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A production planning method to optimally exploit the potential of reconfigurable manufacturing systems

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Abstract

Manufacturing companies must operate in a dynamic environment. Consequently, companies constantly have to adapt their manufacturing systems to stay competitive. One approach to ensure the success of manufacturing companies is to use reconfigurable manufacturing systems (RMS). Current production planning methods cannot quickly realize the production-side adaptions available in RMS and are limited in flexibility. A novel production planning method to optimize the potential of RMS is presented in this paper. First, the key characteristics and planning requirements for an RMS are defined. A feasible configuration is then determined, using a planning method based on mixed integer linear programming (MILP) to realize capacity scalability and functionality changes within planning processes. Finally, an application scenario to validate the method is outlined.

1. Introduction

More than ever, manufacturing companies are affected by challenging dynamics [1] caused by shortening product and technology life cycles [2] and increasing numbers of product variants as the demand for individualized products rises [2; 3]. To meet these challenges, manufacturing companies need to provide more individualized instead of standardized products and, in doing so, transform themselves into single- and small-batch producers. In the transformation towards production of small batch sizes, the number of units produced decreases, whereas the number of orders and the coordination effort that is required increase. Consequently, manufacturing companies constantly have to adapt their manufacturing systems to ensure their competitiveness [4]. In particular, to remain sustainable they need to be able to reconfigure their manufacturing resources frequently and increase their efficiency. One approach that makes this possible is the use of reconfigurable manufacturing systems (RMS) [5].

'Reconfigurability' is defined as the ability to customize the behavior of a system by changing its configuration [13], while 'configuration' is defined as a sequence of workstations in a layout or the set-up of a workstation setting [5].

Although an RMS allows for frequent adjustments and flexibility in manufacturing processes on the one hand, it increases the complexity of the planning and scheduling processes [6] on the other. Existing production planning and control (PPC) systems cannot deal with these dynamic characteristics. Undefined interfaces and incorrect planning parameters are further challenges in production planning and control [7]. In particular, the existing production-planning and control algorithms are fixed in terms of possible objectives and planning parameters and can therefore not meet the market demand [8]. To exploit the inherent flexibility of an RMS, the production planning and control system needs to become more sophisticated [9].

In this article a production planning method, as part of a planning system using reconfigurable manufacturing systems,

is outlined. The proposed production planning method for RMS is then presented. Finally, an application scenario and the validation of the planning method are discussed.

2. Approaches to production planning with RMS

Since the concept of reconfigurable manufacturing systems was raised by Koren et al. [5], several research publications have analyzed and discussed the characteristics and potential of these systems [e.g. 4; 5; 10; 11; 12]. A key factor of RMS is that they can be adapted quickly in terms of capacity and functionality; hardware and software; technology and structure [5; 10]. The key characteristics of RMS according to [5] are listed in Table 1.

Table 1. Key characteristics of RMS [according to 5].

Characteristic	Description
Modularity	Modular structure of components and controls
Integrability	Standardized interfaces for quick integration of new components and technologies
Customization	Customized flexibility and control
Convertibility	Short conversion times
Diagnoseability	Traceability of product quality during ramp-up

Production planning and control is responsible for planning and controlling production processes in terms of schedule, capacity and output [14]. According to [14] typical objective variables are a high on-time delivery; a constant and high load factor; short lead times; low inventories; and high flexibility.

The main research activities in the field of production planning and control can be divided into *modeling of RMS*, *generation and selection of configurations*, *process planning*, *capacity planning* and *machine scheduling*.

Most of the authors regard the optimal selection of configurations as important elements in the *modeling of RMS* for production-planning and control purposes. Graph theory methods, such as Petri nets, and mathematical approaches have been used to model systems behavior and reconfiguration processes [15; 16; 17].

The main purpose of research activities focusing on the *generation and selection of configurations* is to identify an optimal configuration. To this end, different optimization approaches, mainly based on heuristics, have been developed [18; 19] and different selection strategies used. These strategies include a comparison of the component requirements and the available resource capabilities [20].

The optimization approaches gave rise to different research activities for *process planning* with RMS, such as the specification of part-families [21] and the design of adaptable process plans [22]. Different kinds of process planning tasks for RMS, such as macro process planning and parameter optimization, have also been developed [23].

For *capacity planning* with RMS, it is essential to describe and integrate scalability in terms of the capacity of the systems. In general, capacity scalability is described on a system level by adding and removing manufacturing equipment. By determining the system's capacity and functionality needs based on the market demand, researchers

have developed different capacity strategies [6; 24; 25]. The use of reconfigurable machine tools (RMT) for capacity adjustment was also identified [26].

Different mathematical modeling approaches have been used as the basis for *machine scheduling*, with heuristic algorithms mainly being used to solve formulated scheduling problems. Examples include approaches based on fuzzy logic, tabu search, simulated annealing and genetic algorithms [27; 28; 29]. In particular, the minimization of production costs and the reduction of lead times have been formulated as objective variables.

To summarize, the state of the research concerning the use of RMS in the field of production planning suggests that a continuous approach involving different planning phases has not yet been developed. Thus far, the research activities have only focused on specific tasks and aspects of PPC.

The main enabler of reliable planning results with RMS in production planning and control has been the integration of scalability in terms of the capacity and functionality of systems. To ensure scalability, the key characteristics of RMS need to be integrated in the production planning and control process, and production planning parameters must be used to specify the configurations of RMS. In this context, one possible approach could be to use different capacities that are subject to configuration-dependent cycles (systems) or processing times (resources). In addition, feasible configurations need to be selected and assigned within planning procedures. Given the fact that existing approaches only focus on specific areas of production planning and control rather than presenting a continuous approach, new methods for production planning need to be developed.

3. Specification of RMS for production planning

To develop a production planning method for reconfigurable manufacturing systems it is essential to describe the characteristics of RMS in terms of planning capabilities. Thus, in the following sections configuration-dependent processing times and the resultant scalable capacities are outlined as essential basics for the subsequent planning method.

For the production planning method, an RMS is divided into system (SC_k) and resource ($RC_{i,j}$) (i.e. workstation) configurations. Target times are used for production planning, e.g. for capacity planning. Target times consist of set-up and processing times. As the performance of the resource is related to its configuration, a configuration-dependent processing time (t_{ij}^p) of a resource i is defined. On the system level, the processing time of the bottleneck resource determines the cycle time (t_k) for the actual system configuration *k*.

The production capacity that can be provided by the system depends on the cycle time of the system configuration. With the help of reconfigurations, the cycle times can be adjusted. The maximum capacity is described by the fastest system configuration and the available working time. The capacity demand and the available capacity are synchronized

by means of capacity scalability through reconfigurations. A capacity time-profile for a specific planning period is divided into a reconfiguration and a processing component for a production quantity (see Fig. 1). The capacity requirement for the processing part (CAP^P) consists of the required production quantity (m^q) and the configuration-dependent cycle time of the system configuration (t_k). Furthermore, the capacity requirement for reconfiguration processes (CAP^{Re}) depends on the reconfiguration effort (A_{mj}^{Ri}) of each manufacturing resource. The reconfiguration smoothness factor of Youssef & ElMaraghy [30] was adapted and is applied to the resource level and multiplied with a resource-specific time factor (α_t).
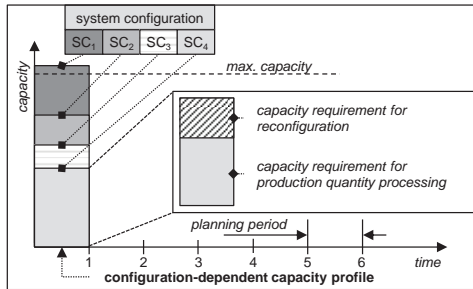

Fig. 1. Capacity profile with a reconfiguration and processing part.

The calculation of the configuration-dependent capacity profile is illustrated in Table 2. In calculating the capacity profiles, the essential basics of the planning method that aims to optimally exploit the potential of RMS are revealed.

Table 2. Capacity profile and necessary parameters.

Capacity profile

$$CAP^T = CAP^P + CAP^{Re} = t_k \cdot m^q + \sum_{i=1}^{i^{max}} \alpha_t \cdot A_{mj}^{Ri} \qquad (1)$$

Parameters	
CAP^T	Total capacity requirement [hours per period]
CAP^P	Capacity requirement for part processing [hours per period]
CAP^{Re}	Capacity requirement for reconfigurations [hours per period]
t_k	Cycle-time for system configuration k [minutes per part]
m^q	Required production quantity [items]
i	Index for resources
α_t	Resource-specific reconfiguration time factor [minutes per reconfiguration effort]
A_{mj}^{Ri}	Reconfiguration effort for change from resource configuration m to j of resource i

4. Production planning method

The goal of this article is to show the development of a production planning method that exploits the potential of reconfigurable manufacturing systems. The main focus is to integrate scalability in terms of capacity and functionality into the production planning.

This method is the core element of the planning system described in [31] and [32]. The production planning method is divided into *requirement planning*, *resource planning* and *production sequencing* phases. The goal is the definition of minimum-cost configurations for a target production program. The first two phases of the method are mainly based on the modeling and description approaches described in [32]. In particular, the specification of resource and system configurations in terms of planning (e.g. configuration-dependent key performance indicators) and manufacturing capabilities (e.g. manufacturing processes) are highlighted.

The focus here is thus the remaining phase, i.e. the production sequencing model. The three phases with steps and the schematic structure of the method for production planning are illustrated in Fig. 2. Each phase is described in the following sections.
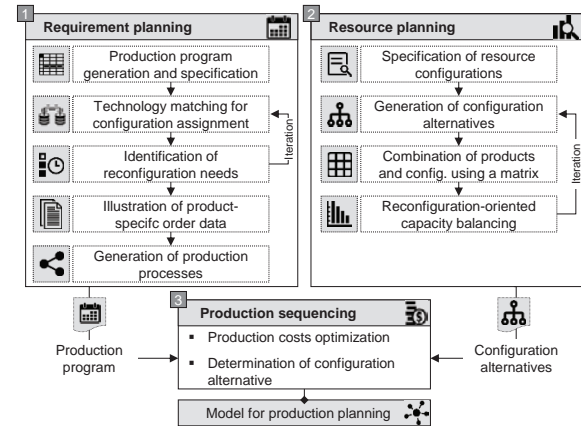

Fig. 2. Overview of the production planning method.

The *requirement planning* phase plays a decisive role in structuring the product-side requirements of production planning. This planning step pursues the goal of adequately recording the production side as well as the product-specific requirements.

Based on demand planning and product descriptions, a production program is generated and specified. The production program is divided into macro und micro periods. In this step, the demand is fixed for the macro periods. A technology matching based on a previously developed classification scheme [32] determines the feasible resource configurations for the product-specific requirements. If there is no correspondence between resource capabilities and product-specific requirements, reconfiguration needs are determined in terms of technology, and adaptions can be made to extend the configuration area of the resources. After the technology matching, the planning results and the production-specific order data are documented in an expanded, configuration-dependent work plan. Finally, configuration-dependent production processes are generated and transformed into a production graph.

The main tasks during the *resource planning* phase are generating and describing system configurations and achieving reconfiguration-oriented capacity balancing.

To achieve the goal of continuous production planning, the relevant planning information is summarized in a resource specification. The specification includes the configuration-dependent processing times, the necessary modules of the

particular configurations and the feasible production operations. The operations of the production processes are linked to the configurations. Based on the resource specifications and a configuration combination matrix ($\mathbf{M}^{CM}$), possible system configurations, which are evaluated within the production sequencing, are generated (see Fig. 3). The resource configurations are combined until all possible combinations have been created. Each of the system configurations is specified with cycle times and an hourly rate. With the help of the $\mathbf{M}^{CM}$, restrictions in terms of the combination between different resource configurations can be indicated.
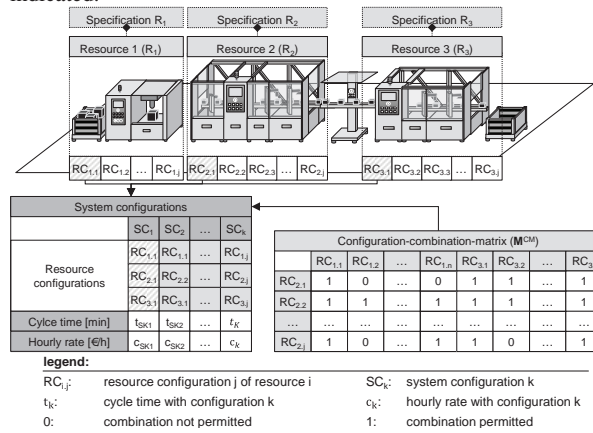

Fig. 3. Generation of system configurations with the help of the $\mathbf{M}^{CM}$.

In the next planning step, the system configurations and the producible products are combined into the product configuration combination matrix ($\mathbf{M}^{PC}$). This matrix combines products and configurations for the production sequencing.

Lastly, a first reconfiguration-oriented capacity balancing is carried out. The goal of this planning step is to identify reconfiguration needs in terms of capacity. The resulting capacity profiles are therefore compared to the capacity demand for each planning period. If reconfiguration needs to be done, possible adaptation measures help to generate new configurations based on existing ones. The necessary planning information for the next phase – production sequencing – can now be specified.

The *production sequencing* phase is the last task in determining a production plan and is based on the results of the previous planning steps. After considering the configuration alternatives, a minimum-cost configuration option is determined for each planning period. In addition, production quantities, configuration sequences and product-related inventories are evaluated. To solve the problem of optimal configuration determination, a mixed-integer linear programming (MILP) production-sequencing model is used. This model allows for capacity scalability and functionality adaptions. Table 3 summarizes the model parameters and decision variables.

Table 3. Parameters for the production-sequencing model.

Input parameters	
$p \in P := \{1, ..., P^{max}\}$	Number of products
$t \in T := \{1, ..., T^{max}\}$	Number of macro periods
$s \in S := \{1, ..., S^{max}\}$	Number of micro periods
$k \in K := \{1, ..., K^{max}\}$	Number of system configurations
Model parameters and indexes	
c^{idle}	Costs for idle time per time unit [Euro per minute]
c_k	Hourly rate of system configuration k [Euro per hour]
c_p^L	Inventory costs for product p per macro period t [Euro per part]
c^{Re}	Constant reconfiguration cost factor [Euro per reconfiguration effort]
c^T	Total production costs [Euro]
CAP_{T_s}	Max. capacity in macro period t [hours]
i	Index for resources
k or l	Index for system configurations
$m_{p,t}^q$	Demand of product p in period t [items]
s	Index for micro periods
$\bar{S}_{(t)}$	Last micro period of macro period t
t	Index for macro periods
t_{kl}^{Re}	Reconfiguration time for change between system configuration k and l [minutes]
t_k	Cycle time of system configuration k [minutes]
t_s^{idle}	Idle time in micro period s [hours]
T_s	Assignment of macro and micro periods
$\tau_{\bar{S}_{(t)}}$	End of the last micro period s of macro period t
y_p^{max}	Max. inventory of product p [items]
z_{pk}	Product configuration compatibility
Decision variables	
$q_{p,s,k}$	Production quantity of product p in micro period s with configuration k [items]
τ_s	Duration of micro period s [hours]
η_{kls}	Configuration sequence
δ_{ks}	Configuration indicator in micro period s
y_t^p	Inventory of product p in period t [items]

The planning object of the production-sequencing model is an RMS characterized by configuration alternatives. Each configuration varies in either functionality or capacity, or both. The configuration can change once per micro period. The reconfiguration process is described in a reconfiguration matrix in terms of time and cost. The compatibility between products $p \in P := \{1, ..., P^{max}\}$ and configurations $k \in K := \{1, ..., K^{max}\}$ is described by the product configuration combination matrix ($\mathbf{M}^{PC}$). The continuous production is represented by the division of the finite planning horizon into macro and micro periods. Fixed and equidistant macro periods $t \in T := \{1, ..., T^{max}\}$ can be described as months. The event-based micro periods $s \in S := \{1, ..., S^{max}\}$ are continuous and non-equidistant. In particular, the length of a macro period is given by a maximum working time. Furthermore, the production of the products is carried out sequentially within

the periods. Inventory capacity restrictions are given for each product and inventory costs arise for products in stock.

The objective function (2) minimizes the total production costs, which consist of reconfiguration, processing, inventory and idle time costs (see Table 4). Constraints (3) to (17) describe the solution space and requirements.

Table 4. Objective and constraints of the production sequencing model.

Objective	
$\min c^T = \sum_{k \in K} \sum_{l \in K} \sum_{s \in S} \eta_{kls} \cdot t_{kl}^{Re} \cdot c^{Re} + \sum_{p \in P} \sum_{s \in S} \sum_{k \in K} q_{p,s,k} \cdot t_k \cdot c_k$ $+ \sum_{p \in P} \sum_{t \in T} c_p^L \cdot y_{p,t} + \sum_{s \in S} t_s^{idle} \cdot c^{idle}$	(2)

Constraints		
$y_{p,1} = y_{p,0} + \sum_{k \in K} \sum_{s \in S_t} q_{p,1,k} - m_{p,1}^q$	$\forall p \in P, t \in \{1\}$	(3)
$y_{p,t} = y_{p,t-1} + \sum_{k \in K} \sum_{s \in S_t} q_{p,s,k} - m_{p,t}^q$	$\forall t \in T \setminus \{1\}, p \in P$	(4)
$q_{p,s,k} \geq 0$	$\forall p \in P, s \in S, k \in K$	(5)
$y_{p,t} \geq 0$	$\forall p \in P, t \in T$	(6)
$\sum_{k \in K} \sum_{l \in K} \eta_{kls} \cdot t_{kl}^{Re} + \sum_{p \in P} \sum_{k \in K} q_{p,s,k} \cdot t_k$ $\leq CAP_{T_s}(\tau_s - \tau_{s-1})$	$\forall s \in S$	(7)
$y_{p,t} \leq y_p^{max}$	$\forall p \in P, t \in T$	(8)
$q_{p,s,k} \cdot t_k \leq CAP_{T_s} \cdot \delta_{ks} \cdot z_{pk}$	$\forall p \in P, s \in S, k \in K$	(9)
$\sum_{k \in K} \delta_{ks} = 1$	$\forall s \in S$	(10)
$\sum_{k \in K} \sum_{l \in K} \eta_{kls} = 1$	$\forall s \in S$	(11)
$\delta_{k,s-1} + \delta_{ls} - 1 \leq \eta_{kls}$	$\forall k \in K, l \in K, s \in S\setminus\{1\}$	(12)
$\delta_{k1} = \delta_{k0}$	$\forall k \in K$	(13)
$t_s^{idle} = CAP_{T_s}(\tau_s - \tau_{s-1})$ $- \sum_{k \in K} \sum_{l \in K} \eta_{kls} \cdot t_{kl}^{Re}$ $- \sum_{p \in P} \sum_{k \in K} q_{p,s,k} \cdot t_k$	$\forall s \in S$	(14)
$\tau_{S_{(t)}} = t$	$\forall t \in T$	(15)
$\delta_{ks} \in \{0,1\}$	$\forall k \in K, s \in S$	(16)
$\eta_{kls} \in \{0,1\}$	$\forall k \in K, l \in K, s \in S$	(17)

The first two constraints state the inventory for the first planning period (3) and the subsequent macro periods (4). Constraints (5) and (6) ensure that the production quantity and the inventory do not take on negative values. The sum of reconfiguration and processing time must be less than the maximum working time in each macro period (7). Constraint set (8) limits the inventory up to a maximum. A product can only be produced in the system if the compatibility between the set-up configuration ($\delta_{ks} = 1$) and the product is given ($z_{pk} = 1$) (9). In addition, constraint (10) ensures that in each micro period a feasible configuration is set. Simultaneously, reconfigurations can only be preceded once per micro period (11). Constraint set (12) describes the connection between the configuration and the configuration sequence indicator. The

start configuration for the first planning period is set by (13). Constraint (14) ensures the calculation of idle time within the micro period. Furthermore, each micro period is linked to its corresponding macro period (15). The constraint sets (16) and (17) declare the indicators for the configuration state and the configuration sequence as binary variables.

In the following section, the application and the validation of the production sequencing model are discussed.

5. Application and validation

The described planning method (reference model) was set up in a prototypical planning system. The model was validated in a scenario based on an industrial use case. Here, an RMS consisting of four resources, which have been simplified and modeled with realistic behavior, is designed to produce different products with variable demands. For the validation, a realistic production scenario, described by its annual demand and the necessary products, was evaluated. For the specification of the input data, the requirements and resource planning were carried out. To enable analysis of the reference model, a conventional production planning model with one configuration, i.e. no reconfigurations, and thus static planning data as well as suboptimal planning parameters, was set up as a comparison model. In general, the developed method synchronized the available capacity and the demand. Furthermore, the capacity scalability within the scalability corridor became apparent by providing a demand-depending capacity for each macro period. Fig. 4 and Table 5 illustrate the planning results for the application scenario.
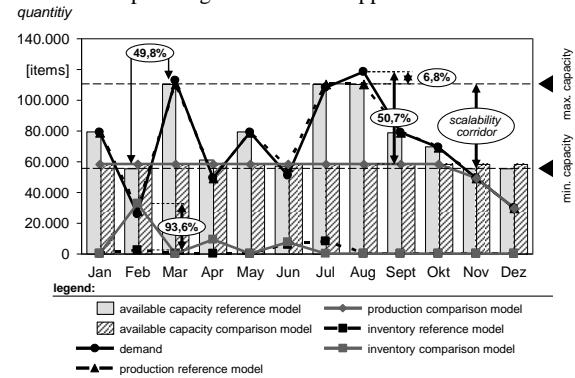

Fig. 4. Planning results for the reference and the comparison model.

The reference model was able to meet the demand (850.000 items per year) by scaling the capacity and building up inventories. In contrast, the comparison model had to cope with constant capacities and was not able to fulfil the annual demand (662.493 items per year). Consequently, overtime needed to be included in the planning results to cover the gap between planning output and demand. In addition, the average inventory was reduced by 3.355 items (-71,7%). In terms of productivity, an increase of 28,3% was realized. A reduction of 5,6% in the utilization of the system can be observed. As a consequence, low inventories as well as a reduction of the lead time are possible. To summarize: the production planning

method that was developed is able to integrate capacity scalability and enables the use of reconfigurations in PPC.

Table 5. Comparison of the planning results for the application scenario.

	Comparison model	*Reference model*	*Difference*
Output	662.493 items	850.000 items	-28,3%
Avg. inventory	4.680 items	1.325 items	-71,7%
Productivity	1,20 items/s	1,54 items/s	+28,3%
Utilization	94,6 %	89,3 %	-5,6%

6. Conclusion

In order to ensure their success, manufacturing companies constantly need to adapt their production systems. One approach to cope with these changes is to use reconfigurable manufacturing systems. To support the inherent flexibility features of RMS while optimizing efficiency, appropriate planning methods are necessary. In this article a production planning method using RMS has been developed and validated in an application scenario. Further research, which needs to include extended analyses of different production scenarios, is needed to identify the feasible solution space for this planning method.

Acknowledgements

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