

EVALUATING PRODUCTION PLANNING AND CONTROL SYSTEMS IN DIFFERENT ENVIRONMENTS: A COMPARATIVE SIMULATION STUDY

Wolfgang Seiringer¹, Balwin Bokor¹, Altendorfer Klaus¹

¹Dept. of Production Operation Management, University of Applied Sciences Upper Austria,
Wehrgrabengasse 1-3, A-4400 Steyr, Austria

ABSTRACT

Selecting the appropriate production planning and control systems (PPCS) presents a significant challenge for many companies, as their performance, i.e. overall costs, depends on the production system environment. Key environmental characteristics include the system's structure, i.e. flow shop, hybrid shop, or job shop, and the planned shop load. Besides selecting a suitable PPCS, its parameterization significantly influences the performance. This publication investigates the performance and the optimal parametrization of Material Requirement Planning (MRP), Reorder Point System (RPS) and Constant Work In Progress (ConWIP) at different stochastic multi-item multi-stage production system environments by conducting a comprehensive full factorial simulation study. The results indicate that MRP and ConWIP generally outperform RPS in all observed environments. Moreover, when comparing MRP with ConWIP, the performance clearly varies depending on the specific production system environment.

1 INTRODUCTION

The main goal of production planning is to ensure that production systems output precisely aligns with customer demand, serving as a critical bridge between operational capabilities and market expectations. This objective places production planning and control at the core of manufacturing companies, embodying both challenging and important roles. The challenge arises from the necessity to manage a tremendous amount of complex information, such as customer demand, Bill of Materials (BoM), work plans, and more (Reuter et al. 2017). Meanwhile, their importance is highlighted by its impact on the production system performance, i.e. overall costs (Hopp and Spearman 2011).

To address the complexities of information and enhance efficiency, various production planning and control systems (PPCS) have been developed. Among these, Material Requirements Planning (MRP), Reorder Point System (RPS), and Constant Work In Progress (ConWIP) are widely recognized in research and frequently adopted in practice. Selecting the most suitable PPCS presents a significant challenge for many companies due to the unique nature of their production system environments. A critical factor in this decision-making process is the production system environment, encompassing aspects such as the production system structure or the planned shop load. Particularly, the structure of the production system, whether it is a flow shop, hybrid shop, or job shop can significantly impact the performance of a PPCS. In a flow shop, production orders move through a series of sequential workstations. Conversely, a job shop the processing sequence is tailored to the specific requirements of the production order. A hybrid shop merges aspects of both, enabling flexible operation sequences at certain workstations while others follow a predetermined order (Hillier et al. 1999).

Transitioning from the discussion on the critical role of production system environments on PPCS performance, it's noteworthy that despite the extensive research conducted on these systems, the comparative analysis remains relatively scarce. Gupta and Snyder (2009) identified only 20 articles comparing two or more PPCS. Since, their research merely three significant studies emerged comparing PPCS: Jodlbauer and Huber (2008), Miclo et al. (2019) and Thüerer et al. (2022). Jodlbauer and Huber (2008) evaluated MRP, Kanban, ConWIP and DBR, focusing on parameter stability and environmental robustness for a multi-item multi-stage flow shop production system. They found ConWIP to be superior

when optimally parametrized but also noted its lack of robustness, as minor deviations from optimal parametrization led to significant performance deviations. Moreover, they highlighted the robustness of MRP against environmental uncertainty and mentioned the necessity for additional parametrization of Kanban in case environmental uncertainty diminishes. Miclo et al. (2019) then compared Demand Driven MRP (DDMRP) with MRP and Kanban within a flexible multi-item multi-stage flow shop production system, taking into account different levels of demand uncertainty. Their simulation study led to the conclusion that DDMRP outperformed both methods, while MRP was found to be the least effective, regardless of the level of demand uncertainty. Thürier et al. (2022) adapted the model of Jodlbauer and Huber (2008) by integrating a single bottleneck and different due date tightness, in addition to neglecting stochastic aspects, i.e. machine breakdowns, scrap parts, lot sizes, to compare MRP, Kanban, DBR, DDMRP. Their findings emphasized the superiority of DBR and DDMRP, especially over MRP. Moreover, they highlighted that tighter due dates require PPCS which realizes shorter production lead times, i.e. time span from actual production start to actual production end. Yet, comprehensive comparisons of different PPCS remain scarce, and the findings are largely inconclusive. Additionally, the examination of various environmental characteristics, especially the performance impact of different production system structures, is still lacking. This gap is particularly critical as real-world production systems continue to increase in complexity (Bergmann and Heinicke 2017).

Therefore, this publication conducts a comprehensive full factorial simulation study to evaluate the performance of MRP, RPS, and ConWIP across different stochastic multi-item and multi-stage production system environments. In doing so, we explore three distinct production system structures: flow shop, hybrid shop, and job shop, alongside three levels of planned shop load. The performance is evaluated based on various cost components, including WIP costs, finished goods inventory (FGI) costs and tardiness costs. Moreover, the study also discusses the optimal parameterization of each PPCS at different production system environments. Thus, the following research questions are addressed:

- RQ1: *Which production planning and control system (MRP, RPS, ConWIP) demonstrates superior performance across diverse production system structures (flow shop, hybrid shop, job shop) and different planned shop loads?*
- RQ2: *How do environmental characteristics, especially production system structures and planned shop load, necessitate adjustments in the parametrization of MRP, RPS, and ConWIP for optimal performance?*

This research offers valuable insights for both the academic field and managerial practice. Academically, it contributes to addressing the scarce research on PPCS comparisons and explores the research gap in evaluating PPCS across various environmental characteristics, focusing on production system structures. Managerially, it provides decision-makers with a detailed analysis of the most effective PPCS method under specific environments and investigates PPCS performance as well as the approximated optimal parameterization for different environments.

This publication is structured as follows: Section 2 provides a brief overview of PPCS characteristics and delves into the operational specifics of MRP, RPS, and ConWIP. In Section 3, we introduce our complex simulation model and examine the three production system structures observed. The comprehensive numerical study is outlined in Section 4, followed by a discussion of the results in Section 5. The publication concludes with final thoughts and suggestions for further research.

2 PRODUCTION PLANNING AND CONTROL SYSTEMS

To provide an overview of the investigated PPCS, we first detail four key characteristics that allow for differentiation. Subsequently, we explore these characteristics as well as the production planning and order release mechanisms together with the planning parameters for the three investigated PPCS. Lastly, we include *Table 1* to summarize the PPCS based on the outlined characteristics.

2.1 Characteristics

Firstly, PPCS can be classified based on their *operational mechanism* as either *push* or *pull*. The literature offers numerous definitions for these mechanisms, which have been effectively summarized by Bertolini et al. (2015). We align upon the definition provided by Hopp and Spearman (2004), where a pull system restricts the amount of WIP within the production system, in contrast to push systems, which do not impose an explicit limit on WIP. Secondly, we differentiate PPCS by their *demand orientation*, distinguishing between *demand-driven* systems and those *authorizing production*. *Demand-driven* systems leverage information on future demands to plan production, whereas systems that authorize production rely on downstream demand or customer withdrawal (Cochran and Kaylani 2008). Thirdly, the *control structure* is identified as either *centralized* or *decentralized*. *Centralized* systems rely on a single authorization unit for production planning and order release, whereas *decentralized* systems distribute decision-making to individual units on the shop floor level (Woschank et al. 2021). Lastly, we evaluate the *planning complexity*, reflected in the number of planning parameters, distinguishing between *system-level parameterization* and *item-level parameterization*. *System-level parameterization* applies universally across all items, whereas *item-level parameterization* involves setting parameters specifically for each item, respective component. This distinction is crucial, as *system-level parameterization* significantly reduces the effort needed for maintaining accurate master data, which is crucial for ensuring performance (Pansara 2023).

2.2 Material Requirements Planning (MRP)

MRP is a *push* PPCS developed by Orlicky (1975) where production planning and order release is based on four *centrally* controlled steps. These four steps are: netting, lot-sizing, backward scheduling, and BOM explosion also described in detail by Hopp and Spearman (2011). At the netting step, material quantities are determined by offsetting gross requirements, derived from customer orders and/or forecasts, against the current inventory, excluding safety stock to prevent depletion during planning, and incorporating scheduled receipts (Matsuura and Tsubone 1991). Given that MRP leverages information concerning customer orders and forecasts, MRP can be characterized as a *demand-driven* PPCS. At the lot-sizing step, the net requirements can be batched based on lot-sizing policies to balance set-up/ordering effort against inventory holding (Yelle 1979). Two commonly applied lot-sizing policies for MRP are Fixed Order Quantity (FOQ) and Fixed Order Period (FOP). FOQ orders a predetermined quantity or a multiple of it upon each time reordering occurs, whereas FOP batches net requirements within predefined time intervals. At the next step, planned start dates are established by backward scheduling from the planned end date based on the planned lead times. Lastly at the BOM explosion, the steps are repeated for the underlying MRP item, systematically to the deepest BOM level. As the WIP is not explicitly restricted by performing these steps, MRP is a *push* PPCS. To perform these four steps, three *item-level* planning parameters are required: safety stock, lot size with the chosen lot-sizing policy, and planned lead time. The safety stock is essential for buffering against shortages due to unexpected demands with short customer required lead times or scrap, yet it raises inventory costs. The lot-size aims to balance set-up/ordering effort against inventory holding, influencing setup frequency, machine occupation per batch and shop load. The planned lead time defines the available time to produce the respective item, including waiting times due to machine occupation and considering the inherited fluctuation of the production system, i.e. stochastic processing time (Altendorfer 2019).

2.3 Reorder Point System (RPS)

RPS is a *pull* PPCS, leveraging on the Economic Order Quantity (EOQ) model, which focuses on minimizing the inventory management costs, i.e. set-up/ordering effort and inventory holding, by employing optimized order quantities at stock replenishment (Silver et al. 1998). Thereby, production planning and order release is *decentralized* for each item based on comparing the reorder point with the inventory position (Vollmann et al. 1997). The inventory position of an item is determined by its current inventory level plus any scheduled receipts minus any backorders. Thus, RPS *authorizes production* without leveraging demand information. If the inventory position falls below the reorder point, a production

order is scheduled and released based on FOQ lot-sizing policy, i.e. a predetermined quantity or a multiple of it (Seiringer et al. 2023). Therefore, the planning parameters are the reorder point and the lot size on an *item-level* basis, where the reorder point must meet the demand during the replenishment time and take into account uncertainties in demand and production. Additionally, RPS has a conceptual connection to the well-known PPCS Kanban, as discussed by Yang (1998). Kanban is considered a subtype of RPS, where the reorder point in Kanban is effectively the sum of all Kanban containers minus one, multiplied by the container lot size. However, it distinguishes itself with its visual signaling or card system to initiate new production orders. This inherent relationship implies that our study, while focusing on RPS, also covers Kanban principles and applications.

2.4 Constant Work in Progress (ConWIP)

Spearman et al. (1990) introduced ConWIP as a *pull* alternative to Kanban, where production planning is based on a work-ahead-window and order release is controlled through cards by associating WIP and WIP-cap with production orders. Setting the WIP-cap based on production orders lead to a constrained ability for load balancing. Addressing this limitation, Thürer et al. (2019) linked the WIP-cap to workload measured in standard processing time, i.e. required time to process production order, rather than on the count of production orders, which improved performance significantly. Building on this, for further discussion, we also associate WIP and WIP-cap with workload, aligning with the approach to enhance performance. In detailing production planning, ConWIP is *demand-driven* as net requirements are determined based on either a Master Production Schedule (MPS) or directly from on customer orders. The MPS can apply lot-sizing policies at the creation of the production orders to balance set-up/ordering effort against inventory holding. Production order release is only permitted if the due date falls within the work-ahead-window extended by the current date, effectively acting as a scheduling window. Thus, the work-ahead-window prevents premature production order release, thereby controlling FGI (Bokor and Altendorfer 2024). These production orders are prioritized according to Earliest-Due-Date (EDD), with *centralized* release permitted only in case the shop floor WIP is below the WIP-cap. The released production orders are then dispatched at conventional ConWIP based on First-In-System-First-Out (FISFO) (Spearman et al. 1990). Both planning parameters, i.e. work-ahead-window and WIP-cap, apply universally across all items, offering a significant advantage through *system-level parameterization* (Spearman et al. 2022). However, as noted by Jaegler et al. (2018), complex production system structures might necessitate additional, independently parameterized ConWIP-loops to sustain performance.

The following *Table 1* summarizes the four characteristics for the three investigated PPCS. To underscore the significance of planning complexity, particularly relevant in simulation studies where combinatorics result in a vast array of combinations during full factorial enumeration, we also include a summary of the number of planning parameters. Full factorial designs are highly valued for their thoroughness and the depth of insight they provide as stated by Law (2014) and (Mongomery 2012). However, they can become resource-intensive and time-consuming with an increase in the number of factors and levels, as the total number of experiments (simulations) increases exponentially (Seiringer et al. 2022). Here, n represents the number of items/components, highlighting how this factor influences the scope and scale of the analysis.

Table 1: Characteristics of Investigated PPCS.

	MRP	RPS	ConWIP
Operational mechanism	push	pull	pull
Demand orientation	demand-driven	authorizing production	demand-driven
Control structure	centralized	decentralized	centralized
Planning complexity	item-level	item-level	system-level
Required planning parameters	$3n$	$2n$	2

3 SIMULATION MODEL

To assess the performance of the three investigated PPCS, we develop a stochastic multi-item multi-stage simulation model and integrated three different production system structures, focusing on flow shop, hybrid shop, and job shop. We first outline the investigated production system structures including the BoM. Afterwards, we discuss the customer demand, including the customer required lead time and the connection to the planned shop load. This is followed by an in-depth exploration of the integrated production planning and order release mechanisms of the observed PPCS, building upon the foundational concepts presented in Section 2 *Production Planning and Control Systems*. Lastly, we discuss the order processing in the simulation model.

3.1 Production System Structure

Each production system structure consists of 8 items, each with a specific share of the total demand, represented by the proportions $\{0.100, 0.075, 0.200, 0.125, 0.075, 0.150, 0.150, 0.125\}$ for the i^{th} item, i.e. for the 1st item, 0.100; and so on. Each item, as well as components at lower levels, requires just one component from the preceding level. However, to process an item or component also more machines can be required at one BoM level. The lowest BoM level at each production system structure correspondence to the item, whereas the highest level of the BoM level represents the raw material, which is always available and not planned. *Figure 1* offers a detailed overview of the three observed production system structures, including their BoM configurations.

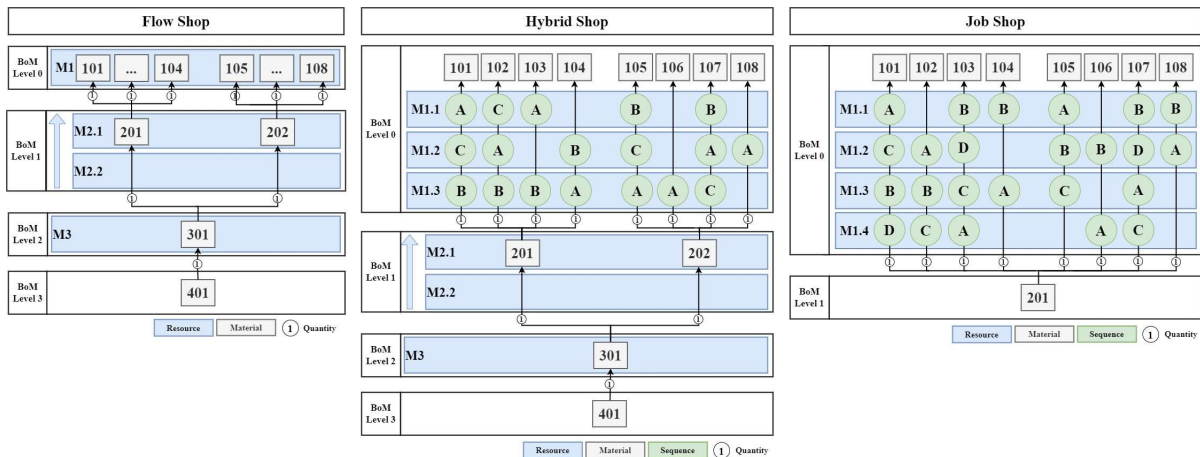


Figure 1: Investigated Production System Structures including Bill of Material.

As depicted in *Figure 1*, the flow shop structure is designed with 4 machines and extends through 4 BoM levels, diverging at both BoM level 2 and BoM level 1 as it approaches the final item. Moreover, at the BoM level 1, two machines are required to produce the components, i.e. component 201 and 202. *Figure 1* also introduces the hybrid shop structure, which incorporates 6 machines and maintains the same 4 BoM levels with a similar divergence. It initiates with a flow shop material flow but transitions into a job shop production system at BoM level 0, where the production path is determined by the item and not all machines are necessary for processing. The sequence of machines at BoM level 0 is indicated the green-bordered letters, starting with 'A' and so forth. Lastly, the job shop structure, as depicted in *Figure 1*, involves 4 machines and 2 BoM levels. Since, the BoM level 1 at the job shop structure correspondence to the raw material, only one BoM level, i.e. BoM level 0, is planned. This BoM level 0 is similar to the identical BoM level at the hybrid shop structure, as the sequence of the machines varies and not all machines are required to process each item.

3.2 Customer Demand

To assess the influence of planned shop load levels on PPCS performance, we adjust the expected mean customer order quantities of the 8 items, resulting in planned shop loads of $\epsilon \{0.85, 0.90, 0.95\}$. Nonetheless, the proportionality of the items remains constant as stated in Section 3.1 *Production System Structure*. Despite varying planned shop loads, a deterministic customer order for each item, containing just that single item, is generated in every period. To include uncertainty in the customer demand, the actual quantities of these 8 items follow the lognormal distribution with a coefficient of variation (CV) of 0.2. The customer required lead time consists of a fixed portion of 10 periods and a lognormal distributed variable proportion with an expected mean of 5 periods and a CV of 0.5.

3.3 Production Planning and Order Release

The production planning and order release mechanism differs for each PPCS and is generally discussed in Section 2 *Production Planning and Control Systems*. To specify for this publication, concerning MRP we apply FOP lot-sizing policy and plan each component respectively item, i.e. BoM level 0, separately. Nevertheless, to mitigate the complexity of combinatorics as detailed in Table 1, we standardize planning parameters across all components and separately across all items. Thus, for instance, the components 201, 202, and 301 depicted in Figure 1 share identical planning parameters. For RPS, the standard configuration is applied, and again distinctions concerning the planning parameters are only made between components and items. For ConWIP an MPS is integrated, which batches gross requirements based on FOP lot-sizing policy to balance set-up effort against inventory holding. Moreover, in scenarios involving more than one planned BoM level, such as in the flow shop and hybrid shop production structures, two ConWIP-loops are implemented to enhance system performance, as described by Huang et al. (2015). One loop is designated for items, i.e. BoM level 0, while the other manages all components. With two ConWIP-loops in place, the planned start dates for items are determined by backward scheduling based on the estimated item lead time, and the planned start date for components is set by further backward scheduling from this point, based on the estimated component lead time. The earliest planned start date for items is calculated by subtracting the work-ahead-window buffer from the planned start dates for items, facilitating earlier release in case components are available. Therefore, the work-ahead-window equals the estimated item lead time plus the work-ahead-window buffer. Upon completion of a production order at the last machine in a ConWIP loop, the WIP level for that specific ConWIP loop is reduced by the workload, i.e. standard processing time including set-up, associated with the production order.

3.4 Order Processing

The released orders are processed based on their required production path. The expected mean processing time varies for each item respective component at each machine. Whereas the expected mean setup time within one machine is consistent, accounting for 10% of the available production time. This results in reduced setup times as the number of items or components processed on a single machine increase, and vice versa. The expected required capacity, i.e. the time to produce demand including setup, as well as the available capacity, are identical across all machines. This uniformity ensures a consistent planned shop load for each machine, regardless of the production system structure. Hence, no bottleneck machine exists. Both the actual processing time and actual set-up time follows a lognormal distribution with a CV of 0.2. Since MRP and ROP do not mandate a specific dispatching rule, First-In-First-Out (FIFO) is utilized, while for ConWIP, FISFO is implemented, following its conventional application as specified by Spearman et al. (1990). After completion the finished goods remain in the FGI until the customer required due date is reached. In case of tardiness, the delivery is executed immediately. The released orders are processed based on their required production path. The expected mean processing time varies for each item respective component at each machine.

4 NUMERICAL STUDY

To comprehensively explore the performance of the investigated PPCS, we conduct a full factorial simulation study for nine different production system environments. Initially, we categorize these environments by their production system structure, i.e. flow shop, hybrid shop, and job shop. Each structure is analysed at three levels of planned shop load, creating nine unique environments. For each environment, we approximate the optimal planning parameters for all three PPCS. For MRP: we set the planned lead time in days; apply FOP lot-sizing policy measured in days; and safety stock levels as a proportion of the item's expected demand per day, or for components as a sum of the demands of items requiring that component. For example, setting a safety stock level of 2 for an item with an expected demand of 50 per day results in a total safety stock of 100. For ROP: we set the reorder-point and the lot size based on similar ratio-based logic. For ConWIP: we apply an MPS which batches gross requirements based on FOQ lot-sizing policy; apply separate ConWIP-loops for items and components, whereby we associate WIP and WIP-cap with workload in minutes and set both WIP-caps identically; we apply an estimated item lead time measured in days for backward scheduling in case of two ConWIP-loops; we use a work-ahead-window buffer, also measured in days, to determine the earliest start date for items by subtracting the work-ahead-window buffer from the planned start date; in cases with only one ConWIP loop, the estimated item lead time serves as the work-ahead-window.

As highlighted in Section 3.3 *Production Planning and Order Release*, to reduce the combinatorial effect associated with setting the planning parameters in a full factorial enumeration for MRP and ROP, we employ identical planning parameters across all items or components within a single production system environment. Since the job shop production system structure features only one planned BoM level, only the planning parameters concerning the items are planned, which also results in a single ConWIP-loop. The following Table 2 summarizes all tested production system environments as well as planning parameters used in our full factorial enumeration.

Table 2: Investigated Environments and Planning Parameters for each PPCS.

		Min	Max	Step size	Iterations
Env.	Production system structure	-	-	-	3
	Planned shop load	0.85	0.95	0.05	3
Different production system environments					9
MRP	Planned lead time items [days]	1	6	1	6
	FOP lot size items [days]	1	4	1	4
	Safety stock items [prop. demand]	0	1.5	0.5	4
	Planned lead time components [days]	1	3	1	3
	FOP lot size components [days]	1	4	1	4
	Safety stock components [prop. item demand]	0	1.5	0.5	4
	Total iterations MRP for flow shop production system environment				13 824
	Total iterations MRP for hybrid shop production system environment				13 824
	Total iterations MRP for job shop production system environment				288
ROP	Reorder-point items [prop. demand]	3	7	0.5	9
	FOQ lot size items [prop. demand]	0.5	3	0.5	6
	Reorder-point components [prop. item demand]	1	4	0.5	7
	FOQ lot size components [prop. item demand]	0.5	3	0.5	6
	Total iterations ROP for flow shop production system environment				6 804
	Total iterations ROP for hybrid shop production system environment				6 804
	Total iterations ROP for job shop production system environment				162
ConWIP	MPS FOQ lot size [prop. demand]	1	3	0.5	5
	WIP-cap item / component [workload in minutes]	10 000	50 000	10 000	5
	Estimated lead time items [days]	1	5	1	5
	Estimated lead time components [days]	1	5	1	5
	Work-ahead-window buffer [days]	0	3	1	4
	Total iterations ConWIP for flow shop production system environment				7 500
	Total iterations ConWIP for hybrid shop production system environment				7 500
	Total iterations ConWIP for job shop production system environment				375
Total iterations for all PPCS and production system environments					57 081
Total simulation runs (by 10 replications per iteration)					570 810

For MRP, we conduct 13,824 iterations for the flow and hybrid shop, and 288 for job shop. For ROP, there are 6,804 iterations for the flow and hybrid shop, and 162 for the job shop. For ConWIP, 7,500 iterations are performed for the flow and hybrid shop, with 375 for the job shop. To ensure robustness, we perform 10 replications per iteration, totaling 570,810 simulation runs. Each replication lasts 400 days with a 150-day warm-up phase. We use parallel computing across 21 computers to enhance efficiency. Parameter combinations are managed using RStudio and a PostgreSQL database, with results stored in the same database.

5 NUMERICAL RESULTS

The performance of the three observed PPCS, i.e. MRP, RPS and ConWIP, across the nine production system environments is evaluated based on overall costs, including WIP costs, finished goods inventory (FGI) costs and tardiness costs. Specifically, the cost structure is as follows: 0.5 cost units (CU) per day for WIP components, 1 CU per day for components, 1 CU per day for WIP items, 2 CU per day for FGI, and 38 CU per item per day for tardiness. At first, we evaluate the performance of the three observed PPCS across the nine different production system environments. Subsequently, we discuss the optimal parameterization, i.e., the planning parameters, of each PPCS necessary to achieve this performance.

5.1 Performance

Following *Figure 2* visualizes the overall costs per day, including a detailed presentation of the cost components for the three observed PPCS at the nine different production system environments, resulting from the three planned shop loads within three production system structures.



Figure 2: Overall Costs per Day of Investigated PPCS.

As Figure 2 implies, RPS is less effective than both MRP and ConWIP across all nine observed production environments. This inferior performance is attributed to the higher FGI costs needed to maintain

low tardiness costs, arising from a lack of demand information utilization and strictly authorized production. This observation is consistent with of Schonberger and Schniederjans (1984), who highlighted the necessity for high inventory levels in traditional inventory control methods compared to approaches that leverage demand information. Comparing ConWIP and MRP, ConWIP demonstrates superior performance in flow and hybrid shop production systems with planned shop loads of 0.85 and 0.90. However, at a planned shop load of 0.95, MRP outperforms ConWIP in these production system structures. These findings closely correspond with Jodlbauer and Huber (2008), who noted the superiority of ConWIP over MRP and Kanban in flow shop production systems, the latter of which is conceptually connected to RPS as discussed in Section 2.3 Reorder Point System (RPS). In the job shop production system, MRP generally surpasses ConWIP, except at the highest planned shop load of 0.95, where ConWIP achieves significantly lower tardiness costs.

5.2 Optimal Planning Parameters

The following *Table 3* shows the approximated optimal planning parameters for the three PPCS across the nine observed production system environments. Observing MRP reveals that a higher planned shop load necessitates a greater safety stock, evident in both the flow shop and hybrid shop production systems. However, this increased workload can be offset by longer planned lead times, as observed specifically at the 0.95 planned shop load in the hybrid shop production system. Both of these findings are consistent with the research presented by Altendorfer (2019). Moreover, MRP implementation in the job shop production system necessitates the longest planned lead time. This requirement is partially due to our modeled job shop production system structure, where the BoM level includes the highest number of machines, i.e. up to four, as depicted in *Figure 1*. Additionally, within this job shop production system structure, a higher planned shop load leads to increased lot sizes, a trend that is uniquely observed in this system.

Table 3: Optimal Planning Parameters at Different Environments for each PPCS.

Env.	Production system structure Planned shop load	Flow Shop			Hybrid Shop			Job Shop		
		0.85	0.90	0.95	0.85	0.90	0.95	0.85	0.90	0.95
MRP	Planned lead time items [days]	1	1	1	2	2	3	3	3	5
	FOP lot size items [days]	1	1	1	1	1	1	1	1	2
	Safety stock items [prop. demand]	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	Planned lead time components [days]	2	2	2	2	2	3	-	-	-
	FOP lot size components [days]	1	1	1	1	1	1	-	-	-
	Safety stock components [prop. item demand]	0.0	0.5	0.5	0.5	1	0.5	-	-	-
ROP	Reorder-point items [prop. demand]	3.0	3.0	3.5	4.0	4.0	4.5	4.5	5.0	6.0
	FOQ lot size items [prop. demand]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0
	Reorder-point components [prop. item demand]	1.0	1.0	1.0	1.0	1.0	1.5	-	-	-
	FOQ lot size components [prop. item demand]	1.0	1.0	1.0	1.0	1.0	1.0	-	-	-
ConWIP	MPS FOQ lot size [prop. demand]	1.0	1.0	1.0	1.0	1.0	3.0	1.0	1.0	1.0
	WIP-cap item / component [workload in minutes]	20 000	≥ 20 000	≥ 30 000	≥ 20 000	≥ 30 000	30 000	20 000	≥ 30 000	20 000
	Estimated lead time items [days]	1	1	1	2	2	3	3	3	5
	Estimated lead time components [days]	3	4	4	4	4	5	-	-	-
	Work-ahead-window [days]	≥ 1	≥ 1	≥ 1	≥ 1	≥ 1	≥ 1	-	-	-

Observing ROP, higher planned shop loads result in increased reorder points for items, i.e. FGI, which significantly contribute to the inferior performance discussed in Section 5.1 *Performance*. This rise in reorder points is primarily due to extended replenishment times, as machines are frequently occupied with production orders, resulting in increased waiting times. Despite this, the reorder points for the components remain largely unaffected in both the flow shop and hybrid shop production systems, even with higher planned shop loads. Yang (1998) also demonstrated a similar connection between planned shop loads and increased reorder points in a single machine production system. However, the lack of impact on reorder points at BoM levels, i.e. components, provides an interesting new insight. Moreover, lot sizes only increase in the job shop production system at the highest planned shop load, mirroring the behavior seen with MRP.

Observing ConWIP, as discussed in the section 3.3 *Production Planning and Order Release*, in case of single ConWIP-loop scenario, i.e. at the job shop production system, the estimated lead times for items function as the work-ahead-window. In contrast, in the other two production system structures, planned start and end dates are determined through backward scheduling, using either the estimated lead time for items or components. The work-ahead-window buffer is used to calculate the earliest start date for items, by further backward scheduling from the planned start dates. Thus, in a scenario with two ConWIP-loops, the work-ahead-window equals the estimated lead time for items plus the work-ahead-window buffer. Concerning the estimated lead times, a similar behavior can be seen as with MRP: a greater planned shop load leads to longer estimated lead times, consequently extending the work-ahead-window which is in line with Bokor and Altendorfer (2024), particular evident in the job shop production system. Interestingly, the estimated lead times for items are identical to the planned lead times in MRP. However, the estimated lead times for components are significantly longer than those planned for MRP components. This discrepancy relates to two factors. Firstly, in ConWIP, the MPS lot size is used for producing both items and components without varying the lot size, so at higher planned shop loads, MPS tends to increase lot sizes to minimize setup times. Secondly, the absence of a safety buffer in ConWIP, which could mitigate shortages from unexpected demand, means that the estimated lead time must compensate for this uncertainty. Interestingly, for ConWIP, the job shop production system does not require increased MPS lot sizes at higher planned shop loads, whereas a 0.95 planned shop load at the hybrid production system structure significantly escalates the optimal lot size. Lastly, it is observed that with regards to WIP-cap and work-ahead-window buffer, often increased values beyond a certain threshold neither improve nor significantly worsen performance. This is particularly noticeable with the work-ahead-window buffer: increasing it from zero to one enhances performance, but higher values do not yield further benefits since the components are not stocked any earlier.

6 CONCLUSION

We evaluated the performance of three PPCS, namely MRR, RPS and ConWIP, across nine distinct stochastic multi-item multi-stage production system environments through a comprehensive full factorial simulation study. Performance was evaluated based on various cost components, including WIP costs, FGI costs, and tardiness costs. In this process, we developed a simulation model and integrated these three PPCS into three different production system structures: flow shop, hybrid shop, and job shop. Each structure was examined under three planned shop loads, creating the nine distinct production system environments. Based on our full factorial simulation study, we approximate optimal planning parameters for each of the three PPCS across all nine production system environments.

Concerning the performance comparison, two key findings emerge: 1) Results indicate a superior performance of MRP and ConWIP over RPS across all nine observed scenarios, stemming from RPS's lack of demand information utilization and strictly authorized production, leading to higher FGI to maintain low tardiness costs. 2) When comparing ConWIP and MRP, ConWIP exhibits superior performance at 0.85 and 0.90 planned shop loads in the flow and hybrid shop production systems. However, MRP outperforms ConWIP at these planned shop loads in the job shop production system.

Regarding the impact of various production system environments on the optimal planning parameters for each PPCS, three observations are identified for each: For MRP: 1) Higher planned shop loads necessitate increased safety stock in both flow and hybrid shop production systems. 2) Longer planned lead times can mitigate the effects of higher shop loads, particularly evident at a 0.95 planned shop load in the hybrid shop. 3) The job shop production systems require the longest planned lead times and an increased lot size at higher planned shop load. For RPS: 1) Higher planned shop loads result in increased reorder points for FGI as replenishment times increase due to occupied machines, negatively impacting performance. 2) Reorder points for components remain stable regardless of shop load in both the flow and hybrid shop production systems. 3) Similar to MRP, lot sizes only increase in the job shop production system at the highest planned shop load. For ConWIP: 1) In scenarios with two ConWIP loops, the estimated lead time of items is identical and exhibit similar behavior as the planned lead time of items in

MRP. 2) Conversely, in each observed environment, the estimated lead time components is generally longer than the planned lead time of components in MRP, to a consistent lot size based on the MPS and the absence of a safety stock. 3) Unlike in MRP, the job shop production system under ConWIP does not require increased lot sizes at higher planned shop loads, though the hybrid production system structure does.

Further research should explore additional production system environments, potentially including variables such as different customer required lead times or the impact of machine breakdowns. Additionally, comparisons with lesser-known PPCS, such as Drum Buffer Rope or Demand Driven MRP, should also be considered.

ACKNOWLEDGMENTS

This work has been partially funded by the Austrian Science Fund (FWF): P32954-G.

REFERENCES

- Altendorfer, K. 2019. "Effect of limited capacity on optimal planning parameters for a multi-item production system with setup times and advance demand information". *International Journal of Production Research* 57(6):1892–1913.
- Bergmann, U., and M. Heinicke. 2017. "Approach for the Evaluation of Production Structures". In *Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing*, edited by H. Lödding, R. Riedel, K.-D. Thoben, G. von Cieminski, and D. Kiritsis, 176–183. Cham: Springer International Publishing.
- Bertolini, M., G. Romagnoli, and F. Zammori. 2015. "Simulation of two hybrid production planning and control systems: A comparative analysis". In *2015 International Conference on Industrial Engineering and Systems Management (IESM)*, 388–397. IEEE.
- Bokor, B., and K. Altendorfer. 2024. "Extending ConWIP by flexible capacity and WIP-Cap adjustment for a make-to-order multi-item multi-stage production system". Accepted in *Flex Serv Manuf J (Flexible Services and Manufacturing Journal)*.
- Cochran, J. K., and H. A. Kaylani. 2008. "Optimal design of a hybrid push/pull serial manufacturing system with multiple part types". *International Journal of Production Research* 46(4):949–965.
- Gupta, M., and D. Snyder. 2009. "Comparing TOC with MRP and JIT: a literature review". *International Journal of Production Research* 47(13):3705–3739.
- Hillier, F. S., S. Tayur, R. Ganeshan, and M. Magazine. 1999. *Quantitative Models for Supply Chain Management*. Boston, MA: Springer US.
- Hopp, W. J., and M. L. Spearman. 2011. *Factory Physics: Foundations of manufacturing management*. 3rd ed. Long Grove, Illinois: Waveland Press.
- Hopp, W. J., and M. L. Spearman. 2004. "To Pull or Not to Pull: What Is the Question?". *Manufacturing & Service Operations Management* 6(2):133–148.
- Huang, G., J. Chen, X. Wang, and Y. Shi. 2015. "A simulation study of CONWIP assembly with multi-loop in mass production, multi-products and low volume and OKP environments". *International Journal of Production Research* 53(14):4160–4175.
- Jaegler, Y., A. Jaegler, P. Burlat, S. Lamouri, and D. Trentesaux. 2018. "The ConWip production control system: a systematic review and classification". *International Journal of Production Research* 56(17):5736–5757.
- Jodlbauer, H., and A. Huber. 2008. "Service-level performance of MRP, kanban, CONWIP and DBR due to parameter stability and environmental robustness". *International Journal of Production Research* 46(8):2179–2195.
- Law, A. M. 2014. *Simulation modeling and analysis*. [S.l.]: McGraw-Hill.
- Matsuura, H., and H. Tsubone. 1991. "Determining Net Requirements for Material Requirements Planning". *Journal of the Operational Research Society* 42(11):981–990.
- Miclo, R., M. Luras, F. Fontanili, J. Lamothe, and S. A. Melnyk. 2019. "Demand Driven MRP: assessment of a new approach to materials management". *International Journal of Production Research* 57(1):166–181.
- Mongomery, D. C. 2012. *Design and analysis of experiments*. 8th ed. Hoboken, N.J, Chichester: Wiley; John Wiley [distributor].
- Orlicky, J. 1975. *Materials requirements planning ; the new way of life in production and inventory management*. 1st ed. NEW YORK: MC GRAW HILL.
- Pansara, R. 2023. "Design of Master Data Architecture". *International Journal of Engineering Applied Sciences and Technology* 8(4):58–61.
- Reuter, C., F. Brambring, T. Hempel, and P. Kopp. 2017. "Benefit Oriented Production Data Acquisition for the Production Planning and Control". *Procedia CIRP* 61:487–492.
- Schonberger, R. J., and M. J. Schniederjans. 1984. "Reinventing Inventory Control". *Interfaces* 14(3):76–83.
- Seiringer, W., K. Altendorfer, and T. Felberbauer. 2023. "Simulating the impact of forecast related overbooking and underbooking behavior on mrp planning and a reorder point system". In *2023 Winter Simulation Conference (WSC)*. IEEE.

- Seiringer, W., K. Altendorfer, J. Castaneda, L. Gayan, and A. A. Juan. 2022. "Potential of Simulation Effort Reduction by Intelligent Simulation Budget Management for Multi-Item and Multi-Stage Production Systems". In 2022 Winter Simulation Conference (WSC), 1864–1875. IEEE.
- Silver, E. A., R. Peterson, and D. F. Pyke. 1998. Inventory management and production planning and scheduling. 3rd ed. New York [etc.]: John Wiley & Sons.
- Spearman, M. L., D. L. Woodruff, and W. J. Hopp. 2022. "CONWIP Redux: reflections on 30 years of development and implementation". International Journal of Production Research 60(1):381–387.
- Spearman, M. L., D. L. Woodruff, and W. J. Hopp. 1990. "CONWIP: a pull alternative to kanban". International Journal of Production Research 28(5):879–894.
- Thürer, M., N. O. Fernandes, and M. Stevenson. 2022. "Production planning and control in multi-stage assembly systems: an assessment of Kanban, MRP, OPT (DBR) and DDMRP by simulation". International Journal of Production Research 60(3):1036–1050.
- Thürer, M., N. O. Fernandes, N. Ziegls, and M. Stevenson. 2019. "On the meaning of ConWIP cards: an assessment by simulation". Journal of Industrial and Production Engineering 36(1):49–58.
- Vollmann, T. E., W. L. Berry, and D. C. Whybark. 1997. Manufacturing planning and control systems. 4th ed. New York: McGraw-Hill.
- Woschank, M., P. Dallasega, and J. A. Kapeller. 2021. "Investigation of the Potential to Use Real-Time Data in Production Planning and Control of Make to Order (MTO) Manufacturing Companies". In Implementing Industry 4.0 in SMEs, edited by D. T. Matt, V. Modrák, and H. Zsifkovits, 165–185. Cham: Springer International Publishing.
- Yang, K. K. 1998. "A comparison of Reorder Point and Kanban policies for a single machine production system". Production Planning & Control 9(4):385–390.
- Yelle, L. E. 1979. "Materials requirements lot sizing: a multi-level approach". International Journal of Production Research 17(3):223–232.

AUTHOR BIOGRAPHIES

WOLFGANG SEIRINGER is a Research Associate in Operations Management at the University of Applied Sciences Upper Austria. Specializing in discrete event simulation and hierarchical production planning, His work addresses the complexities of uncertainty, aiming to enhance operational efficiency and resilience. His email address is wolfgang.seiringer@fh-steyr.at.

BALWIN BOKOR is Research Associate in the field of Operations Management at the University of Applied Sciences Upper Austria. He is a PhD candidate and his research interests are discrete event simulation, production planning, scheduling and energy simulation. His email address is balwin.bokor@fh-steyr.at.

KLAUS ALTENDORFER is Professor in the field of Operations Management at the University of Applied Sciences Upper Austria. He received his PhD degree in Logistics and Operations Management and has research experience in simulation of production systems, stochastic inventory models and production planning. His e-mail address is klaus.altendorfer@fh-steyr.at.