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A COMPUTATIONAL TOOL FOR VIRTUAL PRODUCT DEVELOPMENT EXPLOITING CHANGEABILITY KNOWLEDGE

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Abstract

Shifts in customer needs coupled with highly competitive markets and technological advances, means that product families evolve over time. Product family evolution has an effect not only on how the current and future manufacturing requirements are defined but also on the manufacturing system design process itself and represents one of the main difficulties in designing manufacturing systems. Two types of factory life cycle consequences have been identified which may occur as a result of design decisions during the manufacturing system synthesis design activity. This research therefore contributes a novel changeability knowledge based product development approach framework to reveal and analyse the consequences of commitments made during manufacturing system design on future product capability, hence on product evolution, and factory changeability. This approach was implemented in a computational tool for virtual product development which exploits changeability knowledge to assist, guide and motivate manufacturing system designers into designing more changeable manufacturing systems.

Keywords: Computational design methods, Concurrent Engineering (CE), Integrated product development, Product families

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1 DESIGN PROBLEM BACKGROUND

1.1 Product Family Evolution

One approach for companies to meet customers' needs for ever increasing diversified and customised products, is to employ product development of product families and platforms (Simpson et al., 2001). That said customers are increasingly demanding new products with new capabilities and features on the market. Shifts in customer needs coupled with highly competitive markets and technological advances, means that product families evolve over time with the addition or subtractions of parts or part features (ElMaraghy and AlGeddawy, 2012).

During product development the production development activity during which manufacturing processes and systems are designed (Duhovnik and Tavčar, 2015) is affected by the complexity introduced by evolving product families. In order to deal with evolving product families, factories and their underlying manufacturing systems (MSs) need to be designed with an inherent changeability (Francalanza et al., 2015). The MS synthesis design activity has to therefore deal with the inherent uncertainty in the MS requirements since it cannot be predicted with certainty how future products will evolve over time, as this is dependent on factors such as market volatility. Product family evolution therefore has an effect not only on how the current and future MS requirements are defined but also on the MS design process itself and represents one of the main difficulties in designing MSs.

1.2 Factory Changeability

Factories are multi-million euro investments, with long life cycles which have to evolve with respect to the products which they manufacture. Furthermore decisions which are taken in the early factory life stages can have an impact on the overall productivity and competitiveness of the manufacturing activity. One of the approaches utilised by MS designers, in order to deal with these challenges, is the introduction of manufacturing changeability. The practice of designing MSs with a degree of changeability has been developed in order to support MS designers in dealing with the challenges brought about by product evolution. Wiendahl (Wiendahl et al., 2007) defines changeability as the characteristic to accomplish early, economical and foresighted adjustments of the factory's structures and processes on all levels to change impulses. Many systematic design approaches have been developed for designing changeable manufacturing systems such as Transformable Factories, Flexible Manufacturing Systems (FFMS), Reconfigurable Manufacturing Systems (RMS). More recently Cyber Physical and Evolvable Production Systems or Industry 4.0 developments have also contributed as enablers of changeability within factories (Onori et al., 2010).

From a systems theory perspective, and as explained by Hubka (1973), factories can be considered as higher order technical systems. Westkämper and Zahn, (2007), in fact present the "factory as a product" paradigm which defines factories as complex and long life products which have to be designed and adapted to the needs of markets, production and technologies. As has been presented by Francalanza et al., (2014) this paradigm can be used to apply concepts defined in "Design Theory" research to the design of factories, that is to complex engineered systems.

1.3 Factory Life Cycle Consequences (FLCCs)

As previously argued during the design process of changeable MS, the MS designer has to ideally consider and analyse not only the current product family requirements, but also how the product family may evolve over time. All of this within the parameters of the company's business strategy. Due to the evolution of product families, MS synthesis design decisions can have consequences on future capability and changeability of the MS. This argument is based on the "Theory of Dispositions" by Olesen (1992), who argues that decisions made during the product design activity have consequences on later product life-cycle stages. Moreover Olesen (1992) argues that MS design decisions have a consequence on the product range capability of the MS. Therefore when MS synthesis design decisions have a consequence on future MS capability, as is or in a reconfigured state, to manufacture evolved product families, then this has negative consequences on business performance.

Therefore, since MS design precedes all other factory life cycle phases, it is here argued that decisions taken in the early stages of MS design can have consequences on the future factory life cycle. This research has identified two types of factory life cycle consequences (FLCCs) which may occur as a result of MS design decisions. Manufacturing Capability Consequences (MCCs), which occur when MS elements are no long capable of producing future MS requirements, such as product family features or production volume. Factory Changeability Consequences (FCCs), which occur when a MS cannot be changed or modified to meet future MS requirements.

1.4 Integrated Product Development

In order to handle the interactions between the MS requirements and MS solutions which result in FLCCs, the MS designer has to be knowledgeable of the future MS requirements. MS requirements are developed in other fields of product development, such as business strategy planning and product design. Business strategy planning identifies current and future markets, and how customer requirements evolve over time. In response to this, evolving product families are designed to address both the current and future customer needs. Therefore, for an approach to support MS design it would be beneficial to take into consideration the implications arising from other disciplines involved in product development, such as business strategy planning and product family design. This research therefore makes use of the good theoretical foundation provided by the research work carried out in the field of Integrated Product Development (IPD). IPD prescribes a product development approach involving the whole business, where activities are carried out concurrently with the aim of minimizing the time-to-market of the product. IPD models such as those proposed by Andreasen and Hein (Andreasen and Hein, 1987), and Olsson (Olsson, 1985) represent the idealised product development activities involved in developing a product from the initial stages when customer needs are identified, to the launching of the product into the market (von Specht and Vajna, 2006).

1.5 Product Development Reality

An important and interesting argument put forward in CMS design is that there is nothing like an absolute changeability (ElMaraghy and Wiendahl, 2009). Some researchers, such as Tolio, (2009) 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). Terkaj et al., (2009) contribute a process diagram that details the design activities involved in developing FFMSs. As explained by Stjepandić et al., (2015) Knowledge Based Engineering (KBE) is a comprehensive application of artificial intelligence engineering and can facilitate new product development. An approach which provides a knowledge based framework that facilitates the definition, storage and extraction of knowledge in terms of past production process configurations is that presented by Efthymiou et al., (2015). This approach retrieves and presents knowledge about manufacturing systems, permitting the effective past projects (process and infrastructure knowledge) during the early steps of system design, but does not make MS designers aware of factory changeability consequences (FCCs).
In summary, even though these authors have contributed towards providing such approaches as to support changeability in MS design support is provided late in the MS design process after the MS solution has been detailed, during the MS design analysis activity. Whilst these means further prove the need for supporting MS design, and they cover a wide range of support, they do not assist MS designers proactively during the MS design synthesis activity. Moreover there is lacking means which provide changeability knowledge, which makes MS designers aware of MCCs and FCCs, during the MS design process. The high level research problem addressed by this research therefore concerns how a computational tool can be developed to support the virtual product development activity by exploiting changeability knowledge during MS design.

2 RESEARCH AIM AND HYPOTHESIS

Making MS designers explicitly aware of FCCs and MCCs, here defined as changeability knowledge, simultaneously arising with a MS design solution will reveal any unintended MCCs and FCCs influencing the capability and changeability of the factory, and therefore facilitate future product evolution. Moreover a computational tool is required to support virtual product development by providing guidance knowledge to MS designers in order to guide them in making decision commitments on changeability strategies and enablers. The hypothesis here is that being provided with changeability knowledge will motivate and support MS designers into designing MSs that can handle the challenges related to product family evolution.

The research aim is therefore to develop and evaluate a computational approach framework to support design of MSs during virtual product development. This MS design approach framework will serve as a means to proactively support MS designers during the MS synthesis design activity with changeability knowledge, by revealing FCCs and MCCs, together with solution specific guidance on changeability strategies and enablers that can be employed.

3 SOLUTION DEVELOPMENT

3.1 Methodology

Figure 1 portrays a framework for the development of a computational tool that provides knowledge based support. This computational tool development framework has been adapted from the works of Duffy and Andreasen (Duffy and Andreasen, 1995) who utilise a similar framework for the development of intelligent computational tools for product design. The support which is required is primarily derived from the reality which is studied and the area of influence identified. Phenomena models are descriptive models based on this reality. The knowledge model is a formal representation of the phenomena model, and defines the type of knowledge and knowledge structures.

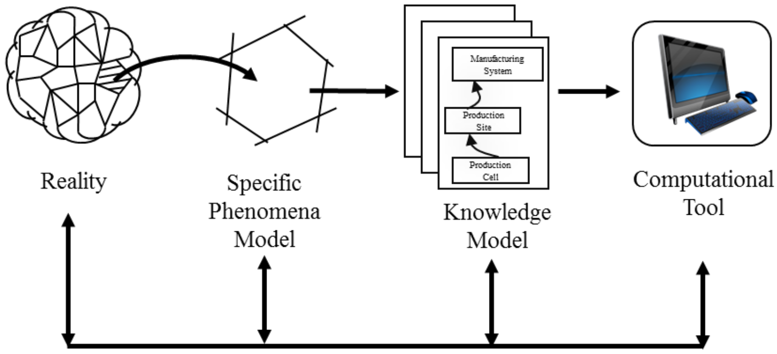

Figure 1. Computational tool development framework – adapted from [9]

3.2 Phenomena Model

As explained by Suh (Suh, 2001) in the Axiomatic Design theory, design can be described as the activity by which we navigate from "what we want to achieve" to "how we choose to achieve it". To understand the MS synthesis decision making activity, this research has adapted the decision commitment model proposed by Borg (Borg and Yan, 1998), as illustrated in Figure 2.

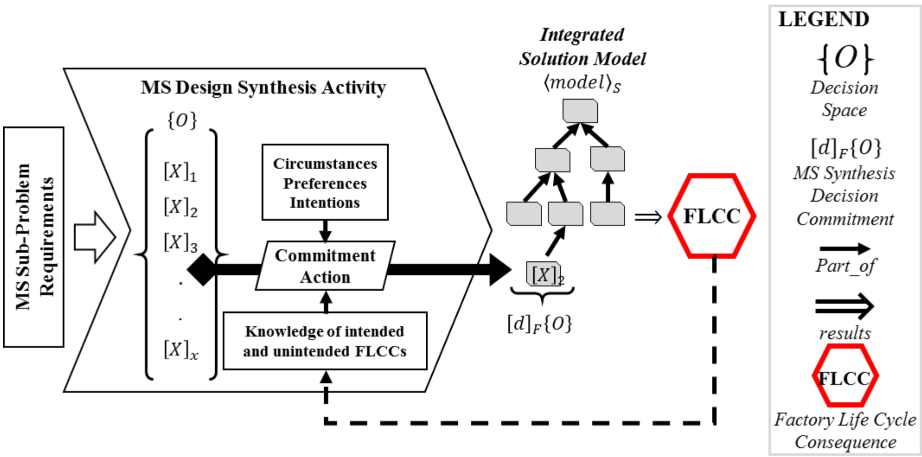

Figure 2. Synthesis decision commitments in MS design

During MS design synthesis, the MS designer carries out a commitment action, by which they decide to choose one of a possible number of options from a decision space. This synthesis commitment is then added to an integrated solution model, in a part-of relationship. The intention of the MS designer is to meet the MS requirements.

3.2.1 Manufacturing Capability Consequences (MCCs)

When making commitments, MS designers have an intended consequence in mind. For example selecting a particular machine to carry out a process has the consequence that the machine is capable of fulfilling the process requirements. MS designers would not intentionally commit to a machine knowing that it cannot perform the required process requirements. It is here argued that unintended consequences may also arise from a MS decision commitment. For example the MS Designer may intentionally select a machine element to fulfil the current requirements, but unintentionally this commitment has a consequence on future product manufacturability. Products may evolve in a direction that falls outside of the current machine element capabilities. This commitment therefore leads to the generation of manufacturing capability consequence (MCC), since the machine is not capable of producing the evolved future product.

3.2.2 Factory Changeability Consequences (FCCs)

In order to develop and implement MSs within a factory, commitments are made on the changeability strategies and enablers to be employed (Francalanza et al., 2014). These decision commitments have consequences on the MS that can be good and intended or problematic and unintended. A MS designer makes a commitment to utilize a scalability enabler to implement a reconfigurable MS. This has the good and intended consequence that the MS will be capable of producing future evolved products. The same decision can also result in unintended and problematic consequences when taken in the context of the MS solution. The commitment of utilizing a scalability enabler can require extra services to be installed or require the current machine to be moved. This in term may have consequences on the calibration of the existing machine and extra costs being or time delays in implementing scalability. These consequences are here defined as Factory Changeability Consequences (FCCs) and have negative impacts on the MS solution feasibility, KPIs and changeability.

3.3 Changeability Knowledge Based Product Development Approach Framework

Human mental processing capabilities limits the amount of information that can be processed by MS designers. Product evolution, due to its uncertainty and complexity, further taxes the MS designers' mental processing capabilities. In order to provide adequate support to MS designers these limitations have to be taken into account. The changeability knowledge based product development approach takes into consideration the difficulties MS designers have in handling interactions that occur between current MS decisions, business strategies and future evolving products. The aims of the changeability knowledge based approach is to:

- Explicitly reveal decision consequences on manufacturing capability and factory changeability to MS designers, arising during the current MS synthesis explorative actions.
- Guide the MS designers by providing information on how to adopt changeability strategies and enablers.
- Provide changeability knowledge in a timely manner which will enable IPD stakeholders to consider and explore alternative commitments that will have different impacts on the capability and changeability of the MS.

More importantly, the approach framework illustrated in Figure 3 provides the required support when the integrated solution model (i.e. business, product, process and MS solution models) is still evolving to help proactively foresee MCCs and FCCs, whilst providing Decision Guidance Knowledge (DGK), in order to avoid or relax MCCs and FCCs.

3.4 Operational Frame

The "Operational Frame" provides an IPD based mode of operation that describes the concurrent processes which make up the working environment. The IPD working environment includes the product development stakeholders who together identify the current and future customer requirements, and develop the business strategies, products, processes and MS to meet these needs. The operational frame also provides a detailed description of the MS designers' working environment during the MS exploration activity, so that they MS designers systematically utilise changeability knowledge at the right time. The MS design working environment also contains a MS decision space D{O}, which contains domain specific MS elements, enablers and changeability strategies that can be utilised by MS designers in synthesising a MS solution.

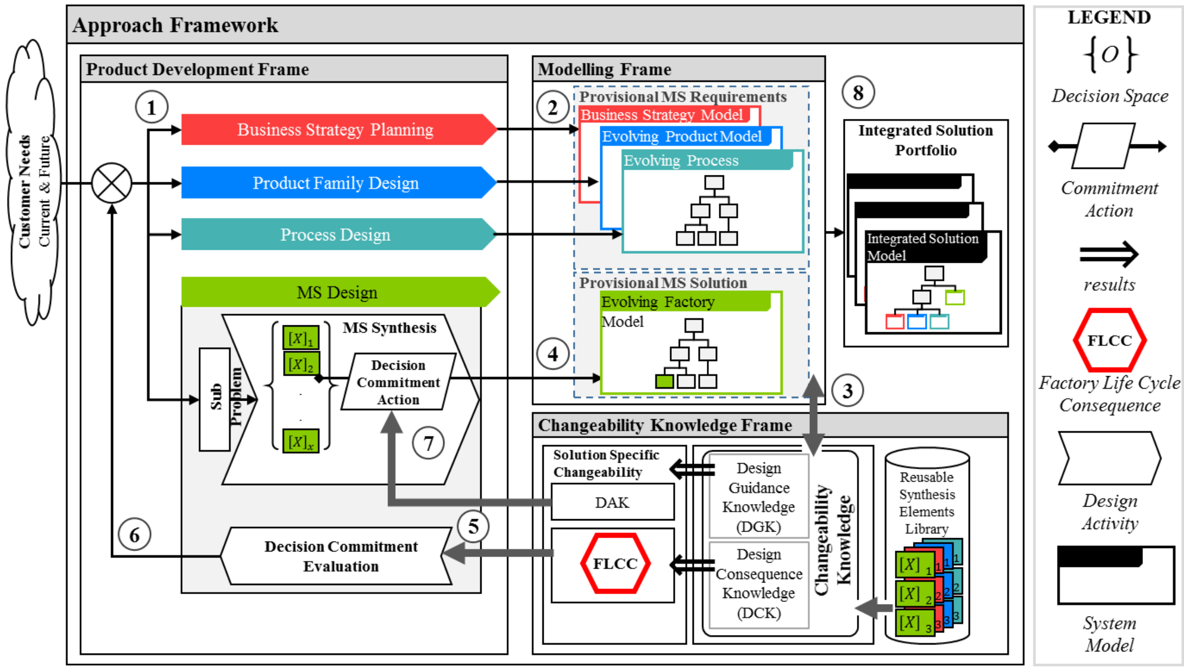

Figure 3. Changeability Knowledge Based Product Development Approach Framework

3.5 Modelling Frame

In order to support the inference of changeability knowledge from MS synthesis design decisions, this research presents formal models of the MS solution and MS requirements. The Systems Modelling Language (SysML) has been adopted by this research to describe the formal MS solution and MS requirement models. This selection is based on a comparison between a number of different modelling languages by Constantinescu et al., (2014), who have concluded that SysML is an ideal tool to model the structure, properties and requirements of a MS. The Integrated Solution SysML model which describes evolving factories and product families, is shown in Figure 4.

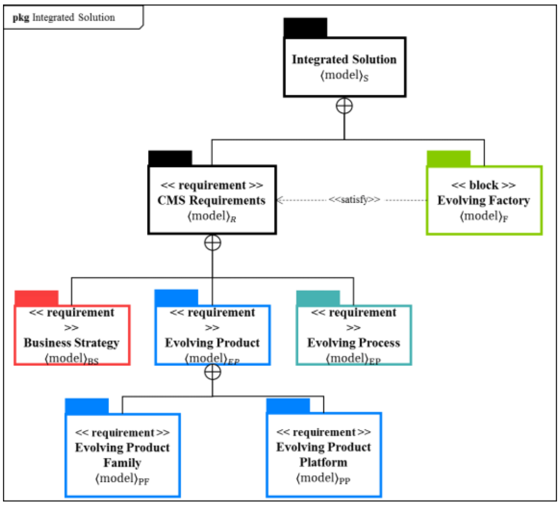

Figure 4. Integrated Solution SysML model

The "Modelling Frame" therefore provides for a specific constructional viewpoint, a formalism for describing the provisional MS requirements formulated by the product development stakeholders and the provisional MS solution being synthesised by the MS designer. The MS requirements and MS solution models are described in both their current and future states. These models allow for relevant changeability knowledge to be inferred by the changeability knowledge frame. These models consists of the evolving Business Strategy Model; Product Model; Processes Model; Factory Model.

3.6 Changeability Knowledge Frame

The Changeability Knowledge Frame is primarily concerned with what knowledge to model and relate, rather than how to transform and infer the solution specific changeability knowledge. This frame provides a means for formally describing decision consequence and decision guidance knowledge.

3.6.1 Decision Consequence Knowledge:

This is the knowledge used to evaluate the interim MS solution model. Relating the current and future product requirements with the factory elements committed to the interim MS solution model results in manufacturing capability knowledge. If the MS resources are not capable of meeting their requirements (either current or future), then MCC knowledge is inferred. FCC knowledge is inferred when changeability committed to the interim MS solution model interact with other factory elements to generate negative consequences on the MS changeability. MS Knowledge can also be used to infer the effects of FCCs on Key Performance Indicators (KPIs) such as cost, MS flexibility and changeover time.

3.6.2 Decision Guidance Knowledge:

This is the knowledge that relates MCCs and FCCs to strategies, enablers and factory elements that can mitigate, alleviate or eliminate the negative impacts of decision commitments on KPIs. Decision Guidance Knowledge (DGK) is utilized to infer recommended changeability strategies and enablers that minimize the effects of MCCs.

3.7 Design exploration based on the approach framework

The product development team analyse the current and future customer needs (STEP 1). Based on these needs, the product development stakeholders then define the current and future MS requirements (STEP 2). As the MS requirements are being defined, these are being monitored by the Changeability Knowledge Frame (STEP 3). To satisfy the MS requirements and solve a particular sub problem, the MS designer interacts with the decision space, and commits a chosen element to the CMS solution (STEP 4). The MS solution is described through the modelling frame as the evolving factory model.

Based on interactions between the MS requirements and MS solution models, the structured Decision Consequence Knowledge (DCK) is utilised to infer relevant MCCs, FCCs (STEP 5). The inferred DCK is explicitly provided to the MS designer for evaluation. This makes it possible for the MS designer's attention to be attracted to MCCs and FCCs resulting from CMS decision commitments. The MS designer can then decide to provide feedback to the Product Development Team (STEP 6) in order to investigate if different MS requirements, such as the future product family evolution, can be explored in order to minimise the impact of product evolution.

The MS designer can also opt to explore different MS decision commitments to avoid or relax the effect of MCCs and FCCs. DGK is used to infer Decision Action Knowledge (DAK) that is provided to the MS designer (STEP 7). DAK is provided in order to rapidly and proactively guide the MS designers' reasoning to which MS decision commitments could be changed or retracted. By using the MS design approach framework the product development team can thus explore different IPD decision commitments to build a portfolio of different integrated solutions scenarios (STEP 8) that address the evolving, i.e. current and future, customer needs.

3.8 Implementation

The underlying approach philosophy, developed on the phenomena and knowledge models was then implemented into a virtual product development tool. The Changeability Knowledge Based Product Development Approach Framework has been implemented as a computational tool. In developing this prototype a number of issues related to the implementation level had to be decided upon. These included domain knowledge and development software and hardware.

The C Language Integrated Production System (CLIPS) environment was used to implement the intelligent rule based system (Giarratano and Riley, 2004). CLIPS is a public domain software and a Java Native Interface (JNI) library was utilized to run the CLIPS rule based system with the JAVA back end.

The Graphical User Interface (GUI) represents the user oriented functionality responsible for managing user interaction with the system. Figure 5 illustrates the customised GUI for the MS design activity. Since the prototype was solely built to demonstrate and evaluate the underlying approach being developed, it was therefore not a requirement to interface with a commercial or off the shelf system. Furthermore, whilst there is the possibility of interfacing the backend of the system with an off the shelf CAD system, this GUI was built in order to have full control over the user interface without having to go into the complexity of reprogramming existing interfaces. The MS design GUI, allows the user to review and edit the MS solution model using a two dimensional (2D) graphical interface, whilst also providing the intelligent support. The 2D display area shows a representation of the factory plan, including doors, columns and manufacturing cells and elements. The MS design interface also provides a knowledge support panel that provides access to factory, MS and element information, and the changeability knowledge based support area.

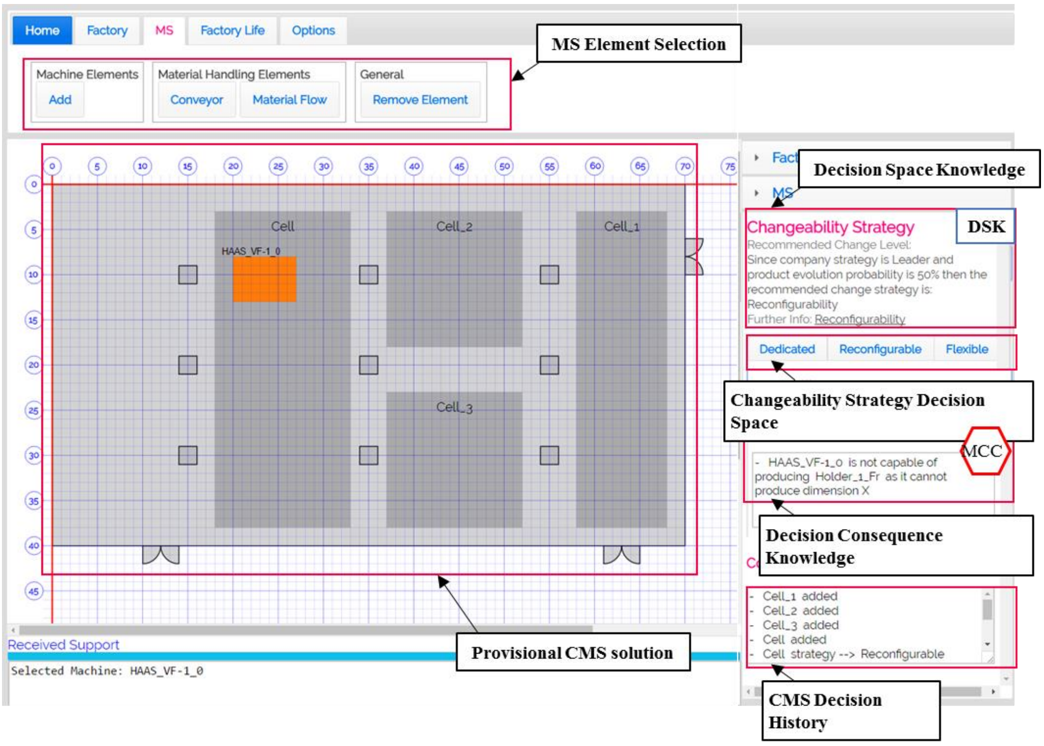

Figure 5. GUI for the Virtual Product Development Tool

4 SOLUTION EVALUATION

An evaluation was carried out in order to establish the effectiveness of the proposed MS design approach framework. Experimentation was therefore required in order to evaluate said hypothesis with respect to the reality situation. This experimentation was carried out utilising the virtual product development tool (a realisation of the MS design approach framework). By carrying out this evaluation of the solution, with respect to a number of evaluation criteria, a degree of validity of the hypothesis put forward during this research was ascertained. To carry out this evaluation a number of formal demonstrations, via the computational tool described in the previous section, were carried out with 25 stakeholders with experience in product development. The background of the participants varied both in terms of their area of and number of years of experience. A number of industrial sectors were also represented, including General and Advanced Manufacturing, R&D, Automotive, and Aerospace.

4.1 Evaluation Case Study

The evaluation of the underlying approach framework was based on a case study which provided a demonstration of all the aspects of the implemented computational tool and follows the steps of the CMS design approach. The case study involved the demonstration of the all product development activities. The subject of the case study was a fictitious company, named Camera Stand Ltd., whose business is the development and manufacturing of accessories for photographic equipment. This scenario begins when the company decides to venture in the market for selfie-sticks and begins a product development project. Whilst the past and current markets were for photos, market research shows that the future market will open up to virtual reality. Hence the case study demonstrated the activities involved in all the streams, business, product, and MS of integrated product development. The case study also explicitly illustrated how MS synthesis design decisions resulted in MCCs and FCCs, and how the computational tool provided not only awareness but also guidance knowledge.

4.2 Evaluation Results

The evaluation results were collected using a semi-structured interview and using Likert Type questions. The evaluation results are illustrated in Figure 6 (a) (b) and (c).

4.2.1 Question 1: Awareness of FCCs and MCCs

In question 1, the evaluators were asked if the approach assisted them in becoming aware of unintended MCCs and FCCs influencing the capability and changeability of the factory. The evaluation results can be summarised by saying that the proposed approach framework makes users aware of MCCs and FCCs (57% Strongly Agree and 35% Agree).

4.2.2 Question 2: Provided guidance

In question 2, the evaluators were asked if the approach provided adequate guidance to MS designers to consciously make decision commitments on changeability strategies and enablers. Figure 6(b), shows that the evaluators agreed that the approach proactively supports stakeholders by providing changeability knowledge on strategies and enablers (56% Strongly Agree and 36% Agree).

4.2.3 Motivated to explore

To determine whether the prescribed approach motivates users in exploring different integrated solution scenarios, in question 3 the stakeholders were asked if the during the case study the support provided by the computational tool motivated them into designing more changeable MSs. As shown in Figure 6(c), the majority of evaluators agreed with this statement (50% Strongly Agree and 34% Agree).

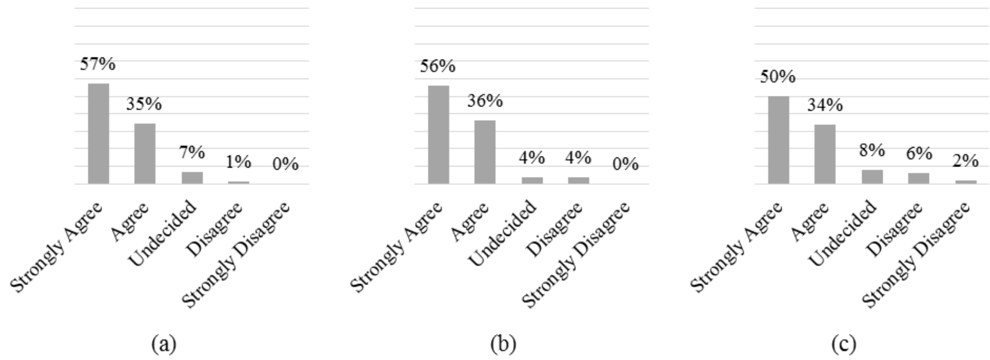

Figure 6. Responses to questions 1, 2 and 3

5 DISCUSSION AND FUTURE WORK

Therefore based on the results obtained through the evaluation of the prototype computational tool it can be concluded that the changeability knowledge-based approach assisted, guided and motivated MS designers into designing more changeable MSs. Moreover the prescribed approach supported product development stakeholders to explore different business, product and MS design solutions. The evaluation results demonstrate that the research hypothesis has been validated, with a degree of proof, by evaluating the results collected from the research evaluation. Future work will concentrate on determining how this approach will be utilised and implemented for other domains, most predominantly the manufacturing assembly system domain and cyber physical production systems.

6 CONCLUSIONS

Current means that support the MS decision making activity during product development provide support late in the MS design activity after synthesis has occurred at the MS solution analysis stage. Few of the mentioned approaches consider the integration between business, product and MS development, and even less so future product evolution and its effects on MS design. To address this gap this research contributed a novel changeability knowledge based product development approach framework. The encouraging results obtained from the evaluation of the developed prototype computational tool leads the path for the development and integration of such knowledge-based decision-making approaches within state of the art virtual product development tools.

REFERENCES

Andreasen, M. and Hein, L. (1987), Integrated Product Development, IFS Publ. and Berlin/Heidelberg: Springer - Verlag, London.

Borg, J.C. and Yan, X.T. (1998), "Design decision consequences: Key to 'Design For Multi-X' support", presented at the *2nd Int. Symposium Tools and Methods for Concurrent Eng*, pp. 169–184.

Constantinescu, C.L., Matarazzo, D., Dienes, D., Francalanza, E. and Bayer, M. (2014), "Modeling of System Knowledge for Efficient Agile Manufacturing: Tool Evaluation, Selection and Implementation Scenario in SMEs", Procedia CIRP, Vol. 25, pp. 246–252.

Duffy, A. and Andreasen, M. (1995), "Enhancing the Evolution of Design Science", *Journal of Engineering Design*, Vol. 4 No. 4, pp. 251–265.

Duhovnik, J. and Tavčar, J. (2015), "Concurrent Engineering in Machinery", in Stjepandić, J., Wognum, N. and Verhagen, W.J.C. (Eds.), *Concurrent Engineering in the 21st Century*, Springer International Publishing, pp. 639–670.

Efthymiou, K., Sipsas, K., Mourtzis, D. and Chryssolouris, G. (2015), "On knowledge reuse for manufacturing systems design and planning: A semantic technology approach", *CIRP Journal of Manufacturing Science and Technology*, Vol. 8, pp. 1–11.

ElMaraghy, H.A. and AlGeddawy, T. (2012), "Co-evolution of products and manufacturing capabilities and application in auto-parts assembly", *Flexible Services and Manufacturing Journal*, pp. 1–29.

ElMaraghy, H.A. and Wiendahl, H.P. (2009), "Changeability – An Introduction", in ElMaraghy, H.A. (Ed.), Changeable and Reconfigurable Manufacturing Systems, Springer London, pp. 3–24.

Francalanza, E., Borg, J. and Constantinescu, C. (2014), "Deriving a Systematic Approach to Changeable Manufacturing System Design", Procedia CIRP, Vol. 17, pp. 166–171.

Francalanza, E., Borg, J. and Constantinescu, C. (2015), "A fuzzy logic based approach to explore manufacturing system changeability level decisions", *CIRP CMS 2015*, Ischia, Naples, Italy.

Giarratano, J.C. and Riley, G.D. (2004), Expert Systems: Principles and Programming, Fourth Edition, 4 edition., Course Technology, Boston.

Hubka, V. (1973), Theorie Der Maschinensysteme [Theory of Machine Systems], Springer-Verlag GmbH.

Olesen, J. (1992), Concurrent Development in Manufacturing - Based on Dispositional Mechanisms, Ph.D., Lyngby.

Olsson, F. (1985), Integrerad Produktutveckling - (in Swedish), Mekanförbundet, Stockholm, Sweden.

Onori, M., Semere, D.T. and Lindberg, B. (2010), "Evolvable Systems: An Approach to Self-X Production", in Huang, G.Q., Mak, K.L. and Maropoulos, P.G. (Eds.), *Proceedings of the 6th CIRP-Sponsored International Conference on Digital Enterprise Technology*, Springer Berlin Heidelberg, pp. 789–802.

Simpson, T., Maier, J. and Mistree, F. (2001), "Product platform design: method and application", Research in Engineering Design, Vol. 13 No. 1, pp. 2–22.

von Specht, E.U. and Vajna, S. (2006), "Integrated Product Development as a Design Philosophy in University Teaching", Vol. 2006, ASME, pp. 911–918.

Stjepandić, J., Verhagen, W.J.C., Liese, H. and Bermell-Garcia, P. (2015), "Knowledge-Based Engineering", in Stjepandić, J., Wognum, N. and Verhagen, W.J.C. (Eds.), C*oncurrent Engineering in the 21st Century*, Springer International Publishing, pp. 255–286.

Suh, N.P. (2001), Axiomatic Design: Advances and Applications, Oxford University Press, USA.

Terkaj, W., Tolio, T. and Valente, A. (2009), "Designing Manufacturing Flexibility in Dynamic Production Contexts", in Tolio, T. (Ed.), Design of Flexible Production Systems, Springer Berlin Heidelberg, pp. 1–18.

Tolio, T. (2009), Design of Flexible Production Systems: Methodologies and Tools, Springer.

Westkämper, E. and Zahn, E. (2007), Wandlungsfähige Produktionsunternehmen: Das Stuttgarter Unternehmensmodell [Transformable Factory: The Stuttgart Enterprise Model], 1st ed., Springer Berlin Heidelberg.

Wiendahl, H.P., Greim, H., Nyhuis, P., Zäh, M., Wiendahl, H., Duffie, N. and Brieke, M. (2007), "Changeable Manufacturing - Classification, Design and Operation", CIRP Annals - Manufacturing Technology, Vol. 56 No. 2, pp. 783–809.

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