Computational Design Synthesis of reconfigurable cellular manufacturing systems: a design engineering model

Johannes Unglert*, Juan Jauregui-Becker, Sipke Hoekstra

*Department of Design, Production and Management, University of Twente, Drienerlolaan 5, 7522NB Enschede, The Netherlands

Abstract

An uncertain business environment makes organizations seek for rather flexible approaches to manufacturing. The concept of reconfigurable cellular manufacturing systems (RCMS) may represent a viable solution, as the possibilities to rearrange the modular system resources enable to balance system capabilities and capacity. Yet at an early stage of designing the RCMS, decision-makers implicitly set the performance boundaries of the system while determining large parts of investments. In this task, software applications based on Computational Design Synthesis (CDS) can support decisions. CDS applications are used to automate design and analysis of design candidates. Consequently they enable set-based concurrent engineering so that users can explore the space of generated design solutions and make comparative assessments of solutions and their performances. The solution space can be narrowed down by making trade-offs and formulating design or performance constraints. This paper presents a design model of RCMS that allows automated design and analysis of system configurations based on CDS. The approach enables decision makers to evaluate different system performances such as costs, utilization and lead times of various designs of the system. Thus it can help to generate an understanding of the implications of design decisions for the performance of the manufacturing system in different product demand scenarios.

1. Introduction

Production systems and their design are important domains for decision processes in manufacturing industries. Fluctuating customer demand and other continuously evolving factors affect industrial agents and embed practical design decisions in uncertainty, however also motivate to develop and adopt new concepts of production systems that offer opportunities to react to changes. This paper introduces the concept of reconfigurable cellular manufacturing systems (RCMS) to strategically approach the design of manufacturing systems with a combination of two well-known concepts: enabling system designers to freely structure production processes and adapting the system over time. While a large number of options in design of RCMS should allow finding satisfactory designs for a broad range of situations, it also encourages the use of design support. Therefore, basic approaches to support design of production systems are compared and it is shown that the way of constraint formulation is a vital factor that distinguishes the approaches. It is argued that applying Computational Design Synthesis (CDS) can be a means to improve usability of design support for production systems in industrial practice. Hence, the paper presents a CDS-suited model of RCMS to visualize how this idea can manifest and to take a first step towards testing the hypothesis. The structure of the paper is as follows: After introducing the background of CDS and CRMS, the design synthesis principles of basic design support approaches for production systems are introduced. Consequently, a model type is presented that allows to express design problems in a CDS-suited way. In the following, the necessary data in- and outputs of the RCMS model are described to show which aspects of the production system are included. Thereafter, the process of algorithmic design generation is explained and an exemplary, formalized model is illustrated. Lastly, the
anticipated effects of a software implementation based on the model are described.

2. Background

2.1. Computational Design Synthesis

Computational Design Synthesis (CDS) corresponds to a set of methods to support decision making by automating the generation of solution proposals to design problems [1]. While CDS primarily supports lean design practices, it is a multidisciplinary science integrating knowledge from different scientific disciplines, among which constraint solving, knowledge engineering and computer science. CDS-based software tools enable decision makers to pass through the loop of synthesis and analysis of design candidates in an automated fashion by using algorithmic procedures to instantiate and to analyze design models. Design models represent the domain specific formulation of design problems and therefore define the structure and components of design solutions, as well as their parameters and relations.

Compared to CAx-tools that mainly focus on facilitating analysis of designs, CDS-based tools enable to extend computational support to design synthesis and evaluation. Therefore, they can be used to generate and analyze multiple designs and enable set-based concurrent engineering. Users of such tools can narrow down the space of possible design solutions with constraints on design and performance of the solutions. In this manner, decision makers can use CDS-based tools with the motivation to explore various designs and free of unwanted biases of the designer [2]. In the engineering domain the approach is used for design of electrical [3] or mechanical systems [4], for instance. Nevertheless, more recent applications also examine the approach in context of the design of socio-technical systems, such as gas distribution networks [5].

2.2. Reconfigurable Cellular Manufacturing Systems

For suppliers of customized and build-to-order products, the design of production systems can be the only strategic decision made independent of company-external stakeholders [6]. Yet, the decision can be influenced by uncertainty originating from hardly predictable development of product demand. As this uncertainty can impair the ability to amortize investments in production, it should be considered in strategic design of production systems. An opportunity to express uncertainty is in terms of characteristics of products produced, such as ranges of demand volume or requirement of production technology. The past 25 years in the automotive industry for instance, have shown a growing variety of car models, while the total production volumes did not grow at the same rate, resulting in a reduced average demand per car model [7]. Such developments challenge traditional approaches to manufacturing that are mostly oriented in economies of scale, and inspire to develop more flexible production systems. Reconfigurable manufacturing systems (RMS) represent one class of systems that aim to combine the benefits of flexible manufacturing systems (product-mix flexibility) with the low cost per part of dedicated systems [8]. Some of the key features that characterize RMS are presented in fig. 1.

Partly coinciding with the objectives of RMS are Cellular Manufacturing Systems (CMS), which can be considered an application of the group technology concept [9]. In CMS, production processes are grouped to cells that perform production of specific part families. The main motivation behind the cellular arrangement of production resources is to reduce planning and handling as typically required for production in high-variety job-shop systems, however also aims at achieving economies of scale in the manner of flow shop systems. Standardized cell layouts can be applied for designing CMSs, for example, using 7-axis robots on a central track as main manipulators of parts and tools (see fig. 1). Along the track, the robot services products and hardware modules that contain tools, fixtures or turning tables, for example. These modules can be changed quickly for the production of other products and therefore enable more options in adaptation of the cells’ process capabilities and capacities than possible with rigid systems. [10] describe some advances of research in robotics that can simplify the set-up of robots as main devices for handling tools or parts and thereby increase the economic attractiveness of reconfiguring CMS by facilitating the implementation of design changes. The similarity of the objectives to be reached with CMS and RMS and partly also their structural similarity can deceiving to use either term. In our understanding, the focus of the RMS concept lies on the ability to evolve the production system over time, whereas in CMS emphasis is put on the freedom of structuring the system’s production and logistics processes. Consequently, describing a concept that combines the ideas of RMS and CMS, while maintaining the integrity of the existing concepts, can be described as reconfigurable cellular manufacturing systems (RCMS).

The key feature of RCMS is the opportunity to evolve the system’s cellular design corresponding to changes of product demand. Using the hardware modules to accommodate equipment for various processes, the production cells’ process capacities can be easily adapted to provide various manufacturing functions, for instance, spot welding or adhesive. In case the required production technologies change over time, new modules can be integrated while redundant ones can be removed. Therefore RCMS represent a technological approach that enables decision makers to change the system’s design and offer opportunities to react. An operational implication of the approach is that in case a product cannot be produced in a single cell, it needs to be...
transported and stored before it can be processed on another cell (see fig. 1). Hence, the main design decisions of RCMS are: the number of production cells the system consists of; the allocation of process capabilities and capacities to cells; and the assignment of products or product families to cells. A central issue, however, is the huge number of combinatorial possibilities in design, for which the term of the cell formation problem is used in literature [11] [12]. Various decisions made on the aspects of system design lead to system-specific profiles in utilization, logistics costs and other performance categories. For decision makers it can be difficult to intuitively grasp the consequences of particular design decisions in multiple performance categories. This makes support of decisions a vital activity in the design of production systems.

3. Design-support principles of manufacturing systems

In general, design of production systems can be separated into two phases: conceptual design and detailed design [13]. The result of the conceptual design phase is the selection of a concept of production system that appears promising to the decision maker, such as RCMS. Then, more detailed design candidates are created as embodiment of the specific concept. As previously described, detailed design of RCMS is a complex activity in which design and performance variables considered simultaneously in many calculations. Therefore design is often supported by computer applications.

Various commercial software tools are available that can be deployed to support production system design. In these practice-oriented support approaches, the design problem is formulated mathematically using techniques from the field of Operations Research (OR). OR approaches typically involve the creation of a model of the design problem and then support the development of a design solution by calculating the performance of specific designs [14]. In our understanding, this provision of support typically implies two distinguishable synthesis mechanisms [15] (see fig. 2): in analysis, mathematical models of the production system and its performances can be created to evaluate the system’s behavior. These models are either generated simultaneously to the instantiation of design variables (implicit modeling) or explicitly, before synthesis (see fig. 3). Choosing an optimization approach also involves creating a model before performances can be evaluated, however, optimization algorithms can be used to change the design variables of the system. This way, the search algorithm can iteratively change the design and evaluate the resulting performance until a design meets the minimization or maximization requirements, as specified in the objective function. Multiple algorithms which can be used for design of RCMS are reviewed in [16]. Hence, the difference between analysis and optimization can be seen in the synthesis mode: manual design synthesis in analysis; automated synthesis in optimization.

[15] describe the problem solving process from a design perspective. In context of production system design, however, modelling is important likewise. Therefore, fig. 3 shows an overview of the design process, adapted to suit also the design of production systems. Originating from the description of the problem and the objectives, firstly a design model is created (see path b). This model can be used to synthesize design proposals. If no explicit model is created (path b), modelling is an implicit activity during design synthesis. In both cases of explicit and implicit modelling, the synthesized design proposals are analyzed afterwards. Once the concrete performance of a design solution is known, it can be evaluated with two possible outcomes: If the performance of a solution proposal does not meet the specifications, the design is discarded and a new proposal is synthesized (path c). If otherwise the performance of the solution proposal is sufficient, the design proposal becomes a candidate solution (path d).

In case of design problems with large combinatorial solution space, such as the cell formation problem, the moment and form of constraint formulation play an important role for the solutions that can be obtained. In all support approaches (analysis, optimization, CDS) the first constraint is given by the developed model. The models determine which degrees of freedom are available to synthesize various
designs. The next activity in which constraints can be introduced is design synthesis. In common analysis, the user is required to instantiate the design variables of the model, which can be quite cumbersome when confronted with many feasible designs. Different from this, the search algorithm used in optimization can instantiate the design variables automatically.

A possible drawback, however, can be seen in the need of specifying an objective function: in the presence of many performances that are used to evaluate complex production systems, it may prove difficult to point out one or two indicators that outperform the relevance of all others. Therefore, it appears arguable if employing the approaches for designing solutions solitarily can be justified: analysis relies on designs specified by the user, at a moment, when consequences of design choices for performance may be hard to forecast; optimization requires the user to restrict the range of considered designs to a narrow scope of target performances that can lead to a confinement of the solution space, which may be stronger than possibly necessary. Therefore, we suggest to impose design constraints at the latest possible stage. The underlying motivation can be explained analogous to the example of car manufacturers who convert anonymous products to customer specific ones at the customer order decoupling point (CODP). By having the option to customize the product at a very late stage producers do not need to modify the product before the CODP, even if customers demand different features, and thereby avoid rework. Similar to this, the use of CDS for production system design can bring about the postponement of design decisions in form of constraints. Using CDS to assign the design constraint decoupling point (DCDP) to the last process in the activity sequence of production system design could be a measure to avoid time-intensive changes of the model or the design, therefore speeding up the process of synthesizing, analysing and evaluating designs. This is particularly important as time pressure was reported a significant barrier to the predetermined and structured evaluation of alternatives [13]. Furthermore a CDS based approach should enable a comfortable exploration of a large number of substantially different designs of the production system and their performance. A software prototype was developed in context of our research to test these hypotheses. The following chapter presents the underlying model of a RCMS, which is used to generate designs in an automated fashion by CDS.

4. Model for Computational Design Synthesis of RCMS

In the following, the specifics of the model are highlighted.

4.1. Fundamental modeling principle

The motivation of the approach is to assess various, feasible designs and thereby present design alternatives to the user without requiring explicit specification of each alternative. To realize this principle, a specific type of model is needed, which considers the design process holistically from an design engineering perspective and – thereby – can emulate the sequence of design activities and decisions of the human decisions maker. Therefore, the cell formation problem is translated into a PaRC model as described in [15], which describes designs based on three activities: parametrize, resolve, constrain. In the parametrize step a design problem is described by parameters that are associated to the domains of the design problem: embodiment (design solutions and components), performance and scenario (see also fig. 4). By using equations and inequalities to describe the relations between parameters, links are created between the design components, solutions, scenarios and performances: resolving equations leads to stepwise instantiations of an increasing number of design parameters; inequalities constrain the values that can be instantiated.

A PaRC model representing a particular type of production system uses a set of parameters that describe the elements of the production system, the system’s structure and performance in different scenarios. Equations and inequalities describe the basic rules for cell formation and define the degrees of freedom for generating alternative designs. Scenario parameters can be used to calculate the performance of the system and to examine various states of the system environment, such as various situations of future product demand. In the CDS-based software application, such models are combined with synthesis algorithms: to generate designs, a synthesis algorithm initializes parameters and gradually resolves and constrains further parameters until the system specification and analysis is complete.

4.2. Input and output of the model

The RCMS model uses two basic categories of input parameters: products scenarios and the equipment instances, which embody the design components. Each product scenario is described by a set of products, which are distinguished by the specific product identifier and the demand volume over multiple years. Also, the time demand of each production step, the sequence of production processes and product family are attributes of a product. Various product scenarios can be formulated to provide analysis and support of decisions that are made under uncertainty of external factors [17]. The other input of the tool is instances of equipment building blocks (EBBs) available for system design, which embody the hardware components of the production system. The standard format of the machine instances contains an identifier of the EBB, the specific process type it is used for, the processing speed of the EBB, the size and investment. These instances

![Fig. 4. CDS-suited model of design problems](image-url)
specify the hardware components that can be combined to production cells in the generation of various designs of the RCMS.

The generation of designs is described in more detail in chapter 4.3. After multiple designs were generated and analyzed, the designs and their performance are presented as output of the model. One result are sets of values for each design candidate: the number of cells the system consists of, the allocation of resources to cells and the allocation of products and/or product families to production cells and resources. Furthermore, also the performance characteristics of each design solution are displayed to give detailed information about the anticipated performance, including investment and costs in different cost categories (see also fig. 5). Moreover, the anticipated product lead times and product cost are shown for each design candidate, as well as space requirement of the system configuration.

4.3. Algorithmic model creation and analysis

After the input parameters are specified, the system designs can be generated. In the first step of design generation, the algorithm calculates upper and lower boundaries for capacity requirement of each process, which is used to determine minimum and maximum values for the number for each equipment component (see step 1, fig. 5). Subsequently, values within these ranges can be instantiated by randomized algorithms (step 2). Firstly, a parameter value for the number of cells is assigned, then the various functional equipment building blocks can be instantiated across the cells. Once the amount of EBBs as determined by the algorithm is distributed and the design requirements for each cell is fulfilled, a system design is complete. The requirements for design solutions can be, for instance, that each cell contains equipment for input, output, processing and in-cell manipulation. The last step in system design is taken by assigning products to cells and to resources inside a cell (3). After completion of the system design phase, the various system performances are analyzed according to the analysis rules specified in the knowledge base (4) and the performance is visualized (5). Each performance of the system can be also used as a constraint for solution generation, so that the user can specify requirements to guide the generation of designs (6). In case the instantiated system does not match the user requirements for either design or performance, a new, distinct instance of the system is created. Once a valid design of system hardware is generated and the analyzed performances are within specifications, the solution becomes a design candidate. Consequently, additional design candidates can be generated.

4.4. Exemplary formalization

Equations 1 to 3 show an exemplary part of the formalization of a simplified model. First, the total time demand $T$ needed for production of the quantity $q$ of $p$ products on machine $M$ is calculated (see eq. 1). Using also the capacity of one instance of $M$, the minimum number of machines $M$ is calculated. Then, the algorithm instantiates a random number $x_{\text{Mact}}$ from a range defined by a heuristic (see eq. 2). By multiplying $x_{\text{Mact}}$ with the investment $I_M$ for a single machine, the total investment $I_{\text{Total}}$ for the used number of machines is eventually calculated. If this number should be subject to constraints, the algorithm instantiates a different value for $x_{\text{Mact}}$ from the range defined in equation 2. Various designs are generated by repeatedly altering $x_{\text{Mact}}$ and analyzing the performance, which in this case only results in different investments. Though equations 1 to 3 only show a small fragment of the parameters and analytic relations of an entire RCMS model, the principle of automated generation of
various designs stays the same. As the equations of our model represent basic and known analytic relations without academic newness, the formal description is limited to the aspects explained. It should be noted that the form and number of designs that can be created is only restricted by the designed preferences, knowledge and ability to express them analytically.

\[
x_{\text{Mmin}} = \frac{\sum_{\text{p} \in \text{F}} (\text{TM} \times q)}{\text{CM}}
\]

(1)

\[
x_{\text{Mmin}} \leq x_{\text{Mact}} \leq 5 \times x_{\text{Mmin}}
\]

(2)

\[
x_{\text{Mact}} \times I_{\text{M}} \leq I_{\text{Total}}
\]

(3)

4.5. Anticipated effects

As explained, the model can be used to instantiate a large number of system design and analyze them. By visualizing the characteristics of multiple designs relative to each other, decision makers can compare the candidate solutions by design or performance characteristics. In case multiple product scenarios are formulated, the performance of the design candidates can be compared also in context of different, possible developments of the business. If the user finds solutions that are not useful, further design and/or performance requirements can be iteratively imposed to eliminate solutions that are not favorable. The approach allows the decision maker to develop an impression of feasible designs and to determine the influence of particular design decision on the system performance. After repeatedly generating and evaluating design solutions and refining the requirements, one or more promising solutions can be selected for more detailed analysis with the traditional decision support approaches. Therefore, using the model in a CDS software application should represent a frontloading activity of the design process, broaden the range of solutions considered and eventually save time for assessing design candidates in the recurring design process of RCMS. The development of a software prototype to allow practical application of set-based concurrent engineering of RCMS based on this model was completed. The next step will be to evaluate the effects of the tool for the design procedure.

5. Concluding remarks

The previous chapters show that production systems are an important asset for companies. In an uncertain business, the structure of RCMS is supposed to make them suitable devices to maintain competitiveness. However, the design freedom brings about the need for decision support. Therefore, traditional decision-support principles used in design of production systems are explained. It is argued that the state-of-the-art approaches can have important limitations when used for design of RCMS and eventually aggravate the comparison of interesting system design options. Offering a different approach to design support, the main chapter describes a type of design engineering model that can be used to enable CDS. Furthermore, the relevant in- and outputs of an software-implemented RCMS model are described, as well as the algorithmic creation of RCMS design candidates. Moreover, an exemplary part of the formalized model is explained to visualize how the detailed RCMS aspects are processed. Lastly, the anticipated usage and benefits of a software application were highlighted, which was developed based on the presented model.

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