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SUPPORTING THE DESIGN OF RECONFIGURABLE CELLULAR MANUFACTURING SYSTEMS BY COMPUTATIONAL DESIGN SYNTHESIS

J. Unglert, S. Hoekstra and J. Jauregui Becker

Keywords: design support system, computational design synthesis (CDS), lean product development, knowledge based engineering, manufacturing

1. Introduction

For manufacturing companies, production systems are an important means of enabling profitable operations. The physical and technical structure of production systems determines the possible range of adaptations and represents a degree of freedom for the designer of the operational system. Concepts such as reconfigurable cellular manufacturing systems (RCMS) enable system design as recurrent activity in which decision makers can frequently decide about system capabilities and capacities [Mehrabi et al. 2000]. Common approaches to support the design of manufacturing systems are analysis and optimization of manufacturing systems [Winston 2004]. The time needed for assessing a large number of designs, however, is a factor that can discourage the use of such tools [Bellgran and Säfsten 2010]. As a result, there is a danger of missing and therefore not evaluating favourable designs if the number and quality of solution candidates evaluated is dependent on human intuition in the large and complex space of potential system design solutions.

Computational Design Synthesis (CDS) is used for the automation of design tasks [Chakrabarti et al. 2011]. Based on the models of design problems, CDS-based software tools can automatically generate design solutions and calculate their performances. Then, users can narrow down the space of design solutions to the most promising designs and in this manner, make CDS-based tools a means to apply the principle of set-based concurrent engineering [Jauregui Becker and Wits 2015]. Various software tools with capabilities to automate the design of production systems have been reported, for instance [Mellichamp et al. 1990] and [Lee et al. 2006], however, most approaches only propose one single solution for a design problem. Moreover, similar to [Borenstein 1998] or [Chan et al. 2000] many approaches treat design parameters rather as result of rigid design synthesis and search procedures, with no or only little opportunities for designers to influence the design generation. To show potential benefits neglected by existing design automation and support methods, this paper shows the rationale and implementation of a design support tool for the design of RCMS based on CDS. The tool assists the users by automatically generating sets of design candidates through CDS and subsequent analysis of these candidates, so that users can iteratively assess and constrain the generated solution space. The desired outcome is to decrease the time needed for evaluating multiple designs of the production system and to offer an intuitive approach to explore the possibilities in design and the consequence of design decisions on system performance in a set-based approach.

To point out the motivation of our research, chapter 2 presents the relevant concepts and related areas of research. The chapter concludes with the discussion of the current state. In chapter 3, the concept and anticipated effects of the prototype software for design automation are presented, which was developed in context of this research. Chapter 4 describes the industrial context of the research and plans for evaluating the prototype.

2. Motivation

2.1 Computational Design Synthesis

Computational Design Synthesis (CDS) is a multidisciplinary science that integrates knowledge from various scientific disciplines, including constraint solving, knowledge engineering and computer science. In industry, this approach can be used to support lean design practices by enabling a set-based design strategy [Jauregui Becker and Wits 2015]. CDS can be applied to automate design synthesis of routine design tasks and accelerating the loop of design synthesis and analysis of design candidates.
To support decision making, CDS-based software tools make use of algorithmic procedures to create instantiations of design models. For this task, the essential information about the elements, parameters, structure and requirements of design solutions is sourced from a knowledge base that contains the domain-specific characteristics of a solution. Described from a generic perspective, the design process starts with a description of the problem, the design process objectives and constraints (see also Figure 1, based on [Wood and Greer 2001], [Schotborgh et al. 2012]). Based on these descriptions, solution proposals can be synthesized (path a, b) and analyzed (c). After that, the predicted performances of the solution proposals are evaluated in two ways (d, e): if the performances of a solution proposal do not meet the specifications, the design is discarded and a new proposal is generated (f); if a solution's performances are found acceptable, the solution proposal becomes a candidate solution (g, h).
Companies use CAx tools to support analysis of solution proposals (see striped area, Figure 1). CDS-based tools can extend the range of computational support to the activities of design synthesis and evaluation. If a high number of possible design solutions can be generated, the user can reduce that number by imposing constraints on design and performance to obtain solutions meeting his requirements. Hence, the approach can be used with the objective to explore design options by facilitating solution generation and analysis [Chakrabarti et al. 2011]. Examples of different design fields in which CDS has been successfully applied range from microelectromechanical systems in electrical engineering [Bolognini 2008] to the design of gas distribution networks [Weidenaar 2014].

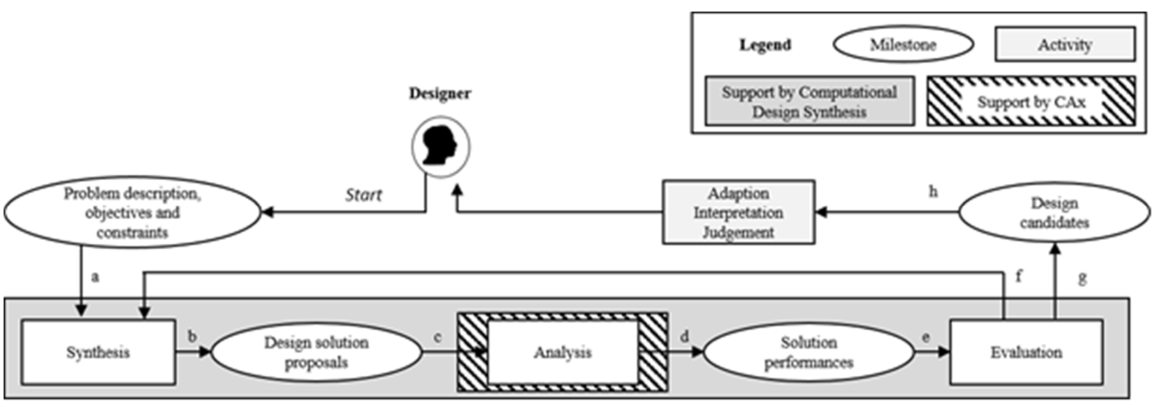

Figure 1. Computational support in design activities

2.2 Reconfigurable cellular manufacturing systems

The design of production systems is a source of competitive advantage for manufacturing companies. The systems inevitably require high investments and represent assets that are financially depreciated over time span of multiple years. Hence, decisions on the design of production systems have long-term effects and represent a commitment to the expected business development [Westkämper 2007]. This

business development is subject to uncertainty [Graves et al. 1996] and can be hardly forecast. Motivated by this uncertainty, the research community and industry have developed production concepts that can be evolved in response to changing product demand. Reconfigurable Manufacturing Systems (RMS) are one class of systems resulting from such research, which have the following key characteristics [Mehrabi et al. 2000] (see also Figure 2): all system components are modular (hardware and software) to enable changeability of the functional structure of the system; the integrability of system components should achieve easy integration of current and future production resources; convertibility of the components enables quick changeovers between existing products and ensure adaptability of the system for the production of future products; customization of the system to adjust the system’s capabilities and flexibility to suit the current product portfolio. RMSs are an opportunity for companies to make production less exposed to uncertainty when compared to rigid production systems, because the system provides opportunities to incrementally check and adapt capabilities and capacities to the market environment. While the initial costs of this kind of system are assumed to be somewhat higher than those of conventional systems, the use of RMS aims to compensate for that over the long term by attempting to combine the advantages of dedicated manufacturing systems (low cost per part) with those of flexible manufacturing systems (product-mix flexibility) [Koren et al. 1999].
Cellular Manufacturing Systems (CMS) partly share the characteristics (e.g. modularity) and also some objectives of RMS (e.g. low cost per part), however by different means: CMS focusses on achieving a manageable design of logistics and production processes in the system [Goldengorin et al. 2013]. For this purpose, similar parts are grouped into part families and production cells are established for each product family, attempting to achieve low efforts required for planning and operation [Askin 2013] (see also Figure 2). Inside of the production cells, robots can be used to connect modules of functional equipment for processing the products. Thus, the two concepts of CMS and RMS are compatible; to maintain the consistency of the existing concepts, however, the term of reconfigurable cellular manufacturing systems (RCMS) will be used in the remainder of this document. In RCMS, individual production resources are modules of the production cells. Each module provides a specific processing capability to the cell that is needed for production, such as spot welding or clinching. The products are produced in one or more cells, depending on the allocation of the resources and products throughout the cells of a system. If not all manufacturing steps of a product can be performed on the functional modules available in one cell, intermediate transport and storage of the product is needed before processing can be continued on another cell.

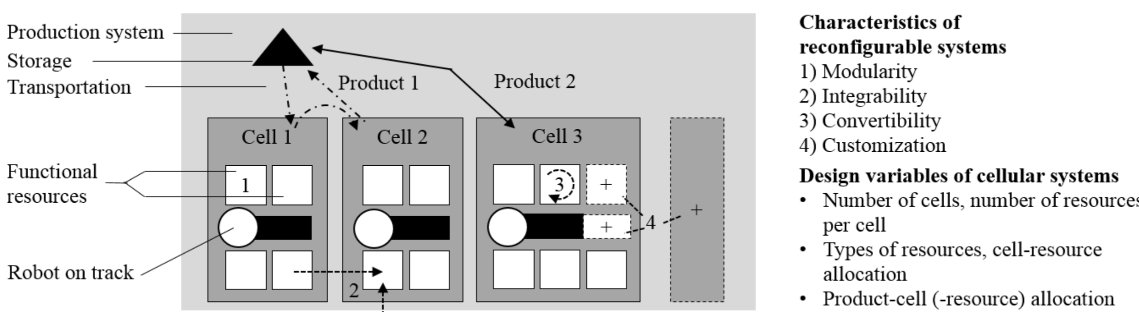

Figure 2. Characteristics and design variables of RCMS

To develop RCMS designs, the capabilities and capacities of resources are allocated to a specific number of cells. By planning the production of products on particular cells, a link is established between the cells in the form of material flows. The order of these three design steps - deciding on a number of cells, allocating production resources and allocating products - is interchangeable and in each step many different decisions can be made, thus a high number of designs can be generated, which result in differing system performances. In Operations Research (OR) literature, this problem is referred to as the cell formation problem [Miltenburg and Zhang 1991], [Selim et al. 1998]. Factories and production system are complex socio-technical products and stakeholders from various corporate departments use multiple and distinctly focused KPIs to evaluate performance from their varying perspectives (for instance from finance, logistics or sales). Even the change of one system design variable can result in notably different system behaviour and make performance evaluation of various designs a time-intensive task.

Consequently, the structure and adaptability of RCMS gives system designers a broad range of opportunities to design and influence the performance of the system, which makes the system suitable for facing uncertainty. However, the high adaptability also creates the chance of not using the full potential of production assets. To profit from the design freedom, a careful investigation of the consequences of system design decisions is needed. As review and changes in system design take place more frequently than in traditional systems, also the efficiency of design support has to be assured.

2.3 Support principles of manufacturing system design

As described by [Bellgran and Säfsten 2010], design of manufacturing system typically starts with conceptual design, followed by a detailed design phase. In conceptual design, system architectures are developed and examined for suitability. Choosing a particular concept, for instance RCMS, enables to create detailed designs by instantiating the design variables of the concept. An essential, but often neglected activity in this phase is performance evaluation of design alternatives [Bellgran and Säfsten 2010].

The field of OR comprises mathematical approaches for performance evaluation, also for the domain of production systems [Winston 2004]. In our understanding, OR implies the application of two distinct principles of supporting the design process, analysis and optimization (see also Figure 3a,b based on [Schotborgh et al. 2007]). By analysis, we understand that mathematical models of production systems are created based on a design candidate and driven by the motivation to evaluate system performance. Different levels of detail can be considered in the analysis, for instance, by treating the performance characteristics of the production system as being deterministic or stochastic, or for simulation of various scenarios [Winston 2004]. In contrast to analysis, optimization makes use of algorithms that can vary system design parameters to find best performances, defined by an objective function [Winston 2004]. Algorithms iteratively change design parameters and analyse the performance of new designs, until a solution exhibits the specified performance. Therefore, optimization can be distinguished from analysis, as the steps in design synthesis are performed by the computer. A literature review that presents state-of-the-art algorithms for design of CMS can be found in [Papaioannou and Wilson 2010].

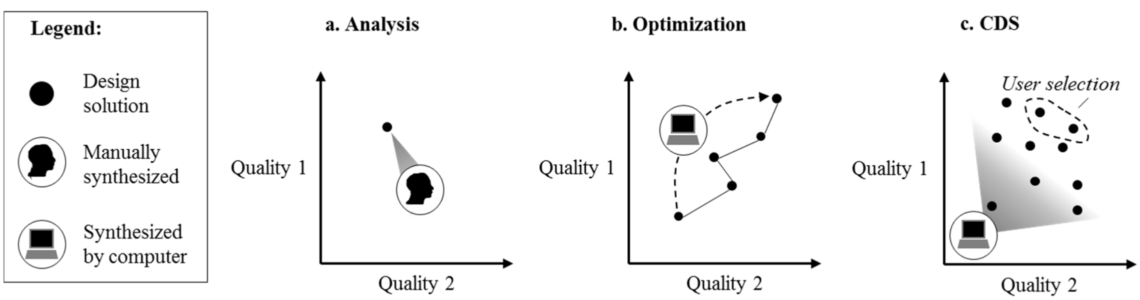

Figure 3. Design synthesis in analysis, optimization and CDS

2.4 Automated design of production systems

Various software systems that automate the design of production systems have been described in literature, particularly for the domain of Flexible Manufacturing Systems (FMS). [Mellichamp et al. 1990] developed an expert system that is capable of automated design of FMS. To accomplish this, the user specifies the performance objectives upfront and the system proposes one design. [Lee et al. 2006] describe a system for automated design of Flexible Assembly Systems, which performs a broad range of design steps, such as determining the number of workstations and the allocation of tasks to workstations. [Khan et al. 2014] describe a knowledge-based tool that automatically generates designs of FMS based on more than 1500 rules and analyses the performance. [Borenstein 1998] presents a prototype tool to support the design of FMS, which selects the best configuration and the control strategy for a specific situation defined through the user. [Chan et al. 2000] propose a support framework that aids the design of flexible manufacturing systems by coupling an expert system with a simulation module and other software for performance evaluation in an automated loop. [Michalos et al. 2012] describe a rather flexible design automation system for evaluating multiple performances of various, computer-generated assembly system designs.

2.5 Discussion

Chapter 2.3. described methods to support manufacturing system design by means of analysis and optimization. Various commercial software tools are available that provide functionality for performance analysis of production systems (e.g. Anylogic or Tecnomatix), for which those techniques can be considered state-of-the-art. Yet, it is important to note that analysis techniques are commonly used on the basis of a concretely specified design. This means that the evaluated design solutions depend on concepts that were initially instantiated by human decision makers. As a result, design solutions are influenced by constraints introduced during design instantiation, a phase in which the effects of particular design decisions may be unknown. In optimization, designs can be synthesized by computers, however, the type and number of designs assessed with optimization models is limited by the initial model of the design, the search algorithms used and the objective function, which carries the risk of not considering favourable design solutions. Furthermore, the need to specify target values for performances in the objective function may be cumbersome if the objective of the evaluation is to create an initial overview of feasible designs in various, distinct performance categories. Additionally, knowledge about the relations of design decisions and performance is often expressed in mathematic models. To establish these models, detailed understanding of the mathematical relations between the design and performance parameters is required. Therefore, many approaches are oriented towards experts in production modelling, though cannot be easily applied by other stakeholders of the production system who have less knowledge about the detailed relations [Delen and Pratt 2006]. Also, the time needed for creating models and analysing the performances plays an important role, as the duration of support activities and time constraints for the design of production systems can reduce the number of design proposals evaluated [Bellgran and Säfsten 2010]. Therefore, both analysis and optimization put the design procedure at risk of neglecting design proposals that would yield satisfying performances, especially in face of large sets of possible design solutions. It can be argued that contemporary design support approaches for production systems mainly focus on performance evaluation, but offer only little guidance for the actual design activity and lack options to make design evaluation accessible to the interest of stakeholders with little modelling knowledge of production systems.

Even though some applications for design automation of production systems were reported, they leave significant potentials unused. For instance, the approaches of [Mellichamp et al. 1990], [Lee et al. 2006] and [Khan et al. 2014] were described to be capable of generating production system designs, however solely generate a single design solution for a specific problem. While the system described in [Borenstein 1998] represents an approach covering a broad range of design steps, consideration is also limited to a single design solution. [Michalos et al. 2012] is the only design automation system among the tools previously presented that generates multiple solutions and presents their performance in a comparative way. In their support tool, the solutions are either synthesized optimization-like, using intelligent algorithms or exhaustive search. A potential approach to the problem of search space assessment that has not been described in any of the reported systems, however, is the role that users could play in assessing the solution space. The rationale we found implemented in many systems is that algorithms are used for synthesizing, analysing and selecting design proposals based on rigid procedures, leaving users only little opportunity to influence the design parameters of solutions.

Different from that, we propose that design automation can be also used as a means to facilitate access to the solution space, using the user's knowledge and experience for selection of suitable designs. The capability of automated design is used only to propose multiple feasible solutions to the users and thereby allows assessing the solution space, specifying (design and performance) constraints and thereby iteratively reducing the solution space to a manageable size. To our knowledge, no such approach has been described. The application characteristics of RCMS makes this system type a viable opportunity to research the benefits and implications of supporting production system design in this way (depicted in Figure 3c). Eventually, the goal is to facilitate set-based design decisions on system configurations.

The following chapter describes the concept, which was implemented in a prototype software tool, and the benefits expected in context of the design process.

3. CDS-based support system for design of RCMS

In this chapter, an approach is presented that aims at obtaining further benefits from design automation than accomplished by existing design support systems. To uncouple the manifestation of modelling knowledge from design generation, we propose a knowledge-based system. Our developed prototype software supports design based on CDS. Section 3.1. presents the underlying concept on a general level, whereas section 3.2. highlights the main characteristics in relation to CDS of RCMS. Additionally, the anticipated effects and an evaluation plan are described.

3.1 Structure of the CDS-based support system

Before the elements of the support system are described in detail, the context of use with the two main activities – knowledge engineering and design instantiation – needs to be outlined.

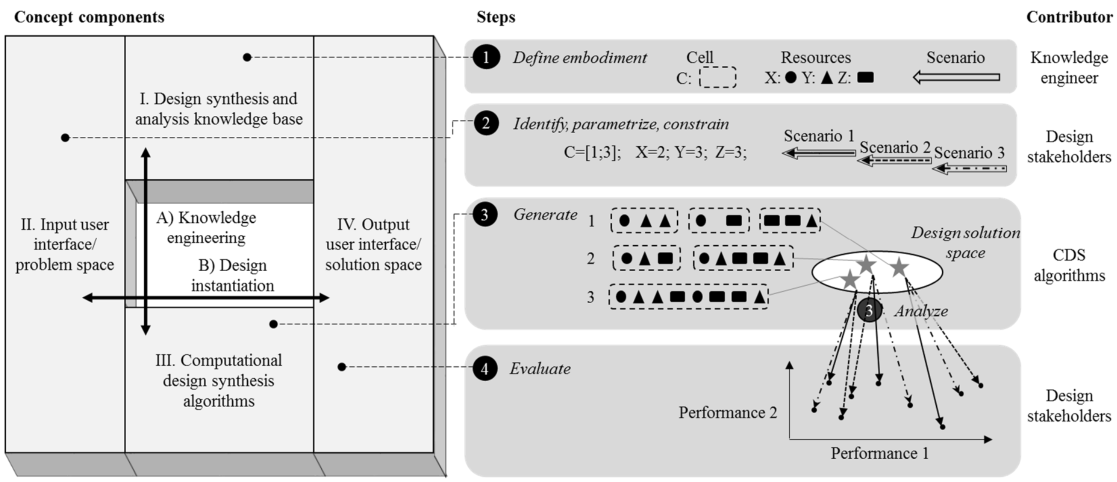

Figure 4. Concept of a CDS-based support system for design of RCMS

Phase A - Knowledge engineering: Objective of this phase is to capture the experts' knowledge about the general parametric and logic relations in domain specific design synthesis and analysis. To store this information, a design knowledge base is created in the software that provides the domain specific definition of design embodiments (also depicted as step 1, Figure 4). In the case of RCMS, the knowledge base contains descriptive information about the design objects and their performance, such as the production cells the system consists of, the production resources that form a cell and the logical and analytic relations between resources, cells and the system. This general model has to be compatible to use CDS algorithms to resolve the relations and dependencies.

Phase B - Design instantiation: Once a complete knowledge model is available, users provide input information to instantiate design solutions that match the specific context of their design problem (see step 2). This input for the tool can be distinguished into three categories: scenarios, solution components and solution requirements. Scenarios can be used to express uncertainty about the system environment, whereas the other two inputs define the opportunities and requirements for system design. Format and way of expressing this information is dependent on the relations defined in the knowledge base. The inputs are used for computational synthesis and analysis of design solutions. Afterwards, the results are presented to the user as output of the tool: design solutions and their performances.

While the characteristics of the design problem, which means the problem's basic representation, dependencies or analysis steps, do not change, the same knowledge base can be used to generate design solutions for various parametrizations of scenarios, solution components or requirements. The following paragraphs highlight in detail the elements of the concept when applied to RCMS:

- I. Design synthesis and analysis knowledge base: The knowledge base contains descriptive information about the structure and relations of the objects of RCMS. In the knowledge base, the representation of the production system is defined on the level of cell modules, as well as on cell and system level (see step 1, Figure 4). This way, a context between separate design elements and the overall system design can be created. Additionally, the analysis methods used to calculate performances of the system are integrated in the knowledge base, as well as the fundamental representation of scenarios to consider different system environments during analysis.
- II. Input user interface: The input user interface serves for the configuration of a design synthesis session, where the user specifies parameter values for scenarios, solution components and solution requirements. Consideration of uncertainty can be achieved by formulating scenarios, for instance by quantifying different expectations of future product demand in terms of production resource requirements that can be used for analysis of designs. Therefore, the interface provides features that assist users in generating multiple settings the design solutions will be exposed to after synthesis and help to achieve a more differentiated impression of systems performances with the goal to help selecting well performing designs. Furthermore, the interface is used to specify discrete parameter values of the design components, for instance to assign the investment and processing speed for each machine module used in system designs. Also the performance requirements and design constraints for system design solutions can be formulated in this component (step 2). In design of RCMS, constraints can be imposed, for instance, on total system investment or the maximum number of cells the systems designs should consist of.
- III. Computational Design Synthesis algorithms: Once concrete scenarios, values of the fundamental properties of solution components and solution requirements are available, designs can be instantiated. For this purpose, design solutions are synthesized by algorithmic procedures and based on the rules specified in the knowledge base. A description of the routine implemented in our prototype for the design of RCMS (step 3) is given in the following sub-chapter. These system designs can be analysed for each product scenario to calculate the designs' performance (step 4). After that, the validity of the design solutions is tested by comparing the created designs and their performances with the constraints defined by the user.
- IV. Output interface: In the last step of using the tool, design solutions and their performances are visualized in case they satisfy specifications of the user. The interface supports the user in exploring and comparing possible designs (step 5): users can examine the impact of differing environment scenarios on the performance of design solutions. This comparison of multiple designs in various scenarios should allow the user to identify suitable solutions and give an indication to impose or ease constraints on performance and embodiment.

The presented structure enables to specify design requirements, generate multiple design solutions and reduce the number of design solutions considered by introducing more and/or higher requirements for solutions in an iterative way. After choosing promising designs, the suitability of the designs can be validated with the traditional support approaches for manufacturing system design and in detail.

3.2 Key design parameters and design synthesis procedure

The key design parameters used to model the system, as well as the synthesis procedure depend on the specific context of use. In our implementation, we use parametric design synthesis, in which the key design parameters are the number of cells the system consists of, the number and type of production resources assigned to these cells and the allocation of products to specific resources and cells as illustrated in Figure 2. Consequently, the number of combinations possible to synthesize depends on the values possible to assign to these parameters and the constraints of the user. Since the problem of cell formation is a combinatorial one, we use a heuristic that analyses the production requirements of all product scenarios to estimate upper and lower boundaries for the number of cells and number of production resources. These boundaries are determined for various design strategies, which can be chosen by the users. For instance, users can chose a strategy designed to obtain systems in which each product family is entirely produced in its own production cell. Another implemented strategy is to generate system designs, in which all products follow the same route across multiple cells. For each design solution to be generated, a random algorithm instantiates the values within the allowed range of the design parameters to obtain a fully specified design. The last step is the heuristics-based allocation of products to the system resources. For each resolved design parameter, a constraint-solving algorithm checks if all constraints are satisfied. If limit values for parameters are violated, for instance by exceeding the limit of total investment when adding an additional machine to a production cell, the design is discarded and a new one is created. In this manner, users indicate the design strategies that seem interesting to them and specify the number of alternative solutions to be generated. Then, the algorithms attempt to generate this number in a given time. In case no solutions can be generated, the constraints have to be relaxed.

3.3 Anticipated effects

The high number of different decisions that can be made when designing RCMS can make the effects on system performance difficult to assess. Practical application of common decision support approaches – such as analysis – can imply that the decision maker has to constrain the number of considered design alternatives substantially due to time constraints, which can lead to an exclusion of valuable solutions from consideration. Employing the presented CDS-based tool prior to the use of traditional approaches for evaluation of more detailed system designs should help to uncouple the range of solutions assessed with traditional approaches from this unwanted effect by using the tool to generate and compare multiple, feasible designs without requiring the designer to explicitly specify design solutions or their objectives in advance. Furthermore, the knowledge base should enable (re)use of existing knowledge and make possible to generate feasible designs without needing the knowledge owner to be present at the moment of design generation and assessment. By front-loading the system design process [Liker and Morgan 2006], the tool should help to shorten the time needed for generating and evaluating design alternatives, which is particularly important for the recurring design activity in RCMS. Another anticipated effect is to expand the ability to generate and assess designs to more people than only the expert himself and to use the tool to facilitate evaluation and discussion of design implications. In this context, stakeholders should be able to focus on capturing their perception of uncertainty in form of scenarios and choosing well-performing designs eventually. Stakeholders are able to develop an experimental attitude to production system design and to get an indication of the sensitivity of designs to different scenarios. This way the presented tool is a means to enable set-based concurrent engineering and indicate opportunities for compromise between conflicting performance objectives in order to increase the quality of designs as perceived by lobbyists of different corporate functions.

4. Evaluation

A thorough study needs to be performed to evaluate the usefulness of the tool in context of the presented design problem. Development of the prototype is inspired by a company facing the problem of RCMS design in the high-mix, low-volume production of spare parts in the automotive industry. Therefore, the goal is to study the implications of using the software in an industrial context. For this activity, Design Research Methodology was adopted [Blessing and Chakrabarti 2009].

The development phase was completed by developing the software prototype of the design automation tool. Main objective of this phase was to provide a system that fulfils the needs of the industrial user in terms of tool interaction, data input and output. For this purpose, knowledge elicitation workshops were held in the company to capture the system performances used to evaluate designs, the representation of resources and the production system, as well as analytical dependencies between design and performance. Another workshop focused on scenario formulation and enabled to detect the basic parameters that render possible future use situations of the production system in form of product scenarios. Furthermore, a study was performed to find suitable user-tool interaction mechanisms in design generation and evaluation, using a low-fidelity prototype. Based on the findings of these activities, the development phase concluded with creation of a knowledge base that can be used in combination with randomized algorithms and constraint solvers to automatically design and analyse configurations of the system. To facilitate data in- and output also suitable user interfaces were designed.

The evaluation phase will be the next step. In this phase, experiments will be conducted concerning the verification and validation of the developed approach. The verification study should make sure that the prototype is capable of synthesizing and analysing designs of production systems and presenting them according to user specifications. Interesting aspects to be observed in this phase will be, if the implemented analytical models will allow the users to detect meaningful differences between designs and if these differences can be interpreted. In addition, the number of solutions and model sensitivity to constraints will be examined. Finally, an empirical study will be conducted to examine if the anticipated effects of the design support approach can be validated. Interesting questions in this context should reveal the benefit of using the tool, such as: Does the use of the support yield different designs than with traditional synthesis? How does it affect the designs developed? Does the support help to speed up the generation of results? Does the support help decision makers in generating an understanding of the design problem? Does the option to involve stakeholders into the system design complicate or facilitate the design procedure, if they traditionally had no or only indirect influence on the design?
In addition to evaluating the presented design support, we contemplate to find out about the important aspects of acceptance and industrial use of decision support in production system design and to get useful insights for further research into design automation and set-based design of production systems.

5. Concluding remarks

This paper highlights the importance of production systems for companies and the different stakeholders within. It discusses that when manufacturing companies are exposed to demand uncertainty, production concepts such as RCMS can be an appropriate strategy. However, the high number of dissimilar system designs and the complex connection between system structure and performances make it necessary to support the design decision. Common decision support techniques used for the design of manufacturing systems are explained. Moreover, existing support systems based on design automation are discussed and a novel purpose is identified for which design automation can be used. Based on this finding, the main chapter shows the structure and rationale of an implemented CDS-based software tool that should help users to derive more use out of the potential of design automation. Consequently, benefits are highlighted that industrial users could anticipate when using such tool to support the design process. Most importantly, the tool enables users to focus on assessing the solution space and formulating design and performance-related constraints. The objective of the design support is to evaluate a broader range of design solutions than possible with existing methods. Eventually, the industrial context of development of the prototype tool is described and the plan for an empirical study outlined for evaluating the tool's effects.

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Johannes Unglert, M.Sc.
University of Twente, Laboratory of Design, Production and Management
P.O.Box 217, 7500AE Enschede, Netherlands
Email: j.m.unglert@utwente.nl