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Towards Life-Oriented Evaluation Support of 'Interface Concepts'

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Abstract
The evaluation of design concepts is a critical early design stage with potential ramifications on subsequent lifecycle phases. During this stage the engineering designer is typically required to evaluate multiple concepts with respect to conflicting criteria. Over the years academic research proposed numerous concept evaluation techniques in order to support the user at this critical stage. Yet this has yielded an additional problem in which the inexperienced user needs also to be guided in the selection of the appropriate concept evaluation technique. The research presented in this paper has the long-term objective of providing computer support to the user on 2 levels: the evaluation of design concepts and the selection of the appropriate concept appraisal technique. The research, presented in this paper focuses on the development of an approach for the evaluation of module interface design concepts.

Keywords: Modularity, compromise, computer support, multi criteria decision making.

Introduction
One of the earliest stages in the design of an artefact is the appraisal of design concepts. The effects of the decisions made during this stage propagate throughout the entire life cycle of the product [1]. The importance of this design stage is also emphasized by the fact that between 60-80% [2, 3] of the total product costs are committed during this stage. The research presented in this paper focuses on the evaluation of module interface design concepts. The term interface is defined as a technical functional surface in a technical system that interacts with another technical functional surface within the technical system or environment [4].
Various authors have conducted research related to the design and development of module interfaces. Blackenfelt and Sellgren [5] proposed an approach in which Finite Element (FE) based topological optimisation was employed in order to generate module interface concept candidates. The set of interface dimensions which result in the most robust design is determined via a two level analysis of variance. Eberhard *et al.*[6] investigated the influence of mechanical interfaces on the performance of reconfigurable machine tools (RMT). Scalice *et al.*[7] proposed a methodology for the design of module interfaces. In this paper [7] the authors identify the evaluation of the generated design concepts as one of the key stages.

However Scalice *et al.* [7] did not specify any evaluation technique that could potentially be employed during this stage of the proposed methodology. The reviewed literature suggests that engineering designers do not have a design tool which is exclusively focused on the evaluation of module interface design concepts. It follows that the objective of this paper will be to develop a means which will support the user in the evaluation of different interface design concepts in modular products.

Over the years researchers have developed numerous tools [8-10] specifically for the evaluation and subsequent selection of design concepts, while other more generic evaluation tools such as the analytic hierarchy process (AHP) [11], elimination and choice expressing reality (ELECTRE) [12] and technique for order preference by similarity to ideal solution (TOPSIS) [13] have been employed for the evaluation of design concepts [10, 14]. The work presented in this paper focuses on the use of multi criteria decision making (MCDM) techniques for the evaluation of module interface design concepts. These techniques present a systematic mathematical framework for the evaluation of different module interface design concepts with respect to conflicting criteria. Each MCDM technique is characterised by the unique way in which the dataset relating the performance of each alternative with respect to every criterion is transformed into an individual score for each alternative. This score determines the rank of a candidate concept with respect to the other alternatives.

Green [15] recognized that a systematic concept evaluation tool could aid engineering designers to appraise design concepts in an objective manner, especially in decision making scenarios where the number of concepts being considered is very large and the time available is limited.

Numerous studies [16-18] suggest that although a large array of evaluation techniques have been proposed as a result of academic research, a significant number of these techniques remain unused by engineering designers in industry. One of the reasons for which these concept appraisal techniques are not employed is typically attributed to the fact that these techniques do not offer a reasonable compromise between the ease of use and the ability to reflect the preferences articulated by the user in a reliable and clear manner. These studies [16-18] suggested that engineering designers need concept evaluation techniques which are easy to use and understand, yet capable of delivering clear and valid results.

Another important issue which emerged from the reviewed literature is that as a result of the large repository of concept evaluation techniques the inexperienced user faces the additional challenge of selecting the most appropriate technique. This problem has already been addressed by various authors [19-22] who assumed different approaches in order to address this issue. The question of what is the ideal approach for the selection of an evaluation technique remains open ended, since each approach has its own strengths and weaknesses.

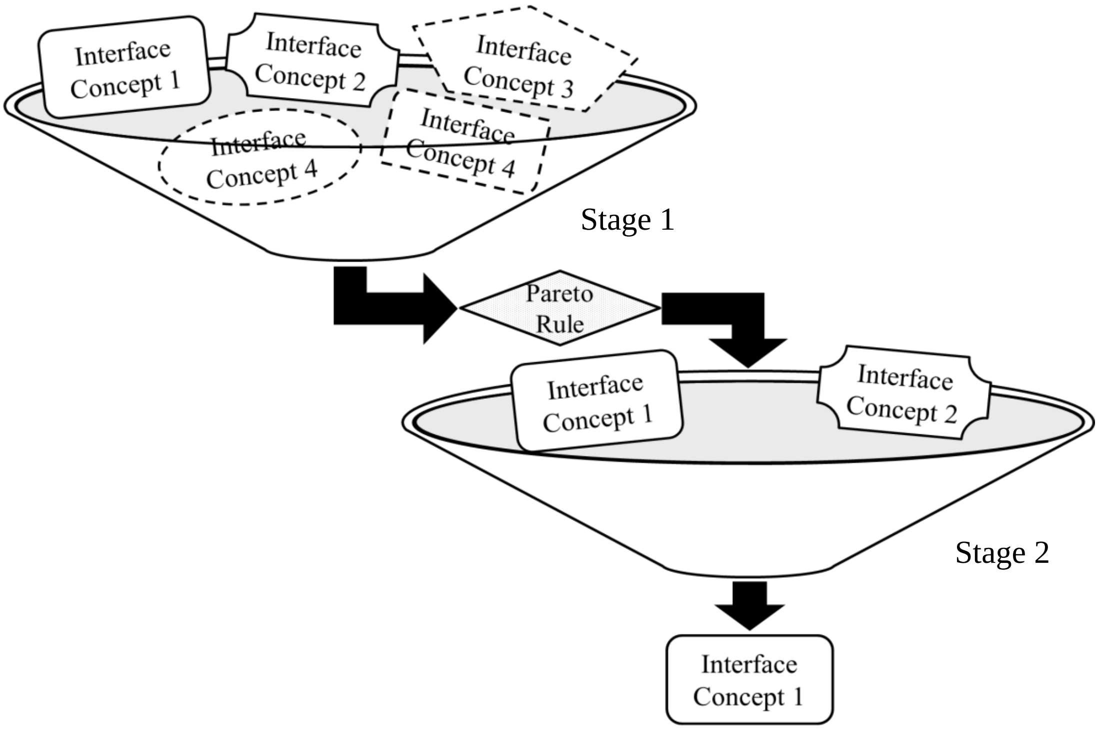
Following the reviewed literature, the research presented in this paper addresses 2 important research questions:

1. How can the user be provided with a practical yet reliable approach for the evaluation of module interface design concepts?
2. How can the user be guided in the selection of the appropriate appraisal technique for the evaluation of module interfaces?

The following section will outline the approach which is being proposed in order to address the two issues described earlier in this section. Section 3 will describe how this approach has been focused exclusively for the evaluation of module interface design concepts. Section 4 will describe and present the results of 2 case studies involving the evaluation of module interface design concepts. Finally section 5 will underline the main conclusions derived from the conducted research.

A two stage hybrid concept evaluation approach

The first problem which is being addressed in this research is related to the fact that the existing concept evaluation techniques are not able to provide the user with a reasonable compromise between the ease of use and the ability to produce valid results which clearly identify the most suitable concept. In order to address this research problem, we propose a two stage hybrid concept evaluation approach (2SHCE). The underlying principle of this proposed approach is that the evaluation of design concepts should be decomposed into 2 stages, where each stage corresponds to a particular multi criteria decision making (MCDM) technique as illustrated in Figure 1.



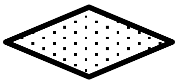
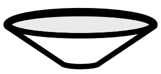
Legend	
	Interface concepts which are eliminated following the appraisal in stage 1
	Interface concepts not eliminated in stage 1 and are input into stage 2
	Pareto rule is employed in order to determine, which of the ranked interface concepts should be eliminated from the original solution space.
	A concept evaluation stage to which a specific MCDM technique is allocated.

Figure 1 Proposed two stage hybrid concept evaluation

The main goal of the MCDM technique which is allocated to stage 1 is that to eliminate weak concepts. This reduction of the solution space contributes to a simplification of the multi criteria decision making problem. The original set of interface concepts are appraised and ranked according to the MCDM technique which is allocated to this first stage. The pareto rule is used in order to determine which portion of the ranked interface concepts should be eliminated from the original solution space. From the description of stage 1, it follows that the MCDM technique allocated to this stage should be easy to use yet able to produce valid results which reflect the preferences articulated by the user.

The interface concepts which are not eliminated in stage 1 are then appraised with a secondary MCDM technique in stage 2. The objective of this stage is to clearly identify the most suitable interface concepts in a reliable manner. It follows that the MCDM technique which is assigned to stage 2 should have the ability to provide a compromise between the ability to pronounce the differences in the scores obtained by the interface concepts while producing valid results.

The second issue being addressed in this paper is related to the fact that users need to be effectively supported not only in the evaluation and subsequent selection of concepts but also in the selection of the appropriate concept appraisal techniques.

Allocation of MCDM techniques for each stage

The hybrid approach presented earlier requires for the allocation of an MCDM technique for each stage. The appropriateness of an MCDM technique for a given stage is determined by the performance of the technique with respect to 3 criteria.

Criterion 1: Clarity of the produced results

This criterion measures the inherent ability of a given MCDM technique to amplify the differences in the scores obtained by each interface concept. This criterion measures the ability of a technique to clearly identify the most suitable interface concept. The performance of any given MCDM technique with respect to this criterion varies from one decision making scenario to another.

Criterion 2: Ease of Use

This criterion represents the difficulty in using a particular evaluation technique. The performance of any evaluation technique with respect to this criterion is based on a subjective appraisal. This criterion is decomposed into 4 sub-criteria illustrated in Table 1.

Table 1 Decomposition of the criterion ease of use into sub-criteria.

Human expertise and knowledge required	This criterion determines the degree of knowledge which is required by the user in order to employ an MCDM technique.
Cognitive complexity	This criterion reflects the difficulty which the user might experience in trying to understand an MCDM technique.
Computational Complexity Type I	This criterion measures the number of steps and/or iterations which are required by a particular MCDM technique to compute the final score for each interface concept.
Computational Complexity Type II	This criterion reflects the difficulty in using an MCDM technique.

Criterion 3: Validity of the obtained results

The performance of an MCDM technique with respect to this criterion is measured using the method proposed by Yeh [23]. This criterion measures the degree to which the ranking of the alternatives obtained by a particular MCDM technique reflects the original dataset containing the performance of the interface concepts with respect to the conflicting criteria.

Aggregation of criteria

Once that the performance of an MCDM technique with respect to each of the 3 criteria is established the next step is that to aggregate these 3 values into a unique metric which represents the suitability of an MCDM technique for a given stage. The equation presented by Gershon [24] was used in order to aggregate the performance of the each technique with respect to 3 criteria into a single metric (L). The notation for equation (1) is shown in Table 2.

$$L = \sum_{i=1}^{i=3} \alpha_i \frac{f_i^* - f_i(x)}{f_i^* - f_i^{MIN}} \quad (1)$$

Table 2 Notation

x	This parameter represents an MCDM technique.
i	Criterion used to determine the suitability of an MCDM technique x for a given stage. In the 2SHCE approach the 3 criteria are : i=1: Clarity of the produced results, i=2: Ease of use and i=3: Validity of the obtained results.
α_i	The relative importance/weight of criterion i as illustrated in Table 3.
$f_i(x)$	The score of an MCDM technique (x) with respect to criterion i.
f_i^*	The highest score obtained by an MCDM technique, from a set of techniques with respect to criterion i.
f_i^{MIN}	The lowest score obtained by an MCDM technique, from a set of techniques with respect to criterion i.

Metric L, which measures the relative closeness of each evaluation technique to a hypothetical ideal method, employs of the criterion weight (α) in order to model the relative importance of each criterion. Since each stage in the proposed approach has a different objective, the weight attributed to each of the 3 criteria varies from stage 1 to stage 2 as illustrated in Table 3.

Table 3 Weighting strategy for each stage of the proposed 2SHCE approach

Criterion i	Clarity of the produced results (i=1)	Ease of use (i=2)	Validity of Results (i=3)
α Stage 1	0.2	0.5	0.3
α Stage 2	0.5	0.2	0.3

A life-oriented approach for the evaluation of module interfaces

This section will outline how the 2SHCE approach proposed has been applied exclusively to the evaluation of module interface design concepts. In the context of multi criteria decision making techniques, the factor which differentiates one multi criteria decision making problem from another is the definition of the criteria used to evaluate the respective alternatives. Due to the goal of this research, a set of generic criteria associated with various life cycle phases of the interface have been defined in order to assist the user in the evaluation of module interfaces. Some of these criteria disclosed in Table 4.

Table 4 Criteria for the evaluation of module interface design concepts

Criterion	Definition of criterion	Associated life phases
Time required for assembly	The time which is required in order to establish the interaction between 2 modules via the selected interface.	Assembly Use Service
Ease of assembly	This criterion measures the difficulty in assembling 2 product modules via the interface concept.	Assembly Use
Resources Required	The number and type of resources required in order for 2 modules to interact with each other via the selected interface.	Assembly Use Service
Reusability	The percentage of interface components which can be reused after disassembly.	Assembly Disposal

Evaluation of the 2SHCE approach

The proposed 2 stage hybrid concept evaluation (2SHCE) approach has been employed for the evaluation and subsequent selection of interface concepts in two case studies. In both case studies a total of 5 MCDM techniques were considered as potential candidates for each of the 2 stages. These evaluation techniques are illustrated in Table 5.

Table 5 List of candidate evaluation techniques considered for the case studies

Simple added weight (SAW) [25]
Weighted product method (WPM) [25]
Analytic hierarchy process (AHP) [11]
Technique for order preference by similarity to ideal solution (TOPSIS) [13]
Elimination and choice expressing reality (ELECTRE I) [12]

Case Study 1

The first case study required the evaluation and subsequent selection of a module interface which was required to convey water from one water treatment module to another. The evaluation problem consisted of 7 pipe fitting (PF) concepts (PF1, PF2, PF3, PF4, PF5, PF6 and PF7) which were assessed with respect to 6 criteria.

The first step was to identify the most suitable MCDM technique for each stage from the 5 candidate MCDM techniques. The L metric (1) was calculated for each MCDM technique were it was determined that the weighted product method should be allocated to stage 1 while TOPSIS should be assigned to stage 2. Out of the 7 interface concepts which were evaluated with the product weighting method only 4 concepts were carried on to stage 2. These 4 interface concepts were then evaluated using TOPSIS. The appraisal of the reduced solution space using TOPSIS resulted in the selection of PF3 as the highest ranking interface concept.

Case Study 2

This decision making scenario involved the evaluation of trailer couplings (TC) used to tow trailers behind a vehicle. In this case study the solution space consisted of 6 trailer couplings (TC) (TC1, TC2, TC3, TC4, TC5 and TC6) which were evaluated with respect to 6 criteria. In this particular case study the simple added weight was allocated to stage 1 while the analytic hierarchy process was determined as the most suitable MCDM technique for stage 2.

The 6 trailer couplings were appraised and ranked using the simple added weight. Out of the original solution space 2 trailer couplings were eliminated, while the remaining interface concepts were appraised using the analytic hierarchy process in stage 2. This appraisal resulted in the trailer coupling TC3 as the highest ranking interface concept.

Discussion of Results

The need for the user to be supported in the selection of the appropriate MCDM technique is illustrated by the fact that different MCDM techniques were considered to be suitable for different decision making scenarios.

In the first case study the weighted product method and the technique for order preference by similarity to ideal solution (TOPSIS) were identified as the most suitable evaluation techniques for stages 1 and 2 respectively. In the second case study the simple added weight was identified as the most suitable technique for stage 1, while the analytic hierarchy process was allocated to stage 2. The allocation of the MCDM techniques to each stage was based on the ability of the technique to provide a compromise between the 3 criteria presented earlier for the allocation of the appropriate MCDM technique.

Conclusion

To address the problem associated with the evaluation and subsequent selection of module interface design concepts the research presented a 2 stage hybrid concept evaluation (2SHCE) approach which supports the user on two levels.

On one level the proposed approach supports the user in a life-oriented evaluation of module interface design concepts. This has been achieved through the definition of some criteria associated with various life cycle phases of interfaces in modular products. These criteria were employed in 2 MCDM techniques which were applied sequentially. Although the user is provided with these predefined generic criteria, this does not imply that the user cannot include other case specific criteria.

On a secondary level the presented 2SHCE approach supports the user in a case specific selection of the appropriate concept evaluation techniques, where a particular combination of MCDM techniques is selected for each specific decision making scenario.

It is concluded that:

1. The presented 2SHCE approach is comprehensively practical yet capable of producing valid results which clearly indicate the most suitable interface concept. The underlying principle of the presented 2SHCE approach is that weaker interface concepts are eliminated as early as possible. This reduction in the number of candidate interface concepts results in a simplification of the decision making problem.
2. The user is exclusively supported in the evaluation of module interface design concepts by means of predefined generic evaluation criteria which are associated with various life cycle phases of the interface.
3. The presented approach addresses the need of the user to be also supported in the selection of the appropriate concept evaluation technique. The relevance of this need was underlined by the fact that there was a significant variation in the performance of the MCDM techniques under different decision making scenarios.

It is therefore worth investing further research in order to address current weaknesses and exploit further the potential of the presented approach. An important objective of this research will be that to implement the underlying principle of the presented approach into a computer evaluation tool, hence facilitating further the complex task of evaluating and subsequently selecting module interface design concepts.

Future Work

The aim of this research in the near future will be that to define other generic criteria associated with various life cycle phases of module interfaces.

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