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Dynamic optimization of manufacturing systems in automotive industries

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ABSTRACT

The automotive industry faces major challenges due to volatile markets and expenses for new technologies. The dynamics of markets and future technological variety demand flexibility. A sustainable transformation strategy is indispensable for upcoming decades. The following paper presents an approach supporting both, tactical as well as strategic decision-making in volatile manufacturing environments. At first, operating costs and performance figures of manufacturing systems are calculated. In step two, a Markovian Decision Process is solved to find a cost minimal policy over planning horizons. The optimization of the manufacturing system is based on capacity adaptations and changes in process steps, suppliers, and locations.

1. Introduction

In today's economic environment, companies are facing complex challenges caused by volatile markets, individualized products, short life cycles, and global competition [1]. Economic interactions, influencing factors and economic parameters are becoming more global and thereby also more complex, while global interdependence also proves to be stabilizing in cases of crises that are locally limited. The automotive industry can be seen as a perfect example for a global and turbulent industry. Within one year, the industry had to manage a decline of over 40% followed by an increase of over 50%, each compared to the year before (compare Fig. 1).

Besides the strong impact of the recent economic and financial crisis, the automotive industry is also facing massive structural changes due to new technologies such as electric powered vehicles. Over the next years, the variety will increase even further. As a result, the complexity in both, development and production will be one of the main challenges over the next years. New forms of cooperation, for example joint ventures, are indicators for the present and ongoing dynamic. Through the long-term ramp-up of new technologies, a probably very volatile market demand and the need to produce conventional cars in parallel a new production planning method is needed. Besides the complex variants, new technologies and processes, companies will face the problem of a lower quantity of conventional engines and cars one day. The concept of the so-called multi-use plant offers the possibility to produce and to assemble cars with combustion and electric powertrains within one plant in an efficient way. An adequate planning method has to identify possible technical and organizational measures and the optimal time for changing between them. The possible changes in the supply chain should be taken into account by expanding the point of view and considering effects in the production network by using an integrated method.

Consequently, there is an obvious need for dynamic production planning as well as production optimization methods. These methods have to incorporate all kinds of uncertainties, especially market uncertainties but also include concrete recommendations for production planners. Above all, the scope must allow capacity changes. A production system with all its factories, external suppliers and outsourced process steps can be seen as part of one global value-generating network. With that in mind, any such method should be able to incorporate these adjustments to the network, e.g. outsourcing or offshoring.

Although literature offers various different approaches of capacity planning, there is still a gap between the strategic approaches of network planning and the approaches of factory planning on a material-flow and process level: Most of the approaches dealing with decision making in production planning found in current literature do not combine mathematical optimization methods with industrial planning problems of realistic sizes and complexity. Moreover the approaches focus either on problems within single locations and plants or manage whole networks from a strategic point of view [3]. A detailed research with regard to an analytical assessment and an

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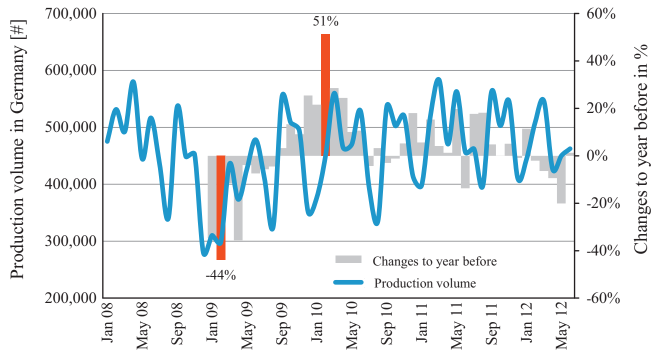

Fig. 1. Versatility of German car production during the last years [2].

optimization approach for manufacturing systems, e.g. material flow planning [4,5], on the one hand, combined with the research of global value networks [6,7] on the other hand in an integrated approach, promise new results and a deeper understanding [8]. As an additional need for research the integration of production specific key figures and its effects on conventional mathematical optimization methods can be seen. Moreover the possibilities enabled through additional degrees of freedom given by the supply chain management must be integrated in production planning approaches [9]. Below the scientific background of such an integrated methodology is presented. Table 1 gives an overview of the main symbols used in this paper.

2. Approach

2.1. Used symbols

2.1.1. Preparation

For reaching the above-defined target of an integrated methodology of dynamic optimization, however, a basic structure for the definition of the globally distributed manufacturing system and its underlying cost assessment model are needed. So the very first step is to deduce the required process steps in a production priority chart. Based on specifications and restrictions of the product development for each process step several alternatives can be defined. At each point in time the manufacturing system has a well-defined configuration based on the current selection of each process alternative. Within this approach a process step and its alternatives are seen as tuples of the used machine equipment and the required employees. For a later assessment, key figures for these tuples are defined such as costs of machines, staff, buffers, materials, maintenance services and production losses. Energy consumption and energy costs can be taken into account by using environmental evaluation procedures such as the ones described in ISO 14955-2, a standard which is currently under development [10]. Afterwards a dynamic, stochastic optimization method is applied in order to be able to respond to changed market conditions in an optimal way at discrete points in time during the life cycle of the system. These reactions can be capacity adjustments (e.g. in the shift model) or changes of currently used process alternatives, so called changes of configuration. Fig. 2 illustrates a manufacturing model, where process steps 2 and 4 come along with different alternatives (see bubbles in the background). The split of the material flow after process 1 illustrates the handling of different routes of different products or variants through the manufacturing system. Process 6 is placed at an external material supplier which is linked by a transport process. Process 10 and 11 are transport processes to other plants and markets while process 12 is a virtual source to fulfill the necessity of one final node in the algorithm.

2.2. The underlying cost model

How to deal with uncertainties plays a decisive role when considering the costs of manufacturing systems. Firstly uncertainties of manufacturing systems caused by the stochastic behavior of machines, plants and staff (fluctuating quality, availability and performance) have to be defined. Secondly uncertainties in planning have to be handled. They are caused by vague or estimated or empirical values during the planning process, particularly at early stages. Finally environmental impacts such as dynamic markets create uncertainty.

Whereas uncertainties in planning can be considered easily by repeated application of the method on various input parameters, for example by the help of Monte Carlo approaches, and surrounding uncertainties are treated by the below described optimization approach, uncertainties of the manufacturing system itself need to be considered in an integrated way. In the context of this method, uncertainties of manufacturing systems are projected on variations of the three vital characteristics: performance (P), quality (Q) and availability (A). While the performance level varies stochastically between single workpieces because of the operating behavior of machines and employees, in the industrial practice the level of quality is conceived as the quotient of good parts divided by the total of all workpieces. Thus, the level of quality is an aggregate quantity comprising several workpieces of one shift or one day. On the basis of time allowances for the single product specific processing times it is easy to calculate personnel and machine costs taking into account quality (Q) and performance (P). Furthermore availability varies over longer periods of time, for example from shift to shift or from day to day. Within the presented methodology performance has a stochastic behavior while the levels of quality and availability are supposed to be deterministic. However, machine failures result in a mean loss of workpieces and expenses for repair and deployment of maintenance personnel. Losses in parts adjusted by buffers and stocks are forwarded by using a recursive term as shown in Eq. (1), where the number of lost parts L_{kj} in process j is caused by a failure in process k. V_j is the index set of all direct predecessors of j. AZ_j stands for the mean time to repair of j, $t_{V,j}$ for the mean process time of all products in j and p_i for the buffer size, while $N_{W,j}$ represents the mean length of arising queues in front of process j. Moreover q_{ij} defines the split ratio of the material flow between process i and j.

$$L_{k,j} = \begin{cases} \dfrac{AZ_j}{t_{V,j}} & \text{if} \quad j = k \\ \sum_{i \in V_j} \left(L_{k,i} - \dfrac{1}{2}\, p_i \right) \cdot q_{ij} - N_{W,j} & \text{if} \quad j \neq k \end{cases} \qquad (1)$$

Since the methodology aims at analyzing the costs over longer periods of time such as quarters, years or whole life cycles, the calculation with the mean value does not lead to a critical distortion of the results at that point. In contrast, the performance level is considered as a normally distributed random variable because the performance level has an impact on the queues which are changing due to the variations from workpiece to workpiece between the single processes. Thus, the assessment approach for the configurations of the manufacturing system consists mainly of an analytic queueing theory model which approximates arising stocks in the form of waiting queues caused by product specific times and routes. Kendall's terminology [11] describes the discussed manufacturing system as an open G|G|m network of service systems which is calculated by means of approximations such as the approximation according to Krämer and Langenbach-Belz [12] on the basis of the Queueing Network Analyzer [13]. The workpieces within the manufacturing system represent the clients within the service system which leave single process steps (server) after a fluctuating