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Product Generation Module: Automated Production Planning for optimized workload and increased efficiency in Matrix Production Systems

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Abstract

Ever increasing demand for individualized and customized products induce the need for high variability in production and manufacturing through Mass Customisation. Mass Customisation requires more flexibility and adaptability capabilities in production systems. Matrix Production is a tact free job-shop like production system enabling variable production routing through a matrix shaped layout of partially redundant machines. Hence, it is one way to increase a production system's flexibility and adaptability. A more powerful production control system comes hand in hand with the evolution towards a tact free Matrix Production System. However, the additional degree of freedom due to the flexibility not only touches production control, but also production planning, thus enabling the production of portfolio external products.

Implementation of a Product Generation Module optimizes the workload of Matrix Production Systems to increase their efficiency by assessing the suitability of co-production of portfolio external products. Generation of suitable production orders increase machine utilization without impeding the original multi-dimensional production goals. Thus, reaching new production strategies that include the creation of value through effective manipulation of minor products and byproducts. The flexibility of Matrix Production Systems acts as the Product Generation Modules enabler, insofar as flexibility is the ability of a system to perform within an acceptable production corridor without layout and planning adjustments. This can be enhanced by making use of the Matrix Production Systems adaptability to increase the set of portfolio external products through layout and planning adjustments. Hence, this strategy leads to a continuous automated planning phase and additional revenue due to the additional manufacture of minor products within a Matrix Production System. Doing so allows the Matrix Production System to react towards external demand related and internal capacity related events without sacrificing precious value creation opportunities.

Keywords: Smart Factory; Industry 4.0; Matrix Production; Production Planning and Control; Mass Customisation; Manufacturing-as-a-Service

1. Introduction

Manufacturing faces a growing number of requirements amplifying the tension for companies to adapt to customer demand and increase efficiency by evolving towards Smart Manufacturing. In addition to increasing cost pressure due to fierce global competition, they are confronted with an increasing demand for individualized and personalized products [1]. The introduction of new materials and technologies is accompanied by a continuously increasing number of variants due to new functions, properties and heterogeneous regional demands [4]. As a result of rapidly developing technologies, manufacturing companies must also find answers to ever shortening product life cycles [16]. For companies, this leads to constant adjustments of existing production systems [10]. Thus, they have to reconcile broad flexibility to fulfill customer demand with the tight budgets from mass production leading to (Flexible) Mass Customisation [2]. Additional requirements that influence manufacturers come in the form of external regulations. These result from current challenges and restrain, for example, the excessive use of natural resources to protect the environment [10, 17].

In order to ensure economic production under such averse conditions there are various approaches to develop production systems meeting these demands [5, 10, 15]. The core of these approaches is reflected in dealing with the two aspects flexibility and adaptability [5].

The concept of a takt-time-independent job shop like production system, called Matrix Production System, is a very promising approach to fulfill the mentioned requirements by maximizing a system's flexibility and adaptability. Due to a

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free material flow, the application of automated guided vehicles (AGV) and a matrix shaped layout of partially redundant machines, adjusting the system depending average cycle time is enabled. Thus, limitations of common production systems can be overcome [6].

The aim of this paper is to introduce the Product Generation Module (PGM) and thus the principle of assessing the suitability of co-production of portfolio external products to optimize a Matrix Production Systems workload and efficiency. These enhancements can be achieved in existing as well as in planned Matrix Production Systems through the application of the PGM.

Therefore, the concept of Matrix Production Systems is outlined in Section 2. It is followed by the introduction of co-production of portfolio external products in Section 3 and the elucidation of the PGM in Section 4. Based on the PGM, an exemplary use case is presented and the PGM as well as the principle are validated by a simulation in Section 5. Finally, a discussion and outlook concludes this paper in Section 6 and 7.

2. Matrix Production Systems

The objective of the concept of Matrix Production Systems is to ensure scalability, universality (regarding different variants) and strategical and customer-oriented flexibility. However, in wake of Flexible Mass Customisation, the system allows high quantity production. Therefore, a matrix shaped layout of partially redundant work cells, based on the flow principle, is presented. Some of these work cells are equipped with the possibility to perform different value-adding activities denoted as processes. AGVs provide a decoupled material flow and supply work cells with needed material and tools at the right time (see Figure 1) [6, 15].

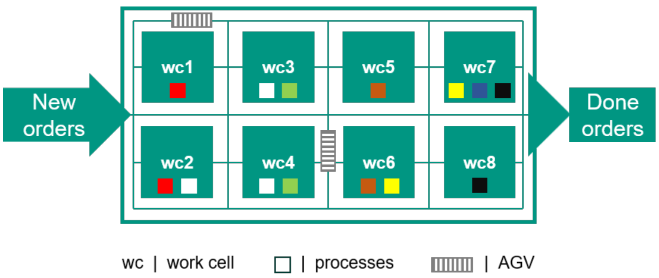

Fig. 1. Exemplary Matrix Production System layout

Due to the ability to run identical value-adding activities in different work cells within the system, individual products can be manufactured in many different ways. Furthermore, in contrast to common production systems, every single work cell has a flexible and unique cycle time. Instead of fixed takt times depending on the longest cycling time, as usual in flow lines, in Matrix Production Systems an average system cycling time can be adjusted as shown by Schonemann [15] and Greschke [7]. Hence, Matrix Production Systems are known to implement tact-free manufacturing.

The application of Matrix Production Systems is characterized by a plentitude of advantages, however the majority of these is yet not obvious or realized. They are usually founded on the flexible flow of materials, the ability to perform value-adding activities on different locations and work cells within the system enabling the tact-free production characteristics [13]. Some additional conceivable advantages include:

- Possibility to rapidly respond to volatile customer demands by adapting the number and layout of existing work cells [6].
- Simplification of new product or variant integration and ramp-up within the system compared to common production lines [8].
- In case of breakdowns, relevant particular work cells can be ignored during repair [6].
- Because of their universality and adaptability the Matrix Production System is nearly product life cycle independent [7].
- Flexible material flow enables flexible remanufacturing activities within a regular manufacturing environment.

Besides the most critical disadvantage of Matrix Production Systems, comparatively high investments, it is worth noting, that in those production systems fully utilized work cells are still not realizable. Normally, down-times, breakdowns or low workloads may occur during production. Even if full utilization was theoretically reachable, it would not be economically viable due to enormous equipment costs for value-adding machines within planned or existing work cells and does not cope with unpredictable disturbances. Even perfectly balanced production systems typically include unused capacity [11]. Thinking about a maximum equipped, maximum flexible and adaptable Matrix Production System with n work cells will lead to a production system which is in theory equal to n identical flow production lines. Thus, the equipment and planning of Matrix Production Systems has to be reasonable and appropriate in relation to manufactured products and variants to ensure economical operations [9].

3. Principle of co-production of portfolio external products

In order to optimize the workload and to increase machine utilization of planned and existing Matrix Production Systems without impeding the original multi-dimensional production goals, in respect to the original main products, the co-production of portfolio external products, called minor products, enables the manufacturing firm to make use of unused machine utilization under certain circumstances.

Due to variable production routes, universal machinery and partially redundant machines within the work cells, Matrix Production Systems facilitate the production of portfolio external products. In fact, a Matrix Production System is capable to produce every type of product and variant which could be produced by one or more of the available or planned manufacturing processes. Thus, for the introduced principle single manufacturing

processes shift into focus instead of complete machines or work cells. For instance an exemplary production environment contains universal machinery that enables processes like welding, milling or painting and can be equipped with various tools, a variety of different products is conceivable.
To optimize Matrix Production Systems in regard to utilization and workload and thereby improving the system's economics, idle times of each process has to be identified and used for the most sensible co-production of portfolio external products or variants of existing ones. Considering high idle time processes at the available machines, it could be profitable to upgrade the product portfolio with value-adding activities like certain coloring under certain circumstances.

3.1. Co-production exploitation

The above exemplified principle can be exploited to further applications. It is conceivable that nearly every manufacturing system with unused production capacities can be optimized by the principle of co-production of portfolio external products. For instance any form of job shop like production, dynamically interconnected assemblies [8] or other modular manufacturing systems can potentially be optimized. It does not matter whether a production system has been running, is about to start ramp-up or is still in a planning phase, the principle of co-production of minor products can be applied. Beyond extending the product portfolio, supplier parts could be substituted.

3.2. Co-production hazards

Even though the principle of co-production of portfolio external products contains great potential for optimization of production systems, its application entails several threats. First, due to its complexity the application can endanger acceptable production control. Especially the control of very dynamic production systems and the corresponding production routing can be challenging [3]. Second, shifting the focus from main products can decrease quality and quantity. Albeit the production of minor products being promising, the purpose of the manufacturing system should still remain at producing the main products. Beyond the mentioned aspects, an application of the principle can entail changing new business models for manufacturers.

4. The Product Generation Module

The Product Generation Module (PGM) represents a procedure for an efficient implementation of the introduced principle in Section 3. It is based on an optimized existing or planned Matrix Production System (also regarding the production control) and entails five phases (see Figure 2). The introduction of portfolio external products to the shop-floor is subject to ensuring the most effective operation of the core business.

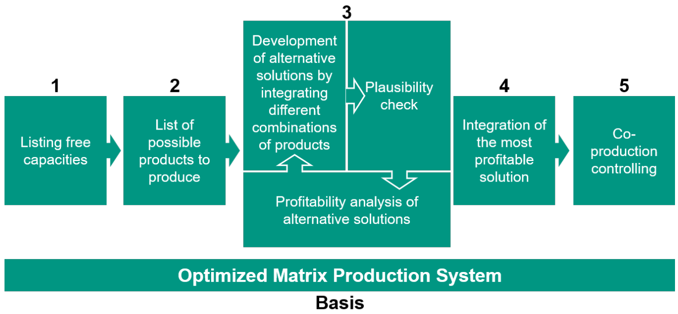

Fig. 2. The Product Generation Module

4.1. Product Generation Module phases

Given a Matrix Production System that is optimized for the main product, the PGM first of all proposes to list free capacities of manufacturing processes, AGVs, tools and human employees. For the following phases it is important to assign the identified unused capacity to specific processes.
The second PGM phase identifies products or variants of existing products which could be produced by using the detected free capacities of phase 1. By considering the existing product portfolio of the regarded Matrix Production System the number of new valuable variants that could be created with the listed free capacities has to be determined. With a systematic search also portfolio external products should be screened to assess the suitability of producing those in times of unused process idle times. This identification has to be in line with the firm's strategic product portfolio.
Once possible products and variants are collected, an iterative procedure takes place in phase 3. At first alternative solutions have to be developed by integrating different combinations of possible products or variants out of phase 2. This alternative solutions have to be checked for plausibility and profitability. In order to verify the feasibility of individual solutions and identify the most profitable one, the application of accurate productions system simulations is reasonable.
The selection and implementation of very efficient Matrix Production System operations constitutes to phase 4. To ensure the efficiency of the chosen solution and to track its performance, a co-production controlling phase (phase 5) completes the application of the PGM and ensures smooth operations during the co-production. Thus, a new base case for the PGM is established. It comprises the original optimized Matrix Production Systems for the main products however its efficiency is improved by a smart extension with product portfolio external products or alternatively different main product variants.

4.2. Automated application of the PGM

Owing to the flexibility required to produce individualized products in mass production quantity, continuous application of the PGM is necessary. Every anomaly, such as disturbances, quantity, product portfolio or system changes can require a reassessment. To efficiently make use of the PGM an automated application is suggested. In order to run an automated application of the PGM, an autonomous production system has to be established. Autonomous production systems can simplify the application of smart methods [14], in particular intelligent production control systems, optimally in combination with a Digital Twin [12]. As a consequence, the Matrix Production System can immediately be responsive to upcoming changes such as shifting demands, missing parts or machine breakdowns. Thus, a continuous optimized production system is achievable. To facilitate this, possible variants or portfolio external products and connected information needs to be provided to the system, as shown in phase 2 in Figure 4.

5. Case Study for validating the introduced principle and the PGM

In order to clarify the above presented PGM and, by association, the principle of co-production of portfolio external products, an exemplary case study is given in this section.
The regarded system, a Matrix Production System with a 2x4 layout and thus 8 work cells is capable of producing one main product. For each main product, the average process time required is 24 time units. To ensure the delivery of material and tools for the work cells at the right time, two AGVs are located in the system. The production control is based on the first-in-first-out (FIFO) priority rule to operate the Matrix Production System. By applying the PGM presented above, theoretical 15% free capacity are identified, due to a workload of the work cells of about 85% on average. Given the lower transport utilization of about 75%, the system provides enough leeway to introduce minor products. To completely conduct the first phase of the PGM unused times of each work cell associated with corresponding processes are listed. As a result of the identified free capacities different portfolio external products are regarded to asses their suitability for co-production.

Based on phase 2, minor products with 1/3 and 1/6 of the main products process time are identified. Additionally, an extension with a more complex main product variant requiring 35 time units is feasible. In order to identify the most viable solution, a simulation is set up.

5.1. Simulation for validating the co-production controlling and the PGM in general

For controlling the mentioned co-production in this case study and for validating the introduced principle and the PGM in general a discrete-event simulation for Matrix Production Systems, written in Python, was used. As performance indicators time units and the number of produced products within every single simulation run are measured, in addition to work cell workload and AGV utilization. In order to perform the validation of the described principle it is important to ensure its operational reliability in different system configurations. Thus, the simulation is easy to adjust the number of work cells, the number of AGVs, the number of main or portfolio products, the number of minor products, process times and the release policy for minor products.

5.2. Simulative confirmation of the principle of co-production of portfolio external products

Starting from the basic case study configuration with a 2x4 layout of work cells, two AGVs and one main product with an average time of 24 time units the principle is simulated with various configurations (see Figure 3). As a decision rule for operating new products the first-in-first-out-rule is implemented. A minor product is released by priority rule, when waiting queues in front of work cells are below a given threshold. If two different minor products are considered, it is randomly decided which one will be produced.

First of all the general applicability of the co-production principle with the basic configuration is validated, which is equal to the comparison of the original design of the case study with the integration of the presented first solution. As mentioned above, the workload of the work cells and AGVs considering the original design of the case studies Matrix Production System in general is approximately 85% respectively 75% (see Figure 3). By ceteris paribus inclusion of one minor product with an average process time of 1/6 of the main product, the performance indicators increase significantly. Thereafter the workload of the work cells and AGVs increases about 2% respectively 9,5%, yielding about 5,000 additionally produced minor products, without sacrificing efficiency in respect to the main product. Even more interesting is the fact, that in less time nearly the same amount of main products is produced.
Further improvements of the case study's manufacturing system can be achieved by integrating further identified solutions. By additionally producing a second portfolio external product with an average time of 1/3 of the main product's average time, the performance indicators are increasing alike. Thus, the best configuration of the case study's Matrix Production System concerning the work cell workload can be achieved by introducing two different minor products instead of fewer (see Figure 3). However, a final decision can only be realized when comparing the monetary benefit of co-producing minor products.
Thus, as suggested before, under several circumstances the ceteris paribus integration of minor products is a feasible extension without compromising on the production speed of main products. This reveals, that the introduced principle of co-production of portfolio external products (see Section 3) can lead to higher utilization and workload in Matrix Production Systems of various sizes. Furthermore this effect is valid for co-production of several minor products and for co-producing minor products when producing various main products (see Figure 3).

5.3. Robustness of the Case Study

For testing the robustness of the case studies solution and, by association, the robustness of the principle of co-production of portfolio external products and the PGM, modified configurations of the simulation are tested (see Figure 3).

				variation of:									
		General configur.		*Number work cells*		*Number AGVs*		*Process times*		*Numb. main prod.*		*Numb. minor prod.*	
Variables	*Layout structure*	2x4	2x4	3x4	3x4	2x4	2x4	2x4	2x4	2x4	2x4	2x4	2x4
	Number work cells	8	8	12	12	8	8	8	8	8	8	8	8
	Number AGVs	2	2	2	2	3	3	2	2	2	2	2	2
	Avg. process time main prod.	24	24	24	24	24	24	35	35	24;35	24;35	24	24
	Avg. process time minor prod.	n/a	4	n/a	4	n/a	4	n/a	5	n/a	4	n/a	4;8
KPIs	*Output main products*	9.997	9.974	9.997	9.968	9.997	9.974	9.997	9.974	9.997	9.974	9.997	9.968
	Output minor products	0	5.031	0	5.537	0	5.031	0	10.914	0	9.414	0	2.769; 2509
	Simulation time [time units]	71.033	70.187	45.509	45.579	67.361	69.809	97.000	98.408	84.452	85.007	71.033	71.969
	Workload work cells	84.50%	**88,63%**	87,58%	**91,58%**	87,63%	**95,63%**	87,75%	**94,50%**	87,50%	**91,13%**	84.50%	**89,13%**
	Workload AGVs	74,50%	**84,00%**	77,25%	**86,50%**	49,33%	**63,33%**	52,50%	**65,00%**	61,50%	**73,00%**	74,50%	**83,00%**

concerning co-production of minor products

Fig. 3. Results to confirm the principle of co-production of portfolio external products

In case of volatile demand it might be reasonable to enlarge or to reduce the systems number of work cells or to adjust the number of AGVs to improve logistics flexibility. As shown in Figure 3, similar results compared to the original case study configuration can be achieved. Thus, the co-production effect can be utilized for different matrix layouts (varying number of work cells) and varying number of AGVs.
Due to product adaptions the average process time of the main product can vary. Moreover, the average process time of the minor product may differ from 1/6 of the main products average time because of adaptions. As shown in Figure 3, the principle of co-production of minor products even is valid in cases of differing average process times of main or minor products (for example 1/7 of the main products average time).
All in all, for a variety of changing parameters within the regarded Matrix Production System the introduction of minor products does no harm in co-production with main products. Thus, the PGM can enable more profitable Flexible Mass Customisation based on a Matrix Production System.

5.4. Further simulation observations

Regarding the simulation results in Figure 3 larger Matrix Production Systems perform better. In this particular case a larger number of work cells in combination with a different layout structure leads to a better main product/time ratio, neglecting the benefits of production of minor products. In the original case eight work cells are producing one main product in about 7.11 time units. By adding four cells, one main product can be manufactured in about 4.55 time units. Hence, in case of 12 work cells one cell is able to produce a main product during an average time of less than 55 time units (4,55 time units · 12), albeit production of a main product with one cell in the origin configuration takes nearly 57 time units in average.
Furthermore, a ceteris paribus increase in the number of AGVs (three instead of two), considering the presented simulation and neglecting the manufacturing of minor products, likewise leads to a better main product/time ratio. Hence, the optimal number of AGVs is another important factor in Matrix Production System design.
Analyzing the available results of this specific simulation, under certain circumstances even more main products/time can be produced by permitting the co-production of minor products, such as the comparison between general confirmation with and without minor products production in Figure 3. Thus, depending on the respective production control, the consideration of co-products may lead to a more efficient usage of the production system even concerning just main products.

6. Discussion

As shown in Section 1 and 2 the concept of Matrix Production Systems is providing new opportunities concerning the two aspects flexibility and adaptability to adequately meet today's manufacturers' requirements. Since underutilized entities like work cells or AGVs still appear (see Section 3 and 5), a potential for improvement is available in those systems. Due to Matrix Production Systems additional degree of freedom, free capacities of manufacturing processes can be used effectively. As pointed out in Section 3 and shown with the PGM in Section 4, Matrix Production Systems efficiency in general can be optimized by the co-production of portfolio external products without affecting or impeding the production of main products or introducing additional resources. Thus, the disadvantage of high investments for Matrix Production Systems can be relativized by co-production boosted turnover. In Section 5, a validation of this principle and the PGM by means of a simulation is given. To efficiently make use of these findings the PGM, consisting of five consecutive phases, is introduced. However, both the selection and release of minor products is not yet formally regarded and an adapted production control can increase the ability to efficiently run the Matrix Production System.

7. Outlook

Intensifying research on control policies for production control and release policies for minor products can prove beneficial in improving co-production. Furthermore, exact studies on the influences of varying Matrix Production System parameters, in particular changeover times, are necessary to facilitate real-world applications. In addition, detailed cost-benefit models which, for instance considering investment costs, real portfolios or concrete product prices, can prove insightful. Yet, beyond practical benefits, changes in business models that come hand in hand with substituting suppliers through co-production or introducing portfolio external products need to be addressed. In case of a development towards sophisticated Manufacturing-as-a-Service, the PGM serves as an advantageous enabler. However, despite the much smaller degree of freedom in respect to potential products and much lower potential of tapping into unused work cell workload capacities, further examining the co-production principle and its applicability to further production systems is promising. Doing so can be extended in simulative studies on the intelligent management of product portfolios in similarly structured production environments, such as production networks.

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