Resilient production control by linking preventive maintenance strategies

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Abstract
The manufacturing industry, particularly in the area of customized single and small series production of complex products, is facing considerable challenges in the course of Industry 4.0. These include unplanned events and production interruptions, increasing customer individuality, and a high number of variants. The difficulties in managing short-term production and maintenance decisions in complex and dynamic environments are critical. Traditional, non-coordinated maintenance measures based on manual tools are quickly reaching their limits here. This often leads to reduced availability of production resources and a waste of resources due to unused time slots. The following concept aims to integrate preventive maintenance strategies into the production control of single and small series production. A major result of this integration is the provision of decision recommendations for planners within the operational planning horizon using a Job Shop Scheduling model. Decision support should make it possible to react effectively to unplanned events and thus make efficient use of unused time slots. The aim is to create resilient processes and generate a solid planning result.

1. Introduction
The manufacturing industry, particularly in the area of single and small batch production of complex products, is confronted with significant challenges in the context of Industry 4.0 [1], [2], [3], [4]. These include unplanned events and production interruptions, increasing customer individuality, and a high number of variants [5], [6], [7]. Short-term maintenance and production decisions, which are often inadequate and inefficient in complex and dynamic environments, are particularly difficult [4], [8]. Examples of unplanned events include new incoming orders, order cancellations, random machine breakdowns, changes to due dates, and material shortages [5], [9].
Uncoordinated maintenance measures that are not synchronized with production planning and control (PPC) and are based on manual tools quickly reach their limits [10], [11]. Unplanned events in the operational planning horizon (typically covering days to weeks) often result in wasted resources due to unused time slots in the production schedule on the one hand, and lower availability or the same utilization of production resources on the other hand [4], [5].

In current practice, maintenance is often viewed as a separation from production control, particularly in the operational planning horizon [1]. This separation often leads to inefficient decisions that are mainly based on traditional and manual methods [5], [7]. Existing algorithms and models developed for stable production conditions, e.g. in mass production, are often inadequate for the dynamic requirements of single and small batch production [7], [12]. Traditional reactive and rigid maintenance, e.g. based on fixed time intervals without the possibility of dynamic adjustments, increases these problems and leads to further interruptions, longer throughput times, and thus to rising costs [4], [5], [7].

The positive effects of maintenance planning can be seen on the one hand in the reduction of costs, and on the other hand, with optimal use, the speed of product delivery to the customer, product quality, and reliability can also be improved. An optimal maintenance strategy can therefore have a significant impact in many respects [3], [6], [13]. Predictive maintenance is a branch of preventive maintenance that can forecast failures by analyzing condition data [14], [15]. In customized single and small series production of complex products, this approach is not always suitable [16]. The production conditions here are so specific and variable that a standardized prediction of maintenance requirements is often not possible. The focus is therefore on preventive maintenance strategies, which are more useful for the conditions of single and small batch production [3], [17]. The closer linking of preventive maintenance strategies with production control should lead to more resilient processes as well as increasing planning reliability in the event of unplanned events. The aim is to sustainably increase the responsiveness and efficiency of production through these adjustments [3], [4], [16].

The application of dynamic maintenance measures offers considerable potential for reducing machine failures and maintenance costs [5], [12], [13]. Existing planning models often do not take sufficient account of the effects of maintenance measures and the resources required for them on production capacity and the specific requirements of single and small-batch production in complex production environments [5], [7], [18].

Therefore, there is a need for a concept that enables the areas to be linked and supports dynamic planning [9] in this environment to overcome the abovementioned challenges and increase efficiency. Such a concept would close the gap between maintenance planning and production control and promote a flexible approach.

The concept is relevant for production and maintenance planners in the area under consideration, as they can react more quickly to unplanned events within the operational planning horizon. By advancing maintenance measures into unused time slots caused by unplanned events, preventive maintenance strategies can be implemented and these time slots can be used effectively, either through targeted maintenance measures or by rescheduling production orders. This helps to reduce the waste of resources, especially personnel. Other restrictions, such as delivery times and machines, are not only considered, but positively influenced, especially critical machines with higher failure rates. The model is intended to assist/support the planner with decision recommendations in the operational planning horizon in order to optimize their planning processes. This can increase the flexibility and efficiency of production in the long term. The planner is also relieved because they no longer have to search for solutions manually.

1.1. Research gap

The introduction explains the challenges of current maintenance and production planning and highlights the need to integrate preventive maintenance strategies into production control, especially in the focus area. The dissertation aims to improve the area under review by developing a concept. In order to illustrate the area under review, it is visualized as a morphological box (see Figure 1). This visualization serves as a structured tool to present the relevant parameters and their possible characteristics comprehensively and concisely. The research gaps identified are briefly presented below, always against the background of the specific area under review.

The selection of characteristics and their characteristics in the morphological box was made according to the area under review of the concept in order to briefly capture the essential aspects of the production system. The characteristics cover the areas of production, including product type, production structure, production orders, quantity, variety of variants, production process, production stages, type of manufacturing, form of manufacturing, flexibility, productivity, planning horizon, machine load, machine type, machine inventory, and operator qualification. This selection makes it easier to view the production environment and creates a basis for the development and optimization of production processes. Each of the criteria was selected based on its relevance. For example, the product type influences the requirements for flexibility and productivity, while the production structure is decisive for the complexity of the production processes. The selection of specific characteristics such as "make-to-order" for production orders and "low" for quantity reflects the focus on customer-specific, low-volume production, which places specific demands on flexibility and planning. The terms in the morphology box are based on the sources [14], [19], [20], [21] and [22].

1.1.1. Research gap (Linking production control and preventive maintenance in the area under review)

In production environments, as shown in Figure 1, there is a challenge for specially developed maintenance strategies that can be effectively integrated into operational production control. This is confirmed by the literature research for the area under review and has not yet been systematically investigated [23], [24]. The production environment is characterized by a high degree of complexity and variability, and each order can have individual requirements in terms of materials, processes, and personnel skills.

Existing manufacturing approaches often do not have the flexibility and adaptability to respond to unplanned events. Maintenance strategies based on regular maintenance intervals are not sufficient for dynamic production requirements [5]. There is

	Characteristic	Characteristic value					
Product	Product	Piece goods		Liquid bulk		Bulk goods	
	Product type	Customized product		Prototype		Standard product	
	Product structure	Multicomponent with complex structure		Multicomponent with simple structure		Minor components structure	
	Types of production orders	Make-to-Order		Assemble-to-Order	Make-to-Stock	Engineer-to-Order	
	Quantity	Low		Medium		High	
	Variety of variants	Low		Medium		High	
Production process	Production process	Continuous			Discontinuous		
	Production stages	Single-stage		Two-stage		Multi-stage	
	Type of manufacturing	Nonrepetitve production		Single and small batch production		Series production	Mass production
	Form of manufacturing	Matrix production	Job shop production	Flow line production		Batch production	Cellular production
	Flexibility	Low		Medium		High	
	Productivity	Low		Medium		High	
	Planning horizon	Operational		Tactical		Strategic	
Production resources	Machine load	Continuous		Low	High	Variable	
	Type of machinery	Specialized or custom machines		Simple machines		Highly complex universal machines	
	Machine inventory	Homogeneous			Heterogeneous		
	Operator qualification	Inexperienced or untrained operators		Semi-skilled operators		Skilled operators	

Figure 1: Area under review, own representation of the morphology [14], [19], [20], [21], [22].

therefore a need to adapt preventive maintenance strategies and develop a concept so that they can be proactively embedded in production control and integrated into a decision support system. This should promote more resilient processes and enable a solid planning result for the operational planning horizon [6].

1.1.2. Research gap (Resilient and priority-based maintenance)

Another issue is the risk assessment, prioritization, and effective integration of maintenance measures into production control, especially in the case of unplanned events, which often create unused time slots in the production schedule. There is a need for a systematic approach with recommendations to decide which maintenance work can be brought forward for specific machines, how these measures can be efficiently integrated into the time slots that arise, and how the decision should be made based on urgency, available resources, and the time required.

1.1.3. Research gap (Predictive Maintenance)

The area under review, which is characterized by constantly changing production parameters and a heterogeneous machine park, proves to be critical for predictive maintenance. These strategies, often developed and tested under idealized laboratory conditions, reach their limits in dynamic production contexts. Their effectiveness and direct transferability to real production conditions can therefore only be implemented to a limited extent. For this reason, it is necessary to adapt existing preventive maintenance approaches to the complexity and dynamics of the production environment to meet these requirements [14].

1.2. Research theses

The central research theses of this dissertation result from the identified research gaps. They aim to identify the solutions that address the above research gaps. The theses address the subsequent implementation of the methods to close the research gaps.

1. The concept developed enables decision support for planners by linking both areas. Potential for improvement in single and small series production of complex products is exploited, especially in the case of unplanned events in the operational planning horizon.
2. Adapting methods from stable production types such as mass production requires applicable strategies for single and small batch production of complex products due to the process differences. While these stable production types are based on standardized production processes with constant workflows, low variability of product specifications, and predictable demand, single and small batch production requires flexibility and adaptability. Productivity in this area can be increased through the targeted selection of methods to meet production requirements.

3. Predictive maintenance does offer the possibility of reducing costs and minimizing downtimes. However, in production environments with variable parameters and the manufacture of complex, customer-specific products, it reaches its limits due to the high implementation costs and strong data dependency, which is why it is not recommended for these use cases.
4. The risk assessment and prioritization of important maintenance measures and their targeted integration into production control can reduce the downtime of systems by combining various preventive maintenance strategies using different selection criteria. These measures increase production efficiency, especially in the event of unplanned events in the operational time horizon.
5. Implementing the concept of decision support networking maintenance and production control has the potential to increase the resilience and reliability of complex production systems by creating an improved and solid planning basis with a uniform database. This allows unplanned events to be dealt with more quickly and unused time slots to be used more effectively while minimizing process time.

1.3. Novelty and state of research

In this section, the current state of research is presented based on the systematic literature review method (see section 2.1). The results of the literature review and the presentation of the novelty also make it clear where the present work differs from the literature and where there is a need for additions.

Research Approaches and SLR

The topic of general production planning and control (PPC) and maintenance has received a lot of attention in research in recent decades [1]. The challenge of linking production and maintenance in particular has been the focus of numerous studies. Various algorithms, heuristics, and models have been developed to analyze and optimize the dependencies between PPC and maintenance [2], [25].

Against the background of increasing demands on the availability of technical systems, systematic approaches to robustness assessment have been developed in the field of maintenance [26], [27]. These methods provide a basis for the selection of maintenance strategies and the specific use of maintenance resources, depending on factors such as system structure, type of use, and changes in condition. In most scientific papers, however, only one maintenance strategy, such as predictive maintenance, is addressed [27].

The scientific papers only focus on one maintenance strategy. In the literature, maintenance is divided into two categories (see Figure 2), each of which is further divided:

- reactive maintenance
- preventive maintenance

Preventive maintenance includes measures such as preventive and regular maintenance and planned repairs. Reactive maintenance, on the other hand, deals with unexpected breakdowns and emergencies [15]. In planned maintenance, maintenance activities are often seen as time constraints that must be considered in any production plan to ensure trouble-free production [16].

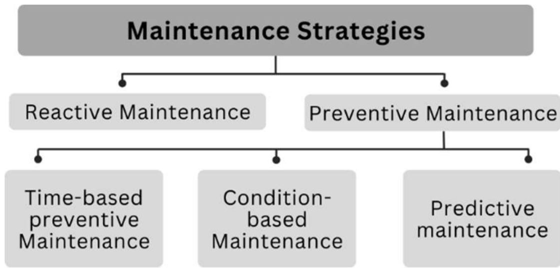

Figure 2: Maintenance Strategies [14], [15].

The high potential of data-driven maintenance, known as predictive maintenance, is often discussed, particularly in the context of Industry 4.0. Predictive maintenance, a sub-area of preventive maintenance, draws on historical data and, where necessary, maintenance-relevant data collected in real time. Comprehensive data collection is required for a significant evaluation and analysis of this data, often using artificial intelligence (AI), for example. These data volumes must be collected by the machines continuously and over longer periods. [14], [15], [16].

The systematic literature search shows that many studies have examined the interface between production planning and maintenance. Studies such as [28] and [29] provide an overview of the targets of production planning, such as lead times and production costs. In order to increase system availability, avoid system failures, and reduce maintenance costs, [30] and [31] provide an overview of various maintenance strategies. While [32] proposes a method to determine optimal production, replacement/repair, and preventive maintenance strategies, [33] argues that preventive maintenance can reduce failure frequency and develop corresponding production and maintenance strategies based on inventory levels. In contrast, the papers [34] and [35] deal with the impact of production schedules on equipment wear, especially in systems with one machine producing one type of product and serving a random demand over a limited period.

The conclusion from the literature review makes it clear that production planning models tend to assume constant availability and maximum performance of the systems, while the effects of maintenance activities on production capacity are often ignored in maintenance models and there is no explicit consideration of production requirements [10], [18]. These differences mean that unplanned maintenance, triggered by unplanned faults, can have a significant impact on production. The integration of a combination of maintenance strategies into production is therefore essential to ensure the operational readiness of the machines and to stabilize the production processes. The integration of production and maintenance processes corresponds to the real requirements of production environments and is an essential element to maximize process resilience. The development and implementation of resilient processes that take into account both production and maintenance schedules are therefore crucial [10].

In a follow-up SLR, it was found that many models already exist in the literature. These models deal with the integration of maintenance measures into production planning and are closely linked to solution approaches from the field of mathematical optimization. A brief excerpt from the SLR is presented below.

Considering machine downtime and regular maintenance, [17] and [36] consider production scheduling, with the former focusing on job stop and the latter on single machine scheduling problems. In [37], these considerations are extended to flexible job stop with integrated maintenance and transportation planning, although further research is seen to be needed for resource constraints and search strategies. The simultaneous optimization of production and maintenance planning is investigated in [38] and [13], where the former uses genetic algorithms and the latter a heuristic solution without considering dynamic events. In [39], a dynamic control algorithm for optimizing production planning is presented, which, however, can lead to increased maintenance costs. A dynamic planning strategy for machine failures is proposed by [40] but may be limited by the complexity of the algorithm configuration.

Some of the publications focus on minimizing lead times, which leads to an increase in capacity and flexibility requirements [7], while others focus on preventive maintenance strategies in (partially) automated production systems.

Research into single and small batch production, which requires a high degree of flexibility and adaptability, nevertheless remains limited. This type of production, characterized by its specific requirements and the possibility of operational optimization, is particularly underrepresented in the literature [19], [20].

1.4. Novelty of the work

The novelty of this work lies in the development of a concept that increases the resilience of complex production systems by integrating preventive maintenance strategies into production control. In contrast to existing studies, which often assume a static production environment and constant machine availability [6], the work has a particular focus on unplanned events and production downtimes and their short-term use. By making decision recommendations for planners such as maintenance and production planners, especially about unpredictable events, this work differs from previous approaches that do not fully incorporate the dynamic aspects of production and maintenance. A usable algorithm aims to increase efficiency in an operational planning horizon and thus provides, in the best case, real-time support for planners [5]. This work thus contributes to a new planning approach that places a special focus on maintenance and emphasizes the practical relevance and applicability in dynamic production environments.

2. Methods

The next section presents the methods used in the paper. The methods are used to close the research gaps and to verify the research theses.

2.1. Systematic Literature Review

The systematic literature review was used to evaluate existing publications. This method was chosen because it enables an analysis of existing research and thus leads to research gaps being identified and closed [41]. As a result, an understanding of current research in the field of production planning and control with a particular focus on maintenance in the area under review should be gained. The searches are based on a combined search chain consisting of key terms and their synonyms, including:

- "Production planning and control"
- "Individual and small batch production"
- "Maintenance Strategies"
- "Smart Maintenance"
- "Job Shop"
- "Production Scheduling Optimization"
- "Manufacturing Scheduling"
- "Optimization"
- "Operations Research"

The terms presented here are only generic terms; synonyms have not been listed. The literature from the years 2013 to 2023 was taken into account. The snowball technique was also used when conducting the SLR. This resulted in the discovery of additional older, relevant literature sources published before 2013. The SLR was carried out in scientific databases such as Dimensions.ai and Scopus Elsevier. A total of 45 sources were identified, from which a selection was made for further analysis. Relevance to the research topic and methodology were used to select the studies.

The SLR shows that many studies have been conducted on the link between production planning and maintenance. However, most studies do not focus on the integration of preventive maintenance strategies into production control in the operational planning horizon. In addition, they only marginally consider the effects of a volatile production environment, as in the area under review, and the reaction to unplanned events and production downtime [41].

The results of the SLR were discussed in a brief summary in section 0.

2.2. Selection, evaluation, and combination of maintenance strategies

The method presented is an essential part of the concept for linking preventive maintenance with single and small series production of complex products. The core of the method is the selection and combination of preventive maintenance strategies that are to be integrated into production control. These maintenance strategies are listed in Figure 2. A significant aspect is the investigation of the downtimes of critical machines to bring forward maintenance measures in unused time slots caused by unplanned events. The method focuses on the downtimes of critical machines that are in the transition from the Useful-Life phase to the Wear-Out-Failure phase. This can be recognized by the failure rate of a machine. The basic course of the failure rate of a machine over its service life is often described with a so-called "bathtub curve" [14]. In this work, the Wear-Out-Failure phase of the bathtub curve is considered, which means that these machines have a higher risk of failure. Different stresses, such as increased strain or improper operation by untrained personnel, as well as operating outside the specified parameters, can shorten the Useful-Life phase (low and constant failure rate) of a machine (see Phase 2 in Figure 3) [6], [44].
In addition, maintenance measures are selected and prioritized, which can be brought forward in unused time slots if necessary. Decision-making is to be supported by a Job Shop Scheduling model, creating a solid production and maintenance plan for the operational planning horizon. This method promises an improvement in maintenance processes and integration into production processes, which leads to an increase in resilience.

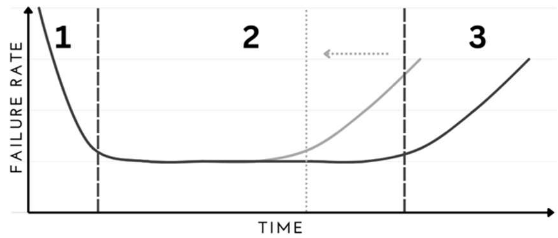

Figure 3: Bathtub Curve, Phase 1: Early-Failure Phase, Phase 2: Useful-Life Phase - Random Failures, Phase 3 - Wear-Out-Failure Phase. Own representation based on [2].

2.3. Job Shop Scheduling

The application and integration of a mathematical optimization algorithm, in this case, the Mixed Integer Programming (MIP) model, is central to the linking of production control and maintenance planning in this work [42], [43]. By using MIP, both integer and continuous variables can be included in order to efficiently manage the complex requirements of the Job Shop Scheduling and to find an optimal solution [42], [45]. Job store scheduling is a method of scheduling many jobs (tasks) on a limited number of machines in such a way that throughput time is minimized and efficiency is maximized [46].

This systematic framework enables improved production control and increases the resilience of maintenance processes by efficiently allocating production orders and maintenance measures in the event of unused time slots caused by unplanned events. Time dependencies and resource availability are taken into account in the operational planning horizon. This means that the model can flexibly react to unplanned events by planning maintenance activities in these time slots without disrupting the production flow [47].

In a typical MIP model, decisions are represented by integer variables, while continuous variables can represent aspects such as time, costs, or quantities [20]. Integer variables can be, for example, the number of machines or the assignment of jobs to machines, while continuous variables represent times or the duration of operations [46]. The challenge is to find an optimal combination of these variables [48]. This combination should maximize or minimize a given objective function while at the same time satisfying a set of linear constraints [46].

The objective function in this work is to minimize the total production time over a given time period, while constraints ensure that no machine runs multiple orders simultaneously and that the delivery dates of the orders are met [47]. Especially in the problem of production control, a MIP model is suitable for problems with different variables and constraints to find feasible solutions in a reasonable time [42].

In summary, mixed-integer programming provides a framework for modeling and solving decision problems involving both discrete and continuous variables. The MIP model plays a further relevant role in the development of the concept with regard to rapid response in the case of short-term decisions [45].

2.4. Expert knowledge of industry comparison

Another method focused on is a comparison with industry partners through semi-structured expert interviews in order to gain practical knowledge about the integration of maintenance into production control. Expert interviews are conducted by selecting experts from relevant industry sectors to record experiences, challenges, and best practices [49]. The evaluation of these interviews makes it possible to compare the concepts with real conditions and gain practical insights for the work. For the systematic evaluation of the information gained from the expert interviews, the qualitative content analysis method according to Mayring is to be used [50].

2.5. Research design approach to method development

When selecting and developing the methods for answering the research gaps and the present research theses (see section 1.1 and section 1.2), the context is discussed below. The methods are processed in a partially specific order (see Figure 4). The methods (sections 2.1 - 2.3) have already been started in the thesis. The following section provides a brief overview of the methodological approach in relation to the individual research theses and shows which methods could be adopted directly and for which a new approach is being pursued. For theses 1 and 5, the systematic literature review led to the identification of the current state of research, which serves as the basis for the development of a decision support concept for linking maintenance and production control.

This analysis makes it possible to gain deep insights into existing research work and proven methods, which can not only be adopted but also used as abasis for further research.

Particularly useful in this context is the own development of the selection of maintenance strategies, which will be specifically linked to Job Shop Scheduling in order to react quickly to unplanned events and thus create a resilient process. These methods and their integration into the concept play a central role in providing decision support for planners in dynamic production environments such as the area under review.

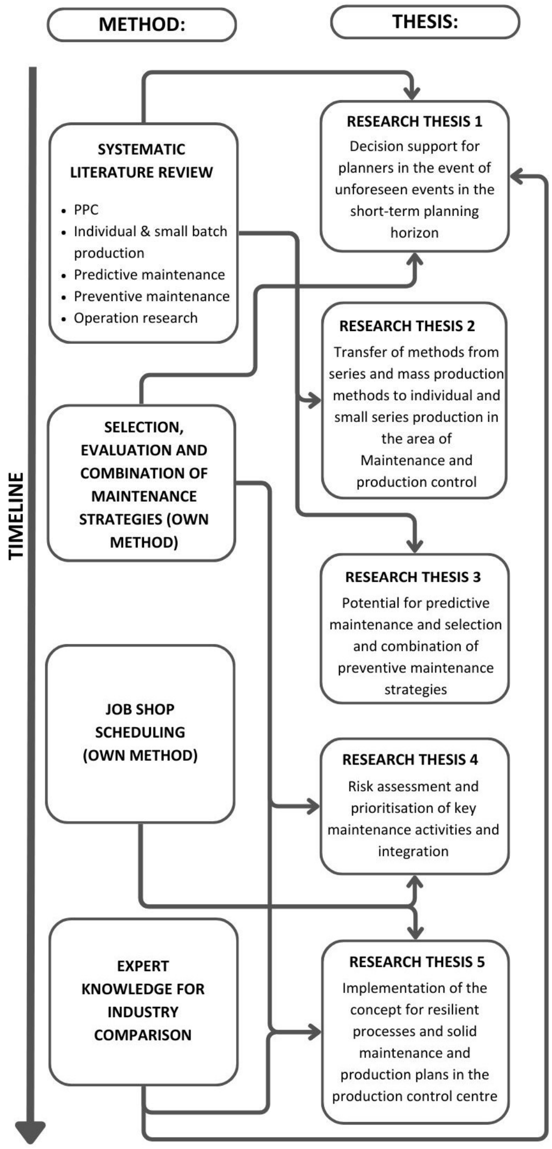

Figure 4: Research Design

Theses 2 and 3 focus on adapting mass production methods to single and small series production of complex products, as well as researching the limits of predictive maintenance in dynamic and complex production environments. The systematic literature review deepens this knowledge and provides information on methods and strategies. In addition, interviews with experts from the industry will provide direct insight into practical challenges and current solution approaches in order to enable a comparison.

To answer research thesis 4, a systematic approach for selecting preventive maintenance strategies is developed. This establishes the link between Job Shop Scheduling and the application and thus increases the responsiveness of production control. The combination of these maintenance strategies represents a separate development in order to create a solution specifically for the problem in the area under review. As part of answering the 4th research thesis, a strategy for selecting preventive maintenance strategies will be developed and implemented by integrating it with job stop scheduling. This link is intended to increase resilience and the ability to react to unplanned events. The combination of these maintenance strategies as a separate development method is central to creating specially tailored solutions for the area under review.

3. Results and Discussion

3.1. Results

The SLR was briefly introduced in chapter 0. It highlighted the gaps in the field of research. These consist of the consideration of individual maintenance strategies, the neglect of a dynamic and complex production environment, and the insufficient consideration of the specific requirements of single and small series production [16]. Another result of this work is the development of the mixed-integer programming model to solve the complex Job Stop scheduling problem regarding the integration of maintenance tasks (see Figure 5). This approach makes it possible to efficiently distribute many jobs, consisting of several subtasks (maintenance and work orders) with specific sequences, to different machines [47].

The model is characterized by the fact that it takes into account not only integer decisions, such as the allocation of orders to machines but also continuous variables, such as the time and duration of the orders. The resources can also be considered. The objective function is to minimize the lead times of all orders to ensure an optimal production sequence. By including the earliest possible start times, processing durations, and the latest due dates for each job part, the model enables exact planning. It also considers the possibility of multiple machines performing the same tasks and integrates maintenance activities directly into the manufacturing process. The challenge of creating an efficient production plan that both minimizes the overall duration and reduces waiting times between jobs is solved by optimizing the decision variables within the MIP framework [47].

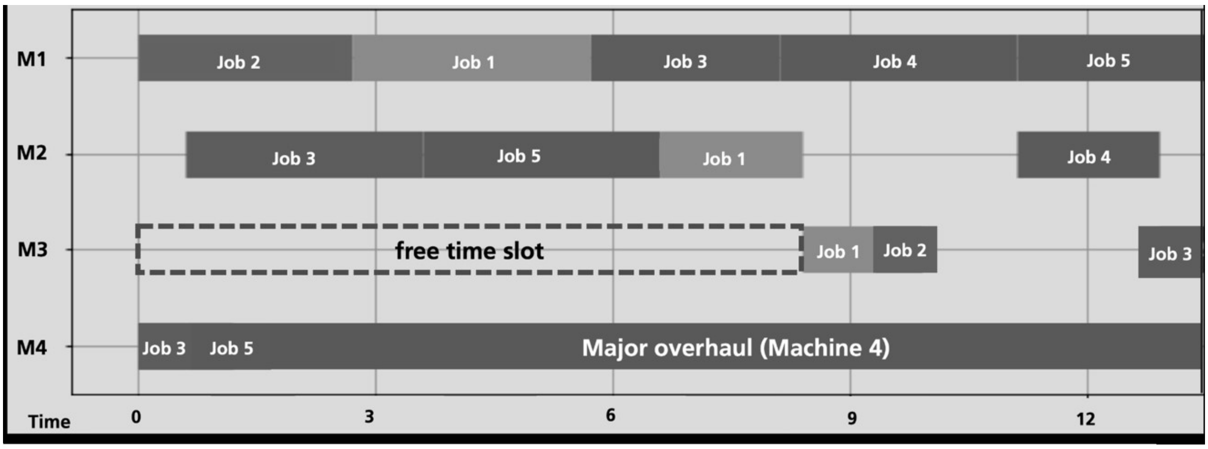

Figure 5: Output Job Shop Scheduling - Machine allocation plan (maintenance and work orders)

3.2. Limitation and possibilities

Job Shop Scheduling problems belong to the NP-hard problems [42], [46]. This means that the time required to find the optimal solution increases exponentially with the number of jobs and machines. This complexity results from the need to consider a large number of possible job-machine assignments and their order [48]. The model is therefore more suitable for an operational planning horizon [46]. Another aspect where the model reaches its limits is the quality, accuracy, and completeness of the underlying production data. Due to information islands or inadequate recording systems, it can be difficult to obtain this detailed data in practice. Integration into existing systems also presents a challenge.

The implementation of the MIP model or the entire concept requires seamless integration into the existing IT infrastructure of manufacturing companies. Challenges in the technical and organizational sense, such as incompatible IT systems and employees' reservations about new processes, can make it difficult to use. In addition, the risk of user acceptance is a critical factor that should not be underestimated. Accepting and using new technologies often depends on the ability of end users to accept change.

3.3. Verification and validation

To ensure the effectiveness and reliability of the proposed methodological approach for the selection, evaluation, and combination of preventive maintenance strategies, verification, and validation is beneficial. A theoretical review can be carried out by critically comparing the SLR results with established theories and models from the literature. For the MIP model and the selection of preventive maintenance strategies, this review is particularly relevant. The plausibility can be verified by comparing it with existing models. The next step in validating the methodology is to obtain feedback from experts.

A comparison from the areas of maintenance and production is important in order to gain insights into the practicability and possible potential of the approach. This feedback not only provides an external perspective but can also help to increase the relevance and effectiveness of the approach in real-life application scenarios. In addition, the peer review process at scientific conferences plays a role in the validation of research results. Publication at scientific conferences makes it possible to subject the approach to a critical review by the scientific community. Two scientific papers have currently been submitted to conferences for the present work:

- Concept for a Robust and Reliable Manufacturing and Logistics System that Combines Production Planning and Control with Predictive Maintenance – published [16]
- Job Shop Scheduling in the operational planning horizon for the integration of maintenance measures into production planning and control – unpublished [47]

4. Conclusion

The scientific paper follows a concept of integrating production and maintenance planning into the production control of single and small series production. A key result is the provision of decision recommendations for production planners and maintenance staff in the operational planning horizon. This enables them to react quickly to unplanned events and make effective use of unused time slots.
Other important targeted results are:

- methods for selecting and combining preventive maintenance strategies,
- development of the Job Shop Scheduling algorithm and
- combination in a concept with possible visualization through mock-ups.

Next Steps

In the next publication "Job Shop Scheduling in the operational planning horizon for the Integration of maintenance measures into production planning and control", which is still in the submission phase, the mathematical model for Job Shop Scheduling was presented, which shows a step toward a closer link between maintenance and production processes. [47]

The next step is to plan the implementation and visualization of the model, using fictitious data to test the model. When real data is available, it will be exchanged with the fictitious data and tested in order to ultimately increase the practical relevance of the research. Another planned step is the development of the concept for selecting and combining preventive maintenance strategies, as described in section 2.2, with the aim of integrating maintenance measures into production control in such a way that the resilience of the overall process is increased while at the same time minimizing susceptibility to unexpected disruptions.

Finally, it is planned to evaluate the model and the concepts developed in consultation with industry. This discussion with experts from the field will serve to improve the model and validate its practical suitability. The comparison should not only provide valuable insights into the practical feasibility but also improve the adaptability of the model to various use cases, for further work and to identify points of contact. One approach for further work is the integration of artificial intelligence (AI), metaheuristics, or heuristics into the developed concept. These extensions offer the potential to improve the speed and accuracy of production and maintenance planning with more data and over a longer planning horizon. The decision to use Job Shop Scheduling as the focus of this scientific paper was made due to its established foundations and proven methods, which offer a solid basis for developing and evaluating innovative approaches before integrating complex solutions such as AI.

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