4b. If the answer is No, proceed to question Q5.

Mark with "**X**" only one.

	Yes
	No

Q4b. If yes, how long have you held your motorcycle license?

In Years

Motorcycle Experience

Q5. What motorcycle/s do you currently ride or used to ride? *

	Bike 1	**Bike 2**	**Bike 3**	**Bike 4**
Brand:				
Model:				
Year:				
Type: (select from list provided **below**)				
Engine Size: (in CC)				
Frequently Used: (Yes/No)				

Used for long distance rides: (Yes/No)					
Uses: (Commute/Sport/Hobby/Travel)					

Super Sports	Sports Street-Naked	Sports-Tourer	Tourer
			
Classic/Retro	**Classic Cruiser**	**Power-Cruiser**	**Chopper**
			
Standard Street-Naked	**Adventure-Tourer**	**Off-Road**	**Scooter**
			

Q6. How frequently do you use your motorcycle? *

Mark with "**X**" only one row for each motorcycle **outlined in Q5.**

	Bike 1	**Bike 2**	**Bike 3**	**Bike 4**
Once a month:				
Once a week:				
2 days a week:				
5 days a week:				
Every day:				

Q7. What is the average distance that you cover with your motorcycle per year? *

Mark with "**X**" only one row for each motorcycle **outlined in Q5.**

	Bike 1	**Bike 2**	**Bike 3**	**Bike 4**
0 - 2,000 km / year (0 - 38 km / week)				

2,000 - 5,000 km / year (38 - 96 km / week)					
5,000 - 10,000 km / year (96 - 192 km / week)					
10,000 - 20,000 km / year (192 - 385 km / week)					
Over 20,000 km / year (Over 385 km / week)					

Q8a. Have you ever made long-journey trips, exceeding 200 km? *

If the answer is Yes, continue to questions Q8b. If the answer is No, proceed to question Q9a.

Mark with "**X**" only one row for each motorcycle **outlined in Q5.**

	Bike 1	**Bike 2**	**Bike 3**	**Bike 4**
Yes:				
No:				

Q8b. If yes,

	Bike 1	**Bike 2**	**Bike 3**	**Bike 4**
How long was the trip? (in Hours)				
How long was the trip? (in Kilometers)				
For how long did you ride before taking a break? (in Hours)				
For how long did you ride before taking a break? (in Kilometers)				

Q9a. Have you ever had any accident with your motorcycle? *

If the answer is Yes, continue to questions Q9b and Q9c. If the answer is No, proceed to question Q10.

Mark with "**X**" only one row for each motorcycle **outlined in Q5.**

	Bike 1	**Bike 2**	**Bike 3**	**Bike 4**
Yes:				
No:				

Q9b. If yes, what was the cause of the accident?

Select appropriately. Multiple rows can be marked with "**X**" for each motorcycle/s **outlined in Q5.**

	Bike 1	**Bike 2**	**Bike 3**	**Bike 4**
Non-adherence to road traffic-rules:				
Road hazard/defects:				
Bad weather conditions:				
Driving under the influence of alcohol/drugs:				
Recklessness, e.g. Over-speeding:				
Failure to see other vehicles/pedestrians:				
Vehicular defects:				
Loss of control:				
Other:				

Q9c. Briefly describe the accident/s:

Motorcycle Ergonomics

Motorcycle Ergonomics is the study of how motorcycles can be modified/adjusted so that these vehicles fit the riders who use them for increased comfort and safety.

Q10. During trips, how often do you experience the following pains/numbness? *

Insert your motorcycle model/s (**outlined in Q5**) which best describe/s the following statements.

E.g. With a particular motorcycle "*Bike 1*" you **Constantly** feel **Pain in the neck** while with "*Bike 2*" you **Never** feel the **Pain** and with "*All your bikes*" you have **Constant Back pain.**

	Never	Sometimes	Often	Constantly
Pain in Neck:				
Pain in Shoulders:				
Pain in Arms/Elbows:				
Pain in Wrists:				
Numbness of Arm:				
Back Pain:				
Pain in Waist region:				
Pain in Calves:				
Pain in Ankles:				
Cramps/Numbness of Legs:				
Other:				

Q11. To what extent do you think the following pains/numbness impact motorcycle rider-control? *

Insert your motorcycle model/s (**outlined in Q5**) which best describe/s the following statements.

	No Impact →					**High Negative Impact**
	0	**1**	**2**	**3**	**4**	**5**
Pain in Neck:						
Pain in Shoulders:						
Pain in Arms/Elbows:						
Pain in Wrists:						
Numbness of Arm:						
Back Pain:						
Pain in Waist region:						
Pain in Calves:						
Pain in Ankles:						
Cramps/Numbness of Legs:						
Other:						

Q12. How often do you change the following parts of the body while riding? *

Insert your motorcycle model/s (**outlined in Q5**) which best describe/s the following statements.

E.g. With a particular motorcycle "*Bike 1*" you **Constantly** change your **Arms position** while with "*Bike 2*" you **Never change** and with "*All your bikes*" you **Often** have to change your **Legs position.**

	Never	**Sometimes**	**Often**	**Constantly**
Arms position:				
Legs position:				

Back inclination:				
Position on the seat:				
Other:				

Q13. To what extent do you think the following parameters impact motorcycle rider-control? *

Insert your motorcycle model/s (**outlined in Q5**) which best describe/s the following statements.

	No Impact					**High Negative Impact**
	0	**1**	**2**	**3**	**4**	**5**
Motorcycle Vibrations:						
Air-Speed:						
Posture:						
Front Shock-absorber:						
Seat Shock-absorber:						
Other:						

Q14a. Have you ever made changes to your motorcycle? *

For example extending the handlebars, lowering the seat or adjusting fuel tank.

If the answer is Yes, continue to questions Q14b. If the answer is No, proceed to question Q15.

Mark with "**X**" only one.

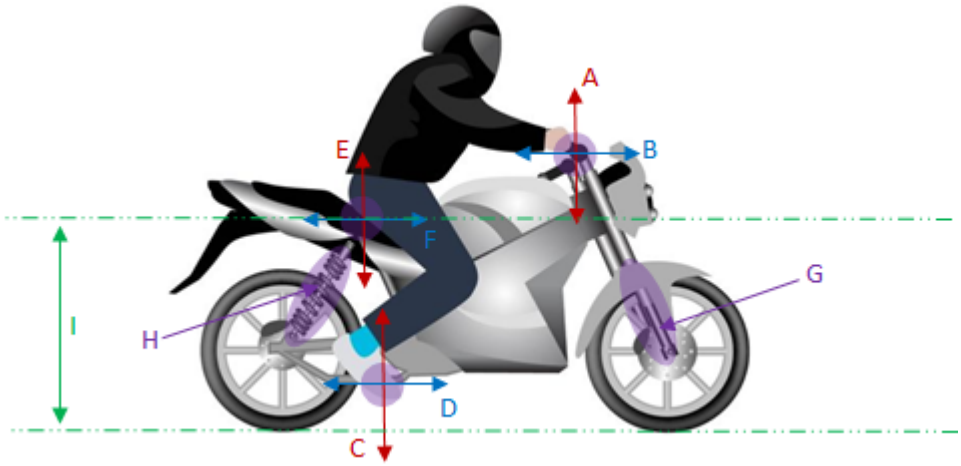
	Yes
	No

Q14b. If yes, what did you change? And for what reason?

Q15. To what extent do you think that the following adjustable motorcycle features would improve safety (through better motorcycle control)? *

Mark with "**X**" only one from each row.

E.g. A bad positioned **handlebar** won't affect your control, thus a score of **0**. *Or*, a bad positioned **handlebar** will highly affect your control, thus a score of **5**.



No ffect ——— **Highly ect your ontrol**

	0	1	2	3	4	5
(A) - Handlebar rise:						
(B) - Handlebar pull-						
(C) - Footpegs rise:						
(D) - Footpegs forward						
(E) - Seat rise:						

(F) - Placement on						
(G) - Front Shock-er:						
(H) - Seat Shock-er:						
(I) - Motorcycle ride						
Other:						

The above image is adopted from:
https://images.vexels.com/media/users/3/70229/raw/734ae57a473a1acc0bff6ab5fd545575-man-riding-motorbike.jpg

Q16. From 1 to 10 (1 being the least and 10 being the most), what importance score would you give to Ergonomics in relation to the choice of motorcycle? *

Mark with "**X**" only one.

1	2	3	4	5	6	7	8	9	10

Q17. From 1 to 10 (1 being the least and 10 being the most), what importance score would you give to Aesthetics in relation to the choice of motorcycle? *

Mark with "**X**" only one.

1	2	3	4	5	6	7	8	9	10

Q18. Do you have a personal suggestion on how to improve motorcycle safety through better control and ergonomics? If so, give a brief explanation.

Thank You

Thank you for taking the time to complete this survey. We truly value the information you have provided. Your responses will contribute towards this research specifically to develop safer motorcycles through better ergonomics and improved emotional experiences.

You can find the latest project updates on our website and you can also follow us on our Facebook page.

Facebook Page Link: https://www.facebook.com/RideAndSafe

If you have any comments on the survey or the research, please leave a comment below.

Many thanks,

Ing. Sean Agius

Comments:

Appendix C: Semi-Structured Interview with DOP Designers (*Study C*)



L-Università ta' Malta
Faculty of Engineering

Department of Industrial & Manufacturing Engineering

Information Letter to Participants

Dear Sir/Madam,

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For further information, or any questions regarding this research, please do not hesitate to contact me.

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The participation will be audio recorded to aid the researcher. The recordings will be kept safe and strictly private and confidential, used only by Ing. Sean Agius for the scope of the research only.

By giving consent, I am:

• Allowing Ing. Sean Agius to lead the activities and allow this questionnaire exercise to be used in the study.

• Aware that I retain the right to withdraw from this study at any time, without giving any reason whatsoever.

• Authorise Sean Agius to audio record my participation.

• Treating this information as private and confidential.

Participant's Signature / Initials	Date

Questionnaire to investigate current challenges designers face when designing motorcycles

1: Background Information

Q1. What is the highest level of education attained?

	Secondary school
	Higher national diploma or equivalent - Level 5
	Bachelor's degree or equivalent - Level 6
	Master's degree or equivalent - Level 7
	Doctoral degree or equivalent - Level 8
	Other: _____

Q2. What is your academic/professional background?

Q3. What is your work position/title?

Q4. How long have you been in this position?

In Years

Q5. What are your key responsibilities in this position, particularly in relation to motorcycle design?

2: Current Work Practices

Q6. During the motorcycle design phase, how often do you design for the following target customers?

	Never	Sometimes	Often	Constantly
Customise the design for a particular customer (Bespoke)				
Design for a general customer segment *E.g. Design motorcycles to be used in India or design scooter motorcycles only.*				
Universal design (For general riders)				
Other:				

2.1: Ergonomics

Motorcycle Ergonomics is the study of how motorcycles can be modified/adjusted so that these vehicles fit the riders who use them for increased comfort and safety.

Q7. To what extent does your company give priority to motorcycle ergonomics?

No priority ⟶ **High priority**

0	1	2	3

Q8. If the answer to *Q7* is *2 or 3*, how ergonomics are taken into consideration during motorcycle design, and in what design phase?

Refer to the Motorcycle Design Phase illustration

Q9. To what extent does your company use anthropometric data during motorcycle design?

Never used ⟶ **Highly used**

0	1	2	3

Q10. If the answer to *Q9* is *2 or 3*, how anthropometric data is taken into consideration during motorcycle design, and in what design phase?

Refer to the Motorcycle Design Phase illustration

2.2: Aesthetics and Emotions

Emotion is a mental state associated with thoughts, feelings, behavioural responses, and a degree of pleasure or displeasure.

Q11. To what extent does your company give priority to motorcycle aesthetics?

No priority ⟶ **High priority**

0	1	2	3

Q12. If the answer to *Q11* is *2 or 3*, how motorcycle aesthetics are taken into consideration during the design, and in what phase?

Refer to the Motorcycle Design Phase illustration

Q13. To what extent does your company give priority to riders' elicited emotions to different motorcycle styles and shapes?

No priority ⟶ **High priority**

0	1	2	3

Q14. If the answer to *Q13* is *2 or 3*, how riders' elicited emotions are taken into consideration during the design, and in what phase?

Refer to the Motorcycle Design Phase illustration

2.3: Persona

Persona in relation to motorcycles refer to human characteristics which influence their behaviour whilst riding a motorcycle in a way which can affect health and safety. An example of a persona is the experience of a rider on a motorcycle or their personality type (e.g. aggressive or calm personality).

Q15. To what extent does your company give priority to riders' road experiences?

No priority ⟶ **High priority**

0	1	2	3

Q16. If the answer to *Q15* is *2 or 3*, how riders' road experiences are taken into consideration during motorcycle design, and in what design phase?

Refer to the Motorcycle Design Phase illustration

Q17. To what extent does your company give priority to riders' personas in relation to the chosen type of motorcycle?

No priority ⟶ **High priority**

0	1	2	3

Q18. If the answer to *Q17* is *2 or 3*, how riders' personality type are taken into consideration during motorcycle design, and in what design phase?

Refer to the Motorcycle Design Phase illustration

3: Suggestions for a Motorcycle Design Support Tool

Q19. Rate how much it is important to consider ergonomic factors whist designing motorcycles.

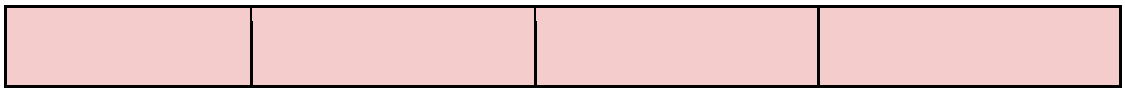
Not important ⟶ **Very important**

0	1	2	3

Q20. Rate how much it is important to consider riders' elicited emotions to different motorcycle styles and shapes while designing motorcycles.

Not important ⟶ **Very important**

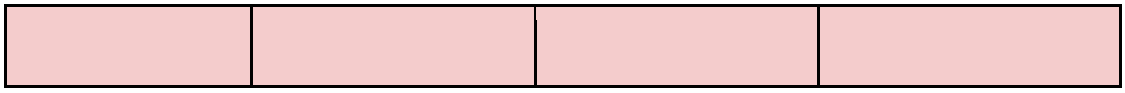
0	1	2	3



Q21. Rate how much it is important to incorporate brand image while designing a motorcycle.

Not important ⟶ **Very important**

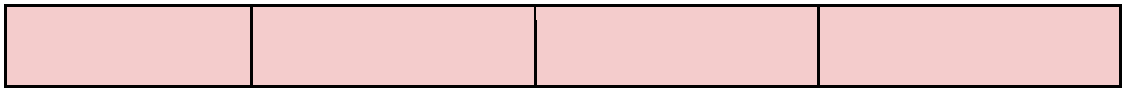
0	1	2	3



Q22. Rate how much it is important to consider riders' personas and their motorcycle experiences while designing motorcycles.

Not important ⟶ **Very important**

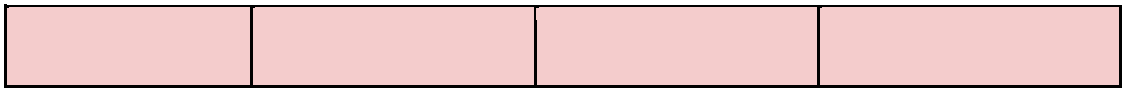
0	1	2	3



Q23. Rate how much it is important to understand the target customers' requirements.

Not important ⟶ **Very important**

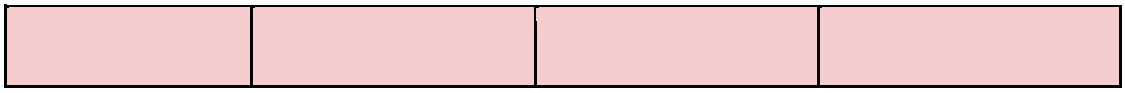
0	1	2	3



Q24. Rate how much it is important to acquire real customer postural data and ergonomic feedback.

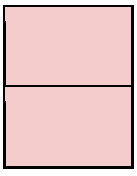
Not important ⟶ **Very important**

0	1	2	3



Q25. In which design phase, it is likely that such Design Tool will be used? Also, explain why?

Refer to the Motorcycle Design Phase illustration



(A) Conceptual Design

(B) Embodiment Design

	(C) Detailed Design
	Other: _____

Q26. In which activity, it is likely that such Design Tool will be used? Also, explain why?

Refer to the Motorcycle Design Phase illustration

	1. Problem Definition
	2. Synthesis
	3. Simulation
	4. Evaluation
	Other: _____

Q27. What kind of Design Tool you imagine to be working with? Also, explain why?

	Manual based - Formal guidelines
	Computer Support System
	Computer Autonomous System
	Other: _____

Q28. What requirements or features would you recommend incorporating in this Design Tool to help you design new motorcycles from the perspective of human factors?

Q29. Do you have any additional comments in relation to this topic which you feel we have not covered?

Appendix D: Preliminary Validation of the *DESMO* Framework



L-Università ta' Malta
Faculty of Engineering

Department of Industrial & Manufacturing Engineering

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Participant's Signature / Initials

Date

Questionnaire to investigate the preliminary impressions of the *DESMO* framework

Q1. Do you use or have you ever used an approach similar to *DESMO*, which captures customers' elicited emotions, human and ergonomic factors to different motorcycle designs?

☐ Yes

☐ No

Q1a. If the answer to Q25 is <u>Yes</u>, what is it and how it is used?

Q1b. If the answer to Q25 is <u>No</u>, to what extent do you think that *DESMO* would help the designers, to design safer motorcycles (through better ergonomics) and improved user emotion experience while considering human factors at the same time? Also, explain why?

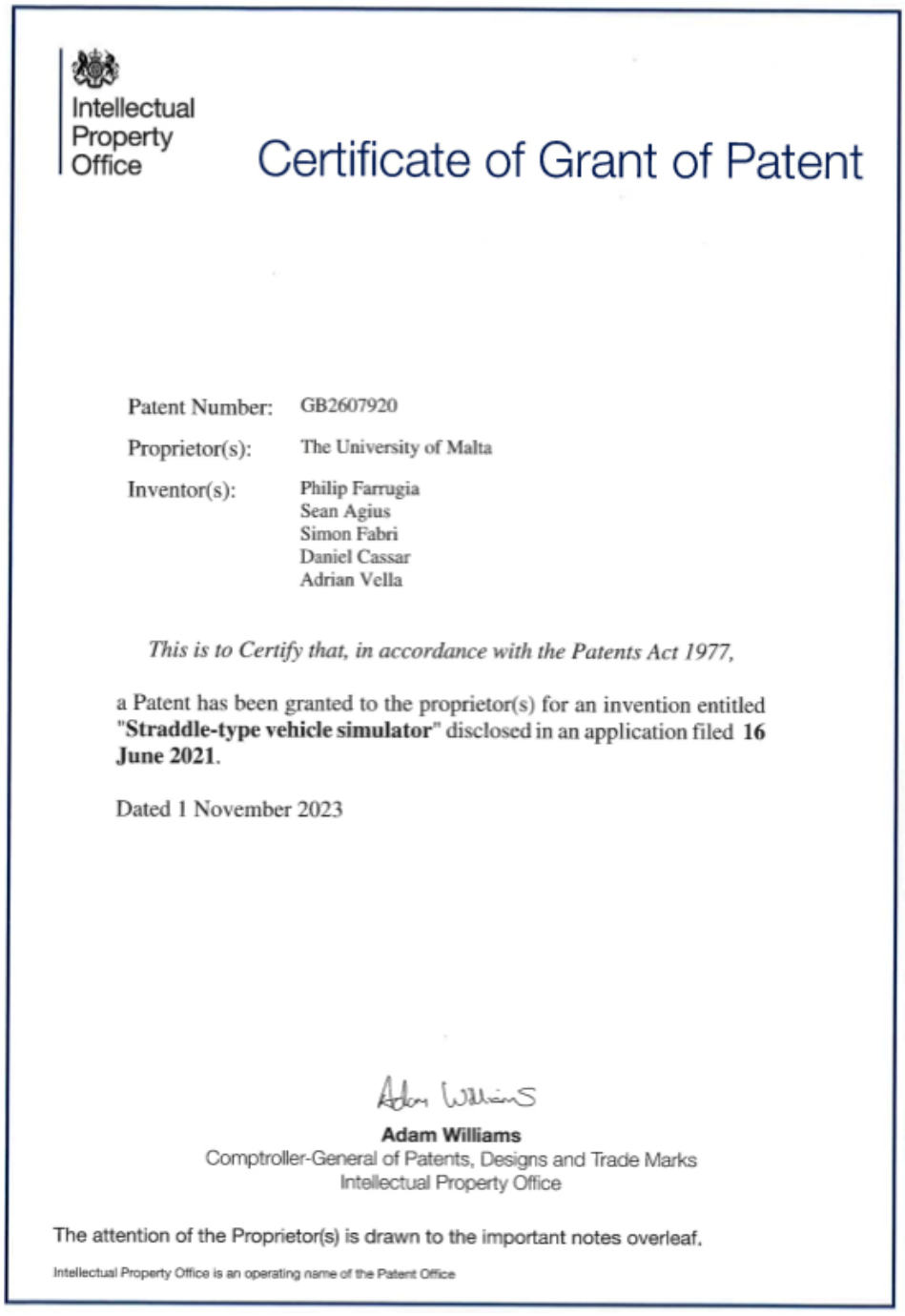
Q2. What is your perspective of the *DESMO* framework?

Q3. How likely will you be using DESMO? Also, explain why?

Q4. Any additional feedback or concern that you have with regards to the presented approach? Explain your reasoning?

Appendix E: *ADAMS – DESMO-APP* Patent

The patent (illustrated below) resulted as a spin-off of this doctoral research. *DESMO-APP* can be used in conjunction with *ADAMS* to assist (i) designers in developing ergonomically sound motorcycles and (ii) motorcycle riders to try, or select the right motorcycle for them before purchase or alteration. This innovative combination ultimately led to the successful acquisition of a patent, highlighting the practical and commercial impact of this research.



Intellectual Property Office

Certificate of Grant of Patent

Patent Number: GB2607920

Proprietor(s): The University of Malta

Inventor(s): Philip Farrugia
Sean Agius
Simon Fabri
Daniel Cassar
Adrian Vella

This is to Certify that, in accordance with the Patents Act 1977,

a Patent has been granted to the proprietor(s) for an invention entitled "**Straddle-type vehicle simulator**" disclosed in an application filed **16 June 2021**.

Dated 1 November 2023

Adam Williams

Adam Williams
Comptroller-General of Patents, Designs and Trade Marks
Intellectual Property Office

The attention of the Proprietor(s) is drawn to the important notes overleaf.

Intellectual Property Office is an operating name of the Patent Office

Appendix F: *ErgoSim-Study*

F.1 ErgoSim-Study Data Collection Instrument

This data collection instrument represents a concise excerpt of the comprehensive data gathering conducted in the study. It is provided to offer the reader a snipet, rather than including the complete dataset, owing to the constraints on the length of the dissertation.

Rider Attributes

Rider Attributes

* Indicates required question

Information Letter to Participants
Dear Sir/Madam,

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This Ph.D. work is related to the research project, "RIDE+SAFE" (reference no. R&I-2017-003-T), funded by the Malta Council for Science and Technology (MCST).

For further information, or any questions regarding this research study, please do not hesitate to contact me.

Sincerely,

Ing. Sean Agius
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Email: sean.agius@um.edu.mt

Consent Form

This is to certify that, I, give consent to my participation in the above-mentioned research project carried by Sean Agius, supervised by Prof. Ing. Philip Farrugia and co-supervised by Dr Ing. Emmanuel Francalan As indicated above and as briefed by Sean Agius, I will be giving my anthropometric measurements and be participating in motorcycle ergonomic simulation runs.

Anthropometric measurements and ergonomic feedback will be kept safe and strictly private and confidential, used only by Sean Agius for the scope of the research only. Participation in this research is voluntary. You can withdraw your consent to participate at any time.

By giving consent, I am:

- Allowing Sean Agius to lead the activities and allow this exercise to be used in the study.
- Aware that I retain the right to withdraw from this study at any time, without giving any reason whatsoever.

1. By signing this form, I am agreeing that I have read and understood the information provide above and I am giving my consent to participate in this research study. I understand and consent that the findings will be anonymously used for this Ph.D. study and related published studies.

Background Information

2. Prospective Participant Name/Initials

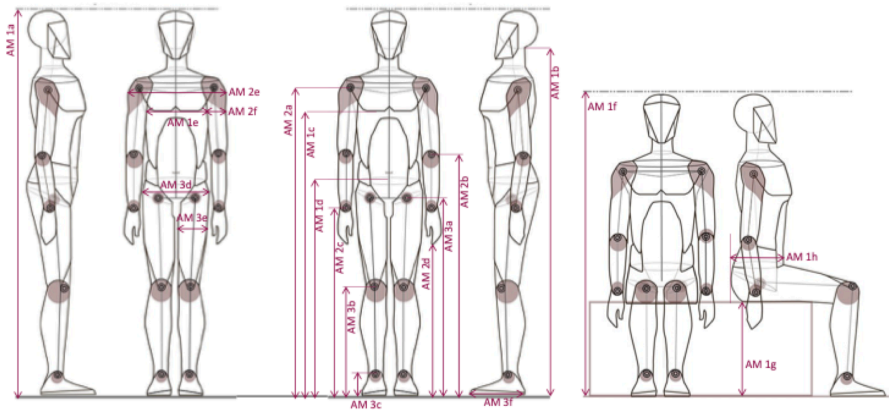
   For traceability use only.

3. How old are you?

Anthropometric Measurements

To minimise the time spent of participation, the researcher recommends the participants to self-take the anthropometric measurements (physical measures of a person's size, form, and functional capacities). The participants are encouraged to use the below chart to guide them in taking their anthropometric measurements. The measurements are then to be jotted in the space provided below. If there are any difficulties in taking certain measurements, the researcher can take them prior starting the simulation on the motorcycle simulator.

Anthropometric Self Measurement Chart



4. Standing Height (AM 1a):
   In centimetres. See above "Anthropometric Self Measurement Chart"

5. Neck Height (AM 1b):
   In centimetres. See above "Anthropometric Self Measurement Chart"

6. Chest Height (AM 1c):
   In centimetres. See above "Anthropometric Self Measurement Chart"

7. Weist Height (AM 1d):
   In centimetres. See above "Anthropometric Self Measurement Chart"

8. Chest Width (AM 1e):
   In centimetres. See above "Anthropometric Self Measurement Chart"

9. Sitting Height (AM 1f):
   In centimetres. See above "Anthropometric Self Measurement Chart"

10. Sitting Bottom Height (AM 1g):
    In centimetres. See above "Anthropometric Self Measurement Chart"

11. Weist/Belly Width (AM 1h):
    In centimetres. See above "Anthropometric Self Measurement Chart"

12. Shoulder Width (AM 2a):
    In centimetres. See above "Anthropometric Self Measurement Chart"

13. Elbow Height (AM 2b):
    In centimetres. See above "Anthropometric Self Measurement Chart"

14. Wrist Height (AM 2c):
    In centimetres. See above "Anthropometric Self Measurement Chart"

15. Finger Point Height (AM 2d):
    In centimetres. See above "Anthropometric Self Measurement Chart"

16. Shoulder Width (AM 2e):
    In centimetres. See above "Anthropometric Self Measurement Chart"

17. Upper Arm Width (AM 2f):
    In centimetres. See above "Anthropometric Self Measurement Chart"

18. Hip Height (AM 3a):
    In centimetres. See above "Anthropometric Self Measurement Chart"

19. Knee Height (AM 3b):
    In centimetres. See above "Anthropometric Self Measurement Chart"

20. Ankle Height (AM 3c):
    In centimetres. See above "Anthropometric Self Measurement Chart"

21. Hip Width (AM 3d):
    In centimetres. See above "Anthropometric Self Measurement Chart"

22. Tigh Width (AM 3e):
    In centimetres. See above "Anthropometric Self Measurement Chart"

23. Foot Length (AM 3f):
    In centimetres. See above "Anthropometric Self Measurement Chart"

24. Weight:
    In kilograms

During Simulation

ErgoSim Test

- For Researcher -
For each different real motorcycle to simulate.

* Indicates required question

1. Prospective Participant Name/Initials *

2. Prospective Participant's Motorcycle ID *

Motion Capture System (Notch App)
- Put motion capture sensors on participant.
- Calibrate sensors (i.e. when participant is in standing position).
- Start recording the motion capture on the Notch App.
- Invite participant to sit on the physical jig and take the riding posture.

Variant 0 - Participant's Real Motorcycle

Variant 0 = Jig adjustment settings will be replicating exactly those of the Real Motorcycle.

>>> Time 0 - on same jig variant set-up <<<

3. Time on the same jig variant set-up.

4. Take note of the time on the Notch App
Participant is in Standing Position

5. Discomfort Ergonomic Feedback

0 - No Discomfort, 10 - Extreme/Unbearable Pain/Numbness (See below Discomfort Scale)

Mark only one oval per row.

	0	1	2	3	4	5	6	7	8	9
Neck										
Chest										
Upper Back										
Lower Back										
Weist										
Bottom										
Shoulder										
Upper Arm										
Fore Arm										
Wrist										
Hand										
Hipps										
Upper Leg										
Lower Leg										
Ankle										
Foot										

Discomfort Scale

Rating Scale to Quantify Discomfort	Perceived Discomfort	Notes/Comments
0	No Discomfort	No Discomfort
1	Minor Discomfort	Feel of discomfort sometimes but not perceivable.
2	Moderate Discomfort	Discomfort is clearly perceivable. Discomfort is reduced if posture is slightly shifted.
3	Severe Discomfort	Discomfort is prominent. Discomfort is not reduced if posture is slightly shifted.
4	Minor Fatigue	Feel of fatigue sometimes but not perceivable.
5	Moderate Fatigue	Fatigue is clearly perceivable. fatigue is reduced if posture is slightly shifted.
6	Severe Fatigue or Minor Pain	Fatigue is not reduced if posture is slightly shifted. *It feels good to stop for a short brake and stretch.*
7	Moderate Pain	Pain is clearly perceivable.
8	Severe Pain	Loss of cognitive ability due to severe pain. One can go on, but has to really push.
9	Severe Numbness	Loss of control due to numb body parts. One can go on, but has to really push.
10	Extreme/Unbearable Pain/Numbness (Need to Stop)	Pain and numbness are so extreme that one has to stop immediately. No cognitive ability and/or control.

6. Adjustment Required (to improve ergonomics)?

   Mark only one oval.

   ◯ Yes
   ◯ No

7. Reason for Adjustment

   Mark only one oval.

   ◯ High score of Discomfort Egonomic feedback
   ◯ Other: _____

>>> Time 1 - on same jig variant set-up <<<

8. Time on the same jig variant set-up.

9. Take note of the time on the Notch App
   Participant is in Standing Position

Discomfort Scale

Rating Scale to Quantify Discomfort	Perceived Discomfort	Notes/Comments
0	No Discomfort	No Discomfort
1	Minor Discomfort	Feel of discomfort sometimes but not perceivable.
2	Moderate Discomfort	Discomfort is clearly perceivable. Discomfort is reduced if posture is slightly shifted.
3	Severe Discomfort	Discomfort is prominent. Discomfort is not reduced if posture is slightly shifted.
4	Minor Fatigue	Feel of fatigue sometimes but not perceivable.
5	Moderate Fatigue	Fatigue is clearly perceivable. fatigue is reduced if posture is slightly shifted.
6	Severe Fatigue or Minor Pain	Fatigue is not reduced if posture is slightly shifted. *It feels good to stop for a short brake and stretch.*
7	Moderate Pain	Pain is clearly perceivable.
8	Severe Pain	Loss of cognitive ability due to severe pain. One can go on, but has to really push.
9	Severe Numbness	Loss of control due to numb body parts. One can go on, but has to really push.
10	Extreme/Unbearable Pain/Numbness (Need to Stop)	Pain and numbness are so extreme that one has to stop immediately. No cognitive ability and/or control.

Variant 1 - Participant's Real Motorcycle

Variant > 0 = Jig adjustments w.r.t. the Real Motorcycle.

31. Vertical Footpeg distance [yFV_FH]
[min. = XX.X, max. = XX.X] (cm)

32. Horizontal Footpeg distance [xFH_FT]
[min. = XX.X, max. = XX.X] (cm)

33. Spanwise Footpeg distance [zFF]
[min. = XX.X, max. = XX.X] (cm)

34. Footpeg Rotation angle (horizontal = 0, clockwise = +ve, anticlockwise = -ve) [beta]
[min. = XX.X, max. = XX.X] (degrees)

35. Vertical Front Seat distance [ySC2_SV2]
[min. = XX.X, max. = XX.X] (cm)

36. Vertical Back Seat distance [ySC1_SV1]
[min. = XX.X, max. = XX.X] (cm)

37. Horizontal Seat distance [xSH_SM]
[min. = XX.X, max. = XX.X] (cm)

38. Push/Pull Top Handlebar distance [xHP1_HF1]
[min. = XX.X, max. = XX.X] (cm)

39. Push/Pull Bottom Handlebar distance [xHP2_HF2]
[min. = XX.X, max. = XX.X] (cm)

40. Rise/Lower Handlebar distance [yHV_HM]
[min. = XX.X, max. = XX.X] (cm)

41. Spanwise Bars distance [hfm]
[min. = XX.X, max. = XX.X] (cm)

42. Bars Pull angle (spanwise = 0, clockwise = +ve, anticlockwise = -ve) [theta]
[min. = XX.X, max. = XX.X] (degrees)

>>> Time 0 - on same jig variant set-up <<<

43. Time on the same jig variant set-up.

44. Take note of the time on the Notch App
Participant is in Standing Position

F.2 Ergo-Persona Table

Rider Attributes		Anthropometric Measurements		Motorcycle Adjustment		Ergonomics	
Age	**Scenario**	**My Anthropometric Measurements**	**Engineered**	**Real Physical Motorcycle Geometry**	**Engineered**	**Posture**	***Ergonomic Discomforts***
18-19	Intermitant *(Short Trip)*	Standing Height (AM 1a)	Neck Length (AM 1a - AM 1b)	Horizontal distance of the Handlebar-grip from the rear tyre touching the ground [pHH_Ox]	HB-X from S [pHH_Ox] - [pSS_Ox]	Head [Flexion(+)/Extension(-)]	Neck
20-24	Repeated *(Traffic)*	Neck Height (AM 1b)	Upper Back Length	Vertical distance of the Handlebar-grip from the rear tyre touching the ground [pHH_Oy]	HB-Y from S [pHH_Oy] - [pSS_Oy]	Thoracic [Flexion(+)/Extension(-)]	Thoracic
25-29	Static *(Long Trip)*	Waist Height (AM 1d)	Lower Back Length	Spanwise distance of the Handlebar-grip from the rear tyre touching the ground [pHH_Oz]	HB-Z [pHH_Oz]	Lumbar [Flexion(+)/Extension(-)]	Lumbar
30-34		Hips Height (AM 3a)	Waist Depth	Bars Pull angle (spanwise = 0, clockwise = +ve, anticlockwise = -ve) [theta]	HB-X, Y, Z @ [theta]	Clavicular [Flexion(+)/Extension(-)]	Waist
35-39		Waist Depth (AM 1h)	Bottom Depth	Rake angle (vertical = 0, clockwise = +ve, anticlockwise = -ve) [alpha]	HB-X, Y, Z, [theta] @ [alpha]	Clavicular [Elevation(+)/Depression(-)]	Bottom
40-44		Sitting Height (AM 1f - AM 1g)	Shoulder Width	Horizontal distance of the Seat from the rear tyre touching the ground [pSS_Ox]	S from S [pSS_Ox] - [pSS_Ox]	Arm [Flexion(+)/Extension(-)]	Shoulder
45-49		Shoulder Width (AM 2e)	Upper Arm Length	Vertical distance of the Seat from the rear tyre touching the ground [pSS_Oy]	S from S [pSS_Oy] - [pSS_Oy]	Arm [Abduction(+)/Adduction(-)]	UpperArm
50-54		Shoulder Height (AM 2a)	Forearm Length	Seat Inclination angle (horizontal = 0, clockwise = +ve, anticlockwise = -ve) [phi]	S angle [phi]	Arm [MedalRotation(+)/LateralRotation(-)]	ForeArm
55-59		Shoulder to Elbow Length	Hands (Palm) Length	Horizontal distance of the Footpeg from the rear tyre touching the ground [pFF_Ox]	FP-X from S [pFF_Ox] - [pSS_Ox]	Forearm [Flexion(+)/Extension(-)]	Wrist
60-64		Elbow to Wrist Length	Hips Widt	Vertical distance of the Footpeg from the rear tyre touching the ground [pFF_Oy]	FP-Y from S [pSS_Oy] - [pFF_Oy]	Forearm [Pronation(+)/Supination(-)]	Hand
65+		Hand-Palm to Wrist Length	Thigh Length	Spanwise distance of the Footpeg from the rear tyre touching the ground [pFF_Oz]	FP-Z [pFF_Oz]	Hand [Flexion(+)/Extension(-)]	Thigh
		Hip Width (AM 3d)	Lower Leg Length	Footpeg Rotation angle (horizontal = 0, clockwise = +ve, anticlockwise = -ve) [beta]	HB-X, Y, Z @ [beta]	Hand [RadialDeviation(+)/UlnarDeviation(-)]	LowerLeg
		Knee Height (AM 3b)	Ball of Foot Length			Thigh [Flexion(+)/Extension(-)]	Ankle
		Ankle Height (AM 3c)	Weight			Thigh [Abduction(+)/Adduction(-)]	Foot
		Ball of Foot Length				Thigh [MedalRotation(+)/LateralRotation(-)]	
		Weight				Leg [Flexion(+)/Extension(-)]	
						Leg [MedalRotation(+)/LateralRotation(-)]	
						Foot [Dorsiflexion(+)/PlantarFlexion(-)]	
						Foot [Eversion(+)/Inversion(-)]	

Appendix G: *EmoPersona-Study*

G.1 Stylistic and Positional PDEs used in the Prototype Tool

Design Class of Factors	Design Factors	Design Sub-Factors	Options	Emotion Levels [Visceral (Style), Behavioural (Experience), Reflective (Persona)]
Form	Construction Width		[Lean, Mid, Bulk]	Visceral
Form	Wheels	Rim Style	Styles {Cast, Spoke, Cover}	Visceral
Form & RideExp	Wheels	Wheel Diameter	[Small, Mid, Large]	Visceral & Behavioural
Form & RideExp	Wheels	FR Wheel Diameter Ratio	[R>F, R=F, R<F]	Visceral & Behavioural
Form & RideExp	Wheels	Tyre Thickness	[Thin, Mid, Thick]	Visceral & Behavioural
Form & RideExp	Wheels	F&R Tyre Thickness	[R=F, R>F]	Visceral & Behavioural
Form & RideExp	Wheels	Tyre Width	[Narrow, Mid, Wide]	Visceral & Behavioural
Form	F Fender	F Fender Type	[No, Short, Mid, Long]	Visceral
Form	F Fender	F Fender Style	Styles {}	Visceral
Form	Front Facia	Front Fascia Type	[No, Small, WindShield, Cover]	Visceral
Form	Front Facia	Front Fascia Style	Styles {}	Visceral
Form	Front Facia	Head Light Style	Styles {1x Circular, 1x Trapiziod, 1x Rectangular, 2x Circular, 3x Circular}	Visceral
Form	Handlebars	Handlebars Style	Styles {T, Y, ApeHangers}	Visceral
Dynamism & Form	Handlebars	Handlebars Vertical-position	[Up, Mid, Down]	Visceral & Behavioural
Dynamism & Form	Handlebars	Handlebars Horizontal-position	[Fwd, Mid, Back]	Visceral & Behavioural
Dynamism & Form	Handlebars	Handlebars Spanwise-position	[In, Mid, Out]	Visceral & Behavioural
Form	Handlebars	Handlebars Pull Angle	[Rabbit, Line]	Visceral & Behavioural
Form	Fuel Tank	Fuel Tank Style	Styles {}	Visceral
Dynamism & Form	Fuel Tank	Fuel Tank Orientation	[Positive-Inclination, Horizontal, Negative-Inclination]	Visceral
Form	Seat	Seat Style	Styles {}	Visceral
Dynamism & Form	Seat	Seat Orientation	[Positive-Inclination, Horizontal, Negative-Inclination]	Visceral
Unity & Form	Seat	Seat Horizontal-position	[Fwd, Mid, Back]	Visceral & Behavioural
Dynamism & RideExp	Seat	Seat Vertical-position	[Up, Mid, Down]	Visceral & Behavioural
Form	R Fender	R Fender Type	[One Piece - Cover type, One Piece -Fender type, Two Piece]	Visceral
Form	R Fender	R Fender Style	Styles {}	Visceral
Unity & Form	R Fender	R Fender to Seat-position	[United, Spaced]	Visceral
Unity & Form	R Fender	R Fender to Wheel-position	[United, Just, Spaced]	Visceral
Form	Side Fairings	Side Fairings Type	[No (naked), Half, Full]	Visceral
Unity & Form	Side Fairings	Side Fairings Position	[United, Just, Spaced]	Visceral
Dynamism & Form	Side Fairings	Side Baggage Type	[No, Yes]	Visceral
Form	Side Fairings	Side Baggage Style	Styles {}	Visceral
RideExp	Engine	Power (Speed focused)	Low, Mid, High power	Behavioural
RideExp	Engine	Power (Torque focused)	Low, Mid, High power	Behavioural
RideExp	Engine	Power (Speed-Torque Balanced)	Low, Mid, High power	Behavioural
Form	Exhaust	Exhaust Type	[1,2]	Visceral
Form	Exhaust	Exhaust Style	Styles {}	Visceral
Dynamism & Form	Exhaust	Exhaust Orientation	[Positive-Inclination, Horizontal, Negative-Inclination]	Visceral
Form	Exhaust	Exhaust Vertical-position	[Ground, Mid, Seat]	Visceral
				Visceral
Colour & Texture	Colour	Hue	[R,O,Y,G,B,V + Bk]	Visceral
Colour & Texture	Colour	Lightness and Chroma	[Light, Normal, Dark]	Visceral
Colour & Texture	Colour	Scheme	[1 Colour, 2 Colour]	Visceral
Colour & Texture	Texture	Paint Texture	[Plain (Matt), Glossy (Metalic)]	Visceral
Colour & Texture	Texture	Chrome Level	[All Black, All Chrome, Mix]	Visceral
Unity	Unity of Form	Feature Line Unity	[Unity, Some, No]	Visceral
Unity	Character & Feature Lines	Unity between Character & Feature Lines	[Allignment, Dissonance]	Visceral
Unity	Unity of Form	Engine Bay	[Fully Filled, Empty Spaces]	Visceral
Dynamism & RideExp	Geometrical Parameters	Wheel Base	[Long, Mid, Short]	Visceral & Behavioural
Dynamism & RideExp	Geometrical Parameters	Rake Angle	[High, Mid, Low]	Visceral & Behavioural
Dynamism & RideExp	Geometrical Parameters	Length:Height	[Rectangular, Squarish]	Visceral & Behavioural
Dynamism	Visual Imbalance	Frame Skewness	[+ve, 0, -ve]	Visceral
Form	Footpegs	Footpegs Style	Styles {}	Visceral
Dynamism & Form	Footpegs	Footpegs Vertical-position	[Up, Mid, Down]	Visceral & Behavioural
Dynamism & Form	Footpegs	Footpegs Horizontal-position	[Fwd, Mid, Back]	Visceral & Behavioural
Dynamism & Form	Footpegs	Footpegs Spanwise-position	[In, Mid, Out]	Visceral & Behavioural
Form	Footpegs	Footpeg Controls Orientation	[+ve, 0, -ve]	Visceral & Behavioural

G.2 *EmoPersona-Study part 1* (with Experts)

This data collection instrument represents a concise excerpt of the comprehensive data gathering conducted in the study. It is provided to offer the reader a snipet, rather than including the complete dataset, owing to the constraints on the length of the dissertation.

Identifying PDEV Emotion Profile

Deconstruction of Motorcycle Emotions

* Indicates required question

Information Letter to Participants
Dear Sir/Madam,

I am a researcher at the University of Malta and a Ph.D. student. The purpose of my research is to suppor motorcycle designers in developing safer, rider-focused and aesthetically pleasing motorcycles.

In order to do so, during this survey, questions will be asked on the deconstruction of motorcycle/elemen emotions. Your responses will be kept safe, strictly private and confidential, and used only by myself for t scope of the research only.

This Ph.D. work is related to the research project, "RIDE+SAFE" (reference no. R&I-2017-003-T), funded by the Malta Council for Science and Technology (MCST). Further details on this project are available on our website: https://www.um.edu.mt/projects/rideandsafe/ and facebook page: https://www.facebook.com/RideAndSafe/

For further information, or any questions regarding this research study, please do not hesitate to contact me.

Sincerely,

Ing. Sean Agius
Mob: (+356) 79300688
Email: sean.agius@um.edu.mt

1. Thanking you for your time and participation

   We know your time is valuable and we want to make it worthwhile. By participating, you will get a €3 voucher to be redeemed at the WKD shop for any item/service. Kindly fill in your email/phone numb in the space below, so we can contact you to redeem the voucher.

2. Enter your submission number, given by the moderator. *

Deconstruction of Motorcycle Emotions 13/05/2024, 10:53

Q1. For each of the below motorcycle/elements, which emotion (from the given list) comes to mind? Furthermore, for the identified emotion, can you quantify the intensity of the emotion on a scale from 1 to 3?

Emotion type:
S - Sobriety (Serious);
G - Glamour (Elegant);
D - Dynamism (Lively);
I - Intimidation (Scary).

Intensity of emotion:
1 - Low intensity;
2 - Medium intensity;
3 - High intensity

An example is given below to help determine the emotion type and intensity. This will be followed by a bri explanation from the moderator.

Deconstruction of Motorcycle Emotions 13/05/2024, 10:53

Please answer each of the following items as honestly as possible. Select your answers quickly and don' spend too much time analysing your answers. There are no right or wrong answers!

3. By checking the box, I am agreeing that I have read and understood the information provide above and I am giving my consent to participate in this research study. I understand and consent that the findings will be anonymously used for this Ph.D. study and related published studies.

Tick all that apply.

☐ Accept and Proceed

Rim Style

4. Cast Rim Style 1



Mark only one oval.

- ◯ S - Sobriety (Serious)
- ◯ G - Glamour (Elegant)
- ◯ D - Dynamism (Lively)
- ◯ I - Intimidation (Scary)

5. Intensity of the identified emotion ^

Mark only one oval.

	1	2	3	
Low	◯	◯	◯	High intensity

8. Cast Rim Style 3



Mark only one oval.

- ◯ S - Sobriety (Serious)
- ◯ G - Glamour (Elegant)
- ◯ D - Dynamism (Lively)
- ◯ I - Intimidation (Scary)

9. Intensity of the identified emotion ^

Mark only one oval.

	1	2	3	
Low	◯	◯	◯	High intensity

Front Fender Type

28. No Front Fender



Mark only one oval.

- S - Sobriety (Serious)
- G - Glamour (Elegant)
- D - Dynamism (Lively)
- I - Intimidation (Scary)

29. Intensity of the identified emotion ^

Mark only one oval.

	1	2	3	
Low	◯	◯	◯	High intensity

30. Short Front Fender



Mark only one oval.

- ◯ S - Sobriety (Serious)
- ◯ G - Glamour (Elegant)
- ◯ D - Dynamism (Lively)
- ◯ I - Intimidation (Scary)

31. Intensity of the identified emotion ^

Mark only one oval.

	1	2	3	
Low	◯	◯	◯	High intensity

32. Mid Front Fender



Mark only one oval.

- ◯ S - Sobriety (Serious)
- ◯ G - Glamour (Elegant)
- ◯ D - Dynamism (Lively)
- ◯ I - Intimidation (Scary)

33. Intensity of the identified emotion ^

Mark only one oval.

	1	2	3	
Low	◯	◯	◯	High intensity

34. Long Front Fender



Mark only one oval.

- ◯ S - Sobriety (Serious)
- ◯ G - Glamour (Elegant)
- ◯ D - Dynamism (Lively)
- ◯ I - Intimidation (Scary)

35. Intensity of the identified emotion ^

Mark only one oval.

	1	2	3	
Low	◯	◯	◯	High intensity

Front Fender Style

Identifying Motorcycle Emotion Profile

Deconstruction of Motorcycle Emotions (7)

Please answer each of the following items as honestly as possible. Select your answers quickly and don't spend too much time analysing your answers. There are no right or wrong answers!

* Indicates required question

1. Enter your submission number, given by the moderator. *

Motorcycles

2. Power = 21 hp . . . . Torque = 15 lb.ft . . . . Combustion Engine

Mark only one oval.

- ◯ S - Sobriety (Serious)
- ◯ G - Glamour (Elegant)
- ◯ D - Dynamism (Lively)
- ◯ I - Intimidation (Scary)

3. Intensity of the identified emotion ^

Mark only one oval.

	1	2	3	
Low	◯	◯	◯	High intensity

4. Power = 60 hp . . . . Torque = 46 lb.ft . . . . Combustion Engine



Mark only one oval.

- ◯ S - Sobriety (Serious)
- ◯ G - Glamour (Elegant)
- ◯ D - Dynamism (Lively)
- ◯ I - Intimidation (Scary)

17. Intensity of the identified emotion ^

Mark only one oval.

	1	2	3	
Low	◯	◯	◯	High intensity

18. Power = 159 hp . . . . Torque = 95 lb.ft . . . . Combustion Engine



Mark only one oval.

- ◯ S - Sobriety (Serious)
- ◯ G - Glamour (Elegant)
- ◯ D - Dynamism (Lively)
- ◯ I - Intimidation (Scary)

63. Intensity of the identified emotion ^

Mark only one oval.

	1	2	3	
Low	◯	◯	◯	High intensity

64. Power = 121 hp . . . . Torque = 94 lb.ft . . . . Combustion Engine



Mark only one oval.

- ◯ S - Sobriety (Serious)
- ◯ G - Glamour (Elegant)
- ◯ D - Dynamism (Lively)
- ◯ I - Intimidation (Scary)

81. Intensity of the identified emotion ^

Mark only one oval.

	1	2	3	
Low	◯	◯	◯	High intensity

82. Power = 94 hp . . . . Torque = 114 lb.ft . . . . Combustion Engine



Mark only one oval.

- ◯ S - Sobriety (Serious)
- ◯ G - Glamour (Elegant)
- ◯ D - Dynamism (Lively)
- ◯ I - Intimidation (Scary)

G.3 *EmoPersona-Study part 2* (with Potential Motorcycle Customers)

This data collection instrument represents a concise excerpt of the comprehensive data gathering conducted in the study. It is provided to offer the reader a snipet, rather than including the complete dataset, owing to the constraints on the length of the dissertation.

Supporting the development of safer, rider-focused, and aesthetically pleasing motorcycles.

* Indicates required question

Information Letter to Participants

Dear Sir/Madam,

I am a researcher at the University of Malta and a Ph.D. student. The purpose of my research is to suppor motorcycle designers in developing safer, rider-focused and aesthetically pleasing motorcycles.

In order to do so, during this 10 min survey, questions will be asked on motorcycle rider's elicited emotior and their correlation with the rider's personality. The questions asked regarding the latter are intended to describe yourself in an honest manner. Your responses will be kept safe, strictly private and confidential, and used only by myself for the scope of the research only.

This Ph.D. work is related to the research project, "RIDE+SAFE" (reference no. R&I-2017-003-T), funded by the Malta Council for Science and Technology (MCST). Further details on this project are available on our website: https://www.um.edu.mt/projects/rideandsafe/ and facebook page: https://www.facebook.com/RideAndSafe/

For further information, or any questions regarding this research study, please do not hesitate to contact me.

Sincerely,

Ing. Sean Agius
Mob: (+356) 79300688
Email: sean.agius@um.edu.mt

1. Enter the chance to Win!

   We know your time is valuable and we want to make it worthwhile. By participating, you will become part of the lucky draw to win a Battery Tender charger/maintainer. If you wish to participate kindly fi your email/phone number in the space below, so we can contact you if you are the winner.

2. By checking the box, I am agreeing that I have read and understood the information provide above and I am giving my consent to participate in this research study. I understand and consent that the findings will be anonymously used for this Ph.D. study and related published studies.

   Tick all that apply.

   ☐ Accept and Proceed

Describe yourself

3. Q1. What is your age group?

   Mark only one oval.

   ◯ 18 to 24
   ◯ 25 to 34
   ◯ 35 to 44
   ◯ 45 to 54
   ◯ 55 to 64
   ◯ 65 or over
   ◯ Prefer not to answer

4. Q2. For how long have you been riding motorcycles?

   Mark only one oval.

   - ◯ 0 to 2 years
   - ◯ 3 to 5 years
   - ◯ 6 to 10 years
   - ◯ 11 to 15 years
   - ◯ 16 to 20 years
   - ◯ 21 to 25 years
   - ◯ 26 to 30 years
   - ◯ 31 years or over
   - ◯ Prefer not to answer

5. Q3. How frequently do you use your motorcycle?

   Mark only one oval.

   - ◯ From Monday to Sunday
   - ◯ From Monday to Friday
   - ◯ Saturday and Sunday only
   - ◯ Less than three times a month
   - ◯ Prefer not to answer

6. Q4. When purchasing a motorcycle, what is your preference?

   Mark only one oval.

   - ◯ Ergonomics (Comfort)
   - ◯ Aesthetics (Looks)
   - ◯ Performance (Speed & Power)

7. Q5a. Have you ever had any accident with your motorcycle?
   If the answer is Yes, continue to the next questions. If the answer is No, skip the next question.

   Mark only one oval.

   - ◯ Yes
   - ◯ No
   - ◯ Prefer not to answer

8. Q5b. If yes, what was the severity of the accident?
   In case you had many select the seve one.

   Mark only one oval.

   - ◯ No Scratches
   - ◯ Bruises
   - ◯ Hospital Admission
   - ◯ Surgical Interventions
   - ◯ ITU
   - ◯ Prefer not to answer

Correlation between Personality types and Emotions

The purpose of my Ph.D. research is to support motorcycle designers in developing safer, rider-focused a aesthetically pleasing motorcycles. In order to correlate the elicited emotions with the personality type, questions in the following section will be on your personality.
As such, please answer each of the following items as honestly as possible. Select your answers quickly and don't spend too much time analysing your answers. There are no right or wrong answers!

Your responses will be kept safe, strictly private and confidential, and used only by myself for the scope c the research only.

9. Q6. For each statement below indicate whether it is (a) True, or (b) False as a description of you.

   Mark only one oval per row.

	True	False
I don't talk a lot	◯	◯
I sympathize with others' feelings	◯	◯
I leave my belongings around	◯	◯
I get stressed out easily	◯	◯
I have a rich vocabulary	◯	◯
I deliberately block drivers who tail gate me	◯	◯
I "drag race" other drivers at stop lights to get out in front	◯	◯
I get very irritated when I get stuck in a traffic jam	◯	◯
I feel comfortable around people	◯	◯
I am not interested in other people's problems	◯	◯
I pay attention to details	◯	◯
I am relaxed most of the time	◯	◯
I have difficulty understanding abstract ideas	◯	◯
I keep in the background during a group event	◯	◯
I am not a really good listener	◯	◯
I often forget to put things back in their proper place	◯	◯
I worry about things	◯	◯
I am quick to understand things	◯	◯
I would tail gate a driver who annoys me	◯	◯
I will illegally pass a vehicle that is going too	◯	◯

slowly		
I get impatient and/or upset when I fall behind schedule whilst driving		
I start conversations		
I take time out for others		
I like to be in command		
I get upset easily		
I spend time reflecting on things		
I am quiet around strangers		
I feel others' emotions		
I follow a schedule		
I change my mood a lot		
I like coming up with ideas		
I feel it is my right to strike back, if I feel another driver has been aggressive toward me		
I will weave in and out of slower traffic		
I get irritated when a vehicle in front of me slows down for no reason		

Emotions generated by motorcycles

Please answer each of the following items as honestly as possible. Select your answers quickly and don't spend too much time analysing your answers. There are no right or wrong answers!

Q7. From 0 to 5, how much do you like the following motorcycles?

Where:
0 - I Dislike the motorcycle
1 - I Slightly Like the motorcycle
2 - I Somewhat Like the motorcycle
3 - I Like the motorcycle
4 - I Like the motorcycle Very Much
5 - I Absolutely Love the motorcycle

10. Power = 21 hp . . . . Torque = 15 lb.ft . . . . Combustion Engine



Mark only one oval.

	0	1	2	3	4	5	
Desl	◯	◯	◯	◯	◯	◯	Love it

18. Power = 159 hp . . . . Torque = 95 lb.ft . . . . Combustion Engine



Mark only one oval.

	0	1	2	3	4	5	
Desl	◯	◯	◯	◯	◯	◯	Love it

41. Power = 121 hp . . . . Torque = 94 lb.ft . . . . Combustion Engine



Mark only one oval.

	0	1	2	3	4	5	
Desl	◯	◯	◯	◯	◯	◯	Love it

50. Power = 94 hp . . . . Torque = 114 lb.ft . . . . Combustion Engine



Mark only one oval.

	0	1	2	3	4	5	
Desl	◯	◯	◯	◯	◯	◯	Love it

G.4 Emo-Persona Table

Rider Attributes						Personality Traits					Driving Behaviour			Rider Emotion Profile (REP)			
Age	**Experience**	**Frequency of motorcycle use**	**Motorcycle accident**	**Severity of accident**	**Preference**	**Extraversion**	**Agreeableness**	**Conscientiousness**	**Neuroticisim**	**Openess to Experience**	**Aggressive Driving**	**Emotional Experiences**	**Risky Driving**	**S**	**G**	**D**	***I***
18-19	0-2	7 days a week	Yes	No Scratches	Aesthetics (Looks)	Sociable	Sympathetic	Planner	Composed	Imaginative	Benevolent	Easy-going	Cautious	(0-3)	(0-3)	(0-3)	(0-3)
20-24	3-5	5 days a week	No	Bruises	Ergonomics (Comfort)	Introvert	Uncompromising	Live for the moment	Sensitive	Conservative	Nuisance	Irritable	Reckless				
25-29	6-10	2 days a week		Hospital Admission	Performance (Speed & Power)												
30-34	11-15	Less than 2 times a month		Surgical Interventions													
35-39	16-20																
40-44	21-25																
45-49	26-30																
50-54	31+																
55-59																	
60-64																	
65+																	

Appendix H: Evaluation Semi-Structured Interview with Designers



L-Università ta' Malta
Faculty of Engineering

Department of Industrial & Manufacturing Engineering

Information Letter to Participants

Dear Sir/Madam,

I am a researcher at the University of Malta and currently reading for a Ph.D. which is being supervised by Prof. Ing. Philip Farrugia and co-supervised by Dr Ing. Emmanuel Francalanza. The purpose of this Ph.D. is to develop a solution which proactively support design engineers/designers to develop rider-centred, safer (through improved ergonomics) motorcycle designs, while at the same time enhance the aesthetic emotional values of such artefacts. This semi-structured interview will highlight the evaluation by motorcycle designers, of DESMO's approach and the proof-of-concept prototype tool (DESMO-App).

For further information, or any questions regarding this research, please do not hesitate to contact me.

Sincerely,

Ing. Sean Agius

Mob: (+356) 79300688

Consent Form

This is to certify that, I, give consent of my participation in the above-mentioned research project carried out by Ing. Sean Agius supervised by Prof. Ing. Philip Farrugia and co-supervised by Dr Ing. Emmanuel Francalanza. In this semi-structured interview, questions will not be personal and will not be linked to my personal identity. Questions will be solely on the approach of DESMO and the computer-based implementation (DEMO-App).

The participation will be audio recorded to aid the researcher. The recordings will be kept safe and strictly private and confidential, used only by Ing. Sean Agius for the scope of the research only.

By giving consent, I am:

- Allowing Ing. Sean Agius to lead the activities and allow this questionnaire exercise to be used in the study.
- Aware that I retain the right to withdraw from this study at any time, without giving any reason whatsoever.
- Authorise Sean Agius to audio record my participation.

Participant's Signature / Initials	Date

Background Information

Q1. What is the highest level of education attained?

- Secondary School
- Higher national diploma or equivalent - Level 5
- Bachelor's degree or equivalent - Level 6
- Master's degree or equivalent - Level 7
- Doctoral degree or equivalent - Level 8
- Other

Q2. What is your academic background?

For example: Design Engineering or Mechanical Engineering, Electrical Engineer, Artistic Designer, etc.

_____

Q3. What is your work position title?

For Example: Designer, Design Engineer, Design Manager, Chief Technical Officer, etc.

_____

Q4. How long have you been working in the motorcycle industry?

_____ year(s)

For each of the below question, kindly rate from 1 to 5 whether you agree or disagree with the statements.

The ratings represent the following:

5 – Strongly Agree / Definitely Yes

4 – Agree / Yes

3 – Uncertain

2 – Disagree / No

1 – Strongly Disagree / Definitely No

Harmonistic Design Approach

Q5. To what extent do you agree that through the approach adopted, DESMO supports design for multiple human factors aspects such as, ergonomics, persona and emotions?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: _____

Q6. To what extent do you agree that through this approach, DESMO guides and supports to find a harmonised/balanced solution for the evolving motorcycle model?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: _____

Q7. To what extent does DESMO provide the right knowledge, given at the right time, to make motorcycle design decisions?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: _____

Q8. To what extent do you consider that the approach adopted proactively assists in the design process of motorcycles?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: Does the approach support your role and compliment your workflow? In which way?

Q9. To what extent do you think the approach adopted demonstrates a rider-centred approach, which provides awareness on potential customers' requirements?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: What are your views in having a tool which can supplement you with information about the characteristics of general riders?

Does it help the designer to better identify the user for which the motorcycle is to be made?

Design Guidance

Q10. To what extent do you agree that the approach adopted to develop the solution provides awareness on:

a) Design stage conflict between ergonomics and aesthetics during the evolving motorcycle model, such as interaction between geometry and aesthetic element positioning?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: _____

b) Conflicts between target users and general riders during the evolving motorcycle model?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: _____

c) Use-phase consequences that may affect the ergonomics and aesthetics of the motorcycle model based on target users and general riders, such as the total level of discomfort and deviation between the emotion profiles?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: Will the given consequences and recommendations given by DESMO improve your designs? Are they sufficient?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: _____

Q11. To what extent do you agree that through this approach DESMO supports with the necessary knowledge to avoid or mitigate human factor consequences when the motorcycle would eventually be in its use-phase?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree

1	2	3	4	5

Comments: _____

Q12. To what extent do you consider the awareness of human factor and harmonisation consequences to motivate in exploring alternative commitments?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: Does this approach give you the ability to discover new design perspectives which you would have never thought of when designing motorcycles?

Q13. To what extent do you consider that the approach would hinder the creative and motorcycle design freedom?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: _____

Tool Functionality

Q14. To what extent does DESMO-App demonstrate how a motorcycle model can be defined using:

a) Ergonomic properties such as dimensions and component-positioning?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: _____

b) Design factor elements such as, components, features, colouring scheme?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: _____

Q15. To what extent does DESMO-App demonstrate how a user model can be defined using:

a) Ergonomic properties such as, anthropometrics?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: _____

b) Persona properties such as, personality types?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: _____

c) Emotions through emotion profiles?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: _____

Q16. To what extent do you think DESMO-App is flexible in:

a) Representing and modelling different motorcycle types, for example, cruisers, scooters, sport-bikes?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: _____

b) Representing a wide variety of rider properties?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: _____

Q17. To what extent do you think that DESMO-App is scalable?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: What are your views on the fact you can add rider properties and motorcycle elements directly in the database?

Q18. To what extent does DESMO-App demonstrate how information content can be manually changed?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: _____

Q19. Given the necessary time to learn the tool, to what extent is it intuitive and easy to use?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: (For example, how the GUI is set-up [modularity], information structure, results view, and information flow from module to module. How about the tool bar, workspace, tooltips, and the access to the database?)

Would it be helpful for novice, experienced designers, or both? Why?

Relevance to Industry

Q20. To what extent do you consider DESMO would be beneficial for:

a) Designers who develop bespoke/custom motorcycles?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: _____

b) Designers who develop motorcycles for mass production?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: _____

Q21. To what extent do you think that this approach would help designers, to design: ergonomically safe, aesthetically pleasing motorcycles?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: Comments: Does it support you to improve your designs?

Q22. Have you ever come across a tool which is similar to DESMO that is, assisting designers to find a balanced solution catering for ergonomics, aesthetics, target users and general riders?

Yes

No

Comments: If yes, in which aspect?

Q23. Assuming more knowledge was embedded within DESMO, to what extent would you consider the proposed motorcycle design approach to be useful and beneficial in practice?

Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1	2	3	4	5

Comments: Are you willing to use it? Do you recommend it? Why?

Which area of DESMO-App have you found the most interesting and innovative? Why?

Q24. Do you foresee any cases where DESMO-App would be useful to your work? In which way?

_____

Q25. In your opinion does the demonstration highlight any other issues not mentioned above? If yes, what are these?

_____

Q26. Do you have any other recommendations to improve DESMO-App or the approach?

For example, features to add you normally use in your process?

_____