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Towards decision-support for reconfigurable manufacturing systems based on Computational Design Synthesis

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Abstract

The efficiency of production systems largely influences the profitability in the automotive industry. Recent trends challenge traditional manufacturing concepts and promote the adoption of more flexible approaches. Reconfigurable manufacturing systems have key characteristics that make them a potential solution for the prevalent issues. Decision makers can change the configuration of the manufacturing system to respond to changing requirements, though they are confronted with a large solution space. A case from industry illustrates the need for support of design decisions in this domain. Computational Design Synthesis generates an overview of the solution space and supports the decision maker in exploring the generated range by making trade-offs for many key performance indicators concurrently by generating sets of feasible solutions that can later be narrowed down by design constraints. Therefore, an investigation is proposed that explores the role of Computational Design Synthesis tools to support decision-making in the design of reconfigurable manufacturing systems and to show potential benefits. Furthermore, research questions are shown that are relevant for the development of such a tool and a suitable research methodology is suggested.

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Keywords: decision making; design; synthesis; reconfiguration; manufacturing systems;

1. Introduction

The development of new concepts in the production of automobiles and their components is promoted by various factors such as an increasing product variety and customized production. Reconfigurable manufacturing systems may represent a viable option for companies that produce in such highly dynamic environments. If resources are reconfigured to respond to changing requirements, decision makers in industry have to be aware of the impact of their decisions. Decision-support systems can improve the quality of decisions made by providing special functionality for analysis and visualization that assists the user to identify opportunities. While many methods focus on the optimization of a single solution, Computational Design Synthesis provides the decision maker with an overview of possible solutions (the solution space) that is generated by algorithms. Further functionality supports the user in exploring the generated range by making trade-offs for many key performance indicators concurrently. This design approach to dealing with complex tasks has been coined as set-based design. The basis of set-based design is to enable concurrent design by generating sets of feasible solutions that can later be narrowed down by superposing different stakeholders' criteria in the form of design constraints. Also, the method represents a formalized way of using knowledge that is often only implicitly available. Therefore, this paper proposes an investigation that explores the role of Computational Design Synthesis tools to improve decision-making in the design of reconfigurable manufacturing systems. Final objective of the research is to lean-up the development of production systems and to enable managers to assess their alternatives in production design in the face of changing market needs.

To achieve this, research based on Design Research Methodology is proposed to support the development of the tool. Expected advantages of the tool are to speed up

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conceptual design and design evaluation. Also an improved quality of the decision process should be achieved by involving different stakeholders into evaluation of a broad range of solutions. Finally this should facilitate decisions that affect economical and technical aspects simultaneously and allow to formulate an equipment strategy.

The structure of the paper is as follows: In Chapter 2 research motivation is described by illustrating current developments that affect manufacturing companies and how reconfigurability of manufacturing systems can help to face them. Furthermore an industrial case is described that highlights the importance of design support of manufacturing systems. Chapter 3 describes the method of Computational Design Synthesis and points out its benefits. Chapter 4 links the topics by proposing the use of Computational Design Synthesis to support design of reconfigurable manufacturing systems. Furthermore it gives an outline for research that should support the development of the tool.

2. Background

The following paragraphs introduce to challenges found in the automotive industry and present reconfigurable manufacturing systems as a possible solution. Additionally, an industrial case is described to show topicality of the approach.

2.1. Issues of manufacturing in the automotive industry

Since 1980s Original Equipment Manufacturers (OEMs) from the automotive industry have put considerable effort into the mass production of customized products [1]. Today, increasing levels of product customization complicate the efficient planning and production affecting automotive Supply Chains [2]. Body panels represent car parts where customization is most obvious, as they cannot be used in different models and their shape give each model its distinctive look. When OEMs outsource production of those parts it can create a direct dependency of the supplier to the sale figures of the specific model. The implicit transfer of demand uncertainty represents an impact factor on the supplier's design of production.

Another influence factor affecting the production of the supplier is the variety of products offered to the customer by the OEM. Considering the example of Mercedes-Benz passenger cars division, the number of different models has increased from 5 in 1990 to currently 23 basic car shapes [3]. Interviews conducted with managers from a tier-1 supplier revealed that the number of parts sourced from suppliers is correlated with this development. This impairs the supplier's ability to produce profitably with its current design of operations as concurrently declining average production volumes per model make economies of scale increasingly difficult to achieve. Additionally, shorter manufacturing lifecycles of the products ordered by the OEMs make it unattractive for suppliers to invest in equipment dedicated to the production of a certain model [4].

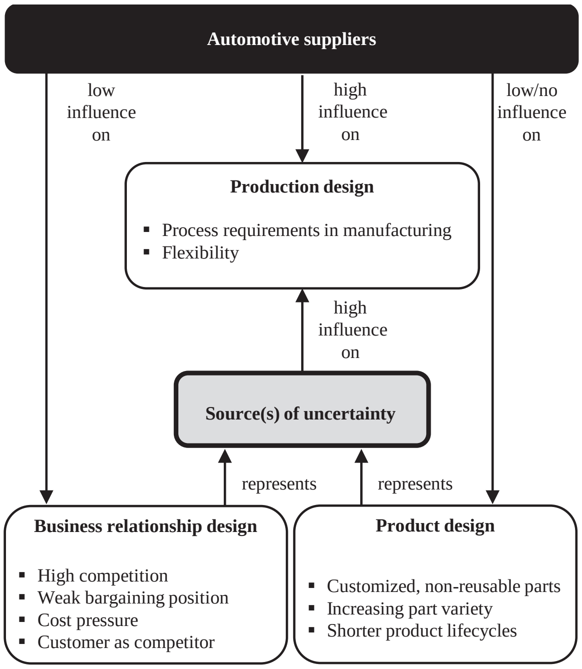

Fig.1 Degrees of freedom for automotive suppliers

Furthermore, for many suppliers it is necessary to align with quantitative and qualitative requirements of the OEMs because many products can be also supplied by other companies, creating intense competition. Manifestation of this weak bargaining position can be found in OEMs determining part prices and margins to be realized [5]. If OEMs demand lower prices the only way for those suppliers to absorb this cost pressure is productivity and efficiency gains in the production process, which imposes additional cost pressure [6].

Summarizing the strategic degrees of freedom of manufacturing companies in the design of business relationships, products and production, a considerable amount of suppliers may find themselves in a position in which they neither have significant influence on the relevant aspects of the product, nor on the parameters of the business relationships to their customers or suppliers (cf. fig. 1). For those companies the design of production systems represents the only remaining degree of freedom and has to consider the rising number of variants, lower production volumes per variant and increasingly shorter product lifecycles. Additionally, heteronomous business relationships and product design represent causes for uncertainty that may directly affect investment decisions in production design. This further promotes importance of the design of production systems as pro-active function to respond to dynamic customer needs.

2.2. Reconfigurable manufacturing systems

The need for industry to deal with these issues resulted in a number of approaches in production design that possess the potential to (partly) resolve them. One concept that aims to achieve this by combining high throughput of dedicated manufacturing systems (DMS) with the flexibility of flexible manufacturing systems (FMS) is reconfigurable manufacturing systems (RMS), a concept based on the group structuring of production cells [7] [8]. One of the core ideas of RMS is to adjust the production system according to market demands, which means to add, remove or modify process steps in hardware or software as needed [10].

Facing the described challenges, the key characteristics of RMS are supposed to help as follows [10]: Modularity of the production system aims to achieve reusability of components that in turn should lead to higher utilization and lower cost. Integrability reduces the effort needed to integrate new production resources while convertibility allows for quick system adaption to produce new products. Furthermore, customization means to provide the right capability and flexibility of the system. RMS should extend the economic benefits of flexible manufacturing by reducing lead times on ramp-up of new systems and for reconfiguration of existing systems, also enabling faster integration of new technologies and functions [9].

Due to the underlying concepts RMS represent an interesting option with regard to the issues that suppliers are facing. An increasing part variety and changing production technologies can be included into production by acquiring new modules. Deriving from integrability, additional modules can be integrated with low effort. Furthermore, using flexible resources should allow for increasing utilization in comparison to dedicated production capacity, especially regarding increasingly shorter lifecycles. Thus, RMS can be considered a promising way to respond to the presented developments and especially uncertainty by aiming at systems that are scalable in capacity and functionality [8].

2.3. Industrial case

The situation found at a first tier supplier of body parts from the automotive industry shows that for the company, the trends described in 3.1 are prevalent. Competition increases uncertainty of business development and thus affects the company’s investment decisions. The current production system is result of a reactive approach to past market developments. It represents a hybrid concept of universally usable equipment for products with low production volumes and dedicated equipment for high volumes. In the light of the rising part variety that has to be produced throughout the whole product lifecycle and co-evolution of manufacturing technologies, a lack of shop floor space and high logistical efforts are expected. Thus, the company identified a need to develop a new concept that allows for regular assessment and rearrangement of production resources and intends to adopt the idea of RMS to their production system. The company expects to benefit from the future concept by having the possibility to cluster equipment differently, while respecting available hardware and seeking profitable investment opportunities. It is the target of the company to formulate an equipment strategy that is based on a qualitative comparison of performance criteria such as cycle times, storage levels and investments, also considering logistical implications of alternative configurations. With regard to these criteria, considering multiple configurations eventuates in a large and complex solution space. The company is seeking support for exploring the solution space and associated design tasks on different levels, in particular formation of configurations, detailed layout planning and production planning.

2.4. Concluding remarks

The chapter presented issues for automotive suppliers and how they promote the relevance of production design as independent decision process. Furthermore, the concept of RMS was presented as potential way to encounter the developments. Finally, the case of an industrial company illustrated the topicality of approaches and showed need for design support that comes with large solution spaces.

3. Computational Design Synthesis

The chapter gives a brief introduction to Computational Design Synthesis and its benefits.

3.1. Purpose and principles

Computational Design Synthesis (CDS) is a multidisciplinary science that studies algorithmic procedures with the target to automate the generation of designs [11]. It is a design method that is based on a generic way of structuring design problems as depicted in figure 2.

A common way to come to a design solution is that the designer choses a form of representation by describing the design problem, its objectives and constraints (cf. path a, fig. 2). After that, solution proposals can be generated for the particular problem (b). Each generated solution proposal passes through analysis (c) and is evaluated thereafter (d):

- If the quality of the solution proposal or candidate solution does not meet the specifications, it is discarded and new solution proposals are generated (f).
- If quality is close to the requirements, an improvement of candidate solutions is attempted (e).
- If the quality meets the requirements the candidate solution is added to the solution space (g).

In commercial environments, computational support of activities is most commonly directed at analysis, evaluation and optimization of design solutions by means of computer-aided/CAx technologies (cf. grey box, fig. 2). CDS extends the range of computational support to the synthesis and evaluation step, so that generation of candidate solutions and assessment of the quality of a solution can be automated (cf. blue box).

To achieve this, the steps and parameters for manual solution generation are captured by knowledge elicitation of an expert and implemented in a structured software model. This model also contains suitable analysis methods to calculate performances of candidate solutions. After implementation in the software model, candidate solutions can be automatically generated, analyzed and evaluated based on rules and procedures.

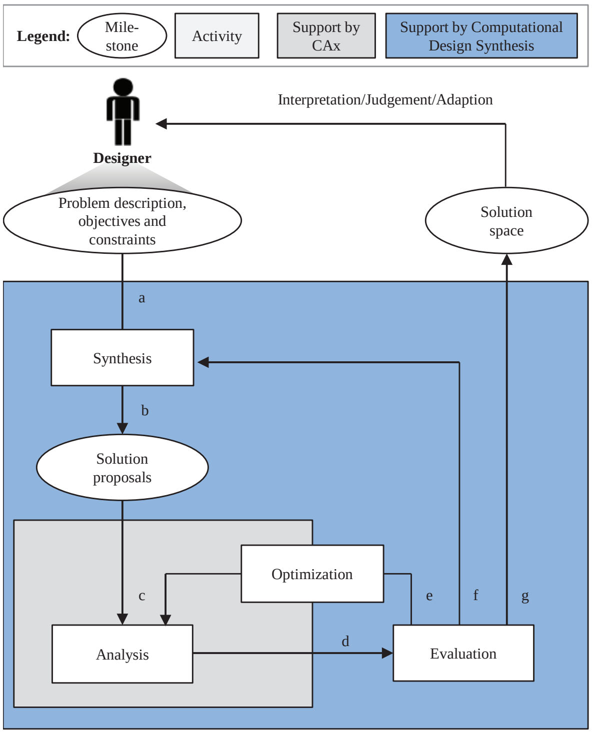

Fig. 2 Generic description of synthesis (cf. [11], [12])

Accordingly, the user only specifies his initial requirements and then assesses different designs in the solution space as well as differences between particular design solutions. This enables to interpret and eventually allows to adopt advantageous designs or to adjust the initial requirements.

CDS as a field of science integrates knowledge from multiple scientific disciplines such as design theory, optimization, constraint solving, knowledge engineering and computer science [11]. Known fields of application can be found in engineering of truss structures [13], or in design of microsystems [14] and gas distribution networks, for example [15].

3.2. Intended outcomes

Design decisions have a large impact on the resulting system behavior process and commonly constrain the space of possible solutions, eventually resulting in a smaller number of solutions considered (cf. blue line, fig. 3). This implies that without comparative analysis of design alternatives, possible solutions are excluded from consideration although they may represent better overall solutions (cf. grey oval).

Reasons for not considering other design solutions may be found in a limited view of the designers in a large combinatorial search space, but also the analytic effort needed to calculate performances for every solution. By implementing the applying design rules and analysis methods in a CDS based tool, these tasks can be executed more efficiently.

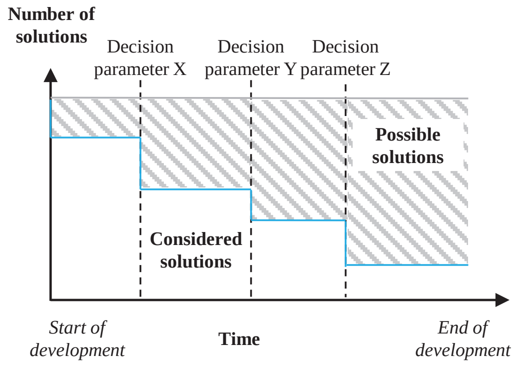

Fig. 3 Qualitative comparison of the solution space of CDS and sub sequential design

Offering insight into the implications of alternative designs should eventually stimulate users to extend their limits of consideration in the solution space and ensure that the design they chose represents the most desirable characteristics. An additional advantage of the method is that it represents a formalization of design knowledge that is often only implicitly available. Eventually it should also reduce the time needed to find a good conceptual design.

4. Supporting design of production systems through CDS

Building on the previous chapters, the first paragraph illustrates a possibility for research. Furthermore goals of research, related questions and a research methodology are proposed.

4.1. Research motivation

The second chapter showed how product related developments and market situation in the automotive industry can affect suppliers and promote the relevance of production as one of few design domains, in which suppliers can make decisions independently. Consequently the principle of RMS was presented and its potential to constitute a way to respond to the challenges was shown. Westkämper considers factories and manufacturing systems as technical products to be judged from a systems theory perspective [16]. Francalanza et al. adopt this thought and argue that the same design theories should be applicable to both manufacturing systems and products [17]. Furthermore, they point out the importance of the synthesis step in the design process and finally reason that in the synthesis step the designer of a manufacturing system makes the commitment to changeability, enablement and design of the future system. Extending this line of thought and considering the presented CDS approach as promising way to improve quality of design solutions, we propose to investigate the application of CDS to automate the synthesis step in the design of manufacturing systems and to support decision making in the design phase.

The relevance of topics described in the industrial case highlights the need of design support from a practitioner's perspective. Considering that representation of manufacturing systems (e.g. stochastic models), evaluation methods (e.g. analysis, simulation) and guidance (e.g. optimization methods) have been focal fields of research in the past decades, it appears intuitive to extend the support of design tasks by means of automation also to the field of manufacturing systems.

Also the design principle behind CDS, formalized as set based concurrent engineering by Allen Ward at the MIT, has already proven its worth in the automotive industry: Toyota developed and used the method in product design and consistently succeeded in its NPD projects, presenting productivity four times better than its rivals [18]. This can be seen as an indication of the potential benefits of applying set based concurrent engineering in the development of complex systems.

4.2. Research goal

The flexibility of the manufacturing system is embodied by the degrees of freedom in configuration and described by the number of possible configurations of the RMS. Thus, the goal of research is to provide a tool to support decisions and assist in formation and configuration of manufacturing systems. Using CDS to automatically generate and analyze system configurations should give users an overview on the total solution space and to identify a target level of flexibility and performance, also taking into account incidental design costs. Accordingly, it has to make the implications of design decisions on the performance of the system visible. Therefore, users need to be able to specify the components that the solutions should consist of and the scenarios that should be considered. This means that an intrinsic motivation of the research is also to answer the question to which extent set-based design is applicable in the development of manufacturing systems.

To assist in the design of configurations, basic modules that can be formed to configurations have to be identified. The relevant characteristics of those modules have to be defined as well as target KPIs and suitable analysis methods. Therefore, the manual development of a pilot concept has to be traced and compared with deviating design practices. Once all steps of the design process are clearly defined, it can be modelled and formalized by implementation in the tool.

In summary, the questions that have to be answered in context of this research are:

1. Which are the target parameters, decision steps and inputs that determine the configuration of the manufacturing system?
2. What are applicable design principles?
3. How can these aspects be modelled by using CDS?
4. What user requirements have to be fulfilled by a tool to achieve usability in multi stakeholder environments?

Offering insight into (alternative) ways of configuring the manufacturing system should eventually stimulate users to extend their limits of consideration in the solution space. An additional advantage of the tool would be that it represents a formalization of company specific design knowledge in combination with knowledge of the field of RMS. Furthermore, an understanding of the trade-offs in performances between different configurations can be achieved by comparing solutions and how they behave in different scenarios, e.g. analyzing the number of possible configurations when restricting the solution space in terms of investment. Considering different corporate functions (e.g. logistics, finance), the tool may also facilitate discussions and decisions in multi-stakeholder environments by offering objective comparison of performances. This should enable to improve design quality and that subsequent efforts to accomplish more detailed design, layout and planning is devoted only to the overall best solution(s). Thus, the significant added value of the approach is expected to derive from involving different perspectives in the judgment of a higher number of suitable alternatives, while assumptions inherent with this approach are that (1) using CDS for a broader solution space than traditional synthesis and (2) the quality of decision-making can be improved by involving multiple stakeholders into the decision process.

4.3. Research methodology

A suitable methodology to serve as framework for conducting the described research is Design Research Methodology (DRM) as proposed by Blessing & Chakrabarti, which is divided into the following stages [19]: (1) Research Clarification (RC): The goal of this stage is to identify the research goals and corresponding questions. (2) Descriptive study I (DS-I): An increased understanding of the targeted design will be accomplished by a literature review of empirical research and undertaking empirical research. (3) Prescriptive study (PS): This stage defines the intended support of design and accommodates the development of the actual design support. (4) Descriptive study II (DS-II): Representing the last stage of DRM, this part evaluates the developed design support and elaborates on the implications.

Given this paper as deliverable of the RC-Phase, the subsequent goals in DS-I can be reached by empirical research in form of literature study and interviews conducted with equipment managers of tier-1-suppliers from automotive and other companies in a comparable situation. Goal in this phase of research is to achieve a proper definition of the design aspects to be considered. Following in the PS-phase, a prototype of the decision support system can be developed, which could be done in context with the case study described in 2.3. Further steps in DS-II should consist of evaluation and extensive discussion of the answers found to the research questions.

5. Concluding remarks

This paper illustrated how challenges in the automotive industry may affect suppliers' production: on the one hand heteronomous and dynamic product design and a high degree of competition in the market on the other. A suitable production concept to respond to these challenges was identified in RMS that could represent a viable option for companies facing the issues. Thereafter, an industrial case was described in which the approach was found topical. In this course, the difficulty inherent with the adoption of RMS was concisely depicted, which is to find good solutions in a large combinatorial search space. The third chapter described CDS as method to support design tasks by automating the generation, analysis and evaluation of designs and the benefits aimed for by applying CDS in form of a software tool.

The fourth chapter stated motivation for research that is supposed to end with the proposition of a CDS tool that addresses the industrial need for design support. Also in this chapter, the key research questions and concurrent assumptions were depicted, that need to be examined in course of developing decision support in the design domain of manufacturing system. Finally, DRM research methodology was presented to serve as possible framework and a close cooperation with industrial partners was suggested for the course of research, to gain valuable theoretical and practical insights into the potentials of set-based concurrent engineering in the design of manufacturing systems.

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