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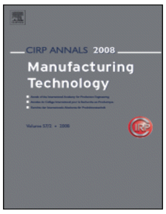

Capacity management for assembly systems with dedicated and reconfigurable resources

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Managing changes and disturbances resulted by fluctuating order streams and diverse product portfolios requires efficient capacity management decisions and production planning strategies. High volume products can be produced cost efficiently on dedicated assembly lines, while the assembly of low runners is more efficient on reconfigurable lines. In the paper a hierarchical planning decision workflow is introduced to assign the products to dedicated and reconfigurable lines, and to optimize the system configuration and the production plan of the reconfigurable system in an integrated way. The proposed solution is demonstrated through the results of an industrial case study.

Production planning, Reconfiguration, Optimization

1. Introduction

Strategic production planning and long-term resource allocation are complex tasks in a sense that they have to deal not only with the available production capacities and order volumes, but also need to consider future stages of the product's life cycle. In case a company has a diverse product portfolio, conventional production systems are not always flexible enough to adapt to the changes that occur and not all product life cycle phases can be handled cost-efficiently [1].

The efficient management of variety in production is one of the most crucial points in today's industry [2]. Depending on the order volumes and the diversity of the product portfolio, different solutions exist to ensure cost-efficient production. Dedicated systems are designed around a certain product/product family, to produce large volumes with low product variety [3]. In contrast, reconfigurable systems are capable of producing a set of different products with high variety by their changeable functionality, scalable capacity, and modularity [2][4][5][6]. The main drawbacks of the reconfigurable systems are the lower throughput and the complex planning and control methods required.

In the paper the authors propose a new capacity planning method that integrates hierarchically the long-term resource investments with short-term modular configurations and optimal production planning. The system applying the proposed approach supports the decisions on the allocation of products to one of the above types of production systems, as well as, simultaneously performs the optimization of the configuration and resource assignment of the modular reconfigurable system.

Though both reconfigurable systems and capacity planning methods have broad literatures, relatively few papers can be found on capacity planning for reconfigurable systems. In [7], Ceryan and Koren introduce a capacity planning method with two products to determine the cost-optimal investment strategies considering dedicated and reconfigurable resources. 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 [8][9][10][11][12]. 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' life cycle [13]. Arafa and ElMaraghy introduce a method for investigating the manufacturing strategy of a firm that faces dynamic market environment, by calculating the volume flexibility of the production [14]. In [15], a performance analysis method is formulated that is based on the universal generating function technique, and can be applied for modular reconfigurable systems. None of the above papers considers an integrated method that is aimed at solving the line assignment problem as well as production planning of the reconfigurable assembly lines.

In a preceding publication the authors of the paper proposed a method for replacing a part of the dedicated assembly lines with a modular, reconfigurable assembly system on the base of standardized assembly processes [16]. The reconfigurable lines are composed of standard, mobile workstations, which are configured sequentially according to the successive assembly operations. The scalability of the system is guaranteed by adding and removing standard, adjustable resources which allow human operators to perform certain assembly processes (e.g., a screwing machine with adjustable torque ranges). The changeable functionality of a system like this provides cost-efficient production for low-volume products. The number and the types of the reconfigurable lines are calculated based on the order volumes, and the throughput is estimated by using automatically generated discrete-event simulation models. The industrial environment considered in this paper is similar, but the focus is on the cost-efficient capacity- and production planning of the reconfigurable lines.

In the following section a detailed formulation of the problem in question is given. The proposed solution approach is presented in Section 3, followed by the experimental results based on the previously stated real industrial dataset.

2. Problem formulation

2.1. The capacity management problem

In an assembly system with dedicated and reconfigurable lines, the key decision within capacity management is allocating each product to a dedicated or a reconfigurable line or, alternatively, outsourcing it to a supplier, while minimizing the total production cost (Fig. 1).

Since in the reconfigurable system the production cost depends on the product mix in question and the production plan adopted, line assignment and production planning of the reconfigurable system are strongly related. Therefore, the proposed method focuses on solving the line assignment and capacity planning problems (Fig. 2).

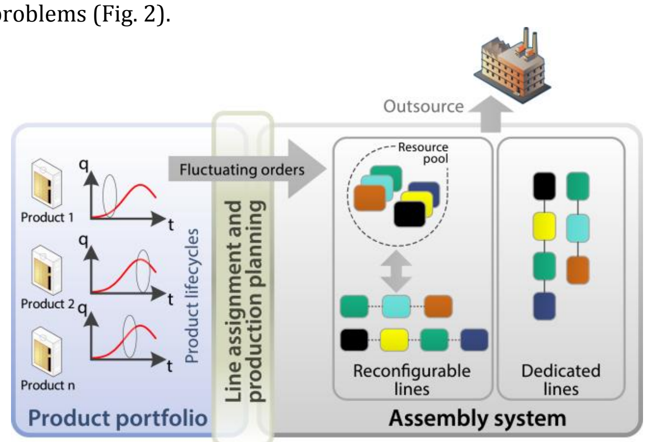

Fig. 1. Illustration of the capacity management problem

When searching for the optimal allocation, the current customer orders as well as the forecast volumes are considered on a predefined time horizon. The total production cost is composed of the investment, the operation, and the personnel costs. The changeover cost in the reconfigurable system is assumed to be an order of magnitude smaller than the above cost components.

The following assumptions are made. Order volumes and forecasts are available for the given time horizon. All products can be assembled in either a reconfigurable or a dedicated line. 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. Although certain products exist in different variants, these variants are always produced together, and therefore, they can be considered as single products on this level of the production planning hierarchy. Machine prices and the costs of human operators are constant over time.

2.2. The underlying cost model

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*.

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*.

2.3. The decision workflow

The proposed hierarchical workflow for integrated line assignment and production planning for the reconfigurable system is depicted in Fig. 2. Integration is established via feedback from production planning to line assignment, in the form of multivariate linear regression for estimating the cost function C^R.

Both line assignment and production planning are iterated over time in a rolling horizon framework, which results in a potential time-to-time relocation of the products among lines as order and forecast volumes vary. In each step of periodic re-planning, investment costs are calculated to reflect the necessary changes in the resource pool with respect to the current capacities. The time horizon of planning is a few months on both levels, with monthly re-planning on a rolling horizon basis. While line assignment is a continuous-time decision that can be revised only during periodic re-planning, production planning is performed on a discrete time scale with time units corresponding to one shift.

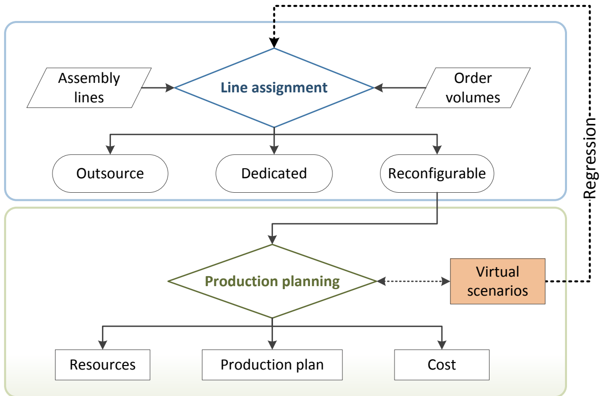

Fig. 2. Workflow of the capacity management method

2.4. Notation

The notation used throughout the paper is presented below.

Parameters:

J set of machine types
P set of products
T set of shifts
e_j purchase price of machine type *j*
o_j operation cost of a machine of type *j* per shift
h cost of an operator per shift
q_p total order and forecast volume of product *p*
p_p processing time of product *p*
r_{jp} required number of machines of type *j* by product *p*
n_j^0 number of machines of type *j* in the resource pool
s duration of a shift

Decision variables (line assignment):

R set of products in the reconfigurable system

Decision variables (production planning):

x_{tp} number of lines producing product p in shift t

n_j number of required additional machines of type j

3. Solution method

3.1. Line assignment

The goal of line assignment is to decide whether a certain product should be assembled on a dedicated or on a reconfigurable line, or it should be outsourced (Fig. 2). While the production costs in the dedicated system and by outsourcing can be computed in closed form from the input parameters, the costs in the reconfigurable system are dependent on the current product mix. Therefore, we propose to predict this cost using multivariate linear regression based on the production costs in randomly generated scenarios. For the regression, the following calculation model is applied:

$$C^R = \beta_0 + \beta_1|R| + \sum_{p\in R}\left(\beta_2 p_p q_p + \sum_{j\in J}\beta_{j+2} r_{jp}\right) + \varepsilon\ , \qquad (1)$$

where the βs are unknown parameters that are estimated, β_0 is the intercept and ε is the error term [17]. By neglecting ε, the formula above can be rearranged as follows:

$$C^R \approx \beta_0 + \sum_{p\in R}\left(\beta_1 + \beta_2 p_p q_p + \sum_{j\in J}\beta_{j+2} r_{jp}\right) = \beta_0 + \sum_{p\in R}\alpha_p \qquad (2)$$

Thus, it is enough to estimate only the α_p values subsequently. The regression was computed on randomly generated production scenarios in the reconfigurable assembly system, solved by the production planning model presented in Section 3.2. The scenarios were divided into independent training and test sets. As regression assigns a separate production cost α_p to each product p, line assignment can be performed for individual products, by comparing the production costs associated to the three candidate production modes. Products p where α_p is the lowest among the costs will be produced on reconfigurable lines, and hence, constitute the set R for production planning.

3.2. Production planning for the reconfigurable system

Medium term production planning in the reconfigurable system addresses the integrated configuration optimization and resource assignment of the system. Planning is solved on a discrete time horizon with time units corresponding to individual shifts. The planning problem is formulated as a mixed integer linear program as follows:

minimize

$$\sum_{j\in J} e_j n_j + h\sum_{t\in T}\sum_{p\in R} x_{tp} + \sum_{t\in T}\sum_{j\in J}\sum_{p\in R} o_j r_{jp} x_{tp} \qquad (3)$$

subject to

$$n_j + n_j^0 \geq \sum_{p\in R} r_{jp} x_{tp} \qquad \forall j,t \qquad (4)$$

$$\left\lceil \frac{q_p p_p}{s} \right\rceil = \sum_{t\in T} x_{tp} \qquad \forall p \qquad (5)$$

$$n_j \geq 0, \qquad x_{tp} \in \{0,1\} \qquad \forall j,t,p \qquad (6)$$

The objective is to minimize the total production cost (3), composed of the purchase price of the machines that are not readily available in the current resource pool, the personnel costs, and the operation costs. Constraint (4) specifies the required number of machines from each type in each shift, while equality (5) states that every customer order must be fulfilled. Constraints (6) define the variable domains, and require that at most one reconfigurable line should produce the same product in the same shift.

The resulting production plan specifies the set of machines to be purchased and the system configuration in each shift. The above model, however, ignores the cost and time of reconfiguration, and leads to a plan in which the sequence of the shifts can be changed arbitrarily. In order to minimize the number of reconfigurations, a sequencing problem is solved that re-orders the shifts, but leaves the system configuration unchanged within each shift. This can be represented as a symmetric Travelling Salesman Problem (TSP), in which the vertices are the shifts, while the cost of an edge is the number of different lines between the configurations in the two corresponding shifts.

4. Experimental results

The proposed capacity management and production planning method was tested on an industry-related dataset, considering historical order and forecast volumes, as well as real production lines. The product portfolio consists of 67 products with diverse order volumes and assembly processes. The training dataset for the regression contained 80 production planning problem instances, generated by assigning a random production volume to each product. The multivariate regression was computed using the *R* environment, by applying its general linear regression function, which took ca. 2 seconds [18]. This provided an appropriately precise prediction of the production cost in the reconfigurable system, with a coefficient of determination of R^2=0,987, as shown in Fig. 3.

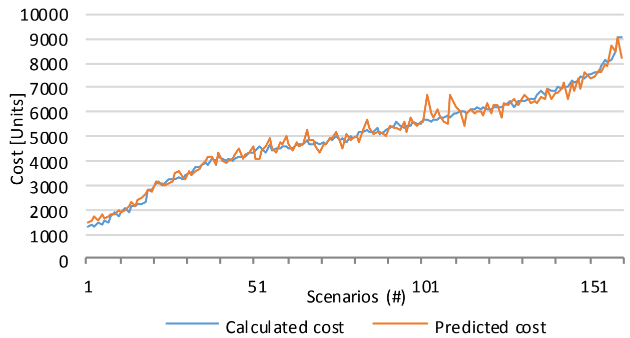

Fig. 3. Comparison of the production costs predicted by multivariate linear regression and calculated by production planning (scenarios are ordered by increasing total order volume)

The line assignment problem was solved iteratively using a rolling horizon scheme, with a fixed horizon of 3 months in each iteration. In order to evaluate the efficiency of the method, a reference solution is considered in which all products are assembled on dedicated lines. The results show that applying reconfigurable lines and the proposed planning method results in significant cost savings even in case of fluctuating order streams. It is typical that savings are higher (up to 30%) in periods with lower production volumes, whereas they are lower (10-15%) around peak production volumes (Fig. 4.).

Since most products in the industrial data set were in the *maturity* stage of their life cycle, their production volumes typically decreased over the four-year horizon. Accordingly, the number of products assembled in the dedicated system slightly decreased, whereas the number of products in the reconfigurable system and products outsourced increased over time (Fig. 5).

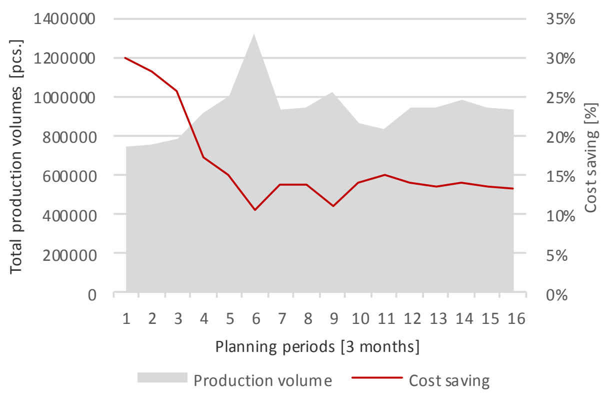

Fig. 4. Results of line assignment: cost savings and production volume over a four-year horizon

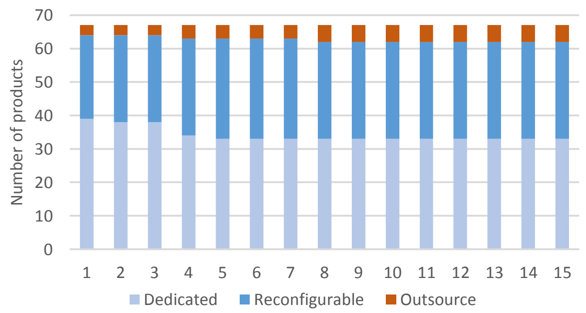

Fig. 5. Results of line assignment: number of products assembled using the three production modes over a four-year horizon

The production planning model was run on the products assigned to the reconfigurable system. The proposed MIP model was solved using *FICO Xpress* and its default branch and bound method. The search was run until an optimality gap of at most 4% was achieved, which required 116 seconds on average. The subsequent sequencing problem was solved using the open-source solver *LKH* [19], which implements the Lin-Kernighan heuristic [20]. Solving the problem using the default randomized restart strategy with 10 runs required 59 seconds altogether. Sequencing reduced the number of reconfigurations by 51%, resulting in a significantly smoother production plan, as depicted by Fig. 6.

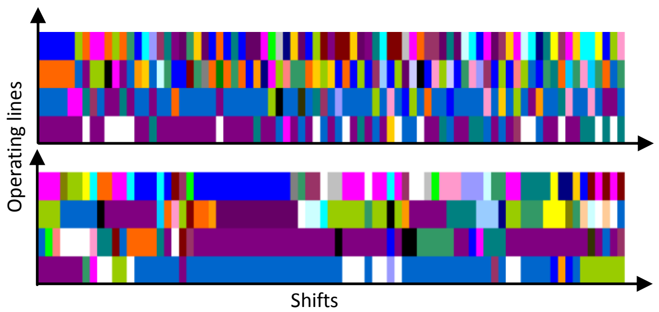

Fig. 6. Part of the production plan before (above) and after (below) performing the sequencing: each product is identified by a unique colour

5. Conclusions

Both dedicated and reconfigurable assembly lines can show up benefits and drawbacks, consequently, their co-existence in industrial practice is natural and frequent. In the paper, a novel approach for capacity management for assembly system with dedicated and reconfigurable assembly lines was presented that facilitates the economical production of a diverse, varying product portfolio consisting of high- and low- volume products. 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. The applicability of the proposed method was demonstrated by results of experiments, using industrial data. Further research and development activities will include the refinement of the underlying models in the course of further industrial applications.

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