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Deriving a systematic approach to changeable manufacturing system design

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Abstract

It has long been argued that Factories are long life and complex products. The complexity of designing factories, and their underlying manufacturing systems, is further amplified when dealing with continuously changing customer demands. At the same time, due to research fragmentation, little if any scientific explanations are available supporting and exploiting the paradigm that "factories are products". In order to address this weakness, this paper presents research results arising from a comparative analysis of systematic "product design" and "manufacturing system design" approaches. The contribution emerging from this research is an integrated systematic design approach to changeable manufacturing systems, based on scientific concepts founded upon product design theories, and is explained through a case study in the paper. This research is part of collaboration between the CERU University of Malta and IAO Fraunhofer aimed at developing a digital decision support tool for planning changeable manufacturing systems.

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Keywords: Changeability; Design; Manufacturing Systems

1. Introduction

The design of changeable manufacturing systems poses many challenges to the stakeholders involved. Hence in order to develop efficient and effective solutions these stakeholders need to be supported [1]. As part of the Digital Factory initiative this research aims to develop digital support tools aimed at supporting stakeholders during the design activities.

To develop such tools we must first gain a good understanding of the design activities involved. Therefore this research paper begins by analysing the current state of the art in systematic approaches for changeable manufacturing system design. Based on the paradigm "Factories are long-life and complex products" [2] this research then looks at the different schools of thought of product design and how "Design Theory" can be applied to manufacturing system design.

As defined by Chryssolouris [3] manufacturing systems are a combination of humans, machinery and equipment that are bound together by a common material and information flow. A manufacturing system, which can also be referred to as a production system or facility, forms a part of the factory. The authors will be using the term factory in the following sections to benefit from terms like factory life cycle that have been coined by several authors such as Westkämper [2], Schenk [4], Wiendahl [5].

It is during the manufacturing system design that decisions taken directly contribute and impact the product range capability. The authors also recognize manufacturing system design as one of the important stages of the factory life cycle, since it is one of the earliest stages and precedes the other phases of the factory life cycle. Therefore in this paper the authors will focus on the aspect of manufacturing system design in factory design.

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2. Changeability in Manufacturing System Design

Chryssolouris [3] defines manufacturing system design as the mapping from performance requirements of the manufacturing system onto suitable values of decision variables, which describe the physical design or the manner of operation of the manufacturing system.

An important requirement for modern factories is the need to deal with product families and their evolution over time. In order to deal with these challenges manufacturing systems designers have to resort to changeability. Wiendahl [6] defines changeability as “Changeability is the characteristic to accomplish early and foresighted adjustments of the factory’s structures and processes on all levels to change impulses economically”. In order to develop and deploy changeable system strategies in industry, changeability design processes need to be established.

2.1. Changeability Design Processes

ElMaraghy & Wiendahl [7] define a factory life cycle oriented process with two changeability phases: a design and implementation phase and a performance phase. In [8], Azab et al., go deeper into understanding and mapping the mechanics of change and present a change framework and control loop in order to systematically assess the need for reconfiguration and implement the required changes.

An important and interesting argument put forward in changeable manufacturing system design is that there is nothing like an absolute or hundred percent changeability [7]. Some researchers, such as Tolio [9] argue that the best trade-off between productivity and flexibility needs to be found. Hence Tolio proposes the concept of Focused Flexibility Manufacturing Systems (FFMS). In [10] Terkaj et al. contribute a process diagram that details the design activities involved in developing FFMSs.

Based on a set of six core characteristics (or enablers), of reconfigurable manufacturing systems Koren [11] proposes a set of reconfiguration principles upon which reconfigurable manufacturing systems should be designed. The enablers identified by Koren are; customization, scalability, convertibility, modularity, integrability and diagnosability.

Schuh et al. propose an object-oriented design approach for changeability based on four steps [12]. Step one to step three describe how to identify, analyze and classify the dynamic drivers and how to specify the manufacturing system. Step four explains how the complexity of manufacturing systems can be controlled by object-oriented design.

2.2. Synthesis in Changeable Manufacturing System Design

A central part of the design process is the synthesis design activity. The synthesis of manufacturing systems is classified into four levels: the system, factory, machine and product level [13]. Each level has an associated set of activities as part of the manufacturing system design process.

During the course of this research, due to fragmentation, it was felt that there was a gap in theory describing the synthesis design activity of changeable manufacturing systems especially at a system and factory level.

3. Paradigm Factory as a Product

In [2] Westkämper presents the paradigm “a factory is a long life and complex product”. At the basis of this paradigm is the argument that manufacturing systems can be modelled as complex technical systems from a systems theory perspective.

Therefore if we treat the factory as a technical system the same design theories which we apply in product design can be applied to factory design and manufacturing system design. The following section presents some of the principles behind established systematic product and manufacturing system design theory. The aim of this comparative analysis is to contribute to an overall systematic approach to changeable manufacturing system design. At the same time this comparison contributes as a valuable theoretical foundation to the “factories are products” paradigm.

4. Different Schools of Thought: Same Problem

4.1. Systems Theory and Design Science

Engineering design science has its origins in the “Theory of Technical Systems by Vladimir Hubka [14]. According to both Hubka [14] and Westkämper [2], who base their arguments on systems theory, technical systems are made up of a hierarchical structure of a finite set of elements. Certain definite relationships can also be described to exist between elements and their environment. Hubka explains that technical systems may be divided into four classes according to their degree of complexity, namely plant or equipment, machines, assemblies and parts.

Therefore based on the theory of technical systems, factories can be viewed as higher order technical systems. Wiendahl [6] also describes a factory as a complex socio-technical system consisting of elements or objects. Wiendahl also defines the main scope of factory design having three aspects: the planning of facilities, the organization and the employees. Whilst understanding the importance of the organization and employee fields of factory design and their effect on changeability, this research focuses its attention on the technical facility aspects.

4.2. Design Elements

Mortensen et al. [15] argue that building a product model requires a way to read, model and decompose the product assortment into elements and sub elements. Hence design synthesis is defined by Andreasen [16] as the determination of the elements of a product and how they are built together.

For the purpose of deriving clearly defined factory objects that are objects of changeability, Nyhuis [17], uses the classification of means, organization and space. Schuh et al. [18] use the classification for factory objects of resources, processes and organization. Since this research is strictly focusing on the technical not social aspects of changeability, manufacturing systems elements are classified as layout, machine, material handling, and services as shown in Figure 1.

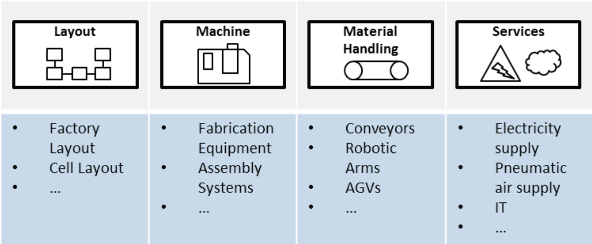

Figure 1 Manufacturing System Design Elements

4.3. Life Phases

There are many definitions to and terms associated with the product life cycle. In this research we define the product life as the total elapsed time it takes from when the need for a product is established to when the product is removed from existence. A product life is composed of a number of phases. A phase is defined as a time segment in the product's life. For instance, Hubka and Eder [19] state that for technical systems the life-span can be divided into four phases: origination, distribution, operation and liquidation. Tjalve [20] explains that all products are created, used and eventually discarded. By expanding and arranging these events in a sequence, Tjalve provided one of the first product life models. Olesen [21] provides a more detailed life model by including typical systems affecting the transformations occurring in each phase.

Constantinescu et al. [22] propose that the modern view on manufacturing engineering resides in incorporating the life cycle paradigm into the factory as a whole, its corresponding products, manufacturing processes and technologies. Constantinescu et al. describe a factory life cycle model made up from the following factory life phases; investment planning, engineering, process planning, construction & ramp-up, production, service and maintenance, and finally dismantling or reconfiguration. In the design phase of changeable manufacturing systems it is important to consider that the factory life cycle is longer than the product life cycle [23]. In fact a manufacturing system has to cope with several product evolutions and variants over its useable life.

It is also important to note that the factory and product families are developed concurrently to each other with decisions being made during the planning phases of the independent life-cycles affecting each other. The two life-cycles then meet at what is defined as the crossing life cycles point [22] where the product is produced by the manufacturing system.

4.4. Structure Viewpoints

In his "Domain Theory" Andreasen [24] explains that many structural solutions are superimposed in a product. Thus a product structure can be viewed from different perspectives. Based on this theory Mortensen et al. [15] argue that the product carries more functionalities at the same time. The designer therefore has to design based on multiple system and structure views.

This research is proposing that changeable manufacturing system structures can also be viewed from different viewpoints. During the synthesis activity the designer can view the manufacturing system structure from the following perspectives: Functional View, Changeability View, Change Enabler View, and Object View. These views are depicted in Figure 2.

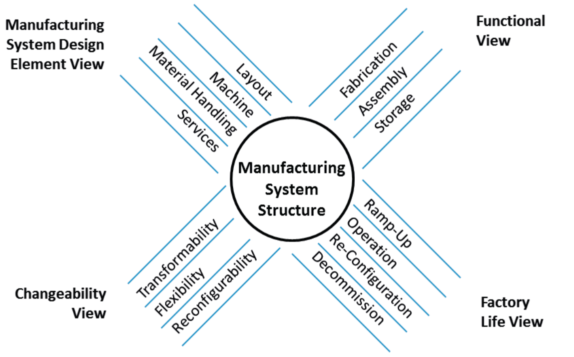

Figure 2 Changeable manufacturing system structure viewpoints

4.4.1. Functional View

A manufacturing system can be viewed as a set of functional areas. These include areas where parts are fabricated, areas where products are assembled and storage areas for work in progress, incoming materials or finished goods.

4.4.2. Factory Life View

Another viewpoint that can be used by designers is a factory life-cycle perspective. Manufacturing system designers would do this to try and envisage the manufacturing system requirements for the different life phases. In designing changeable manufacturing systems it is critical to design the manufacturing system by considering the requirements of the reconfiguration life phase.

4.4.3. Changeability View

Since manufacturing systems can implement all levels of changeability, a manufacturing system can be viewed as a transformable, flexible, and/or reconfigurable system.

4.4.4. Manufacturing System Design Element View

As previously explained and based on systems theory, observing a changeable manufacturing system from a design element viewpoint gives rise to the physical manufacturing system design structure.

4.5. Systematic Design Approaches

The "Theory of Transformation Systems" by Hubka [25] describes engineering design as a transformation process. In this transformation process the future technical system is generated. The design process involves a transformation from the requirements of the system into the detailed description of the desired technical system.

From a technical system and product design perspective VDI 2221 [26] and Pahl and Bitz [27] describe systematic design approaches built on a series of tasks that can be categorized in three stages of conceptual, embodiment and detail design. On the other hand Roozenburg [28] describes the product design activity as a sequence of empirical cycles, in which the knowledge of the problem as well as the solution increase spirally till a solution is achieved. During the basic design cycle, reasoning takes place from goal (the function) to means (the design).

Several factory planning approaches can also be found in literature such as those described in VDI 5200 factory planning procedures [29], the "0+5+X" planning model by Schenk et al. [4], and the classical approaches of Kettner [30], Aggteleky [31]. The flow based approach for a holistic factory engineering and design [32] is well integrated with the digital factory [33] initiative and its concepts.

5. A Changeable Manufacturing System Design Approach

Based on the comparative analysis of systematic "product design" and "manufacturing system design" approaches in Section 4 this research has derived a changeable manufacturing system design approach.

The different activities involved in designing changeable manufacturing systems being proposed by this approach will be described in the next section. Figure 3 illustrates the changeable manufacturing system design approach based on Roozenburg's basic design cycle.

5.1. Changeable Manufacturing System Function

The function of changeable manufacturing system design is to address the results of the activities of product design, process planning and investment planning. Despite the fact that in the approach being proposed these activities are shown as the input to the manufacturing system design cycle it has to be noted that product design, process planning and investment planning decisions are occurring concurrently and continuously to changeable manufacturing system design.

5.2. Analysis of Requirements

When starting a new design cycle the manufacturing system designer is presented with the requirements for the manufacturing system. The first activity carried out in manufacturing system design is an *Analysis* of the requirements that need to be met. During the analysis the designer forms a better understanding of the problems (problem statement) and determines the goals that need to be achieved.

There are several requirements which need to be met by changeable manufacturing systems. Manufacturing system requirements include product range, manufacturing and business requirements.

Product range requirements are the current and future range of products that need to be produced by the manufacturing system. The manufacturing system designer must analyse the current product range requirements, i.e. the range of products that need to be produced at the beginning of the manufacturing system life cycle, to determine the properties of the parts that need to be produced (form, material, surface finish, tolerance, dimensions). Information about future product range evolution should also be part of the changeable manufacturing system requirements. It is only in this way that designers can design optimal degrees of changeability.

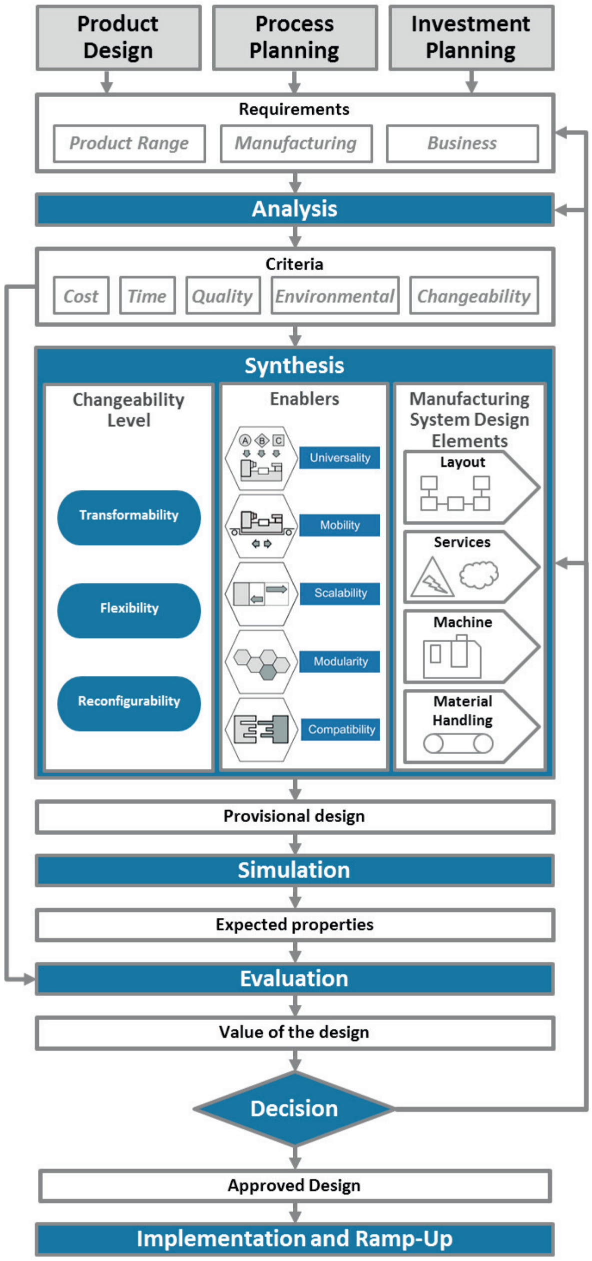

Figure 3 A Changeable Manufacturing System Design Approach

Manufacturing requirements include the manufacturing processes that need to occur to produce the range of products, the area where the manufacturing system will be located, and the manufacturing strategy to be adopted.

Business requirements, i.e. the business goals and targets that need to be achieved, e.g. 'Cost per part', 'investment cost', etc. The business requirements are a product of the Investment and Performance Planning stage.

As explained by Chryssolouris the basic goal of a manufacturing system is to produce the required products at the required time, cost and quality and flexibility [3]. In sustainable businesses the environmental impacts of manufacturing systems may also be considered. The analysis of the manufacturing system requirements will define the criteria by which the manufacturing system solution will be evaluated in future design activities.

5.3. Synthesis

The next activity in the manufacturing system design cycle is *Synthesis*. As previously explained, synthesis can be defined as the combination of components or elements to form a connected whole. It is in this activity of the design cycle that the manufacturing system designer develops solutions for the manufacturing system problems. It is also important to note that designers make commitment based on the requirements defined in the previous stage.

This research proposes that during synthesis of changeable manufacturing systems, consciously or not, designers make commitment in the following three domains: the changeability domain, the enabler domain and in the design element domain. This research is therefore prescribing a synthesis design approach were designers take provisional commitments in these three domains. The result of the synthesis from the different domains of changeable manufacturing system design is a provisional design solution.

5.3.1. Changeability level domain

Within this domain manufacturing system designers commit to the level of changeability to implement. Manufacturing system designers have to commit to either implementing transformability on a factory level, to the generalized flexibility paradigm of FMS or to the customized flexibility of RMS.

5.3.2. Changeability enablers domain

Once the level of changeability has been committed then the manufacturing system designer change enablers. The range of change enabler options available to the designer is dependent on the previously chosen changeability level. If the designer commits to developing a RMS then the designer has the option to commit to the six types of RMS enablers. The commitment is made based on the requirements of the manufacturing system, the knowledge of changeability enablers, and the preferences of the designer.

5.3.3. Manufacturing system design elements domain

In this domain the designer commits to the manufacturing system design elements previously discussed in Section 4.2. The range of options to be considered by the designer may also be constrained depending on the changeability enablers previously committed. These the result of the commitments made in this domain can then be viewed from a manufacturing system structure viewpoint.

5.4. Simulation

The next stage of the design cycle involves the *Simulation* of the provisional design solution. Simulation involves the generation of an artificial history of a system and the observation of that history to draw inferences concerning the operating characteristics of the real system. The result of this study is the expected properties of the provisional design solution.

5.5. Evaluation

During *Evaluation* of the provisional design solution the expected properties are compared to the design criteria established during the analysis stage. A value is then given to that design solution to quantify how well the provisional solution meets the product and business requirements.

5.6. Decision

The manufacturing system designer will then *Decide* whether to continue developing the design by further elaborating the provisional design or whether to try a different type of solution to generate a better design proposal. Once the manufacturing system designer is satisfied that the provisional design meets the requirements and criteria then the status will be upgraded to that of final design and the project can move on to implementation planning.

6. Case Study

6.1. Analysis of Requirements

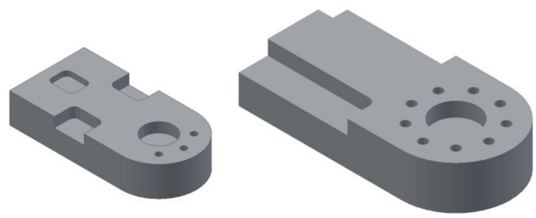

Figure 4 Case Study Parts

In the first stage of the changeable manufacturing system design the designer must review the parts to be produced. Figure 4 illustrates the parts considered for this case study. The designer must analyse the *range of features* of the product family. This includes those features which are the same across the range, in this example the material of the parts (Aluminum), and those features which are different, in this example the size.

It is also critical to have information of probable future changes in the product range. In this case study we consider that the future product range would include parts which are larger.

6.2. Synthesis

The designer first identifies the system element which will provide the changeability in this system. In this case study a CNC Milling *machine element* was chosen, since both the current range and future range of parts can be produced using a similar milling processes.

Since the changeability is required at the part level *reconfigurability* needs to be designed into the system. From the analysis of the product range requirements and the changeability enablers available, the designer chooses the *scalability* enabler. In this case study it would mean that the jig fixtures for the parts need to be designed in such a way that they can be scaled either up or down depending on the parts to be machined.

6.3. Simulation, Evaluation and Decision

Finally the provisional manufacturing system design is modelled and simulated. The results of the simulation are then evaluated until the original requirements are met.

7. Conclusions and Future Work

Based on the paradigm “Factories are long-life and complex products” this research has contributed a systematic design approach for changeable manufacturing system design. This research will continue developing this approach and in the future will use this approach as a foundation for the development of tools supporting the design activity of changeable manufacturing systems.

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