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Potentials of using real-time data to increase the update frequency of production planning and control strategies in MTO: a discrete event simulation study

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Abstract
In recent years, production planning and control strategies have gained increasing importance within manufacturing enterprises to stay competitive by enhancing the ability to meet and quickly adapt to the hyper-dynamic requirements of highly volatile markets. In this context, traditional production planning and control strategies like material requirements planning often result in long lead times and high work in progress due to their weak responsiveness to short-term fluctuations in demand. However, new production planning and control strategies and concepts based on the usage of real-time data, as a fundamental principle of Industry 4.0, may have the potential to compensate for the shortcomings of traditional approaches. By using a discrete event simulation based on the data of an electronics manufacturing company, the potential of using real-time data to increase the update frequency in different production planning and control strategies in make to order production systems is analyzed.

Keywords Production planning and control · Industry 4.0 · Real-time, make to order · Discrete event simulation

1 Introduction

The usage of real-time data in logistics and operations management is considered as one of the main principles of Industry 4.0. Manufacturing processes are constantly generating a large volume of data that can be used as a starting point for real-time-orientated production planning and control (PPC) strategies leading to highly responsive, reconfigurable, and time-efficient production systems (Arica and Powell 2014;

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Dallasega et al. 2019a, 2019b, 2020) based on the principle concepts of mass customization (Bednar and Modrak 2014; Matt et al. 2016).

In this context, the integration of modern information and communication technology, interconnected networks, and physical processes is called cyber-physical-systems (CPS). CPS capture data from the physical world via sensors, use the internet and cloud computing to communicate between the connectors and interact with the physical world using mechatronic actuators (Lee 2008; Zsifkovits and Woschank 2019). This enables autonomous control systems, which can satisfy customer demands in real-time (Spath et al. 2013; Dallasega et al. 2017). CPS, as well as the Internet of Things (IoT), allow enterprises to sense deviations from the schedule as soon as they appear (Magoutas, et al. 2014; Chaopaisarn and Woschank 2019).

However, in many cases, PPC strategies do not use real-time data, even if novel technologies allow generating them. Moreover, to the best of our knowledge, the impact of different levels of update frequency on various PPC strategies has not been investigated yet. Therefore, the paper evaluates the impact of increasing the update frequency by investigating the push and pull PPC strategies that have best established themselves both in the literature and in industrial practice, namely MRP, KANBAN, CONWIP, COBACABANA, and POLCA (Kapeller 2017, 2018; Woschank et al. 2020; Thürer 2016; Thürer et al. 2017). In the first step, the paper investigates the impact of increasing the update frequency on material requirement planning (MRP), as a push-based PPC strategy, and on KANBAN, as a push-based PPC strategy. In the second step, the paper investigates the impact of increasing the update frequency on the pull-based PPC strategies COBACABANA, CONWIP, KANBAN, and POLCA. The approach is validated by using a discrete event simulation based on the data of an electronic make to order (MTO) enterprise. The initial simulation of the production environment was realized with the software Tecnomatix Plant Simulation 16 by Siemens PLM. Since especially the investigation of the update frequency required further modifications of the simulation model, Python 3.10 was used for the final simulations. The resulting data were analyzed using IBM SPSS Statistics 26. Therefore, the main hypotheses to be tested in this research are formulated as follows:

H1 Increasing the update frequency will lead to significant differences in logistics performance between push and pull production planning and control strategies.

H2 Increasing the update frequency will lead to significant differences in logistics performance between COBACABANA, CONWIP, KANBAN, and POLCA production planning and control strategies.

2 Related works

For the review of related works, the authors conducted a systematic literature review (SLR) in Scopus to identify the state-of-the-art research on PPC strategies which consisted of a keyword search supplemented by a subsequent backward and forward search (Woschank et al. 2020). The SLR was performed by using a modified version of the PRISMA methodology based on Miklautsch et al., Page et al., and vom Brocke et al. (Miklautsch and Woschank 2022; Page et al. 2021; Brocke et al. 2009). Figure 1 shows the results of the SLR based on the search string in Scopus. Thereby, the authors focused on studies dealing with production planning and control strategies in the context of Industry 4.0. We considered only studies in the English language which pertain to the subject areas of engineering and business, management, and accounting. Specifically, more recent works were considered, and, therefore, a time horizon from 2017 until 2023 was set. Moreover, according to Wohlin (Wohlin 2014) we used a backward and forward snowballing approach to include relevant works. While in 2020 only 10 out of a total of 52 studies were classified as highly pertinent, the screening in 2022 has isolated 20 out of a total of 91 studies which speaks to the timeliness and relevance of the research.

Cadavid et al. present a SLR analyzing the state-of-the-art machine learning (ML) approaches applied to PPC. According to their results, scientific literature rarely considers customer, environmental, and human-in-the-loop aspects when linking ML to PPC. Moreover, applications rarely link PPC to product and process design as well as to the logistics processes. Considering future research directions,

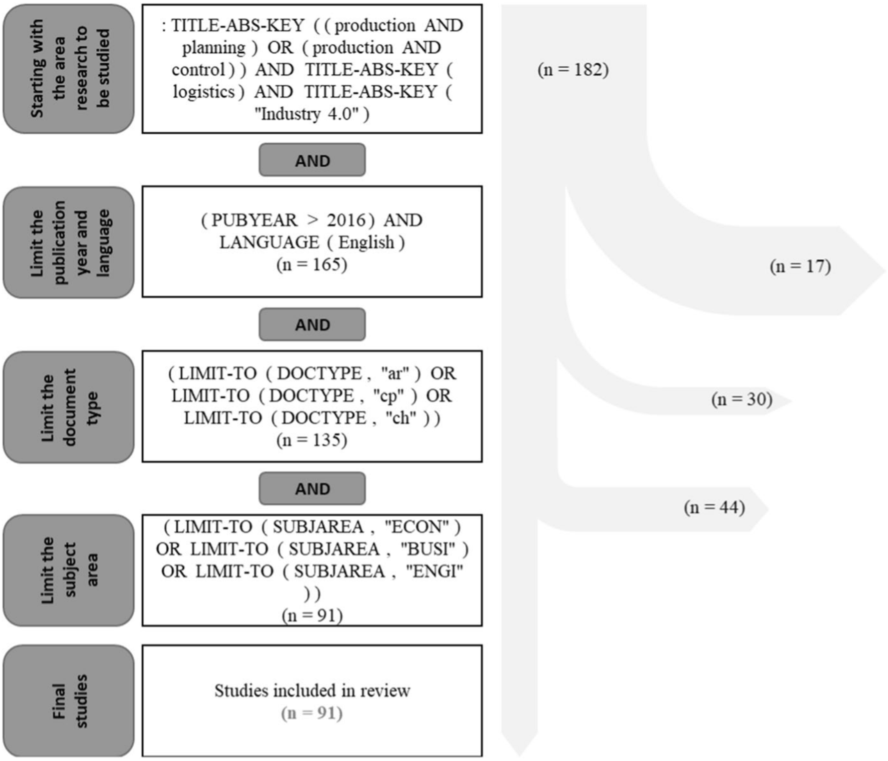


Fig. 1 Systematic literature review based on PRISMA (Miklautsch and Woschank 2022; Page et al. 2021; Brocke et al. 2009)

they further suggest using IoT technologies to collect data and update the ML model to adapt it to manufacturing system changes (Cadavid et al. 2020).

Panetto et al., summarize the challenges for Cyber-Physical-Production systems (CPPS) as studied by the IFAC research community. According to their results, an infrastructure is needed that supports the adaptation of models according to the changing environment over time to support modification and (self-) adaptation (Panetto et al. 2019). Similarly, Bendul and Blunck present the vision of Industry 4.0 to assign tasks of production control to ‘smart’ objects, such as machines, parts, and products, to reach distributed control architectures with higher flexibility, higher adaptability, and, as such, a higher logistics performance (Bendul and Blunck 2019). According to Ivanov et al., Industry 4.0 technologies enable data interchange between the product and workstations, flexible stations able to execute various technological operations, and real-time capacity utilization control. However, modern production and supply chains are challenged by increasing uncertainty and risks as well as multiple feedback cycles where control theory could contribute to gaining further insights regarding the management of these challenges (Ivanov et al. 2018).

Gräßler and Pöhler describe the change of a milling workstation by adding different sensors and computers to reach a self-controlling cyber-physical device in a laboratory environment. In more detail, the system is distributed and decentralized whereby, through the negotiation of resources, a common planning schedule for all orders is reached. The real-time measurement of data is used to improve assessments in the planning process, for the improvement of process execution as well as for the identification of consequences of disturbances. However, no quantitative improvement of logistics performance indicators compared to a conventional workstation was reported (Gräler and Pöhler 2018). Similarly, Choi et al. state that, in a smart manufacturing environment, procurement, production, logistics, service, and the product itself are connected to the network and controlled in real-time based on CPS. According to them, to establish a CPS in manufacturing, real-time information exchanges from the shop floor level to the business level need to be enabled. They argue that data acquisition from non-equipment factors, like human operators, is much more difficult to obtain than from machines because of issues like non-standardized working environments and data protection regulations (Choi et al. 2017). Hortskemper and Hellingrath present the concept of order allocation flexibility and the potential of CPS in implementing and empowering the concept leading to a further increase of flexibility in the production system. However, they argue that the concept might introduce further complexity into the PPC system and the costs for such a system might not be worthwhile for all companies (Horstkemper and Hellingrath 2016).

According to Strandhagen et al., a shift towards real-time control requires new conceptual models for planning and control. They state that real-time control is, today, mostly applied at machine and production line levels, while, on the planning levels, existing methods are based on conventional concepts like cyclic data processing and re-planning. However, according to them, Industry 4.0 technologies have the potential to enable real-time planning and control of all planning activities. They argue that real-time planning and control is easier to be applied in repetitive production environments because collecting data may be easier, enabling higher volumes and quality of production data (Strandhagen et al. 2017). Similarly, Ruiz Zúñiga et al. state that, even in more advanced Industry 4.0 manufacturing companies, real-time data gathered at the shop floor level are mostly used for monitoring different machines and work centers (e.g., processing times, failures, waiting times, and blocking times) and not for optimizing PPC processes (Ruiz Zúñiga et al. 2017).Crawford et al. describe the advantages of using a machine learning framework with a dataset knowledgeability to improve local decision-making with the novel approach of integrating domain expertise directly into the dataset and model-building activities by using a case study in autoclave manufacturing (Crawford et al. 2021). Figueiras et al. investigate the usage of big data provision in Industry 4.0 logistics processes in the automotive sector by focusing on the areas of the optimization of stock and inventory and the planning of new parts arrivals (Figueiras et al. 2021). Altenmüller et al. and Marchesano et al. focus on the usage of different reinforcement learning approaches to improve decision-making processes in the production control of flow shop lines. Thereby, a significant reduction in logistics costs was reported and it was demonstrated that the Q-learning algorithm can be successfully applied to manage order dispatching in a complex environment including time constraints (Altenmüller et al. 2020; Marchesano et al. 2022).

Considering production scheduling, Fernandez-Viagas and Framinan investigate the benefits of integrating real-time shop floor status with advanced upstream/downstream processes data to support the scheduling of manufacturing processes using a simulation. According to their results, stochastic procedures are better than deterministic ones, both in the predictive and predictive-reactive scenarios (Fernandez-Viagas and Framinan 2022). According to Framinan et al. the usage of real time information about job completion is beneficial for rescheduling in a flow shop environment, as long as the variability of processing times is not to high (Framinan et al. 2019). Ghaleb et al. investigated the impact of real-time updates on the current shop-floor status to create and update schedules compared to the conventional approach where activities are anticipated and postponed as needed. Event-driven rescheduling (ER) policies, where the rescheduling is triggered only when a disruption happens, outperform continuous rescheduling policies because they are more computationally efficient (Ghaleb et al. 2020). Similarly, Ghaleb et al. propose a real-time optimization-based system of maintenance plans and production schedules in a flexible job shop environment to react to several production disruptions, including random breakdowns, due date changes and new job arrivals. According to their results, the real-time optimization-based system outperforms the commonly used approach in practice (e.g. fixed sequencing) by reaching a cost-saving of about 27% on average (Ghaleb et al. 2021).

Summing up, the content analysis of the SLR highlights that it is difficult to use real-time production monitoring data to support PPC strategies. Indeed, modern Industry 4.0 approaches enable the generation of real-time data on the shop floor but most of the data generated in production systems are frequently not completely exploited for PPC purposes. Therefore, this research investigates the effect of using real-time data, to increase the update frequency of push and pull PPC strategies on logistics performance indicators.

3 Research design and methodology

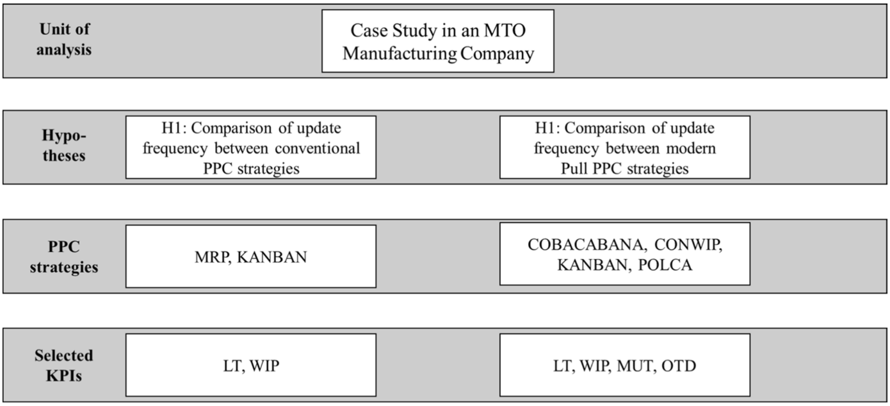
The research is based on the Design of Experiments (DoE) approach, where the aim is to plan, design and analyze the experiment to derive valid and objective conclusions (Antony 2014). Here, changes are made intentionally to the input variables (machine or process factors) to observe the related changes in the output variables. To reduce the experimental bias, the principles of (1) randomization, (2) replication, and (3) blocking were applied (Antony 2014). Randomization was applied in the assignment of orders to the PPC system to make sure that all orders are equally affected by noise factors (e.g., MTBF, MTTR, MTTF, MTTA). Replication was guaranteed by conducting a number of 8,100 simulation runs under the individual settings of the respective production planning and control by varying the update frequency. Blocking was applied by arranging similar simulation runs into blocks to mitigate external noise factors by considering, a daily, weekly, and monthly update frequency (forming so the different blocks).

The paper investigates the impact of increasing the update frequency on logistics performance between push and pull production planning and control strategies. Therefore, the authors focused on material requirement planning (MRP) and KANBAN because they are considered the most important conventional approaches in industrial enterprises (Kapeller 2018). Within the centralized MRP approach, the material is pushed through production from one machine to the subsequent machine after processing the order. In contrast to MRP and KANBAN, a decentralized pull system is based on the usage of cards as a trigger for the transport of material starting from the outbound storage (Kapeller 2017, 2018; Sendil Kumar and Panneerselvam 2007; Gstettner 1998; Jodlbauer and Huber 2008; Dolgui 2010). Thereby, the logistics performance was operationalized by using lead time (LT) and work in progress (WIP).

In the second step, the paper investigates the potential of increasing the update frequency on lead time logistics performance between different pull production planning and control strategies. Specifically, COBACABANA, CONWIP, KANBAN, and POLCA were selected as the most relevant card-based production planning and control strategies (Thürer 2016; Thürer et al. 2017). In this context, KANBAN is considered to be the pioneering card-based system. Although KANBAN systems were originally used to control a company's internal supply chain, they can also be applied to control problems of all kinds. The basic task of KANBAN systems is to combine processes or flows of resources. In such a system, one process turns to the preceding process to obtain the resources it needs. The preceding process produces the product that is currently needed or will be needed in the future. All KANBAN systems are different, so there is no universal KANBAN system as each of them has different functions. Examples of Kanban types include work in progress (WIP) KANBAN and production KANBAN. While WIP KANBAN deals with the task of replenishing stocks that have been consumed, the production Kanban tries to synchronize production lines with each other (Kistner et al. 2001). CONWIP is similar to production KANBAN by sharing information between internal supply chains. However, in CONWIP systems, only one large loop is formed. This loop is the connection between the start and end points of the production line. However, the biggest difference between the systems is the anonymization of the cards. While, in KANBAN systems, each card is assigned to exactly one order, in CONWIP systems a card only signals that orders have been fulfilled. Thus, the decision of which order to accept next is moved from the end to the beginning of the production line. However, the operation of such a system only makes sense if a straight flow production is practiced (Jaegler et al. 2018; Spearman et al. 1990). POLCA is a card-based production planning and control system that emphasizes short lead times and fast reactions related to customer requirements. In this system, like KANBAN, loops are formed between the different workstations. However, like CONWIP, POLCA uses anonymized cards for production planning and control. This means that a POLCA card signals to the system that a processing step has been completed, and the respective workstation is now available again. Thus, POLCA loops are decoupled from each other. Since the POLCA cards are anonymized, the system is supported by an MRP system, which is designed to ensure that only required intermediate products are produced. The task of the MRP system is to calculate the earliest possible release date for each activity. Due to this calculation, only urgent orders are processed. However, the usage of an MRP system entails certain weaknesses. For example, inaccuracies in the calculation of release dates have a strong impact on the entire system (Riezebos 2010). COBACABANA, as a card-based control system, should be primarily used in production systems with higher complexity of orders. In this system, a central planning entity makes all decisions to release orders. Unlike other systems, no loops are set up between the individual stations. Hence, loops are formed between the individual workstations and the release function. Orders are collected in a central pool, which is located upstream of the production system. These orders are now released in such a way that the workload of the workstations is balanced and delivery dates can be met in the best possible way. Another difference between this system and other production planning and control strategies is that it always focuses on one workstation and one order. This means that each card specifically represents an activity on a workstation. COBACABANA thus makes it possible to control production even in the case of different variants of the process route and widely differing processing times (Thürer 2016; Thürer et al. 2017). The logistics performance was operationalized by using the lead time (LT), work in progress (WIP), machine utilization (MUT), and on-time delivery (OTD). Figure 2 summarizes the concept of our research, which focuses on the investigation of the following two hypotheses:

H1 Increasing the update frequency will lead to significant differences in logistics performance between push and pull production planning and control strategies.

H2 Increasing the update frequency will lead to significant differences in logistics performance between COBACABANA, CONWIP, KANBAN, and POLCA production planning and control strategies.



Unit of analysis	Case Study in an MTO Manufacturing Company	
Hypo-theses	H1: Comparison of update frequency between conventional PPC strategies	H1: Comparison of update frequency between modern Pull PPC strategies
PPC strategies	MRP, KANBAN	COBACABANA, CONWIP, KANBAN, POLCA
Selected KPIs	LT, WIP	LT, WIP, MUT, OTD

Fig. 2 Concept development

Moreover, according to Unver, we derived three levels of update frequency (50, 100, and 150 time units) based on the ISA 95 framework leading to three test groups for the subsequent testing of the hypotheses (Woschank et al. 2020; Unver 2013). The empirical analyses are based on data from an electronics manufacturing company working in the MTO environment. Within an initial analysis of the company, we applied value stream mapping (VSM) as a method for data gathering, where we focused on one specific product group. As displayed in Fig. 3, based on the VSM, we identified the following four value-adding processes: Step 1: raw printing, solver paste printing, printing check (SMT), step 2: picking and placing of components, soldering (THT), step 3: programming and function control (PFC), and step 4: final assembly (FA). Moreover, we recorded the following parameters for every process step: cycle time (C/T), change over time (C/O), lot size, availability, mean time to repair, lead time, pieces per shift, and the number of shifts. In sum, we identified the following problems: (1) The productivity of the production and logistics department is quite low, (2) frequently, the customer demand cannot be satisfied, (3) high costs

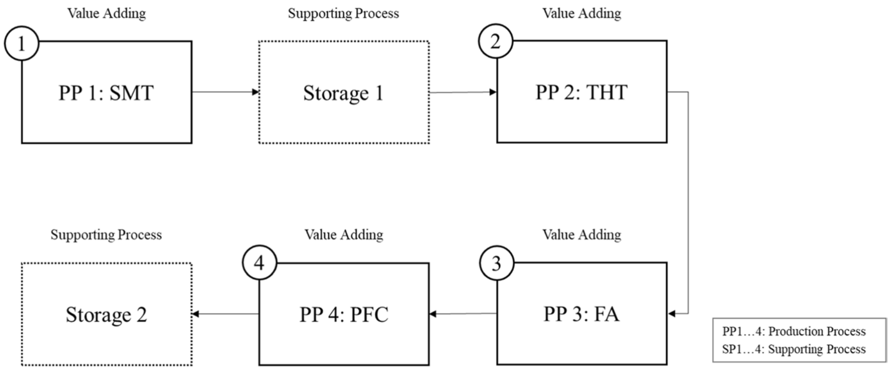


Fig. 3 Simulation development

due to high stock levels within the production, and (4) the planning data in the production planning system are not up to date.

Specifically, we identified a low accuracy of the information for the precise planning of orders (e.g., cycle times, setup times, lead times) as one of the major problems within the current PPC strategy. This is connected to the fact that the company did not use real-time data from the shop floor to update PPC parameters like C/T, lead time, and others. Furthermore, because of not measuring the production progress, the logistics system is frequently challenged with necessary changes in the production sequence, which are mainly forced by rush orders. To compensate for the actual shortcomings, we evaluate the impact of increasing the update frequency within the different push and pull PPC strategies.

4 Simulation

The concept regarding the investigation of different levels of update frequencies and various PPC strategies to enhance PPC in an MTO environment was evaluated by using a discrete event simulation. In this context, simulation as a research methodology is frequently used in empirical research studies for the investigation of theoretically derived cause-effect relationships in complex systems. Thereby, the simulation offers the benefits of high internal validity, reliability, and the isolation of confounders by relying on formal modeling procedures (Cooper and Schindler 2014; Rabe et al. 2008). In addition, the external validity of simulation experiments will be enhanced by using real data from the underlying case study (Bortz and Döring 2007). Moreover, the research design of this paper is based on the VDI 3633 guidelines for the simulation of (production-) and logistics systems which consider the steps of preparation, simulation, and evaluation (März et al. (2011). The simulation process can be divided into the following steps: Reading the data; selecting the simulation according to the PPC principle; initializing the simulation; starting the simulation; performing a simulation run; checking the termination conditions; and retrieving the results and parameters. The authors used the software packages Tecnomatix Plant Simulation 16 by Siemens PLM and Python 3.10. The simulation framework is based on our case study, which includes primary data from the VSM analysis. The simulation approach is displayed in Fig. 4.

For the testing of the first hypothesis, we created a simulation model in Plant Simulation to compare the impact of the update frequency between the centralized and push-based MRP with the decentralized and pull-based KANBAN as the most used conventional PPC systems in industrial enterprises. Thereby, the update frequency was simulated by generating three different test groups and the logistics performance was operationalized by using two indicators (LT, WIP). In this case, we focused on the measurement of LT and WIP in the production system. For the evaluation of the second hypothesis, we created a simulation model in Python to investigate the impact of update frequencies within the card-based production planning and control strategies COBACABANA, CONWIP, KANBAN, and POLCA. Again, the update frequency was simulated by generating three different test groups, and the logistics performance was operationalized by using four indications (LT, WIP,

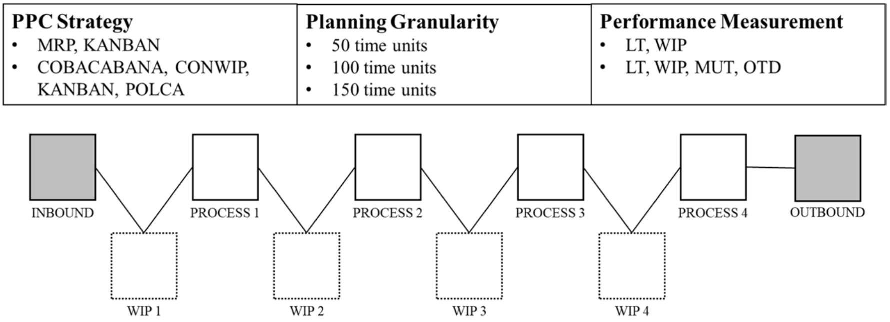


Fig. 4 Simulation approach

MUT, OTD). Moreover, we measured machine utilization (MUT) and on-time delivery (OTD). In sum, we created six different simulation models which were computed by using three different levels of update frequencies and measured by a set of latent indicators for the logistics performance. In total, we computed 5,400 simulation runs. Moreover, we computed additional simulation models with 2,700 simulation runs, which did not show any significant difference ($p < 0.05$) in comparison to the initial simulation results.

5 Results and discussion

In the first step, the authors investigate if an increased update frequency will lead to significant differences in lead time (LT) and work-in-progress (WIP) between push and pull production planning and control strategies. Figure 5 displays that compared to MRP (mean LT: 8578.75; Std.D.: 271.574; mean WIP: 25.29; Std.D.: 0.498), the implementation of KANBAN (mean LT: 6000.78; Std.D.: 633.314; mean WIP: 11.00; St.D.: 0.000) would lead to a reduction of 30.05% in LT and a reduction of 56.51% in WIP.

For the testing of H1, we performed a comparative evaluation of an increased update frequency on logistics performance MRP and KANBAN. As a result, increasing the update frequency leads to a reduction of 0.69% in LT and 0.44% in WIP within the MRP approach and a reduction of 1.79% in LT but no reduction in WIP within the KANBAN approach. Based on the statistical procedures, the independent t-test showed highly significant differences ($p < 0.01$; $F = 593.658$; $T = 2.789$) regarding the impact of an increased updated frequency on LT between MRP and KANBAN. As a result, H1 can be tentatively confirmed, meaning an increased update frequency leads to significant differences in logistics performance between MRP and KANBAN.

In the second step, the authors further investigate if an increased update frequency will lead to significant differences in logistics performance between COBACABANA, CONWIP, KANBAN, and POLCA. Table 1 displays the comparative results

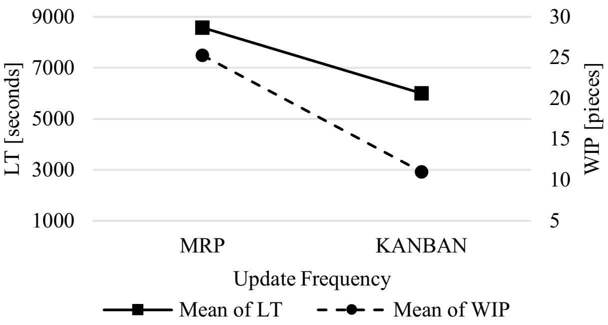


Fig. 5 Comparison of MRP versus Kanban

by showing the change of LT according to the three different update frequency groups.

As displayed in Table 1, the lead time increases substantially with a higher update frequency for COBACABANA and CONWIP, while it increases only slightly for POLCA and considerably decreases for KANBAN. While for the PPC strategies, COBACABANA and CONWIP a slight increase can be observed already when the update frequency is doubled from 100 to 50, for POLCA even a shortening of the lead time can be noticed. The lead time of KANBAN is considerably lower than the lead times of the other PPC methods already at an update frequency of 100. At an update frequency of 10, the lead time of KANBAN turns out to be only one-third of COBACANABA or less than half of CONWIP or POLCA. One explanation of the LT reduction for KANBAN is that the transfer of information in this process consumes a high proportion of the time. Since the individual process steps are directly linked to one another and the information takes a relatively long time to make its way through the production line to the starting point via the KANBAN cards a higher update frequency is very crucial. In addition, having information available more quickly increases the system's ability to process orders faster and thus shorten LT. Moreover, if the update frequency increases, empty containers in Kanban have replenished faster leading also to a positive effect on LT reduction. For POLCA, the increased update frequency does not have a large effect, which could be related to the fact that this method is supported by an MRP system that does not take much advantage of the increased frequency at all. The increase of LT for CONWIP can

Table 1 LT results depend on the update frequency

		Update frequency [min]			Difference [%]		
		100	50	10	100→50	50→10	100→10
[a]	COBACABANA	306.28	316.99	364.39	3.50%	14.95%	18.97%
[b]	CONWIP	233.50	236.87	272.89	1.45%	15.21%	16.87%
[c]	KANBAN	169.30	135.30	111.35	−20.08%	−17.70%	−34.23%
[d]	POLCA	225.24	220.91	234.06	−1.92%	5.95%	3.91%

Table 2 WIP results depending on the update frequency

		Difference [%]	Difference [%]	Difference [%]	Difference [%]		
		100	50	10	100→50	50→10	100→10
[a]	COBACABANA	15.32	15.85	18.22	3.50%	14.95%	18.97%
[b]	CONWIP	11.68	11.85	13.65	1.45%	15.20%	16.87%
[c]	KANBAN	438.21	443.83	454.57	1.28%	2.42%	3.73%
[d]	POLCA	11.26	11.05	11.71	– 1.92%	5.95%	3.91%

Table 3 MUT results depending on the update frequency

		Update frequency [min]			Difference [%]		
		100	50	10	100→50	50→10	100→10
[a]	COBACABANA	0.70	0.82	0.82	16.24%	0.14%	16.40%
[b]	CONWIP	0.52	0.73	0.82	39.90%	11.98%	56.53%
[c]	KANBAN	0.55	0.68	0.76	24.21%	11.56%	38.57%
[d]	POLCA	0.41	0.58	0.78	42.54%	34.38%	91.54%

be explained by the fact that in this process no information about the machine utilization or the progress of the orders is passed on between the start and end of the production line. Increasing the update frequency here has the effect that as soon as a job is finished and a card is free again, the information is passed on more quickly to the start and a new job is started. This can lead to a possible overload of the system. Table 2 displays the comparative results by focusing on the work in progress (WIP).

Table 2 shows that in all four PPC strategies, WIP increases when the update frequency is increased from 100 to 10. Moreover, a substantial increase can be seen for COBACABANA and CONWIP while the increase is much smaller for KANBAN and POLCA. However, considering POLCA, WIP is reduced only by changing the update frequency from 100 to 50. It is worth noticing that within all four PPC strategies increasing the update frequency only leads to a small change in WIP. In comparison, increasing the update frequency from 50 to 10 highly increases the WIP for COBACABANA and CONWIP. Thus, the update frequency has a high influence on the WIP in methods COBACABANA and CONWIP, while the WIP in KANBAN and POLCA does not change much with an increased update frequency.

Table 3 displays the comparative results by focusing on machine utilization (MUT). For COBACABANA, the utilization of machines plays an important role. Thereby, an increased update frequency leads to the fact that the orders are recalculated and, therefore, released to increase the total utilization of the machines. However, this also leads to an increase in the LT. For machine utilization (MUT), all PPC strategies show a substantial increase with higher update frequency. While for COBACANABA we see an increase of 16.24% at the first stage of increasing the update frequency, a further increase of the update frequency from

50 to 10 min only leads to an increase of MUT of 0.14%. In contrast to COBACABANA, we notice a substantial increase in the update frequency within all other PPC strategies. By far the greatest effect was achieved by increasing the update frequency for POLCA, where an increase of 91.54% was achieved when the frequency was from 100 to 10. With this frequency, a better value is achieved than with KANBAN and it is only slightly below COBACABANA and CONWIP. For COBACANA, the small increases can be explained by the fact that already a high starting value was achieved by using the initial update frequency of 100. Thereby, the MUT is 15% higher compared to the best results of the other PPC strategies. This can be explained by referring to the basic idea of COBACABANA, which tries to avoid unnecessary or early idle times. One reason for such idle times can be fluctuating processing times, which lead to large idle times with other PPC strategies. In general, at a high update frequency, a very high value of the MUT is achieved with all PPC strategies. The update frequency is most important for POLCA.

Table 4 displays the comparative results by focusing on on-time delivery (OTD). In OTD, we achieved the best result with KANBAN. While we obtained only a minimal increase in OTD for COBACABANA and CONWIP the increase in the update frequency, led to substantially better OTD values for KANBAN and POLCA. For KANBAN, the increase in on-time delivery can be attributed to the reduction in LT at a higher update frequency. For COBACABANA, CONWIP, and POLCA, the value of OTD reaches saturation at increasing update frequency from 100 to 50. There is only a minimal change by increasing the update frequency for COBACABANA and CONWIP.

For the testing of H2, we performed a comparative evaluation of an increased update frequency on logistics performance between COBACABANA, CONWIP, KANBAN, and POLCA. Based on the statistical procedures, the ANOVA showed highly significant differences regarding the impact of an increased updated frequency between the four PPC strategies. Table 5 summarizes the output of the ANOVA calculations. As a result, H2 can be tentatively confirmed, meaning that an increased update frequency leads to significant differences in logistics performance between COBACABANA, CONWIP, KANBAN, and POLCA.

Table 4 OTD results depending on the update frequency

		Update frequency [min]			Difference [%]		
		100	50	10	100→50	50→10	100→10
[a]	COBACABANA	0.398	0.40	0.40	0.50%	0%	0.50%
[b]	CONWIP	0.399	0.40	0.40	0.25%	0%	0.25%
[c]	KANBAN	0.60	0.80	0.80	33.33%	0%	33.33%
[d]	POLCA	0.20	0.40	0.40	100.00%	0%	100.00%

Table 5 ANOVA results

	Difference [%] UF 100→10	F	*p*-value	Sig
COBACABANA				
LT	18,97%	5511.122	0.000	Significant
WIP	18,97%	5511.122	0.000	Significant
MUT	16,40%	3105.907	0.000	Significant
OTD	0,50%	5.406	0.004	Significant
CONWIP				
LT	16,87%	20,026.756	0.000	Significant
WIP	16,87%	20,026.756	0.000	Significant
MUT	56,53%	32,686.336	0.000	Significant
OTD	0,25%	5.060	0.007	Significant
KANBAN				
LT	− 34,23%	178,055.744	0.000	Significant
WIP	3,73%	9963.611	0.000	Significant
MUT	38,57%	2456.740	0.000	Significant
OTD	33,33%	8.771E+29	0.000	Significant
POLCA				
LT	3,91%	3862.748	0.000	Significant
WIP	3,91%	3862.748	0.000	Significant
MUT	91,54%	95,647.861	0.000	Significant
OTD	100,00%	4292E+30	0.000	Significant

6 Limitations and implications for future research

The limitations of the research are summarized below.

1. Single product manufacturing line: The simulation of the proposed approach is based on a single product manufacturing line. The effect of using real-time data to increase the update frequency of PPC strategies by considering multi-product manufacturing lines has not been investigated.
2. Three levels of update frequency: We derived three levels of update frequency consisting of 10-, 50-, and 100-time units. This is because the focus of our research was to see if there is a significant impact on logistics performance indicators by increasing the update frequency. The authors decided to start with an update frequency of 10 limiting a potential negative impact of inducing system nervousness (Fernandez-Viagas and Framinan 2022) and so deteriorating the performance. However, identifying the limit of increasing the update frequency without inducing system nervousness was not the focus of our study.
3. Pull PPC strategies: We compared just four pull PPC strategies, KANBAN, CONWIP, COBACABANA, and POLKA. Although, these can be considered the most relevant card-based production planning and control strategies (Framinan et al. 2019; Ghaleb et al. 2020).

4. Parameters for the simulation model: The parameters of the simulation model were retrieved from one case study.
5. Job shop versus flow shop: The considered case study is based on a flow shop manufacturing strategy. Thus, the machines/processes were executed in a strict sequence. Considering a job shop manufacturing strategy would increase the complexity of the analyzed problem.

Based on the listed research limitations the following future research directions are suggested:

1. To better analyze the impact of changing the update frequency on the logistics performance indicators, the granularity should be extended from three to more levels. Here, cycle times and change-over times of the simulated processes should be considered.
2. Customer interaction strategies like engineer to order (ETO) or make to stock (MTS) may have a different impact on the logistics performance indicators. Thus, the simulation model should be extended to consider different customer interaction strategies.
3. A sensitivity analysis should be included to analyze how the logistics performance indicators are affected based on changes in the input variables. Other performance indicators like the responsiveness of the PPC system to changing customer demands should be considered.
4. The current simulation model could be extended according to the concept of a digital twin. Here, important manufacturing parameters are reflected in real-time in the digital model and by using the simulation, in case of problems, improvement actions can be suggested and implemented in time. The proposed research will help to identify which parameters are important to reflect in real-time in the digital twin.
5. To better reflect the conditions in practice, the simulation results should be re-verified with the case study data after implementing the real-time update frequency of the PPC system. Moreover, the proposed approach should be empirically re-validated within other manufacturing enterprises to identify and study potential difficulties and implementation barriers.

7 Conclusions

The paper investigates the effect of using real-time data in push and pull production planning and control (PPC) strategies on logistics performance by increasing the update frequency. The approach was modeled based on a practical case study of an electronics company and validated utilizing a discrete event simulation.

According to the analyzed literature, Industry 4.0 approaches enable the generation of real-time data on the shop floor but most of the data generated in production systems are frequently not completely exploited for PPC purposes. Thus, the paper aims to confirm and answer two central research hypotheses. Hypothesis 1

(H1) claims that increasing the update frequency has a significantly higher impact on the logistics performance of pull than push PPC strategies. Hypothesis 2 (H2) claims that by increasing the update frequency there are significant differences in the logistics performance of COBACABANA, CONWIP, KANBAN, and POLCA pull PPC strategies.

Considering H1, increasing the update frequency leads to a significantly higher reduction of LT between push and pull PPC strategies but no reduction in WIP was recorded. Therefore, H1 can only be partially confirmed. Considering H2, the lead time increases substantially with a higher update frequency for COBACABANA and CONWIP, while it increases only slightly for POLCA and considerably decreases for KANBAN. On the other hand, by increasing the update frequency, the level of WIP significantly increases in all analyzed pull PPC strategies. Therefore, also H2 can only be partially confirmed.

In future research, a specific analysis of the parameters that are useful to measure in real-time to be incorporated in a digital twin will be performed (Kaiblinger and Woschank 2022). Also, real-time-orientated production planning and control strategies must in turn be fed back into teaching and learning approaches for engineering students at the tertiary level to provide them with state-of-the-art knowledge and to increase their competences regarding the optimization of modern production and logistics systems (Pacher et al. 2022, 2023; Omazic et al. 2022a, 2022b; Pacher and Woschank 2020). Moreover, that approach will be empirically re-validated within further manufacturing enterprises operating with other customer interaction strategies to identify and study potential difficulties and implementation barriers.

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Declarations

Conflict of interests The authors have no competing interests to declare that are relevant to the content of this article.

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References

Altenmüller T, Stüker T, Waschneck B et al (2020) Reinforcement learning for an intelligent and autonomous production control of complex job-shops under time constraints. Prod Eng Res Devel 14:319–328. https://doi.org/10.1007/s11740-020-00967-8

Antony J (2014) Design of experiments for engineers and scientists, 2. ed. Elsevier insights. Elsevier, London

Arica E, Powell DJ (2014) A framework for ICT-enabled real-time production planning and control. Adv Manuf 2:158–164. https://doi.org/10.1007/s40436-014-0070-5

Bednar S, Modrak V (2014) Mass customization and its impact on assembly process' complexity. Int J Qual Res 8:417–430

Bendul JC, Blunck H (2019) The design space of production planning and control for industry 4.0. Comput Ind 105:260–272. https://doi.org/10.1016/j.compind.2018.10.010

Bortz J, Döring N (2007) Forschungsmethoden und evaluation: für human- und sozialwissenschaftler, 4th edn. Springer, Berlin

Vom Brocke J, Alexander S, Bjoern N et al. (2009) Reconstructing the giant: On the importance of rigour in documenting the literature search process

Cadavid JPU, Lamouri S, Grabot B et al (2020) Machine learning applied in production planning and control: a state-of-the-art in the era of industry 40. J Intell Manuf. https://doi.org/10.1007/s10845-019-01531-7

Chaopaisarn P, Woschank M (2019) Requirement analysis for SMART supply chain management for SMEs. In: Proceedings of the international conference on industrial engineering and operations management Bangkok, Thailand, March 5–7, pp 3715–3725

Choi S, Kang G, Jun C et al (2017) Cyber-physical systems: a case study of development for manufacturing industry. Int J Comput Appl Technol 55:289–297. https://doi.org/10.1504/IJCAT.2017.10006845

Cooper DR, Schindler PS (2014) Business research methods, 12th edn. McGraw-Hill, New York

Crawford B, Sourki R, Khayyam H et al (2021) A machine learning framework with dataset-knowledgeability pre-assessment and a local decision-boundary crispness score: an industry 4.0-based case study on composite autoclave manufacturing. Comput Ind 132:103510. https://doi.org/10.1016/j.compind.2021.103510

Dallasega P, Rojas RA, Rauch E et al (2017) Simulation based validation of supply chain effects through ICT enabled real-time-capability in ETO production planning. Procedia Manuf 11:846–853. https://doi.org/10.1016/j.promfg.2017.07.187

Dallasega P, Rojas RA, Bruno G et al (2019a) An agile scheduling and control approach in ETO construction supply chains. Comput Ind 112:103–122. https://doi.org/10.1016/j.compind.2019.08.003

Dallasega P, Woschank M, Zsifkovits H et al (2020) Requirement analysis for the design of smart logistics in SMEs. In: Matt DT, Modrák V, Zsifkovits H (eds) Industry 4.0 for SMEs. Springer International Publishing, Cham, pp 147–162

Dallasega P, Woschank M, Ramingwong S et al (2019) Field study to identify requirements for smart logistics of European, US and Asian SMEs, pp 844–855

Dolgui A (2010) Supply chain engineering: useful methods and techniques. Springer, London

Fernandez-Viagas V, Framinan JM (2022) Exploring the benefits of scheduling with advanced and real-time information integration in industry 4.0: a computational study. J Ind Inf Integr 27:100281. https://doi.org/10.1016/j.jii.2021.100281

Figueiras P, Lourenco L, Costa R et al. (2021) Big data provision for digital twins in industry 4.0 logistics processes. In: 2021 IEEE international workshop on metrology for industry 4.0 and IoT (MetroInd4.0&IoT). IEEE, pp 516–521

Framinan JM, Fernandez-Viagas V, Perez-Gonzalez P (2019) Using real-time information to reschedule jobs in a flowshop with variable processing times. Comput Ind Eng 129:113–125. https://doi.org/10.1016/j.cie.2019.01.036

Ghaleb M, Zolfagharinia H, Taghipour S (2020) Real-time production scheduling in the Industry-4.0 context: addressing uncertainties in job arrivals and machine breakdowns. Comput Operations Res 123:105031. https://doi.org/10.1016/j.cor.2020.105031

Ghaleb M, Taghipour S, Zolfagharinia H (2021) Real-time integrated production-scheduling and maintenance-planning in a flexible job shop with machine deterioration and condition-based maintenance. J Manuf Syst 61:423–449. https://doi.org/10.1016/j.jmsy.2021.09.018

Gräler I, Pöhler A (2018) Intelligent devices in a decentralized production system concept. Procedia CIRP 67:116–121. https://doi.org/10.1016/j.procir.2017.12.186

Gstettner S (1998) Leistungsanalyse von produktionssystemen. Physica, Heidelberg

Horstkemper D, Hellingrath B (2016) Employing order allocation flexibility in cyber-physical production systems. Procedia CIRP 57:345–350. https://doi.org/10.1016/j.procir.2016.11.060

Ivanov D, Sethi S, Dolgui A et al (2018) A survey on control theory applications to operational systems, supply chain management, and Industry 4.0. Annu Rev Control 46:134–147. https://doi.org/10.1016/j.arcontrol.2018.10.014

Jaegler Y, Jaegler A, Burlat P et al (2018) The ConWip production control system: a systematic review and classification. Int J Prod Res 56:5736–5757. https://doi.org/10.1080/00207543.2017.1380325

Jodlbauer H, Huber A (2008) Service-level performance of MRP, kanban, CONWIP and DBR due to parameter stability and environmental robustness. Int J Prod Res 46:2179–2195. https://doi.org/10.1080/00207540600609297

Kaiblinger A, Woschank M (2022) State of the art and future directions of digital twins for production logistics: a systematic literature review. Appl Sci 12:669. https://doi.org/10.3390/app12020669

Kapeller JA (2017) Explorative potentialevaluierung der kombination von fertigungssteuerungsstrategien. ein simulationsbasierter ansatz zur evaluierung von produktions- und fertigungsverfahren im bereich der linienfertigung. In: Zsifkovits HE, Altendorfer-Kaiser S (eds) Logistisches produktionsmanagement: 4. Wissenschaftlicher Industrielogistik-Dialog in Loeben (WiLD), 1. Auflage. Epubli, Berlin, pp 1–18

Kapeller JA (2018) EoPaMS. Systematische potentialevaluierung der sequentiellen kombination von fertigungssteuerungsstrategien für den bereich der linienfertigung. Ein simulationsbasierter ansatz. Dissertation, Montanuniversitaet Leoben

Kistner KP, Steven M (2001) Produktionsplanung: Mit 71 Abbildungen und 3 Tabellen, 3, vollständig überarbeitete Aufl. Springer Kompetenz in Wirtschaft. Physica-Verlag, Heidelberg

Lee EA (2008) Cyber physical systems: design challenges. In: Proceedings of the 11th IEEE symposium on object/component/service-oriented real-time distributed computing: Orlando, Florida, May 5–7, 2008. IEEE Computer Society, pp 363–369

Magoutas B, Stojanovic N, Bousdekis A et al (2014) Anticipation-driven architecture for proactive enterprise decision making. In: CAiSE forum/doctoral consortium, pp 121–128

Marchesano MG, Guizzi G, Castellano D et al. (2022) On reinforcement learning in production control and its potentiality in manufacturing. In: Proceedings of the Summer School Francesco Turco, pp 1–14

März L, Krug W, Rose O et al. (eds) (2011) Simulation und optimierung in Produktion und logistik: praxisorientierter leitfaden mit fallbeispielen. VDI-Buch. Springer, Berlin

Matt DT, Rauch E (2016) Chapter two designing assembly lines for mass customization production systems. In: Modrak V (ed) Mass customized manufacturing: theoretical concepts and practical approaches, vol 8. CRC Press, Boca Raton, pp 15–36

Miklautsch P, Woschank M (2022) A framework of measures to mitigate greenhouse gas emissions in freight transport: systematic literature review from a Manufacturer's perspective. J Clean Prod 366:132883. https://doi.org/10.1016/j.jclepro.2022.132883

Omazic A, Pacher C, Zunk BM et al. (2022) Systematic derivation of learning objectives for fostering the development of sustainability competences in the education of industrial engineering and management students. In: Proceedings of the 5th European international conference on industrial engineering and operations management (IEOM), July 26–28, 2022, Rome, Italy, pp 1–3

Omazic A, Pacher C, Zunk BM et al. (2022) Empirically-based recommendations for competence profiles for industrial engineering and management students in austria: theoretical framework and preliminary empirical findings. In: Proceedings of the 5th European international conference on industrial engineering and operations management (IEOM), July 26–28, 2022, Rome, Italy, pp 1–3

Pacher C, Woschank M, Rauch E et al (2022) Systematic development of a competence profile for industrial logistics engineering education. Procedia Comput Sci 200:758–767. https://doi.org/10.1016/j.procs.2022.01.274

Pacher C, Woschank M, Zunk BM (2023) The role of competence profiles in industry 5.0-related vocational education and training: exemplary development of a competence profile for industrial logistics engineering education. Appl Sci 13:3280. https://doi.org/10.3390/app13053280

Pacher C, Woschank M (2020) Competencies in the digitalized working environment: a concept for engineering education in higher education institutions. In: Proceedings of the international conference on industrial engineering and operations (IEOM) management, October 20–22, 2020, Harare, Zimbabwe, pp 1203–1212

Page MJ, McKenzie JE, Bossuyt PM et al (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 372:n71. https://doi.org/10.1136/bmj.n71

Panetto H, Iung B, Ivanov D et al (2019) Challenges for the cyber-physical manufacturing enterprises of the future. Annu Rev Control 47:200–213. https://doi.org/10.1016/j.arcontrol.2019.02.002

Rabe M, Spieckermann S, Wenzel S (2008) Verifikation und validierung für die simulation in produktion und logistik: vorgehensmodelle und techniken. VDI-Buch. Springer, Berlin

Riezebos J (2010) Design of POLCA material control systems. Int J Prod Res 48:1455–1477. https://doi.org/10.1080/00207540802570677

Ruiz Zúñiga E, Syberfeldt A, Urenda Moris M (2017) The internet of things, factory of things and industry 4.0 in manufacturing: currentand future implementations. In: Gao J, El Souri M, Keates S (eds) Advances in manufacturing technology XXXI: Proceedings of the 15th international conference on manufacturing research, incorporating the 32nd national conference on manufacturing research, September 5–7, 2017, University of Greenwich, UK, pp 221–226

Sendil Kumar C, Panneerselvam R (2007) Literature review of JIT-KANBAN system. Int J Adv Manuf Technol 32:393–408. https://doi.org/10.1007/s00170-005-0340-2

Spath D, Gerlach S, Hämmerle M et al (2013) Cyber-physical system for self-organised and flexible labour utilisation. In: Proceedings of the 22nd international conference on production research (ICPR ’13)

Spearman ML, Woodruff DL, Hopp WJ (1990) CONWIP: a pull alternative to Kanban. Int J Prod Res 28:879–894. https://doi.org/10.1080/00207549008942761

Strandhagen JW, Alfnes E, Strandhagen JO et al (2017) The fit of Industry 4.0 applications in manufacturing logistics: a multiple case study. Adv Manuf 5:344–358. https://doi.org/10.1007/s40436-017-0200-y

Thürer M (2016) Kartenbasierte Steuerungssysteme für eine schlanke Arbeitsgestaltung: Grundwissen Kanban, ConWIP, POLCA und COBACABANA. Springer Fachmedien Wiesbaden, Wiesbaden

Thürer M, Stevenson M, Protzman C (2017) Card-based control systems for a lean work design: the fundamentals of kanban, conwip, polca, and … cobacabana. CRC Press, Boca Raton

Unver HO (2013) An ISA-95-based manufacturing intelligence system in support of lean initiatives. Int J Adv Manuf Technol 65:853–866. https://doi.org/10.1007/s00170-012-4223-z

Wohlin C (2014) Guidelines for snowballing in systematic literature studies and a replication in software engineering. In: Shepperd M, Hall T, Myrtveit I (eds) Proceedings of the 18th international conference on evaluation and assessment in software engineering. ACM, New York, pp 1–10

Woschank M, Dallasega P, Kapeller JA (2020) The Impact of planning granularity on production planning and control strategies in MTO: a discrete event simulation study. Procedia Manuf 51:1502–1507. https://doi.org/10.1016/j.promfg.2020.10.209

Zsifkovits H, Woschank M (2019) Smart logistics—technologiekonzepte und potentiale. BHM Berg-Huettenmaenn Monatsh 164:42–45. https://doi.org/10.1007/s00501-018-0806-9

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