Investigation of Material Supply Strategies to Increase Resilience in Matrix Production Systems

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Abstract

In order to design a resilient production system, individual system elements have to be flexible and adapt towards changing requirements. In contrast to the prevailing paradigm that complexity in production systems is reduced by standardisation or cycle production, complexity in resilient production systems offers great potential in terms of adaptiveness, robustness and anticipation. Within production control, matrix production is seen as a resilient and versatile system. Flexible routing between workstations makes it possible to compensate for failures more quickly in the event of a malfunction, flexible logistics and control processes allow the workstations to be controlled and used in a job-specific manner. In this paper, challenges and operating principles of material supply strategies are investigated that have the biggest influence on the design of resilient processes in matrix production. Using a simulation model and scenarios from the automotive sector, the potentials, requirements and parameters for describing resilience are specified.

Keywords: Matrix production systems, resilience, flexibility, material supply strategies, simulation

1. Necessity to Design Resilient Processes in Companies

Abrupt changes are nothing unusal to adapt to for many companies. On the one hand, in the course of the digital transformation, new technology and system solutions are entering the companies, which have an impact on the cost structure as well as the process design. On the other hand, profound changes occur due to environmental factors (crises of all kinds, market and customer changes), which come along with new challenges in terms of maintaining the company's ability to operate (Kagermann et al., 2021). Companies are looking for configuration opportunities to increase their resilience in order to be able to quickly react to unforeseen external influences and to be strong enough to deal with sudden upheavals in the market and the environment. The understanding of resilience in this context is based on the ability of a company to maintain its stability despite external influences, to return to its initial state or to adopt a new state of equilibrium (Günther, 2018). The objective in context of resilient value creation systems is therefore to build versatile production systems, sovereign network and agile process structures (Kohl et al., 2021).

The *digital transformation* (especially Industry 4.0) plays a decisive role due to the increasing impact of digitalization, networking and automation on the industrial production environment (Vogel-Heuser et al., 2017). Key technologies such as the Internet of Things (IoT) or artificial intelligence (AI) transform the creation of value into flexible, agile and globally cross-linked value creating systems (Plattform Industrie 4.0, 2022a). Such a cross-linked system includes all production resources (machines, equipment, ICT systems) as well as the human factor (via technical means or assistance systems). In the interplay with digitalisation and the automation of sensor-based production resources, it is possible to build a real-time capable and self-organising value creation system. In the event of a crisis (regardless of whether it is an internal or external disruptive factor), a properly implemented resilience aims at the flexible, robust and anticipatory redesign of corporate structures, or even entire value creation networks. This is where questions must be answered in terms of which callenges and needs can be implemented to support resilience and value creation in companies when introducing new strategies. The following organisational and technological characteristics, that need to be shaped in the course of digitalisation, come into play to design resilient production and logistics systems: Adaptiveness, robustness, anticipation and regenerative capacity (Figure 1) (Kohl et al., 2021). These kinds of system characteristics and the willingness to change are a prerequisite for securing the economic success and survival of the company in the long run.

URI: https://hdl.handle.net/10125/102812
978-0-9981331-6-4

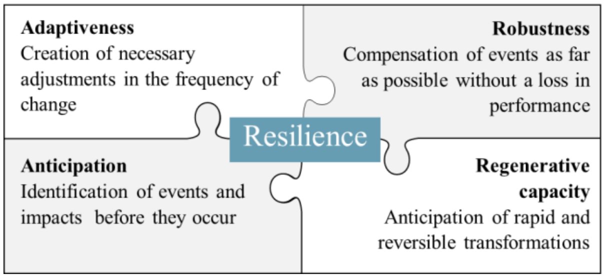

Figure 1. Characteristics for the design of resilient production systems

2. Matrix Production Systems - New Requirements on Production and Logistics

The focus on versatile production concepts is becoming more important in order to meet the dynamic requirements of industrial production and increased market requirements. The realization of a decentral controlled supply usually takes place through several cyber-physical system instances that are represented by autonomous software agents (Bayhan et al., 2020; Popp & Wehking, 2016).

The focus of this paper lies on the modular matrix production system, which realizes an adaptive production as a flexible network of production factors within companies. In terms of spatial structure, this resembles a matrix structure and consists of freely approachable as well as logistically and individually plannable production cells. These cells are connected to one another via a flexible material flow (Plattform Industrie 4.0, 2022b). Those design options predict value creation when situations, such as fluctuations in the number of units, machine downtimes (e.g. due to broken tools or power outages), the increasing diversity of product variants and changing challenges likesupply chain interruptions, have to be mastered.

In essence, matrix production is a production system that allows for small-scale scaling and flexible use of a common production structure by different product variants (Greschke, 2016). An infrastructure is created that is directed towards processes and capacity requirements instead of cycle times and predefined flow charts. Compared to other forms of production organisation (job-shop, flow production) (Schenk et al., 2010), matrix production is suitable for high product variety and a volatile environment. At the same time it is necessary to implement an intelligent order control, which can handle the sum of individual decisions at the control and management level. In the context of digitalisation, matrix production is an alternative solution that combines the advantages of flow production with those of job-shop production (maximum flexibility while maintaining economic efficiency) (Greschke, 2016). Characteristic of these systems are a modular structure, flexible control circles and a high level of information technology networking. In the context of the ICT infrastructure (network infrastructure and IT systems involved), the infrastructure for planning and controlling orders as well as the connection and networking of the individual production cells and units is of major importance (Platform Industrie 4.0, 2022b). Transport processes (of products and materials) are mostly automated in order to realize a material flow as flexible as possible. AGVs (automated guided vehicles) are used for free navigation and are assigned to the corresponding transport orders via a fleet management system. It is essential that the logic for creating the transport orders is not part of the AGV system itself, but takes place via the order control of the ICT system (Plattorm Industrie 4.0, 2022b).

Figure 2 simplifies, the merging of the organisational paradigms in production.

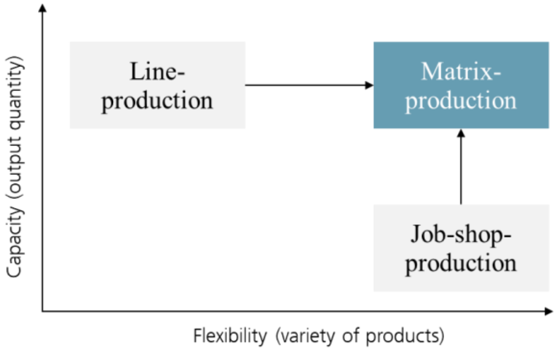

Figure 2. Comparison of production concepts on the basis of production capacity and flexibility

A detailed comparison of the respective forms of production organisation and their advantages and disadvantages can be found in Schmidtke et al. (2021). This paper focuses on assessing the resilience of matrix production systems and the influences of different material supply strategies and requirements for smart order control and logistics processes.

3. State of Research & Research Goal

In scientific discourse and in proto-typical implementation, various forms of matrix production or modular production systems have already been discussed in the form of simulation models or test beds in recent years. The focus often lies on the analysis and evaluation of the performance of the value-added process (machine utilisation, lead time of the products) and the comparison with classic line production in order to be able to demonstrate added value with regards to the flexibility of the system. However, the logistical supply processes of materials and components as well as the organisation of the logistical resources are less focused on within the research work. Plattform Industrie 4.0 (2022b) primarily identifies integration and transfer needs of existing technologies and strategies in order to accelerate the design and operation of cyber-physical matrix production systems (e.g. basic structure, logistics, control processes) in practice. In the context of material supply strategies, it is therefore derived as a central research question which challenges exist when introducing matrix production systems and which characteristics can make the greatest possible contribution to the design of resilient processes in this system structure.

A foundation for the planning and design of modular production systems has already been laid down in Kern (2021) and Stricker el al. (2021) as an organisational form for assembly in the automotive industry. First, the requirements for a modelling language are described and a suitable modelling language is selected. Due to the many degrees of freedom that arise in matrix production, there are many possibilities to compensate for a disruption. However, the complexity of the planning increases exponentially with each solution, which results in losses in system efficiency and solution quality (Stricker et al., 2021). As a solution approach, a Monte Carlo Tree Search-based scheduling algorithm is presented, which adapts itself to the scheduling problem in order to improve solution quality and execution time. Other recent publications deal with the optimisation of matrix-structured production systems in terms of production efficiency or with systematic approaches regarding the analysis and evaluation of matrix production systems. The simulation-based method for analyzing matrix production postulated in Perwitz et al. (2022) proved to be practicable in supporting the transition from line assembly to matrix assembly. Therefore, it was possible to identify the effects of different levels of flexibility in production, thus adding to the picture of simulation-based analysis of matrix production in the literature.

The expertise in Plattform Industrie 4.0 (2022b) summarizes findings on the introduction and operation of cyber-physical matrix production systems and, using maturity models, gives a field of action for the design of structural (e.g. transport system, production cells) and control-focused (e.g. operative PPS, infrastructures) design areas. This paper builds on the findings, in particular from Bauernhansl & Ranke (2020), which focus on the evaluation of logistics and material supply strategies in a modular production system. The strategies of just-in-real-time delivery are placed at the core of the analysis. Thereby, a methodical evaluation of the strategies (just-in-real-time delivery, Kanban, supply basket) for matrix production will be carried out. Theoretical findings are derived; however, these are still subject to further simulation-based analysis. As a result, guidelines for the planning and selection of suitable strategies are presented. While current research continues to focus on the efficiency and performance of matrix production, the target dimension of resilience is of new importance. This is due to the fact that the recent crises had to be overcome largely unprepared by improvised measures and by accepting the loss of delivery capacity as well as the acceptance of production stoppages.

It has been established that sustainable survivability of companies takes place between efficiency and resilience, with the tendency towards resilience predominating. The exclusive pursuit of efficiency makes systems more vulnerable and can trigger subsequent reactions (Lietaer, 2010), whereas the ability to react can be trained and promoted through targeted irritations in routine business and interventions in the value creation system. This in turn strengthens resilience to handle unforeseeable events more quickly and efficiently (Goethe et al., 2013). Automation technology and adaptive processes are considered as the most important, if not the decisive, enabler to ensure resilience (Arlinghaus, 2021).

The establishment of resilience factors in the corporate culture is a path towards new resilient added value systems and business models. The indicators for assessing resilience vary widely and not all indicators can be used for every sector or area. Forms of technical resilience are largely found in the context of critical infrastructures (water, electricity, energy) and effective and coherent crisis and disaster management. In the production environment, the resilient value chain is only addressed to a limited extent, mostly in connection with the topic of risk management (ISO 9001:2015) and at the level of supply chains. The connection between resilience and digitalisation is also barely analyzed with regard to technology-oriented design options in companies. AI-based approaches (Lee et al., 2022) as well as flexible and modular production approaches (May et al., 2021; Tierweiler & Bauernhansl, 2022) are significant development trends and technologies in this context.

4. Model Concept & Use-Case Description

In order to answer the research question, a reference model of matrix production has been derived and simulated. It will allow to successively investigate different material supply strategies with regard to the resilience and performance of the production system. In reflection of Schmidtke et al. (2021), the process sequence as well as the distribution of different product variants within the use case has been adapted and validated in dialogue with experts from the automotive sector. The process model was discussed and edited in two interviews, each interview including members of German automobile manufacturers (from the areas of production and program planning). The conventional processes of final car assembly as well as information about the structure of cars (Klug, 2018; Kropik, 2021; Pischinger & Seiffert, 2016) serve as a starting point. The automotive application domain is particularly suitable because of its underlying properties. The automobile as a product class is characterized by differing product volume per variant that appears suitable as a product for matrix production systems in this context (compared to e.g. household appliances) (Plattform Industrie 4.0, 2022b). Related to the topic of matrix production, the requirements for the design of the production system can also be derived:

- Process setup and the use of technology allow degrees of freedom in process execution and in the course of final assembly, while at the same time also offering the possibility of simulating internal and external incidents (machine failure, delivery failures), so that an ad hoc and flexible selection of workstations can be made.
- Usually, customer order processes in the automotive context are characterized by a high degree of individualisation. The assembly process is therefore based on different variants representing individuality for various products. Special events such as product changes or prioritisations can be mapped.
- The process and cycle times in automotive final assembly are known, and are largely standardized for the same product classes. Consequently, the process times are implemented as realistically as possible and as a comparison with the established organisational forms. In the context of matrix production, process times for different workstations can differ significantly (stroke independence).

4.1. Process Description

The process model, the simulation model is based on, is shown in Figure 3. The processes focus on the assembly of all interior and exterior components including the chassis. After completion of the painting work, the doors are removed from the bodies-in-white first (also referred to as "order" in the following) and passed on to the door assembly second. This process is not considered here, but takes place upstream. The upstream process begins (source) either with the installation of the wiring harness, which is the prerequisite for a large part of all further assembly work, or the marriage of the body-in-white with the chassis (drive, transmission). Afterwards the job can be handled from the outside and from the inside. The front and end modules, as well as the cockpit, are assembled. Furthermore, appropriate additional modules (e.g. additional sensors or further comfort electronics) can be installed. Further stations of the interior (e.g. installation of centre consoles, insulation, ventilation ducts, inner roof lining) or other optional workstations (e.g. the installation of a panoramic sun roof or further connecting lines for electronics) follow. Ahead of completion (sink), seats, tyres and doors are assembled towards the end. Alternatively, additional exterior modules such as a coupling device or a fixed protective undercoating can be built in.

For each workstation, a defined basic module time (minimum process time) and, depending on the additional modules required for the job, further process times (maximum process time) have been derived. This leads to variable process times and stroke independence in the overall system. In addition, more individuality and volatility are achieved with regard to the individual orders in the system.

Different product variants are defined in the model (Table 1): Basic, Performance, Premium. The

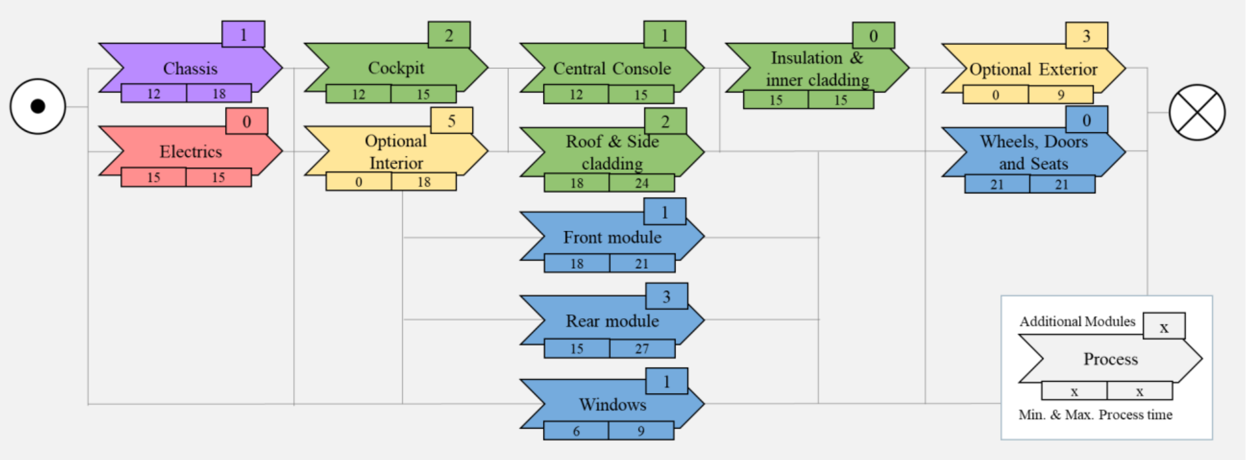

Figure 3. Process model for the matrix-structured production system - Final assembly in automobile production

corresponding process times are fixed (Basic) or distributed in a flexible manner (Performance, Premium). Up to 50 additional process times between a basic variant and a maximum possible premium variant are distributed to additional modules, which can be required stochastically by both Performance and Premium, or only by one of these two variants. The allocation is made on the basis of the respective type and depending on the type of the additional module (obligatory or optional). An order of the type Premium has 11 obligatory additional modules; up to 9 optional modules can be embedded in addition to the obligatory modules. These additional modules each have different process times. Thus, a high degree of individuality of individual orders is given in the model and within the framework of the given possibilities.

Table 1. Product mix and variants

		Basic	Performance		Premium	
			min	max	min	max
Relative frequency of occurrence		30%	40%		30%	
Process Time	Sum of process times	150	159	177	180	201
	Average process time per variant	150	168		190,5	
	Average process time over all variants	173,4				
Additonal Modules	Sum of optional additional modules	0	14		9	
	Sum of mandatory additional modules	3	2		11	

4.2. Model Description

Figure 4 shows the implemented system structure in the form of a matrix production based on the process structure already explained. In this scenario, an ideal-typical Greenfield-planning without specifications for a predefined layout or grid was used.

While a matrix organisation with one workstation per assembly task was realized in Schmidtke et al. (2021), this research paper is building upon the findings and a 4x4 grid with redundant workstations (several stations of the same type) is implemented. Labour-intensive stations (comparatively long process times, many sub-processes) have been placed in duplicate, flexible working stations at the center, and optional working stations rather at the edge of the structure. The coloring is based on the workstation types (e.g. blue = outdoor assembly, green = indoor assembly, yellow = additional modules). Outsourcing and modularisation in final assembly also play an important role here. The modules are manufactured and made available in upstream pre-assembly, the corresponding modules are then installed on the line itself. Each workstation has a process capacity of one order, i.e. one vehicle including a flow object à la AGV, which are linked to each other throughout the entire value creating process. In addition, each station has an input and output buffer in the target station acting as a waiting area for the orders until the next process step. Basically, the product flows (n = number of orders in the system, WIP) and material flows (n = determination of 32 AGVs for material supply) are differentiated in the model. Thereby, the location changes are realized with different operating resources. The material for assembly is stored in a central supermarket, under the assumption there is always sufficient material available. The buffer

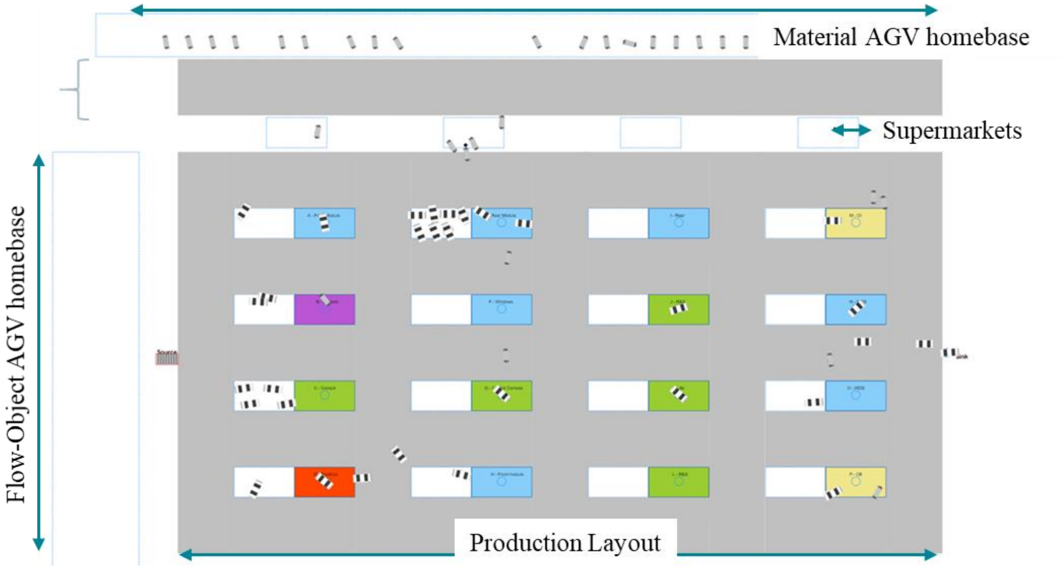

Figure 4. Implemented matrix production system structure (created with “AnyLogic”)

capacity for assembly components (material) is composed of ten units each at the individual stations.

In summary, the following system improvements have been implemented:

- Adaptation of the production layout (shorter logistics routes, redundant workstations)
- Consolidation and expansion of process steps (integration of additional modules, variety of variants and options)
- Distribution of process times (resolution of stroke times)
- Decoupling of material and product flow, also coupling of products (order) and AGV (no additional loading and unloading times, conveyor belts necessary)
- Adaptation of the calculation and allocation algorithm (order allocation at the latest possible time)

5. Scenario Selection & Interpretation

The findings from the analysis of the current research, especially from Bauernhansl & Ranke (2020) with regard to the material flow concepts, have been included as a basis for the simulation and model extension in this publication. Various material supply strategies are implemented in the simulation model connected to a valid database: The supply of individual products (direct delivery of the optimal material quantity to the respective workstation) and the delivery of the shopping cart (pre-picking of the expected next workstations).

With regard to the direct individual delivery, the Kanban concept for small-volume identical parts (e.g. cable harnesses, electronic components) was expanded in the course of the implementation of a valid application reference in automobile production, i.e. the material flow should be controlled according to the "pull principle". For this purpose, self-regulating control circuits are integrated to ensure the continuous supply of materials and to always orientate themselves to consumption in the value chain. The volume of the assembly components is also decisive for the storability of the material at the workstations because at some stations large numbers cannot be stored, e.g. chassis. The materials that are product-specific (individual order) or too large to be stored at the stations are delivered directly to the station as soon as the order makes its way to the relevant station. In the target state, the Kanban system should be optimized together with the shopping cart strategy. The following simulation and scenario evaluation were performed by the software “AnyLogic”, which allows to execute multiple simulation approaches (in this case Discrete Event and Agent-Based Simulation) simultaneously. The predefined material flow modules can be easily and efficiently adapted to the requirements of the use case using Java programming language.

5.1. Scenario Description

Overall two different material supply strategies are distinguished more specifically. In *Strategy A – Direct delivery*, the flow object drives to a workstation and joins the queue. A signal is sent and the material required for the respective process step is delivered by AGV. One station is supplied for each material order. In *Strategy B – Shopping cart delivery*, the flow object is already equipped with a “shopping cart” upon entering the system, which contains an initial stock of materials for the passage of a certain number of workstations (number = 3). This should optimize the material supply control loops implemented by Kanban. The flow object with material attachment then drives to the respective workstation. This way, three workstations can be supplied per production order before a new material supply is implemented. In order to consider a valid model implementation, the materials that are product specific (custom add-on module) or too big to be stored at the stations are delivered directly to the station as soon as the order is on the way to the relevant station.

The number of production orders to be fulfilled is set to 850 pieces (> 5x system settling phase), with 32 to a maximum of 42 orders being processed in the system at the same time in order to map the highest possible utilization of the production system. During the simulation experiment, the system load, in the form of the work in progress (WIP / number of orders in the system), is varied. For each replication of the respective WIP (there are 10 in total) the seed of the random

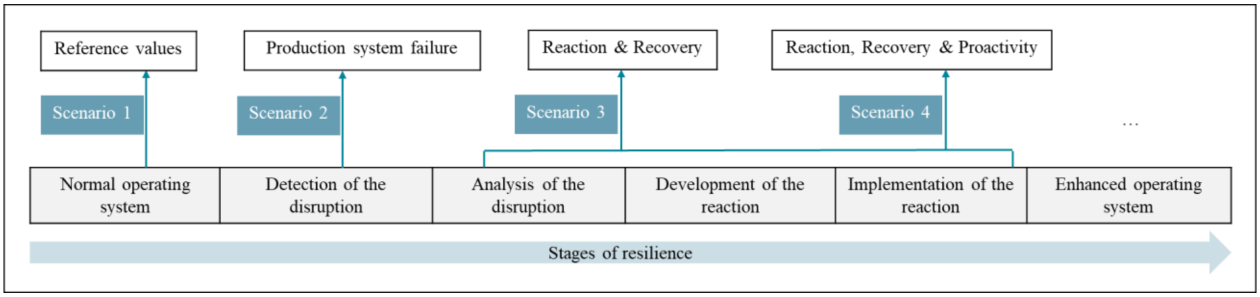

Figure 5: Relation between the implemented scenarios and stages of resilience (Galaske & Anderl, 2016)

number generator is changed. The duration of the simulation is flexible and has no fixed end point. Thefollowing evaluation ensures the system has already settled (150 orders have already been finalized), i.e. a total of 900-1000 orders are produced in one simulation run. The average consumption per station is 1.5 material units, since several work processes take place at one workstation. Regarding Greschke (2019), it is to be expected that the lead time will increase with each additional flow object that is in the system with ongoing development (both in the system and in the buffer areas). The size of the job buffers at the respective stations is not limited and will make up part of the evaluation. To examine the resilience of the two material supply strategies, four scenarios are distinguished (Figure 5).

Scenario 1 - Reference scenario (S1) depicts the necessary reference scenario in which the assembly system operates without incidents or special events in the matrix structure. The purpose of this is, on the one hand, to create reference values for the evaluation of the model and, on the other hand, to be used as a validation variable for the ideal-typical process times in the automotive industry. *Scenario 2 - Station failure without rerouting* (S2) represents an investigation case in which an error occurs during production at one or more independent stations in the system. The failure can occur at all stations regardless of the incidents happening at other stations. In the simulation it is assumed that the disruption time also includes the recovery time. In this scenario, the relevant orders do not act until the error at the workstation has been resolved (no rerouting). It is assumed that this will lead to a material jam at the affected workstation, so that the average processing times will be significantly longer and the station will be less preferred in the process chain. On one side, this event is intended to show the effects of a disruption compared to the reference scenario, on the other side, the limitations (extension of the process duration due to corresponding maintenance and set-up processes) of a rigid manufacturing system are to be examined as part of the resilience study. Disruptive events such as delivery bottlenecks or staff and equipment failures are excluded at this point.

As an extension of the scenario in terms of action, *Scenario 3 - Station failure with rerouting* (S3) is implemented. In this process, orders are rerouted to avoid the station with the disruptive incident in the immediate subsequent step. At the source of the error itself, there is a waiting period until a defined time to see whether the station can be used again (short fault). If this is not the case (long disruption), the orders already at the drop-out station are diverted. This also gives the system an active component, especially with regard to the anticipation of disruptive events. In comparison to S2 this scenario is intended to stress the advantages the concept of matrix production has to offer in relation to the cycle of disruption and recovery.

In *Scenario 4 - Prioritization order* (S4), the previous scenario is expanded by a corresponding prioritization order (rush order, change in demand). Orders with prioritization character are fed into the system, so that an action of the system in terms of adaptivity and necessary adjustments have to be carried out. It should be analyzed to what extent prioritized orders affect the overall system in terms of resilience and individual performance indicators of individual orders (lead time, waiting times, etc.) compared to the previous scenarios.

5.2. Scenario Interpretation

Various parameters can be used to evaluate the resilience in production systems (Sambowo & Hidayatno, 2021). Manufacturing and delivery times, inventories and overall equipment effectiveness are analyzed to describe the robustness of the system. The adaptivity of the system is described by the availability of systems/facilities, operations and personnel as well as the corresponding downtimes. In terms of foresight and anticipation, production and delivery quality in addition to reliability and failure probabilities come into play. Restart times or the duration of a decision-making process are indicators of the ability to learn or to reboot. At a higher level, the resilience of a technical system can be measured by considering performance over time. A resilient system minimizes the loss of performance over time after a disruptive event has occurred (Kohl et al., 2021). A selection of simulation results is shown below. Ten simulation runs are carried out in each case.

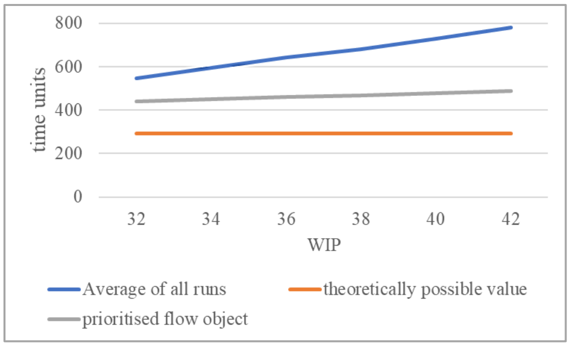

Figure 6. Comparison of production lead times

Figure 6 pictures a comparison of three variants in the context of the product lead time (manufacturing and logistics times). As an ideal-typical reference, S1 depicts an order that can run through the system without restrictions or waiting times. In S2 station failures occur; in S3 the flow objects are rerouted after a defined failure period (15 time units). In contrast, S4 shows a prioritized order in the system that is routed directly to available stations, but still has to wait in front of occupied stations. In addition, any station failures that occur must be dealt with. Compared to the average lead time of all orders, however, there is a clear time advantage, but without having a major impact on the orders already in the system.

This interpretation can also be derived from the following Figure 7. It shows that the implemented material supply strategies work and failures can be continued in terms of robustness in the matrix-structured system with largely the same development. Furthermore, it can be deduced that with an increasing number of orders in the system, a significant increase in lead time can also be recorded (also verified in Greschke (2016)). A proportionality of > 2 in relation to existing workstations and flow objects (orders) should not be exceeded.

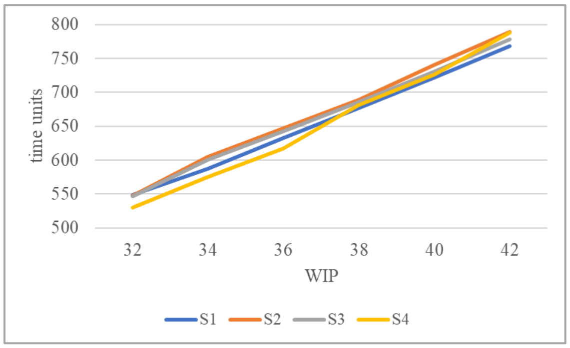

Figure 7. Lead times in dependence on WIP for material supply strategy KANBAN

With regard to the average machine utilization (Figure 8), *Strategy A – Direct delivery* shows that the values level off at around 46% despite different system behavior (with and without rerouting in the event of failures). In the run-up, it was to be assumed that the average machine utilization would be significantly higher, but Filz et al. (2019) only achieved a rather low utilization of the production system (between 44 and 54%) with comparable simulations. An analysis of the simulation runs shows that the optional stations (Figure 4, yellow workstations) are only controlled by around 10% of the orders, so that the utilization of the entire system decreases. Furthermore, the detailed analysis presents some workstations, that are already planned redundantly (rear modules, front modules), are utilized to a significantly higher extent despite the division of all flow objects (orders), but at the same time occupy heavily utilized buffer spaces. At peak times, there are up to 10 orders in a station's buffer, which can lead to waiting times and idle times at other points in the system. Overall, the average buffer capacity per station is only about one order per buffer.

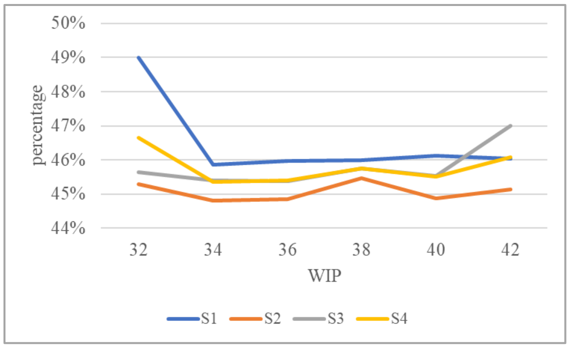

Figure 8. Average utilization of the workstations

Concerning the logistics processes, the average utilization of the AGVs for material and order transport has been differentiated according to the scenarios in Figures 9 and 10. It can be seen that the utilization of the AGVs linked to the production order show a significantly higher utilization than in Schmidtke et al. (2021). The process, transport and waiting times are included in the utilization values, with the latter accounting for a proportion of around 20% and a need to be optimized. The increases result from simulated station failures and rerouting processes. At this point, the question arises as to whether AGVs should only be used for the logistics processes and whether decoupling during the machining process makes sense in terms of resource reduction and adaptivity. Waiting times without an order and empty runs are excluded from the analysis.

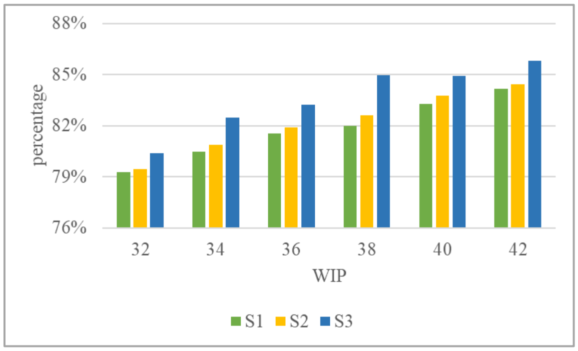

Figure 9. Average utlization of the AGVs for the flow objects

To illustrate the different behavior of the material supply strategy, the direct delivery strategy and the Kanban extension were compared in the case of AGVs for material supply. The results show that in the event of station failures in S3, the situation changes regarding resource utilization. The rerouting processes often require ad hoc delivery to workstations, which leads to higher utilization values and logistics routes in the context of direct delivery. Consequently, the Kanban delivery strategy can act more flexibly and fewer transports are required overall.

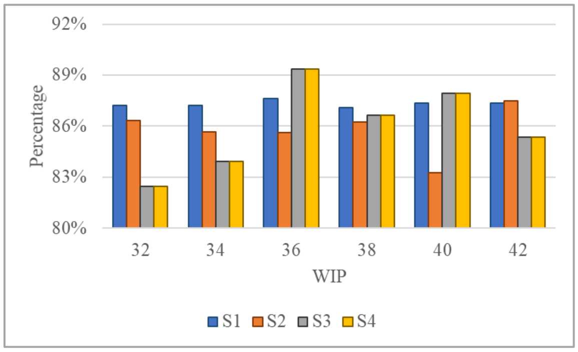

Figure 10. Average utilization of the AGVs for the material supply

5.3. Critical Reflection & Continuation

The present evaluation highlights a section of the simulation runs and experiments carried out. It can be stated that the model example has been made more flexible and valid at the same time due to further development of the simulation model and the order algorithm. In this context, process steps have been combined, process times have been designed to be cycle-independent and material and product flows have been decoupled. The selection logic for the subsequent workstation was adjusted and thus the degrees of freedom for the process flow increased.

With focus on the logistical supply processes and further discussion of the research question, there is a concrete need to map out an optimal trade-off between utilization and route optimization as well as a reliable and robust availability of resources in the system. As a part of upcoming experiments, strategy B - shopping cart delivery will be examined in more depth and conclusions will then be drawn about the ideal number of operating resources (product flow, material flow) depending on the matrix-structured production layout. In the current simulation setup, the number of operating resources (planned in sufficient numbers from a resilient point of view) and the selected layout (4x4 grid) offer further optimization potential.

The supply of materials is determined by the process design, the flow of information, the data management and the logistics structure (Plattform Industrie 4.0, 2022b). The increasing degrees of freedom in control propose a fundamental challenge by making it more difficult to connect demand and material in terms of time, location and quantity. Neither a fixed order nor an early planning of the resources with defined material requirements is found. Instead they develop during the (simulation) operation. This challenge can be met by appropriately designing the supply system, flexible supply processes and elements. Individual elements adapt in short cycles and are geared towards new conditions in the system, so that processes are redefined at the material level or staging areas are adapted. In an autonomous system, decision-making authority is transferred from the planner to the control system (Plattform Industrie 4.0, 2022b). At this point, further modifications in terms of simulation-based AI are planned. Specifically, the self-learning order control will be expanded through reinforcement learning methods (Lang et al., 2020), reward-oriented algorithms based on specified target values (in terms of resilience and efficiency), so that the independent agents learn successful strategies for material supply.

6. Conclusion

Previous research shows that different ideas of flexible, matrix-structured production systems exist and some variants have already been implemented as models or prototypes (Galaske & Anderl, 2016; Greschke, 2016; Kern, 2021). So far there is little to no research that takes a holistic approach of looking at topics such as production and logistics processes. The decoupling of logistics and production in matrix production is described as one of the central requirements of Industry 4.0. The system organization with variable parts logistics has the ability to switch to other workstations in the event of peaks or disruptions. The given example presents insights into the resilient system behavior with a focus on the adaptivity and robustness of processes.

This approach, consisting of simulation and algorithms for order and material supply control, can also be used in conventional production systems. Within the framework of the simulation, the referenced production system has to be included in the simulation tool and the mathematical allocation descriptions for the control processes have to be adapted. Within many applications, the description of the problem is simplified because, in contrast to line production, the assignment of orders does not take place at the latest possible point in time and the reliable supply of the workstations with material can be planned more consistently. Compared to workshop production, matrix production is characterized by a high degree of automation, networking and self-organization (Schenk et al., 2010). The requirements for increasing the resilience of the system are also found at the decentralized control level. Using AI assistance systems and machine learning, a global goal (e.g. with regard to system utilization and availability, product lead time, cost minimization) can be defined within the matrix production as required and the current company situation can be reflected in the production system.

In the context of resilience, the increased requirements regarding the ability to anticipate, as a time advantage to implement a redesign or rerouting, the ability to regenerate quickly as well as to cope with and, in part, to prevent any disruptions, will become the focus of future research and experiments. The findings from the investigations and the experiments should also be given to a logistics planner as a methodical guide. It has been determined that decision-making support for the planning of such versatile production systems must be provided, which supports the pre-selection of capacities and production cells early on in the planning process. Previous work is based on the brownfield approach in its modeling (given production environment) or defines fixed matrix structures for implementation based on assumptions.

7. References

Arlinghaus, J. (2021). Resilienz ist wichtiger als Effizienz. atp magazin 11-12/2021: Industrielle Resilienz als Schutzschild.

Bauernhansl, T.; Ranke, D. (2020). Evaluation of Material Supply Strategies in Matrix Manufacturing Systems, Advances in Automotive Production Technology – Theory and Application, Stuttgarter Conference on the Automotive Production (SCAP)

Bayhan, H.; Meißner, M.; Kaiser, P.; Meyer, M.; ten Hompel, M. (2020). Presentation of novel real-time production supply concept with cyber-physical systems and efficiency validation by process status indicators: Journal of Advanced Manufacturing Technology.

Filz, M.; Gerberding, J.; Herrmann, C.; Thiede, S. (2019). Analysing different material supply strategies in matrix-structured manufacturing systems: 52nd CIRP Conference on Manufacturing Systems

Galaske, N.; Anderl, R. (2016). Disruption Management for Resilient Processes in Cyber-Physical Production Systems, Procedia CIRP 50, 442 – 447.

Goethe, J.; Landes, M.; Steiner, E. (2013). Resilienz und Effizienz – Architektur für nachhaltigen Unternehmenserfolg. In: Psychologie der Wirtschaft. Springer VS

Greschke, P. (2016). Matrix-Produktion als Konzept einer taktunabhängigen Fließfertigung, TU Braunschweig, Institut für Werkzeugmaschinen und Fertigungstechnik, Dissertation.

Günther, E. (2018). Definition: Was ist „Resilienz“? Gabler Wirtschaftslexikon. (Access: 09/06/2022)

Kagermann, H.; Süssenguth, F.; Körner, J.; Liepold, A.; Behrens, J. (2021). Resilienz als wirtschafts- und innovationspolitisches Gestaltungsziel. Acatech Impuls, pp. 6

Kern, W. (2021). Modulare Produktion: Methodik zur Gestaltung eines modularen Montagesystems für die variantenreiche Serienmontage im Automobilbau, Springer Fachmedien Wiesbaden, Chapter 5.1

Klug, F. (2018). Logistikmanagement in der Automobilindustrie. Springer Berlin Heidelberg.

Kohl, H.; et al. (2021). White Paper: RESYST – Resiliente Wertschöpfung in der produzierenden Industrie – innovativ, erfolgreich, krisenfest., Hrsg. Fraunhofer-Gesellschaft e.V., München, pp. 14

Kropik, M. (2021). Produktionsleitsysteme für die Automobilindustrie: Digitalisierung des Shop-Floors in der Automobilproduktion. Springer Berlin Heidelberg.

Lang, S.; Lanzerath, N.; Reggelin, T.; Müller, M.; Behrendt, F. (2020). Integration of Deep Reinforcement Learning and Discrete-Event Simulation for Real-Time Scheduling of a Flexible Job Shop Production, Conference: Winter Simulation Conference (WSC), Orlando, USA

Lee J.; Siahpour, S.; Jia, X.; Brown, P. (2022). Introduction to resilient manufacturing systems. Manufacturing Letters 32 (2022) 24-27

Lietaer, B. (2010). Is Our Monetary Structure a Systemic Cause for Financial Instability? Evidence and Remedies from Nature. In: Journal of Futures Studies, 14 (3)

May, M.C.; Schmidt, S.; Kuhnle, A.; Stricker, N.; Lanza, G. (2021). Product Generation Module: Automated Production Planning for Optimized Workload and Increased Efficiency in Matrix Production Systems, Procedia CIRP, Vol. 96, 45–50

Perwitz, J.; Sobottka, T.; Beicher, N.-J.; Gaal, A. (2022). Simulation-based evaluation of performance benefits from flexibility in assembly systems and matrix production, 55th CIRP on Manufacturing Systems, Procedia CIRP 107, 693-698

Pischinger, S., Seiffert, U. (2016). Handbuch Kraftfahrzeugtechnik. Springer Fachmedien Wiesbaden.

Plattform Industrie 4.0 (2022a). Whitepaper: Resilienz im Kontext von Industrie 4.0, Bundesministerium für Wirtschaft und Klimaschutz (BMWK)

Plattform Industrie 4.0 / acatech – Deutsche Akademie der Technikwissenschaften (Hrsg.) (2022b). Umsetzung von cyber-physischen Matrixproduktionssystemen

Popp, J; Wehking, K.-H. (2016). Neuartige Produktionslogistik für eine wandelbare und flexible Automobilproduktion: Logistics Journal: Proceedings.

Sambowo, A.; Hidayatno, A. (2021). Resilience Index Development for the Manufacturing Industry based on Robustness, Resourcefulness, Redundancy, and Rapidity. International Journal of Technology 12 (6) 1177-1186

Schenk, M.; Wirth, S.; Müller, E. (2010). Factory Planning Manual. Springer Berlin Heidelberg.

Schmidtke, N.; Rettmann, A.; Behrendt, F. (2021). Matrix Production Systems – Requirements and Influences on Logistics Planning for Decentralized Production Structures, 54th Hawaii International Conference on System Sciences, 1665-1674

Stricker, N.; Kuhnle, A.; Hofmann, C.; Deininger, P. (2021). Self-Adjusting Multi-Objective Scheduling Based on Monte Carlo Tree Search for Matrix Production Assembly Systems, CIRP Annals, Vol. 70, No. 1, 381–384

Tierweiler, M.; Bauernhansl, T. (2022). Reconfiguration Process for Matrix Manufacturing Systems, Proceedings of the 55th CIRP on Manufacturing Systems 2022, Procedia CIRP 107, 699-704

Vogel-Heuser, B.; Bauernhansl, T.; ten Hompel, M. (2017). Handbuch Industrie 4.0. Bd. 4: Allgemeine Grundlagen. Springer Reference Technik, 165-260