Novel Capacity Planning Methods for Flexible and Reconfigurable Assembly Systems

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1 STAGE OF THE RESEARCH

The importance of efficient planning methods is increasing with the evolution of manufacturing systems, since flexible and reconfigurable system structures require different planning approaches than the dedicated ones. The research presented in the paper is focused on production and capacity planning methods, which are able to cope with the dynamic changes that occur in the reconfigurable and flexible assembly systems. In the preceding publications of the author, some novel approaches were presented that support the management of modular reconfigurable resources and complex product portfolios.

A simulation-based technique was introduced in (Gyulai et al., 2012) and (Gyulai and Vén, 2012) that defines the boundaries and components of a modular reconfigurable assembly system for companies that face with fluctuating production volumes and have end-of-life-cycle products. In that case, frequent revision of the production system structure is required in order to gain production space and to harmonize the operation of the system with the order stream. The proposed method separates the low- and high- volume products and product families dynamically, and supports system parameter setting and fine tuning of production capacity.

As a generalization of the above described problem, the line assignment for a complex product portfolio and the simultaneous production and capacity planning of a modular reconfigurable assembly system is presented in (Gyulai et al., 2014a) and. The approach offers an integrated way for the assignment of products to dedicated or reconfigurable resources and for the production planning of the reconfigurable ones. An essential element of the system —developed within an industrial project— is that cost predictions computed by multivariate linear regression on virtual production scenarios support the solution of the line assignment problem. The production planning level also incorporates a sequencing module for minimizing the number of reconfigurations.

For the line assignment problem, a novel method is proposed in (Gyulai et al., 2014b) that combines discrete-event simulation with statistical learning models to support the strategic capacity planning processes on a long-term horizon, based on the forecast market conditions.

2 OUTLINE OF OBJECTIVES

Within the PhD research, the primary aims are to define production and capacity planning methods that efficiently support the production and capacity planning of the flexible and the modular reconfigurable assembly systems. Although several different approaches exist for similar problems, many of them consider problem sizes with only a few products and/or limited capabilities regarding the diversity of product mix and degree of system flexibility and scalability. The target planning methods have to meet the following requirements:

- handle several products/product families with different life-cycle stages and thus different yearly volumes;
- solve the line assignment problem (that is often referred to as capacity investment strategy) considering deterministic as well as stochastic cases;
- support the capacity and production planning of modular reconfigurable assembly systems that applies changeable modules for the different assembly processes;
- define reliable production planning models for mixed-model flow assembly lines, where processing times and rework rates (based on the reject rates) vary;

- support the planning processes with flexible methods applying self-building mathematical models;
- in order to ensure the reliability of the methods, such optimization methods should be considered that integrate mathematical modeling with statistical learning, in order to provide reliable plans based on real production data;

The above requirements are summarized on a concept map that emphasizes the problem side of the research topic as well as the considered supporting techniques and technologies (Figure 1). The green boxes highlight the concepts that are going to be investigated to carry out new scientific results, or already supported by new achievements within the current research.

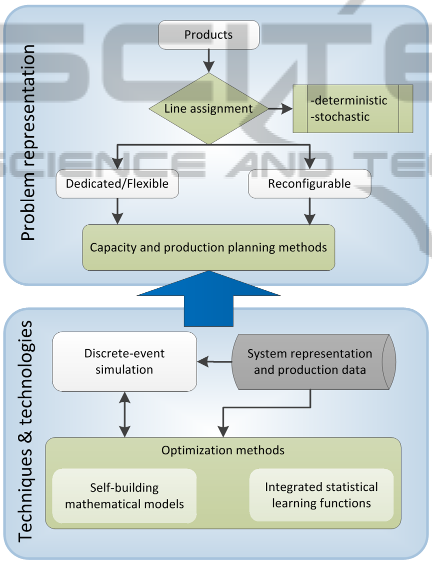

Figure 1: Concept map of the research topic.

3 RESEARCH PROBLEM

In the capacity management problem, different production resources are considered that provide different level of flexibility and capacity to meet the requirements given by the order stream. Dedicated assembly systems provide a large-scale capacity for producing one product in a high volume. Flexible assembly systems are designed for producing a set of similar products/product families with lower capacity but higher flexibility regarding the volume and the product mix. Reconfigurable assembly systems provide better system scalability and product mix flexibility even in case of different product families while keeping relatively higher throughput than the flexible lines.

In order to clarify the research topic, the boundaries of the problem in question are defined around the assembly segment of individual plants, without focusing on the corresponding supply chain processes. The considered capacity management problem is split up into two main sub-problems according to the focus, nature and time horizon of the decisions involved.

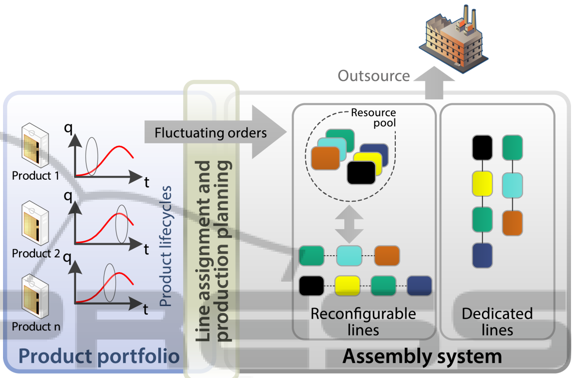

Figure 2: Illustration of the capacity management problem.

3.1 Line Assignment

The line assignment problem is aimed at minimizing the production costs by the optimal assignment of the products to the dedicated/flexible or reconfigurable resources. The time horizon of the decision is some months, and the objective function includes the costs that are relevant on the strategic level. The total production cost is composed of the investment, the operation, and the personnel costs. When searching for the optimal allocation, the actual customer orders as well as the forecast volumes are considered on the predefined time horizon. The line assignment problem can be seen as subdividing the set of products, P, into products assembled on the dedicated lines, D, on the reconfigurable lines, R, and products outsourced, OS. In the relevant literature, the line-assignment problem is often referred to as capacity investment strategy whose objective is to determine the optimal capital investment in types of production capacities with distinct flexibility.

For products $p \in D$ or $p \in OS$, the production costs can be assigned directly to individual products, and denoted by a parameter C_p. In case p is assembled on a product-specific dedicated line, the production cost C_p can be computed as the sum of the investment cost (zero if a dedicated line for p already exists), a high fixed cost, and a volume dependent operation cost. Analogously, for an outsourced product p, C_p is composed of a small fixed cost and a relatively high unit cost.

In contrast, the cost related to the reconfigurable lines depends on the actual product mix and the production plan adopted, and cannot be directly divided among individual products. With a given optimization model for production planning, this cost can be described as a general, non-linear function of the production volumes, resource requirements, and further parameters of the products assembled on the reconfigurable lines. Therefore, the overall production cost incurred in the reconfigurable system is captured by a function C^R, and it incorporates the investment costs and the operation costs related to those lines. A key challenge in the line assignment problem is computing, as well as predicting this cost for an arbitrary set of products R.

3.2 Production and Capacity Planning

On a lower level of the decision hierarchy, the production and capacity planning problems of the flexible and reconfigurable assembly systems are considered, namely to minimize the production costs on a certain discretized time horizon by optimal lot-sizing and capacity allocation policy. In order to find the optimal production lot-sizes and capacity assignment, novel mixed-integer programming approaches are required that capture the dynamic underlying processes that occur in flexible and reconfigurable assembly systems.

On the one hand, many different lot-sizing approaches exist that focus on dedicated and flexible assembly systems, but their applicability on modular systems is limited due to the different nature of the underlying processes. On the other hand, the existing methods are usually based on some assumptions as for example the deterministic process times, capacity requirements or production costs. Therefore, the research is focused on the implementation of novel methods that face such challenges like the variance of the production data and dynamic nature of the processes.

The general objective of the mid-term plans is the maximization of the profit or minimization of the cost corresponding to the execution of the calculated plan. These objective functions are usually composed by different factors. On the one hand, production-related costs like the deviation costs of the order fulfillment (represented by tardiness or delivery performance), operation costs of the machines and control of the human operators strongly depend on the calculated plan. On the other hand, the optimal number of the resources and the cost of the manpower are capacity related factors that affects highly not only the costs but the system's performance as well.

4 STATE OF THE ART

Strategic capacity planning has broad literature, however, the line assignment or capacity investment strategy considering reconfigurable resources is a relatively novel field in production research.

Ceryan and Koren introduce an approach that formalize capacity planning as an optimization problem based on the flexibility premium and determines the optimal resource portfolio for a fixed planning horizon (Ceryan and Koren, 2009). Niroomand et. al propose a method based on mixed integer programming that determines the cost-optimal capacity set based on the lifecycle of a product discretized in time. The method efficiently considers the reconfigurations occurring in a reconfigurable system that applies platforms and changeable modules (Niroomand et al., 2012).

Based on the dynamically changing nature of the order stream, the capacity and system configuration planning process is often formulated as a Markovian Decision Problem that can be solved by dynamic programming or learning algorithms (Asl and Ulsoy, 2003)(Colledani and Tolio, 2005)(Deif and ElMaraghy, 2006). These methods consider capacity planning and management as a sequence of decisions on a longer horizon, and their objective is to find an optimal policy to minimize the costs on the long run. Hon and Xu propose a simulation-based method to optimize the system structure of a reconfigurable system based on the different stages of the products' lifecycle (Hon and Xu, 2007).

The production planning problems of the flexible flow assembly lines are usually aimed at minimizing the costs influenced by the due dates, inventories and capacity requirements (Boysen et al., 2009a) and (Boysen et al., 2009b). In case of manually operated assembly lines, the most crucial point in planning is the workload planning and capacity control of the human operators. In (Giard and Jeunet, 2010), the authors present a mixed-integer programming (MIP) approach to simultaneously solve the production planning and workload smoothing problem in case of mixed-model assembly lines.

5 METHODOLOGY

In order to satisfy the requirements given by dynamic and changeable processes in the flexible and reconfigurable systems, such planning methods are proposed that cope with the underlying production processes and capable of adopting to the changes and disturbances. As depicted by Figure 1., the research is focused on implementing novel capacity management/production planning methods for assembly systems and flexible solutions that support them from technical side (simulation, mathematical models etc.).

5.1 Novel Capacity Management Approaches

5.1.1 Deterministic and Stochastic Models for the Line Assignment Problem

In order to determine the cost-optimal line assignment, deterministic as well as stochastic optimization problems can be defined. In the deterministic case, the following assumptions are made. Order volumes and forecasts are available for the given time horizon. It is assumed that the capacity of a single line is sufficient to assemble the product in the desired volume, and therefore, the option of dividing the order volume between different production modes can be ignored. The price of the machines and the costs of the human operators are constant over time. As previously stated in section 3.1, the greatest challenge in solving the line assignment is the nonlinear nature of the cost-function corresponding to the reconfigurable lines. To tackle this, a regression-based approach is introduced in (Gyulai et al., 2014a), where the multivariate prediction function is integrated in the mathematical optimization model.

In the stochastic line assignment problem, the order volumes and forecasts are given by probability distribution functions. The price of the machines and the costs of the human operators may also change over time. Therefore, the stochastic line assignment problem can represented by a Markovian Decision Process (MDP), whose objective is to find the cost-optimal policy to assign the products to the different types of production lines beside the sufficient amount of capacities. By defining a proper function that gives the production costs in each time step (state), the stochastic line assignment problem can be solved by reinforcement learning methods.

5.1.2 Flexible Mid-term Planning Methods

Within the first stage of the research, a novel production planning method was proposed, that solves the integrated configuration and scheduling of the system. As described in Section 3.2, the production planning models for the different assembly system types need to consider diverse factors to provide the optimal solution. Since there is no tight link among the system types from modeling perspective (e.g. a product is assembled in two different systems, or common material provision constraints), the mid-term planning problem can be decomposed into sub-models for the different systems.

The following model provides and optimal solution for the simultaneous production and capacity planning in a modular reconfigurable system. The problem is solved on a discrete time horizon with time units corresponding to individual shifts. The planning problem is formulated as a MIP as follows.

Parameters and sets:

$J = \{1 \dots l\}$	set of machine types
$P = \{1 \dots m\}$	set of products
$T = \{1 \dots n\}$	set of shifts
e_j	purchase price of machine j
o_j	operation cost of machine j per shift
h	cost of an operator per shift
p_p	processing time of product p
s_p	changeover time for product p
r_{jp}	the required number from machine j by product p

Decision variables:

$N_j = \{1 \dots l\}$	required quantity of machine j
x_{tp}	the number of lines producing p in shift t

$$\min \sum_{j=1}^{l} e_j N_j + h \sum_{t=1}^{n} \sum_{p=1}^{m} x_{tp} + \sum_{t=1}^{n} \sum_{p=1}^{m} \sum_{j=1}^{l} o_j r_{jp} x_{tp}$$

subject to

$$N_j \geq \sum_{p=1}^{m} r_{jp}(x_{tp} + s_p) \qquad \forall j, t$$

$$q_p p_p = \sum_{p=1}^{m} x_{tp} \qquad \forall p$$

$$N_j \geq 0 \qquad x_{tp} \in \{0, 1\} \qquad s_{tp} \geq 0$$

Considering the production planning problem of the flexible assembly lines, the goal is to minimize the total production cost mostly influenced by the capacity usage, inventories and tardiness. This general problem is often referred to as master scheduling, and decides on the type and amount of products to be produced in the planning horizon and assigns them to planning periods (e.g. shifts) (Boysen et al., 2009a). Although several efficient approaches exist to determine the optimal mid-term production plan, many of them disregard the underlying processes that often leads to infeasible plans due to unplanned capacity shortages. These problems are often caused by the varying processing times and failures and reworks, that can be considered in novel planning models that integrate statistical models in order to apply reliable historical data.

5.2 Novel Planning Techniques

5.2.1 Statistical Learning Methods Integrated in Optimization Models

In such models, the constraints and/or the objective function can rely on statistical learning models that are built upon real historical data, and able to predict accurately the parameters like the idle times, capacity requirements. In a preceding publication of the author, a novel decision support method was presented that integrates the mid-term capacity planning results (section 5.1.2) in a deterministic line assignment model by applying prediction models (Figure 3) (Gyulai et al., 2014a). Integration is established via feedback from production planning to line assignment, in the form of multivariate regression for estimating the cost function.

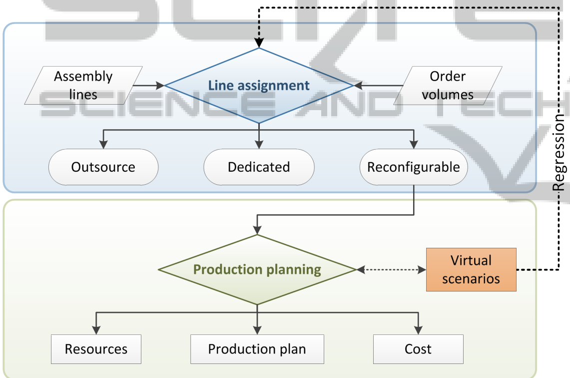

Figure 3: Workflow of the capacity management method.

5.2.2 Self-building Mathematical Models

To extend the scope of the previously described methods, and increase their flexibility regarding the frequent modifications in the system structure, a rule-based, self-building mathematical modeling framework is required. Such self-building approaches are commonly applied in simulation modeling and provide the tight coupling between the physical structure of the production system and the corresponding simulation model, applying low-level control data or high level production data (Pfeiffer et al., 2012), (Popovics et al., 2012).

In order to define the mathematical planning model of flexible and reconfigurable systems, the boundaries of the modeling set as well as the data structure have to be well-defined. The aim of self-building modeling in this case is to set up a meta-modeling framework that is capable of providing feasible mid-term production plans for mixed-model assembly lines and modular reconfigurable assembly systems. The robustness of the plans would be based on real production data collected from the manufacturing execution system (e.g. processing times) and the closed-loop evaluation procedure provided by discrete-event simulation. Although there is a lack of such available solution in the literature, some existing approaches offer high-level ruled-based and meta-modeling techniques for production planning (Bousonville et al., 2005), (Iijima, 1996).

6 EXPECTED OUTCOME

In case of the line assignment problem, the goal is to provide the optimal solution for the deterministic and the stochastic case as well. In the deterministic problem, the objective is to provide the optimal solution by minimizing the total production costs in a particular time considering the orders-on-hand and the forecast volumes. In an ideal case, the line assignment can be iterated over time in a rolling horizon framework which ensures the cost-optimal assignment among lines as market conditions vary.

Regarding the stochastic line assignment problem that considers the volatility of the market conditions more efficiently, the ideal solution would be the optimal, long term capacity management policy that determine when and how to relocate products from reconfigurable lines to dedicated ones (or outsource them), and vica versa. On the one hand, such policy would rely on the product life-cycle that gives an estimation about the production volumes for the upcoming periods with a certain level of confidence. On the other hand, fluctuating order streams and changing parameters (e.g. the price of the resources) can be forecast by applying probability density functions as well. By this way, the problem can be formulated as a Markovian decision process, that can be solved by reinforcement learning or stochastic optimization techniques.

On the mid-term horizon, two main outcomes are expected. For the modular, reconfigurable systems, the mid-term plan should provide the lot-sizes, the required amount of human workforce and the number of reconfigurable resources in discrete time (shifts). The plan must be optimal by minimizing a function that is composed of the cost of reconfigurations, human labor and the investment and operational cost of the resources.

As for the mixed model assembly lines, the lot-sizing models should provide plans that are similar to the previous case, however, these plans have to consider the on-line production data like the rework rates and fluctuating processing times. Furthermore, the optimal number of the operators working at the line and the optimal capacity control of the human workforce are also need to be considered, since their impact on the production planning factors like processing times and WIP are critical.

The implementation of the methods and techniques in a framework (as depicted in Figure 1) would result in a comprehensive production planning and capacity management solution that provide reliable long- and mid-term solutions for companies applying identical assembly system structures. The core of the planning system would be the common production database that could be fed either by the production planners or the MES system. The database would form the basis for the integrated optimization models as well as for the self-building mathematical models that can provide feasible solution for the line assignment problem and the mid-term capacity and production planning problems.

ACKNOWLEDGEMENTS

Research has been partially supported by the Hungary, Grants No. ED_13-2-2013-0002 and VKSZ_12-1-2013-0038.

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