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Digitalization for flexible and resilient production planning and scheduling in engineer-to-order manufacturing

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Abstract

Delivery reliability and customer satisfaction are critical for manufacturing companies that follow engineer-to-order manufacturing. Efficient production planning and scheduling is a vital requirement for flexible and prompt customer delivery. However, the uncertainty and volatility due to specific customer order requirements, production disturbances, and demand and product volume fluctuations result in frequent replanning or rescheduling of the production plans or schedules in engineer-to-order manufacturing. From a theoretical perspective, this article provides an overview of the strategies and solutions to enhance production planning and scheduling in engineer-to-order manufacturing through a literature study. From an empirical perspective, the article provides results from two industrial case studies where digital tools or digitalization were used to facilitate replanning or rescheduling and thereby attain flexibility and resilience in production planning and scheduling in engineer-to-order manufacturing.

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Keywords: production planning and scheduling; engineer-to-order, one-of-a-kind; ETO; flexibility; resilient manufacturing systems; replanning; rescheduling

1. Introduction

Manufacturing organizations worldwide are facing the need to transform themselves due to the changes in consumer behaviour, rapid technology advancements and unexpected global scenarios like the Covid-19 pandemic. The consumer market expects the frequent release of customizable products to suit various users. Production planning and scheduling is a vital function that allows manufacturing companies to plan and deliver their products to customers without delays.

Traditionally, there are manufacturing organizations that specialize in high-volume-low-variety production (process-driven); on the other hand, organizations that focus on high-variety-low-volume kind of production strategy (customer-driven) [1]. There have been many studies on improving the production planning and control (PPC) of high-volume-low-variety manufacturing; however, there are fewer academic research or industrial case studies on effectively performing production planning and scheduling in high-variety-low-volume manufacturing [2,3]. These organizations usually follow an engineer-to-order (ETO) manufacturing strategy, and the customer order decoupling point is in the product design or engineering phase [4,5]. ETO manufacturing produces highly customized products and is also known as one-of-a-kind (OKP) production [3,6,7,8,9,10,11]. It differs from other manufacturing strategies like make-to-order (MTO), assemble-to-order (ATO) or make-to-stock (MTS) as the products or production plan is not predetermined [6]. The difficulty in forecasting customer orders and the lack of standardized products increases the volatility and uncertainty in the ETO environment [2,8,9,12]. Therefore, the number of activities that

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require effective decision-making and the people directly involved in PPC is high in ETO manufacturing [7].

The article explores the capability of digitalization to improve production planning and scheduling in ETO manufacturing organizations from a literature study and two industrial case studies. The first case study was conducted with a space products manufacturing organization in Gothenburg, Sweden, and the second was with a high-end textile manufacturing organization in Pollone, Italy. The literature study results provide general information regarding solutions and strategies to enhance production planning and scheduling in the ETO segment. The case study results provide examples of digital solutions designed respectively to the case companies' production planning and scheduling requirements.

2. Methodology

The methodology adopted in this article consists of both theoretical and empirical parts. The theoretical part is a literature review, and the empirical part consists of two case studies in the ETO segment. The literature review and the case studies were conducted in an exploratory manner to understand how digitalization facilitates production planning and scheduling in the ETO segment.

The ***literature study*** was based on the research question: "What strategies and solutions are used to improve production planning and scheduling in manufacturing companies with an ETO strategy?". The literature study started as a pre-study for both case studies and continued with the case studies. Hence, the authors prioritized articles that provided solutions that could help the case studies. The Scopus database was used to find literature. Two sets of keywords were defined using the terminologies engineer-to-order and one-of-a-kind and used for the literature search with necessary Boolean operators. The first keyword was "production planning and scheduling AND engineer-to-order", and the second was "production planning and scheduling AND one-of-a-kind". Five inclusion criteria were used to find the relevant articles from the available literature. After the final inclusion criteria, fourteen articles were selected. Table 1 shows the article inclusion criteria and the number of articles selected.

Table 1. Literature selection criteria

Article Selection	Inclusion Criteria	Keyword 1	Keyword 2
Initial Search		31	26
Only English language	1	31	25
Between 1992 & 2022	2	28	25
Eliminating duplicates		28	24
Based on title & abstract	3	17	13
Based on introduction & conclusion	4	15	9
Based on relevance to case studies	5	10	4

By backward snowballing, additionally, six articles were selected. The articles on developing and implementing scheduling algorithms, dispatching rules, mathematical models, and other heuristic methods as a solution were not considered as they were irrelevant to the case studies under consideration. Finally, twenty articles were used for the literature review.

The ***industrial case studies*** were research projects conducted in parallel but with different duration, project goals, and partner organizations. The qualitative research approach was considered because the case organizations needed support on what, where, and how to improve their production planning and scheduling operations to cope with the new market demands. Hence, the authors needed to primarily understand both organizations' current planning and scheduling operations to identify the root causes of the issues and develop the most beneficial solutions. The first step was to gather information about the current production planning and scheduling activities for both case studies. The data collection methods include field notes, direct observations from supervised factory visits and interviews with relevant stakeholders. For case study 1, it was possible to have supervised factory visits throughout the project duration as the factory location is in Gothenburg, Sweden. For case study 2, the factory location was in Pollone, Italy, and the pandemic situation in Italy has prevented the authors' capacity to travel to the factory location multiple times. Hence, the factory visit was conducted continuously at the production site for two days.

For case study 1, interviews were conducted with personnel from the planning, purchasing, and production teams and project leaders from different product modules to understand how each customer order is processed, planned, produced, and delivered. For case study 2, the interviews were conducted with the production and planning teams. The interview material analysis starts right after the first interview, and the following interview is affected by the results from the first interview. This interview approach was taken as case studies were conducted as explorative studies. It helped the authors familiarize themselves with case companies' current planning and scheduling processes. All interview discussions were designed in a semi-structured manner and performed so that the interviewee could share more details with the interviewer from their own experiences or views rather than just providing direct and short answers to the questions asked. This method proved very helpful for identifying improvement opportunities in the current process at the case companies. The current state analysis identified the main problems and their root causes. In the next step, the authors conducted discussion workshops with company personnel to find relevant solutions for the issues identified that could enhance the production planning and scheduling process's overall efficiency. In both case studies, pilot solution models were developed using digital tools from a user perspective and delivered to the case companies for verification and validation. Implementing the developed solutions in the case companies was not part of the case studies.

3. Results

3.1. Literature Study

The literature study results are classified into scientific articles that propose solutions from a strategy and an operational perspective. The categorization in Table 2 is based on Gosling and Naim [5]. Initially, the findings on strategy solutions are discussed, and later, solutions or tools beneficial for ETO from an operational perspective are discussed.

The article [4] states that supply chain integration is an effective strategy for ETO manufacturing systems. The article emphasizes the importance of a long-lasting supplier relationship and reducing the number of suppliers to control and coordinate the suppliers effectively [4]. The article [13] suggests that supplier relationships are more critical in an ETO sector when compared to traditional manufacturing systems like ATO, MTO, and MTS. In ETO manufacturing systems, the products are seldom standardized, which calls for increased communication and collaboration with suppliers and vendors [13,14]. The article also reasons that it is essential to transfer the customer product specifications precisely and very early, not only to suppliers but also to all partners in the supply chain, to deliver the right product at the right time and in the correct quantity to the customer [13]. Vertical integration is another vital strategy considered beneficial for ETO manufacturing systems [3,13]. Vertically integrated companies are more flexible in offering a broad range of product configurations and promptly responding to customer requirements [13].

Lean or agile manufacturing strategies have also been considered to increase ETO manufacturing systems' efficiency [7]. However, which strategy, lean or agile, suits the ETO sector has yet to be answered clearly [4]. Many articles propose that the lean approach, with its standardization principles, is more suitable for high-volume-low-variety manufacturing, and the agile strategy is better compatible with ETO systems with a high product mix, low standardization, and low volume [3,7,15]. The article [14] suggests an integrated management framework with structured and agile workflows to support coordination activities in the ETO supply chain. On the other hand, lean concepts like just-in-time (JIT), constant work-in-process (CONWIP) and long-term supplier relationships are considered beneficial for ETO manufacturing systems [3,4,8,13,16]. There is a need for more empirical studies to decide between lean and agile manufacturing strategies for ETO manufacturing systems [4]. The article [11] proposes a conceptual concurrent ETO operational framework that focuses on integrative sales, engineering, manufacturing, and test activities in the ETO environment by applying the concepts of mass customization, lean manufacturing, and concurrent engineering. Another article [17] recommends quick response manufacturing (QRM) as an effective strategy for ETO.

By the beginning of the 21st century, simulation tools are used widely for decision support, optimization, and checking the reliability of manufacturing systems under different circumstances [2,3,13,16]. The articles [7,16] provide a conceptual simulation-based architecture for flexibility in virtual OKP manufacturing systems. The literature review article [3] mentions that simulation stands out as the most adopted research method for OKP manufacturing and suggests digital twins as a future direction of simulation-related approaches in OKP [3]. Article [12] also proposes a digital twin prototype system for prescriptive maintenance and flexible PPC in the ETO segment. Another article [15] recommends a decentralized and agile supply chain control system in ETO manufacturing using discrete event simulation. Simulation-based production system analysis helps production planners, engineers, maintenance technicians and experts find alternative methods for handling or reacting to demand variations, material/resource constraints, planned and unplanned production disturbances, and so on [3,13,16].

Most enterprise resource planning systems (ERP) provide information on what has already happened rather than what is happening in real-time [11]. Real-time data is valuable for production planning and scheduling flexibility in the ETO segment [4,15]. The organization's different decision levels in the ETO segment could also lead to many uncertainties in production planning and scheduling [18]. The decisions taken by different functional teams at varying stages of production planning could be coordinated and managed by a collaborative planning system [18]. The collaborative planning system must gather and visualize real-time information from different sources and provide a system-based view for effective decision-making [18]. This collaborative system-based view will help identify or highlight the individual tasks, how each process flows in the planning and how they hinder or affect each other's performance [18].

In this digital age, the effective use of available data and information is considered the primary factor of success and growth for organizations worldwide [13]. To achieve effective data-driven decision-making, all manufacturing systems, irrespective of their manufacturing strategies, need dynamic, efficient, and reliable information systems [13]. The article [9] evaluates the application of advanced planning and scheduling (APS) systems in ETO manufacturing, and the article [10] develops an integrated planning and scheduling model called ETO project scheduling (EPS) for ETO projects capable of integrating into APS-type systems.

The article [19] says that data analytics could effectively map large sets of data from different sources, analyze the data and provide a system-based interactive visualization of the same in user-friendly graphical forms or patterns. Another article [20] states that using data analytics tools along with the ERP system could support the production planning team in better decision-making based on real-time. Production planners could compile historical data to predict future behaviors, trends, or patterns and create different visualizations using data analytics tools to focus on individual aspects of planning that are relevant based on specific organizational needs [20].

Table 2. Categorization of findings from the literature

Solutions from a strategy perspective	**Articles**
Supply chain integration	[4, 13, 14]
Vertical integration	[3, 13]
Lean manufacturing	[3, 4, 8, 13, 16]
Agile manufactruing	[3, 7, 14, 15]
Concurrent ETO operational framework	[11]
Quick response manufacturing	[17]
Solutions from an operational perspective	**Articles**
Simulation based solutions	[3, 7, 15, 16]
Digital twins	[3, 12]
Collaborative planning system	[18]
Advanced planning and scheduling systems	[9, 10]
Data analytics	[19, 20]

3.2. Industrial Case Study 1 - Space Product Manufacturer

The organization manufactures satellite products and composite structures for the space industry and high-precision products for the semiconductor industry. The products are used for specific applications and have unique product structures, designs, materials, specialized production processes, and high-quality requirements, demanding an ETO manufacturing strategy. Each customer order is considered a separate project, and different departments are involved in project creation, production planning, and shop-order execution. The shop orders are released close to the production start date, and the production planning team releases only those orders with no material shortage. Due to this, any shop order with a missing component or components must be replanned. Thus, material shortage causes a hindrance to the releasing of shop orders based on the predefined production schedule, and the replanning of the shop orders causes a ripple effect, which affects the overall production plan. From a broader perspective, the replanning of shop orders causes a waste of time and resources and affects the delivery to the customer, leading to revenue loss, penalties, and customer dissatisfaction.

Therefore, the main problem was the frequent requirement to replan shop orders due to material shortages. Two leading root causes were identified, one internal within the organization and one external with suppliers. The internal issue was a misalignment between component procurement and shop order planning. The project-specific components are ordered to arrive in inventory just before the planned production starting date of the project. The purchasing team orders the parts in such a manner as to maintain a lean inventory to reduce costs. However, the problem is that the purchasing team did not order components in reference to the shop-order requisition dates in the ERP system. There was no link between the component arrival date and the actual requirement date of the component on the shop floor. Therefore, the production planning team does not know the late arrival of a component until the shop-order release, leading to replanning the shop orders. The external issue was the lead-time uncertainty with the supply of project-specific components. Since each project is highly customized, it is challenging to maintain an accurate lead-time history for each project-specific part. The lead-time uncertainty for the project-specific parts is difficult to solve, as it is also tough to forecast customer orders in an ETO segment. Hence, the project team decided to find a solution to the internal problem.

According to the problem under consideration, the component purchase and shop-order planning need to be coordinated. Hence a comprehensive visual mapping of the project-specific components from the purchase date to their actual need date on the shop floor was considered as the solution to facilitate the replanning process. The case company has already been using a data analytics platform called Qliksense, and the company personnel involved with the production planning and scheduling process had a basic knowledge of using the software. It was also found that the Qliksense software allows automatic data uploading from the company ERP system to the software. Therefore, the project team used the Qliksense data analytics platform to develop the solution.

The project team considered one product unit with the most standardised product structure for analysis as an initial step and was determined based on discussions with the case company. The product structure of the selected unit had different sub-assembly levels. Three data sets were extracted as Microsoft Excel files from all the sub-assembly units from the company ERP system to conduct the analysis. The data sets consisted of ‘Declared Parts List’ (DPL List), ‘Purchase Order Lines’ and ‘Shop Order Requisition Lines’ for all sub-assemblies. The input for the analysis in the Qliksense software consists of specific information from these Excel files. The output after the analysis consists of a material scatter plot where all the mutually present components in the ‘Declared Parts List’ Excel file and the ‘Purchase Order Lines’ file are plotted on the X-axis, and their corresponding purchase receipt dates are plotted on the Y-axis. The Y-axis is a dual axis, also indicating the start date of the shop order requisitions.

Fig. 1 shows the conceptual diagram of the material scatter plot results for a specific product unit. The left side of Fig. 1 represents the area in the Qliksense software dashboard where the users can select a particular part description of a product unit, such as AO1 TOP ASSY, in the diagram. Then a material scatter plot will be displayed with all the components included in the AO1 TOP ASSY while connecting each component’s shop order requisition dates with planned receipt dates from purchase order lines. The circular dots represent the components’ planned receipt date in the scatter plot. All the components (dots) displayed on the scatterplot with red color are estimated late deliveries. The scatter plot thus provides a smooth mapping of the components in the parts list file to their purchase order detail and the actual need date of the corresponding components on the shop floor. Visualizing late-arriving components will help the production planners know what parts could cause replanning. This knowledge will help the planning team take a proactive approach to either arrange the timely delivery of material by coordinating with the concerned purchase team and suppliers or perform an early replanning of production orders to avoid the stress in the shop due to last-minute rescheduling. The solution has also been extended to other product units with the manufacturer.

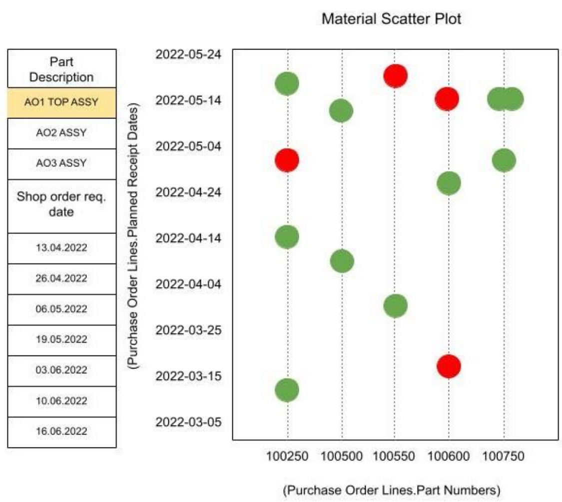

Fig. 1. Material scatter plot conceptual diagram.

3.3. Industrial Case Study 2 - Fabric Manufacturer

The organization manufactures high-quality textiles by sourcing the finest natural fibers like vicuña and cashmere worldwide. Thus, the products are made of unique materials and characteristics with high cost, which demands an ETO manufacturing strategy. For the textile manufacturer, weaving is the most critical process in converting yarns into fabrics, and the production efficiency losses in the weaving process significantly impact overall productivity. The textile manufacturer has a fixed quantity of uniform parallel machines for weaving. Different customer orders are scheduled successively on weaving machines (loom machines), and machines must complete the prior ones before processing the following orders. Hence, a delay in completing a specific order could affect the production pipeline. Therefore, the optimal scheduling of production orders in the weaving machines is vital to meeting customer demands on time.

Customer orders are scheduled for weaving machines based on specific rules, which are defined based on the complexity of the fabric design, yarn material attributes, weaving machine parameters, and machine setup times. Different setup times are required between orders based on the fabric design and the material of the previous yarn type processed on the specific loom machine, and the setup times vary from minutes to hours. In addition, unexpected events such as loom machine failures, operator delays and errors, broken yarns, and material delays also increase the complexity of order scheduling in the weaving process. Hence, order scheduling at the textile manufacturer is a multi-objective problem. The production planners at the manufacturer determine the production schedule with the help of the company's ERP system. The ERP system has an inbuilt method to verify the material and resource availability, and the production schedule is proposed in Gantt Charts for operators.

However, there can be unplanned or urgent orders from three distinct categories – high-priority orders from production, sampling orders, and prototyping orders. These spontaneous orders must be incorporated, and hence there is a constant requirement for replanning and rescheduling and, therefore, the need for efficient replanning or rescheduling tools. Thus, the solution developed consists of a rescheduling tool with two parts - a planning optimization tool (primary part) and a planning validation tool (secondary part) developed by two organizations. The planning optimization tool collects information from the company ERP system on material availability, fabric design parameters, and yarn material attributes. It generates an optimized production plan for the planning validation tool. The planning validation tool considers the loom machine parameters and the production disturbances to verify the delivery feasibility of the optimized production plan using the 3D simulation software Visual Components.

Production disturbances significantly affect productivity, and by incorporating production disturbances' data in the simulation model, the planning validation tool can create a virtual environment for analysis closer to the actual factory environment of the weaving operation. The simulation interface is used to design loom machine models with provisions to add machine-related data like process times, setup times, planned maintenance times, and machine failure data (breakdowns and repair times). Thus, the planning validation tool validates the optimized plan in factory conditions. Fig. 2 shows the framework of the developed solution.

The results from the planning validation tool are fed to a predefined Microsoft Excel file. The Excel file compares the total production time taken in executing the optimized production plan before and after testing with the simulation model, i.e., with or without considering the machine parameters and production disturbances. The variation in the total production time shows the impact of production disturbances and machine parameters. The end-user can decide to verify and validate the optimized production plan proposed by the planning optimization tool every time or on special occasions. These special occasions could be changes in the weaving process operational conditions like machine process times, machine speed, failure patterns, machine repair methods, maintenance schedule, adding or removing loom machines, new product types, and overall factory working conditions. Table 3 shows results on the variation between the planned time and actual time for order completion.

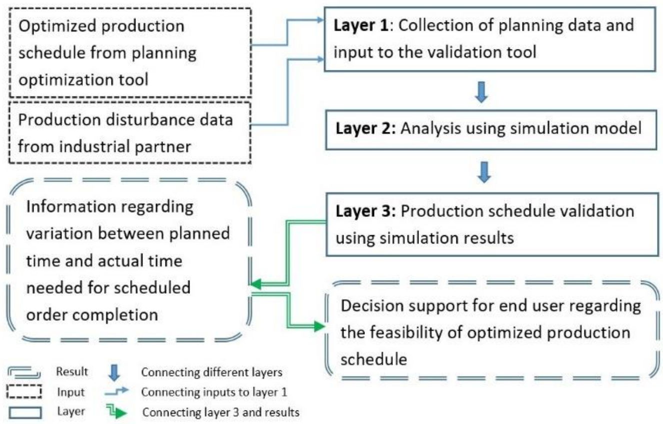

Fig. 2. Solution framework with three layers.

Table 3. Variation between planned and actual time for order completion.

Loom machines	L1	L2	V6	P35	P36
Simulation Hours	200	200	200	200	200
Total fabric pieces	2614	3437	2739	2188	5038
Planned Time (hours)	67.5	91.2	55.6	68.4	179.9
Actual Time (hours)	69.5	93.1	57.0	71.4	183.6
Variation (hours)	**1.9**	**1.8**	**1.3**	**2.9**	**3.6**

4. Discussion & Conclusion

In this part, the authors would like to compare the results between the literature review and case studies and thereby suggest the managerial implications of this article. In connection with the literature study results in Table 2, from a strategy perspective, aspects like supply chain integration and vertical integration and an operational perspective, the application of digital tools like simulation-based solutions and data analytics, and the development of a collaborative planning system are found to be the interesting aspects to compare with the case study results.

A significant aspect of PPC in the ETO segment is the importance of communication and coordination in both external (supplier-manufacturer-customer perspective) and internal (planning and scheduling activities within the manufacturer) environments. From an external perspective, the literature review states that supply chain integration could help better communicate and coordinate with suppliers, and long-lasting supplier relationships are critical in the ETO segment [3, 4, 13]. For case company one, supplier issues were one of the leading causes of material delays. Case company two had fewer material issues as they sourced raw materials from suppliers (animal husbandry) with long-term relationships.

From an internal environment perspective, the literature review suggests that the PPC process in ETO firms is very collaborative and requires a lot of communication and coordination [18]. One common requirement in both case studies was properly communicating updated plans or production schedules to all personnel involved in the planning and scheduling process. Therefore, the literature review and the case studies both propose the requirement of a collaborative planning system that supports effective information visualization to facilitate more data-driven decision-making in the ETO segment [18]. Hence, vertical integration externally and internally is an effective strategy for ETO companies to attain the required flexibility and resilience in production planning and scheduling.

Due to uncertainties, the production plans or schedules were subjected to much replanning or rescheduling in both case studies. The literature study also emphasizes the requirement of frequent replanning and rescheduling in the ETO segment [9]. Therefore, it is evident that ETO companies need support in replanning or rescheduling. The case study solutions developed using data analytics and simulation tools show that digital tools can plan and replan based on real-time data and depicts that digitalization could be an effective means to facilitate replanning and rescheduling in the ETO segment. Nevertheless, the cost of digitalization is a crucial element to consider as there is still a need for maturity and clarity in implementing the necessary systems (sensors, data structures, data security) to achieve full benefits from digital tools.

The literature study states that simulation-related approaches have been the most proposed method from an operational perspective in ETO manufacturing and points out that from a research perspective, digital twins could be the future direction [3]. However, from the overall literature analysis, most solutions proposed in the articles are in the conceptual phase. The executed ones are quite case-specific, like the case studies in this article.

Accordingly, there needs to be more consensus on the most reliable strategies and solutions regarding production planning and scheduling in the ETO segment and indicate the need for more collaborative efforts between the industry and the research community. To conclude, with the support of theoretical and empirical research, this article provides evidence and substantiates the importance of digitalization in improving production planning and scheduling in ETO manufacturing.

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