A Module Interface Concept Evaluation Approach Promoting the Consilience of Design Science, Practice and Emotion

Lawrence Farrugia*, Jonathan Borg*

** University of Malta, lfar0013@um.edu.mt*

The early stages of product design are particularly important due to the fact that the decisions made, have a profound impact on subsequent life cycle phases of the artefact. The research presented in this paper contributes with a design approach, which supports the design team in the evaluation of module interface design concepts. In addition, this evaluation approach comprehensively supports the design team with respect to the multiple challenges which have to be addressed throughout the evaluation process. The intent of the research presented in this paper, is also to render the developed approach sufficiently practical to be employed in a realistic setting. For this purpose the approach framework has been implemented into a prototype computer aided design tool.

Key words: Life-oriented evaluation criteria, modularity, information sources, multiple criteria decision making, computer aided design.

1. Introduction

One of the critical activities which take place during the early stages of product design concerns the evaluation of the synthesised design concepts. The main purpose of the evaluation activity is to select concept or concepts that should be developed further throughout subsequent product design stages. A characteristic of the early stages of product design is that while the actual cost incurred is low, the total costs which are committed as a result of the decisions made can be extremely high. In fact it is estimated that between 60 to 80% [8, 19, 20] of the total product costs are committed during the very early stages of product design. It follows that a poor evaluation of the generated design concepts, can rarely be compensated for at later stages of product design[21].

Design teams can no longer consider the degree to which the intended functions are fulfilled as the only evaluation criteria. Instead, the appraisal of design concepts has to take into consideration the impact of the artefact across multiple life cycle phases. While the early appraisal of design concepts presents the design team with numerous challenges, these challenges have to be addressed within a time frame which is becoming increasingly smaller while at the same time many artefacts are becoming more complex [3].

The objective of the research work presented in this paper is to develop a framework approach, which supports the design team in the evaluation of module interface design concepts as shown in Figure.1. Another objective of the research work is to ensure that the proposed approach comprehensively supports the design team with respect to the multiple challenges which have to be addressed throughout the evaluation process. The evaluation approach being presented in this paper has also been implemented into a prototype computer aided design tool, with the intent to render it practical and desirable to use.

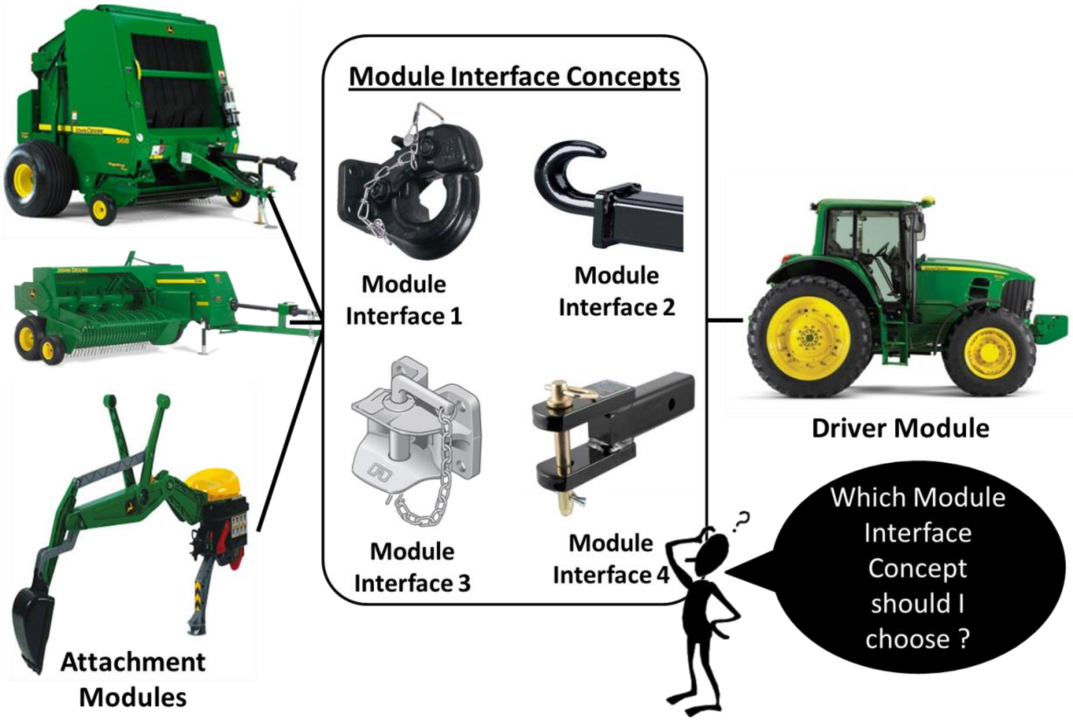

Figure.1 The evaluation of module interface concepts

This research work is divided into 5 main sections. The next section will present a review of the literature from which the research problems were formulated. Following the identification of the research problems, section 3 will present the approach framework and its prototype software implementation which have been developed in order to address these research problems. Section 4 will then present an evaluation of the proposed solution. Finally section 5 will present the main conclusions which outline the contribution of the research work.

2. State-of-the-Art Evaluation Support

The main objective of this research was to provide a design support means for the purpose of evaluating module interfaces. For this reason, the following research question was asked: *What is the state-of-the-art in the provision of approaches which are proposed for the purpose of evaluating module interface design concepts?*

Throughout the years, numerous authors have presented [4, 5, 9, 10, 23] design methodologies for modular products. The review of this literature [4, 5, 9, 10, 23], suggests that many authors recognize the selection of the generated module interface candidates as an important part of the design of modular products. Yet, none of these authors [4, 5, 9, 10, 23] developed an approach which is aimed specifically at providing support in relation to the activity concerning the evaluation of module interface concepts. It should be noted, that this research will only consider attachment interfaces, which provide physical attachment among modules and transfer interfaces which are responsible for transferring mechanical or primary flow from one module to the other.

Due to the lack of design approaches which focus on the evaluation of module interfaces, the next step of the research work was to gain a better understanding of the challenging tasks which constitute the evaluation process. The work by de Boer [6], Derelov [7] and Badke-Schaub [2] suggest that the evaluation activity, involves multiple challenging tasks which include: the identification of evaluation criteria, the acquisition of relevant information and the selection of the appropriate concept evaluation technique.

The research question that stems from this literature review is: *What type of support is provided to design teams in relation to the concept evaluation process, which takes place during the early stages of product design?* The impact that the early decisions have on the subsequent life cycle phases of the product, has motivated many researchers in the field of design science to propose different concept evaluation methods [12, 13, 14, 15, 18, 24, 25]. Typically these concept evaluation methods utilise multiple criteria decision making (MCDM) techniques at their core, in order to mathematically appraise and rank a set of design concepts with respect to numerous evaluation criteria. A shortcoming which is shared by the majority of the reviewed evaluation methods [12, 13, 14, 15, 18, 24, 25]concerns the fact that the type of support provided, is typically limited to the sole provision of a concept evaluation technique, with a complete disregard to other challenging tasks which constitute the evaluation process. It follows, that the answer to the second research question is that at present design teams are not being comprehensively supported with respect to the multiple challenges which make-up the evaluation process.

Another research question derived directly from the literature review was: *What is the degree of utilisation within industry, of concept evaluation approaches which have been developed as a direct result of academic research?* Throughout the years numerous investigations [1, 16, 17, 22] were conducted, with the intent to understand the degree of utilisation of design tools within industry. These independent studies [1, 16, 17, 22] mutually converged to the conclusion, that the degree of utilisation of design tools which stem from academic research is very low. The cognitive effort required to understand a design method, the time required to explain these methods to others and the lack of computer support are partially responsible for the low degree of utilisation of formal design tools. It follows that while many of these academic design tools are based on sound scientific and/or mathematical principles, in reality these are too complex and impractical to be employed in a realistic decision making scenario.

2.1. Research Problem Formulation and Hypothesis

The hypothesis of this research is that: *The introduction of a structured approach for the purpose of evaluating design concepts, which is based on the consilience of design science and practice, will ameliorate the performance of modular products with respect to various life cycle phases.*

Following the literature review which has been presented in the previous section, the following research problems may be formulated. The first research gap which was identified from the literature review concerns the fact that there are no design support means which specifically addresses the evaluation of module interface design concepts. This research gap has been formulated as research problem 1, which is described in Table 1.

Table 1. Research Problem 1

Research Problem 1	There is a lack of design support means which focus exclusively on the evaluation of module interface design concepts.

The next part of the literature review focused on existing concept evaluation methods, which have been proposed throughout the years. Following this literature review a second research problem was identified, as described in Table 2.

Table 2. Research Problem 2

Research Problem 2	The approaches which have been proposed for the purpose of evaluation of design concepts provide support to the design teams in a very limited manner.

Finally the last part of the literature review addressed the degree of utilisation of design tools which emerge from academic research. This literature review suggests that the degree of utilisation, within industry, of formal concept evaluation approaches is extremely low. This is partially attributed to the fact, that most of the design tools which stem from academic research are too impractical to employ in a realistic setting, as defined in Table 3.

Table 3. Research Problem 3

Research Problem 3	The design tools which emerge as a direct result of academic research are typically reliable yet too impractical to employ in a realistic decision making scenario.

Following the identification of these research problems, the research proceeded with the development of the solution which will be presented in the next section.

3. An Approach Framework for the Comprehensive Evaluation of Module Interfaces (FEMI)

This section will present the solution which has been developed in order to address the research problems which have been identified earlier. The solution comprises an approach framework and a prototype software implementation of this framework, as illustrated in Figure.2.

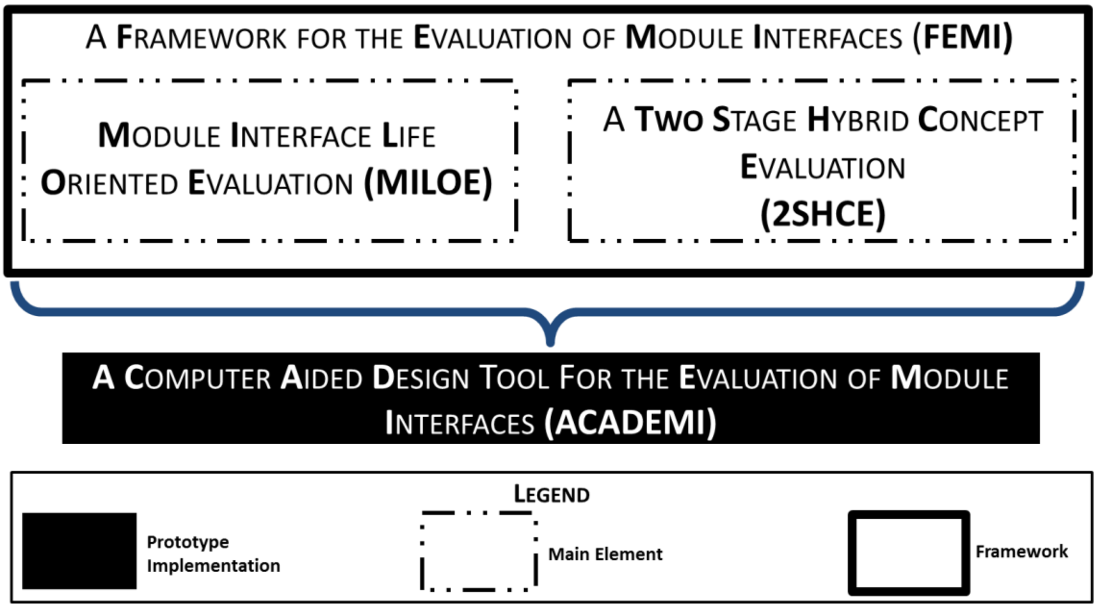

Figure.2 A Framework for the Evaluation of Module Interfaces

3.1 A Framework for the Evaluation of Module Interfaces (FEMI)

The proposed framework consists of two main elements, which are illustrated in Figure.3. The first of these two elements is called the Module Interface Life Oriented Evaluation (MILOE). One of the first challenging tasks which the design team has to address throughout the evaluation process, concerns the identification of a common set of evaluation criteria. In this context the MILOE element, presents the design team with a pre-defined set of module interface, life-oriented evaluation criteria (MILOEC). In addition the design team may also define additional evaluation criteria that are relevant to specific evaluation problems. These criteria, which are generated by the design team, are called domain specific evaluation criteria.

The second challenging task in the evaluation process involves the definition of module interface concepts in terms of the chosen and/or generated evaluation criteria. Due to the fact that this task requires strong information gathering, the FEMI supports the design team with respect to this task, by providing a rapid means of acquiring specific types of information sources. The gathered information allows the design team to create a matrix which describes the performance of each module interface concept with respect to each and every evaluation criterion.

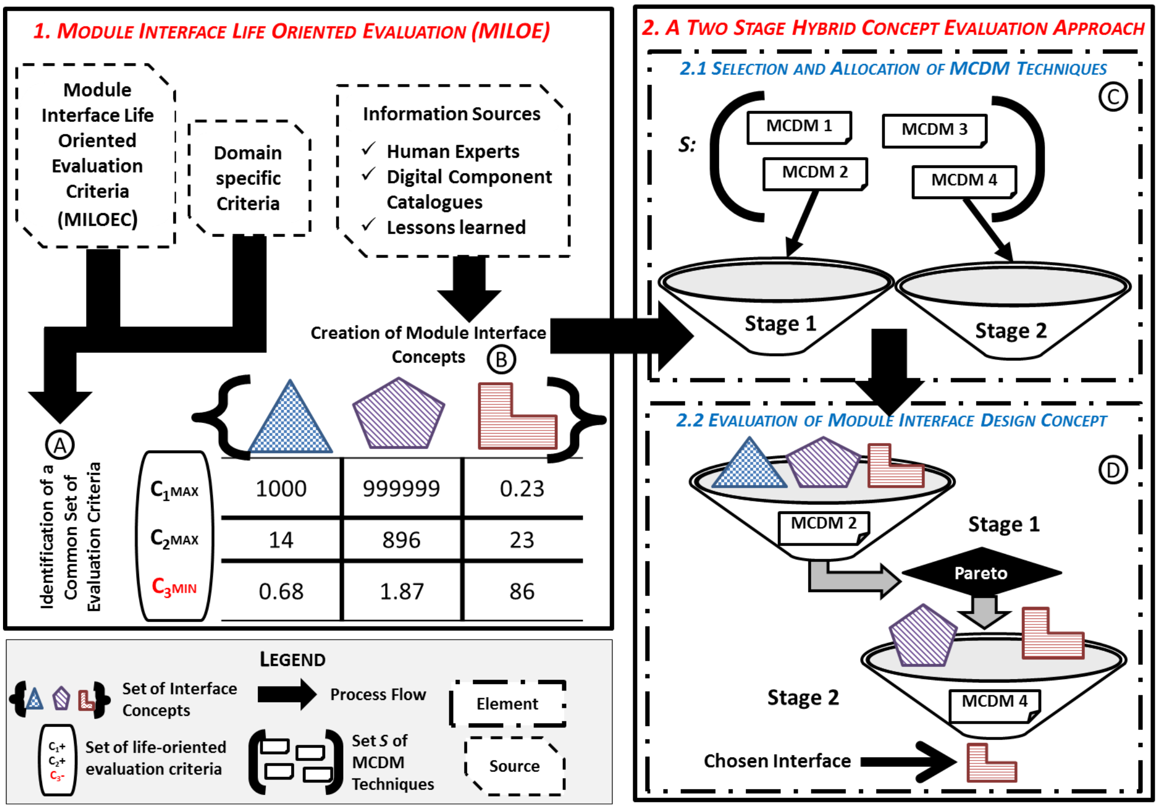

Figure.3 The elements which make up FEMI

The next element of the FEMI approach, is the two stage hybrid concept evaluation (2SHCE) [11] process. As the name implies, this evaluation process is fragmented into two sequential stages, where each stage corresponds to a particular MCDM technique. The underlying principle of this evaluation process is that to reduce the complexity of the decision making problem, by reducing the size of the solution space. This is achieved by eliminating weak alternatives from the solution space at the first stage of the two stage evaluation process [11]. For this purpose the MCDM technique which is allocated to stage 1 provides a first ranking of the module interface concepts in the solution space. At this point the Pareto principle is applied in order to determine which module interface concepts should be eliminated from the original solution space. The stronger alternatives are then passed on to stage 2, where these are appraised once again with respect to a secondary MCDM technique.

The 2SHCE also supports the design team in the selection of the appropriate concept evaluation technique to be allocated to each stage of the evaluation process. In this context each MCDM technique being considered, is appraised with respect to three selection criteria. These selection criteria are: the intrinsic complexity of an MCDM technique, the clarity of the results obtained by an MCDM technique and the validity of the ranking outcome obtained by each MCDM technique. These three MCDM selection criteria are used in order to determine which MCDM technique should be allocated to each of the two stages of the 2SHCE process.

3.2. A Computer Aided Design Tool for the Evaluation of Module Interfaces (ACADEMI)

An important research problem which was identified from the literature review concerns the fact, that most of the outcome which stems directly from academic research, is not rendered practical enough to employ in a design practice. Motivated by this research problem, one of the objectives was to render the FEMI approach substantially practical to be employed by engineering design practitioners. For this purpose the FEMI was implemented into a prototype computer aided engineering design tool which is shown in Figure.4.

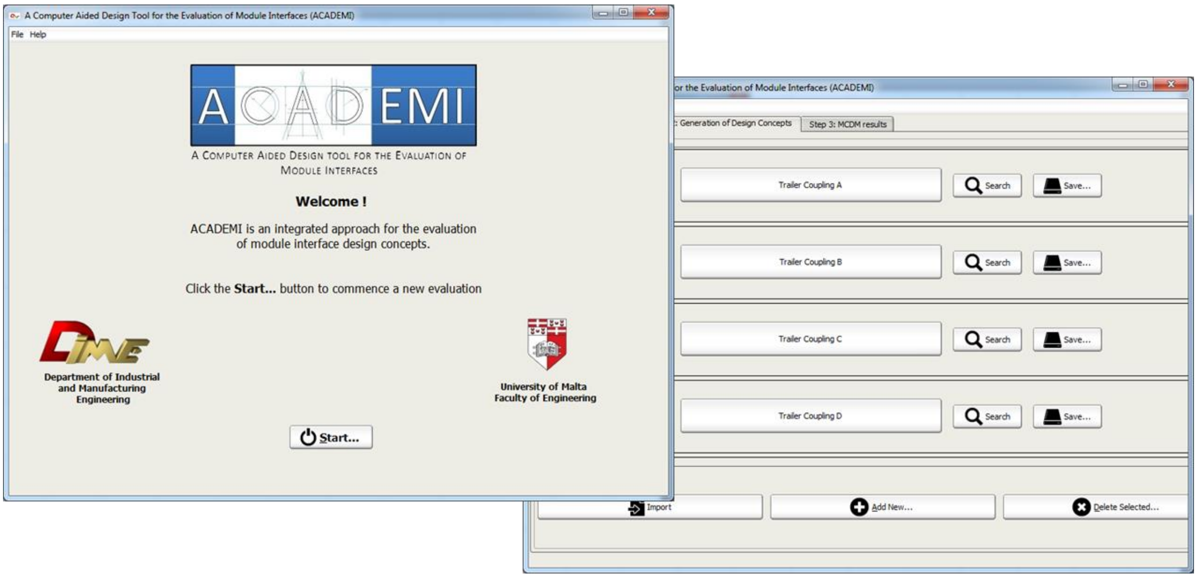

Figure.4 Screen shots of the ACADEMI prototype tool

This prototype tool has been used throughout a number of evaluation sessions, in order to demonstrate the underlying principle of the FEMI approach. The outcome from these evaluation sessions will be presented in the next section.

4. Evaluation of the Developed Solution

The FEMI approach and its prototype software implementation have been subjected to numerous evaluation sessions which saw the participation of thirteen evaluators from both academia and industry, situated in Denmark and Malta. The feedback presented throughout this section is based on an analysis of the responses obtained from the survey questionnaire that was distributed throughout the evaluation sessions, and direct comments which were articulated by the participants.

4.1 Evaluation of the Proposed Framework (FEMI)

The responses of the survey questionnaire indicate that 30% of the respondents considered the pre-defined evaluation criteria to be somewhat effective in facilitating the evaluation process, while 46% of the respondents considered these criteria to be effective in facilitating the evaluation process. In addition, over 68% of the participants considered the provision of the evaluation criteria to be relevant to the evaluation of module interfaces. The results concerning the appraisal of the module interface life oriented evaluation criteria are summarized in Figure.5.

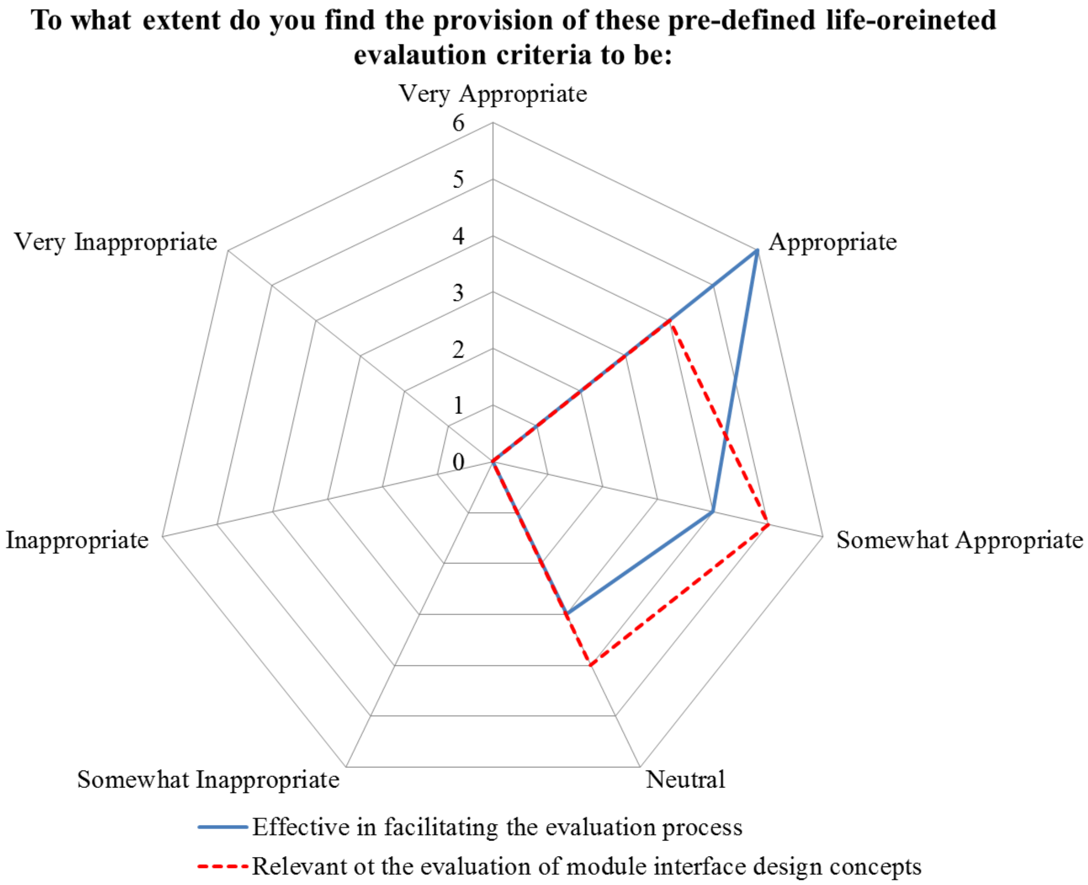

Figure.5 Evaluation of effectiveness and relevance of the pre-defined evaluation criteria.

Another challenging task that was identified throughout the literature review, concerns the acquisition of information which is necessary in order to define the design concepts in terms of the established evaluation criteria. In this context over 76% of the participants considered the provision of support in relation to the acquisition of information to be effective in facilitating the evaluation process.

A weakness that was identified throughout the evaluation session, concerns the fact that the pre-defined set of evaluation criteria encompass a limited number of life cycle phases. Although the provision of a pre-defined set of evaluation criteria was rated positively, many of the evaluators commented that no guidance is provided in the selection of these evaluation criteria.

While the provision of support in relation to the acquisition of information was appraised in a positive manner, a weakness of the FEMI approach is that it assumes that the information which is captured contains no imprecision.

It should also be noted that over 69% of the participants were somewhat in agreement that the adoption of the proposed framework could have a positive influence on the design of modular products. This result, which is shown in Figure.6, provided a confirmation of the research hypothesis which states that: the introduction of a structured approach for the evaluation of module interfaces can have a positive impact on the design of modular products.

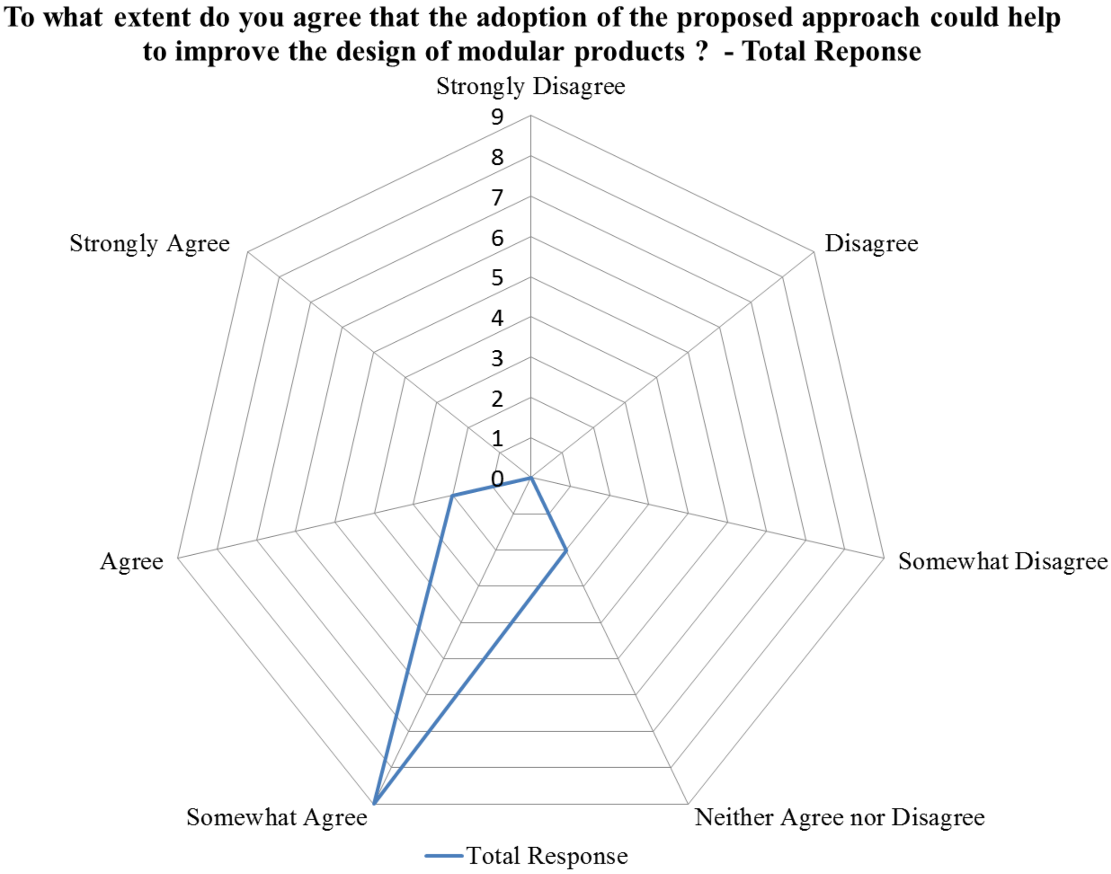

Figure.6 The degree to which the FEMI approach has a positive impact on modular product design.

The main strengths and weaknesses which have been identified following these evaluation sessions are summarized in Table 4.

Table 4. Summary of the strengths and weaknesses of the proposed approach framework

Strengths	Weaknesses
The proposed approach inherently structures the evaluation process.	The evaluation criteria provided encompass a limited number of life cycle phases.
The approach contributes in a positive manner to the design of modular products.	No guidance is provided in the selection of the appropriate evaluation criteria.
The provision of support in relation to the identification of evaluation criteria and the acquisition of information, are considered to be relevant to the evaluation of module interfaces.	The proposed framework assumes that the information is precise and contains no uncertainty.

4.2. Evaluation of the Prototype Software Implementation (ACADEMI)

One of the positive comments shared by many of the participants concerned that fact that the prototype software implementation is easy to use and able to provide results quickly. In fact the responses from the survey questionnaire indicate that over 61% of the participants agree that the prototype software implementation is somewhat easy to use. An interesting result which emerged from the survey questionnaire was that the software implementation rendered the proposed approach framework desirable to use. In fact, 76% of the participants from both industry and academia, somewhat felt that the adoption of the proposed framework into a prototype tool, rendered the approach at least somewhat emotionally desirable to use as shown in Figure.7.

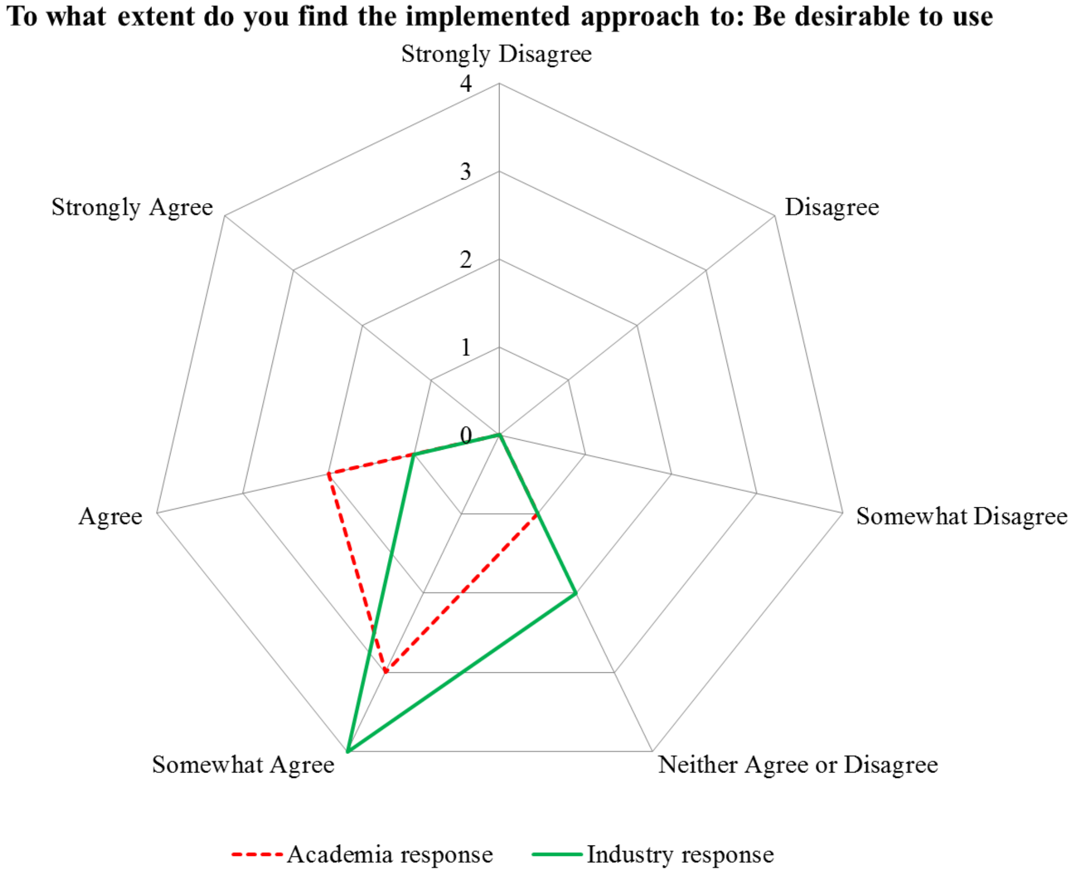

Figure.7 The extent to which the ACADEMI prototype renders the approach desirable to use

A weakness that was identified throughout the evaluation sessions is related to the fact that ACADEMI is still required to be updated as new information and knowledge is made available. The majority of the participants from industry expressed their wish to see this prototype software integrated with existing commercial computer aided design tools. Another comment that was shared by the majority of the participants from industry was in relation to the way the results are presented. Many of these participants expressed their wish to see the results presented in a more graphical format. The strengths and weaknesses of the prototype tool are summarized in Table 5.

Table 5. Summary of the strengths and weaknesses of the prototype software implementation

Strengths	Weaknesses
The implementation renders the proposed approach practical to employ in a realistic setting.	No integration with commercial CAD software.
The adoption of the approach into prototype software renders the approach desirable to use.	Results are not presented in a graphical format.
The software implementation is easy to use and provides clear results.	The software implementation may still require for the embedded data to be updated as new information and knowledge is gathered.

5. Conclusions

The research work presented in this paper has addressed a number of research problems which have been disclosed earlier in section 2. Following the appraisal of the FEMI approach it may be concluded that:

i. The provision of a structured approach (FEMI) for the purpose of evaluating module interfaces is considered to have a positive impact on the design of modular products. This may be considered as one of the important contributions of this research.
ii. Unlike previous evaluation methods, the FEMI approach addressed the multiple challenges that are part of the evaluation process. This distinguishing characteristic of the FEMI approach is considered facilitate the evaluation process.
iii. The FEMI framework can be exploited by CAD system developers to implement new means for supporting interface concept designs.

The conclusions regarding ACADEMI

i. The ACADEMI prototype renders the FEMI approach emotionally desirable to employ in a realistic setting, while at the same time contributes towards rendering the FEMI approach more practical.
ii. The prototype software implementation inherently proves that the FEMI framework developed, can in fact be implemented into a computational tool.
iii. Due to the overall positive evaluation feedback, it can be concluded that further research work to improve the FEMI framework and address the ACADEMI prototype weaknesses is feasible.

The aim of the research work in the near future will be to address the weaknesses which have been pointed out throughout these evaluation sessions. One of the objectives of the research work in the near future will be to provide of additional evaluation criteria which encompass other life cycle phases. Another objective of this research will be to cater for the imprecision in the information which is captured during the early stages of product design. In addition, this research will aim at extending the underlying principles of the FEMI approach beyond the appraisal of module interfaces.

6. References

[1] Araujo C. S. and Benedetto-Neto H., (1996) *The utilization of product development methods: A survey of UK industry,* Journal of Engineering Design, vol. 7, no. 3, pp 265

[2] Badke-Schaub P. and Gehrlicher A., (2003) *Patterns of Decision in Design : Leaps, Loops, Cycles, Sequences and Meta-processes,* In Internation conference on Engineering Design ICED pp

[3] Biren P., (1998) *Designing products for variety and how to manage complexity,* Journal of Product and Brand Management, vol. 7, no. 3, pp 208-222

[4] Blackenfelt M. and Sellgren U., (2000) *Design of Robust Interfaces in Modular Products* In Proceedings of ASME Design Engneering Technical Coferences, pp

[5] Blackenfelt M., (2001) *Managing complexity by product modularisation,* Department of Machine Design, vol. Doctoral Thesis no. pp 90

[6] DeBoer S. J., (1990) *Systematic Decisions in Methodical Engineering Design,* In Proceedings of Scriftenreihe WDK 17, pp

[7] Derelov M., "On Evaluationa of Design Concepts," Doctor of Philosphy, Department of Management and Engineering, Linkopings universitet, Sweden, 2009.

[8] Duffy A. H. B., Andreasen M. M., Maccallum K. J., and Reijers L. N., (1993) *Design Coordination for Concurrent Engineering,* Journal of Engineering Design, vol. 4, no. 4, pp 251-265

[9] Ericsson A. and Erixon G., (1999) *Controlling Design Variants* Society of Manufacturing Engineers, Michigan.

[10] Erixon G., "Modular Function Deployment - A method for Product Modularisation," Doctoral Thesis, The Royal Institute of Technology, Stockholm, 1998.

[11] Farrugia L. and Borg J. C., (2012) *Towards Life-Oriented Evaluation Support of 'Interface Concepts',* In NordDesign 2012, Aalborg University, pp 1-8.

[12] Green G. and Mamtani G., (2004) *An Integrated Decision Making Model for Evaluation of Concept Design,* Acta Polytechnica, vol. 44, no. 3, pp 62-65

[13] Hao-Tien L., (2011) *Product design and selection using fuzzy QFD and fuzzy MCDM approaches,* Applied Mathematical Modelling, vol. 35, no. 1, pp 482-496

[14] Jiao J. and Tseng M., (1998) *Fuzzy Ranking for Concept Evaluation in Configuration Design for Mass Customization,* Concurrent Engineering: Research and Applications, vol. 6, no. 3, pp 189-206

[15] Karsak E. E., (2002) *Distance-based fuzzy MCDM approach for evaluating flexible manufacturing system alternatives,* International Journal of Production Research, vol. 40, no. 13, pp 3167-3181

[16] Kikuo F. and Takahiro M., (2005) *Utilization of Product Development Tools and Methods : Japanese Survey and International Comparison,* In International Conference on Engineering Design ICED 05, pp

[17] López-Mesa B. and Bylund N., (2011) *A study of the use of concept selection methods from inside a company,* Research in Engineering Design, vol. 22, no. 1, pp 7-27

[18] Mikenina L. and Zimmermann H. J., (1999) *Improved feature selection and classification by the 2-additive fuzzy measure,* Fuzzy Sets and Systems, vol. 107, no. 2, pp 197-218

[19] Nevins J.L., (1989) *Concurent Design of Products and Proceses: A Strategy for the Next Generation in Manufacturing,* Mcgraw-Hill,

[20] Römer A., Pache M., Weißhahn G., Lindemann U., and Hacker W., (2001) *Effort-saving product representations in design—results of a questionnaire survey,* Design Studies, vol. 22, no. 6, pp 473-491

[21] Roozenburg N.F.M., (Eekels, J.) *Product Design: Fundaments and Methods,* Wiley,

[22] S. Mikko and P. Matti, (2005) *Utilization of Concept Selection Methods: A Survey of Finnish Industry,* ASME Conference Proceedings, vol. 2005, no. 4742Xa, pp 527-535

[23] Scalice R., Segalin de Andrade L., and Forcellini F., (2008) *A Design Methodology for Module Interfaces* In Proceedings of 15th ISPE International Conference on Concurrent Engineering (CE 2008), pp 297-304.

[24] Shafin T. and Gul O., (2007) *Fuzzy Information Axiom Approach for Design Concept Evaluation,* In Proceedings of Proceedings of the 16th International Conference on Engineering Design (ICED07), pp

[25] Wang J., (2001) *Ranking engineering design concepts using a fuzzy outranking preference model,* Fuzzy Sets and Systems, vol. 119, no. 1, pp 161-170