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# The ConWip production control system: a systematic review and classification

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In the past decade, a growing body of literature has investigated the CONstant Work In Progress (ConWip) production control system (PCS). In view of the current industrial challenges entailing adaptability, product customisation, decreasing leadtimes and customer satisfaction, ConWip seems to be an effective and adaptive PCS for manufacturers. This paper aims to update the last ConWip systematic review that dates back to 2003 and to provide a guide for understanding through an original classification method. This method enables the differentiation of papers that concentrate on Con-Wip sizing, performance and context as well as a comparison with other PCSs. In addition to providing a key to interpreting the research approaches, the criteria considered answers questions on how to implement, how to optimise and why and when to use ConWip. Finally, the most relevant research avenues are highlighted to provide future lines of research.

**Keywords:** ConWip; systematic review; Production control; Research avenues; Kanban; MTS; MTO; push/pull systems

## 1. Introduction

Manufacturing competitiveness is increasingly driven by customer satisfaction. Consequently, product variety, short and predictable leadtimes, and reliable delivery times constitute three primary customer expectations. In this context, the effectiveness of the chosen production control system (PCS) constitutes a key element. Indeed, effective PCS enables production lines to deliver the right product at the right time and at a controlled cost. Among existing PCSs, Constant Work in Progress (ConWip) was first described by Spearman, Woodruff, and Hopp (1990) as a pull alternative to Kanban. Indeed, based on the elemental mechanism identified by Jackson (1963), Spearman, Woodruff, and Hopp (1990) opened the way to ConWip by describing its entire methodology. Generally speaking, the main aim of ConWip is to control the total amount of work on the environment considered (ConWip is mainly employed on production lines) by keeping it constant. It finds its theoretical roots in Little's Law (Little 1961):

$$\text{Work in Process} = \text{Throughput} \times \text{Average Leadtime} \quad (1)$$

The part numbers and the related quantities to be produced are determined by work orders, which can come from MRP. ConWip takes the lead in managing the amount of WIP. Before an order is sent to the production line, it must be associated with a ticket that corresponds to an 'authorization to produce'. In the event that all of the available tickets are associated with production orders, any new orders must wait at the beginning of the assembly line. Completion of an order at the end of the line releases the associated ticket that then becomes available for a new order. The entire process is illustrated in Figure 1.

At that time, the first Kanban pull systems began to achieve significant results, and in particular reduced WIP (work in progress) and average leadtime (the time difference between the start and finish of a sequence of tasks) in different manufacturing areas. Nevertheless, as Hall (1981) pointed out, Kanban was designed for repetitive and stable manufacturing systems. In this context, Spearman, Woodruff, and Hopp (1990) defined ConWip to provide a more flexible and efficient PCS for a large range of manufacturing environments, especially those characterised by product variety and shifts between product types. This approach was highly relevant, as Child et al. (1991) explained, 'managing complexity can significantly improve competitiveness by simultaneously lowering costs, reducing response time and improving customer benefits.' Moreover, MacDuffie, Sethuraman, and Fisher (1996) demonstrated the essential need to efficiently

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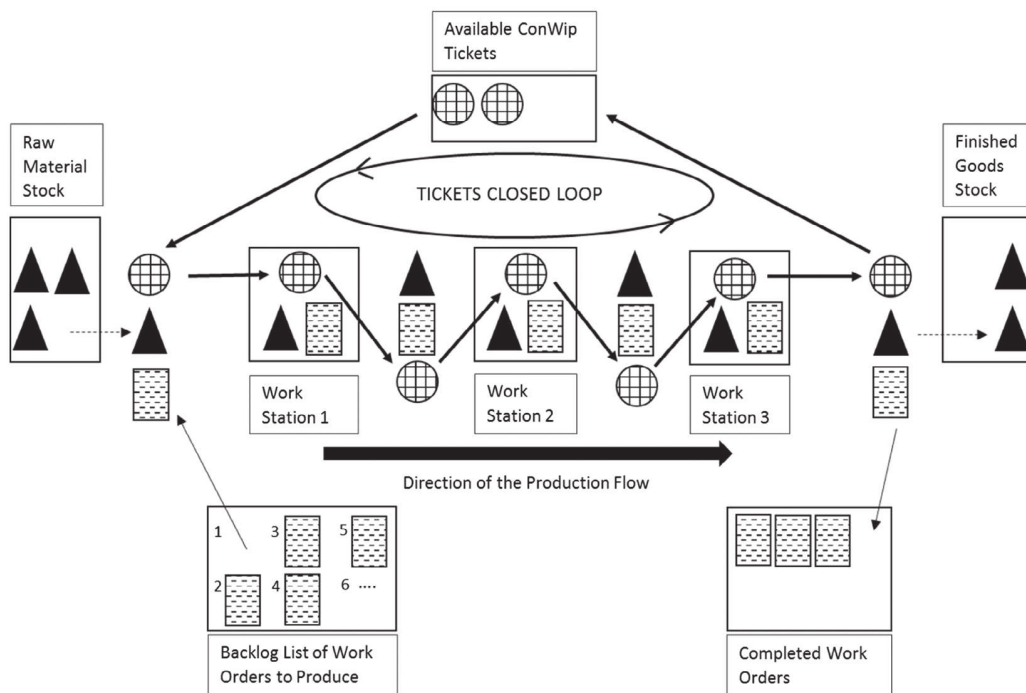


Figure 1. Fundamentals of ConWip.

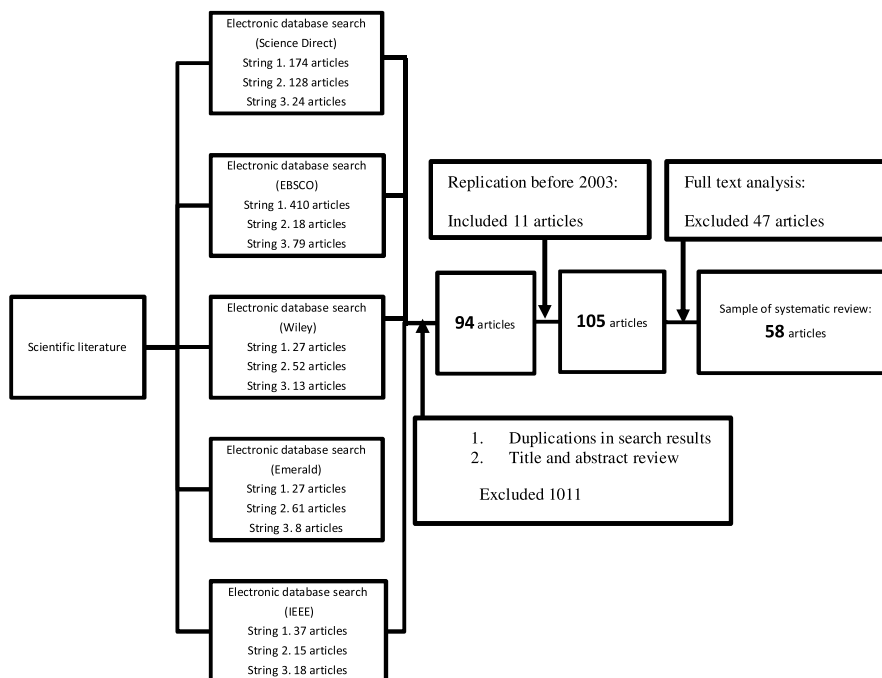


Figure 2. Mapping the scientific literature research.

manage product variety; otherwise, the related complexity would negatively affect both direct and indirect labour productivity and quality.

Regarding this important topic, a large number of articles address how to make PCS more suitable for the challenges of modern-day manufacturing. This paper provides a systematic literature review of ConWip consisting of the latest research improvements (Figure 2).

To achieve this goal, we build a review protocol according to Schulze et al. (2016). The major source of information used to identify the papers eligible for this review were the following scholarly databases: Elsevier ([www.sciencedirect.com](http://www.sciencedirect.com)), Emerald ([www.emeraldinsight.com](http://www.emeraldinsight.com)), Springer ([www.springerlink.com](http://www.springerlink.com)), Wiley ([www.wiley.com](http://www.wiley.com)), EBSCO ([www.ebsco.com](http://www.ebsco.com)), and IEEE. To identify the papers, we define three different strings:

Search string 1: 'ConWip' (TITLE, KEYWORDS, ABSTRACT) OR 'modified ConWip'(TITLE, KEYWORDS, ABSTRACT) AND YEAR > 2003 AND DOCUMENT TYPE (peer-reviewed) ARTICLE.

Search string 2: 'production control system' (TITLE, KEYWORDS, ABSTRACT) AND 'review' (TITLE) AND YEAR > 2003 AND DOCUMENT TYPE (peer-reviewed) ARTICLE.

Search string 3: 'production control system' (TITLE, KEYWORDS, ABSTRACT) and PUSH (TITLE, KEYWORDS, ABSTRACT) AND PULL (TITLE, KEYWORDS, ABSTRACT) AND YEAR > 2003 AND DOCUMENT TYPE (peer-reviewed) ARTICLE.

This method has been commented upon and challenged by other researchers after a preliminary study of the present work was presented at a conference (Jaegler, Burlat, and Lamouri 2016). The authors, as independent reviewers, used abstracts and titles to initially evaluate the studies. To ensure complete coverage, the research was performed for the period from 2000 to 2017. 11 articles withheld by Framinan, González, and Ruiz-Usano (2003) were also added. The full text of the selected articles was extracted into a Microsoft Excel worksheet. The articles were reviewed according to four bibliographic characteristics and topics.

As stated, the aim of this paper is to update the last ConWip literature review that Framinan, González, and Ruiz-Usano (2003) executed. Indeed, since 2003, the sheer number of published works makes a systematic review of these studies not only of interest, but also necessary. The goal is to address the differences between the earlier studies, reviewed by Framinan, González, and Ruiz-Usano (2003), and new research. Some research avenues have been exploited, some are still valid, and others have appeared. The synthesis of the systematic review consists of classifying ConWip research according to four channels that were determined thanks to various references:

- Sizing characteristics have been chosen according to Spearman, Woodruff, and Hopp (1990), Hopp and Spearman (1991) and Hopp and Roof (1998), who explain that a ConWip system can be sized according to two main characteristics, the card count and the lot sizing,
- Environmental characteristics have been chosen according to Stevenson, Hendry, and Kingsman (2005) who provide a fundamental study of production planning and control. Their study highlights Make to Order (MTO) /Make to Stock (MTS) as a fundamental distinction and shows that shop floor configuration is a major determination for PCS choice.
- The comparison between PCS topics has been chosen according to the large number of papers dedicated to it and to the value it can bring in the evaluation of ConWip as a PCSs. The categories of PCSs that appear in the section dedicated to this topic (push system, Kanban, Hybrid Kanban, Hybrid ConWip, POLCA) were determined among most usual categories (various Push systems, Kanban, hybrid and extensions of Kanban, hybrid and extensions of ConWIP, Polca, Cobacabana, Based to stock, Workload, TOC) as the most representative of the body of literature on comparisons between ConWip and other PCSs, methodology (Mathematical models, simulation, Rex), and research avenues.
- The topic of research methodology has been chosen to provide a full synthesis of the papers reviewed through three previous classification view angles. Mathematical model, Simulation, Literature Review and Return of experience have been determined to be the most representative research methodologies for the body of literature considered.

They provide a guide corresponding to the points of view of practitioners and researchers. The first three questions explain how to implement ConWip to practitioners and highlight the different avenues to researchers; the last one helps researchers choose the best methodology.

Research question 1: How can ConWip be sized?

Research question 2: How does ConWip work in different implementation contexts?

Research question 3: How does ConWip perform compared to other PCSs?

Research question 4: Which methodologies are used in the different ConWip studies?

To answer these four key questions, the paper is structured as follows: Section 2 focuses on ConWip implementation studies, Section 3 is dedicated to the context in which ConWip contributions have been conducted, Section 4 deals with the comparison of ConWip and other PCSs, Section 5 discusses the different models and approaches used, Section 6 proposes a decision and implementation guide for practitioners and links it with the literature review given in Sections 2 to 5. Finally, Section 7 concludes and focuses on future research avenues of interest.

## 2. ConWip sizing

This section aims to answer research question 1: How can ConWip be sized?

In this frame, it proposes a review of studies based on ConWip implementation issues (Table 1).

As different studies have shown, the implementation of a ConWip system is characterised by one major endogenous criterion, sizing, and by two endogenous minor criteria, the number of loops (Ip et al. 2007) and visual management (Burlat 2015) implemented on the production line. According to Spearman, Woodruff, and Hopp (1990), Hopp and Spearman (1991) and Hopp and Roof (1998), a ConWip system can be sized according to two main characteristics: the card count and the lot sizing, which are expected to deliver the targeted average leadtime or throughput depending on the decision-makers' requirements. The link between these different parameters is shown in Figure 3.

Table 1. Analysis of the papers that deal with an implementation topic.

Reference	Implementation		
	Card count (CC)/lot sizing (LS)	Throughput (T)/WIP level (W)/average leadtime (ALT)	Number of ConWip loops (CL)
Aglan and Durmusoglu (2015)	LS	ALT	
Belisário, Azouz, and Pierreval (2015)	CC		
Belisário and Pierreval (2015)	CC		
Bonvik, Dallery, and Gershwin (2000)		ALT	
Cao and Chen (2005)	LS		
Economopoulos and Kouikoglou (2008)		T/W	
Eng and Sin (2013)			CL
Helber, Schimmelpfeng, and Stolletz (2011)		T/W	
Herer and Shalom (2000)	CC	T/ALT	
Huang et al. (2015)		T/W/ALT	CL
Huang et al. (2017)			CL
Ip et al. (2007)			CL
Jodlbauer and Huber (2008)		W	
Li (2010)		T	
Marek, Elkins, and Smith (2001)	CC		
Mhada and Malhamé (2011)		W	
Olaitan, Yu, and Alfnes (2017)		T	
Parvin et al. (2012)		T	
Pergher and Vaccaro (2014)	CC	ALT	
Pierreval et al. (2013)	CC	W	
Prakash and Chin (2017)			CL
Romagnoli (2015)		T/ALT	
Ryan and Vorasayan (2005)	CC		
Sastry and Garg (2017)		T/W/ALT	
Satyam and Krishnamurthy (2013)	LS		
Srinivasan, Ebbing, and Swearingen (2003)		W/ALT	
Tardif and Maaseidvaag (2001)	CC		
Thürer et al. (2017)		T	
Wang, Cao, and Kong (2009)	CC	T	
Zhang and Chen (2001)	LS		

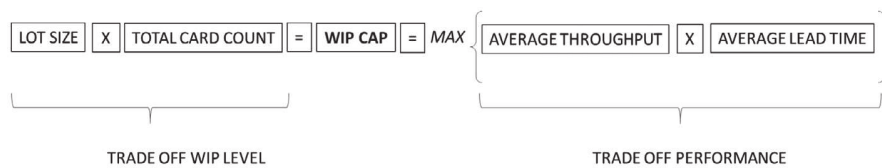


Figure 3. Implementation of a ConWip.

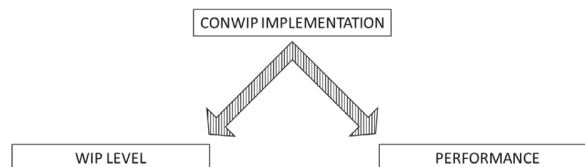


Figure 4. ConWip implementation factors.

Papers studied in this section are synthesized in Table 1 and classified according to the reading key proposed in Figure 4.

This section will first focus on the papers referring to WIP level and thereafter on those dealing with performance, as synthesised in Figure 4. The first column indicates papers that are interested in card count or lot sizing issues, the second column indicates papers that are involved in throughput, WIP level or average leadtime research questions and the third column indicates papers that focus on the number of ConWip loops that shall be used.

## 2.1 WIP-level

As illustrated in Figure 1, the card count determines the amount of work in progress on the production line. As Little’s law demonstrates, this quantity is highly relevant since an increasing number of cards would also increase the average leadtime. In other words, defining the number of cards consists of finding the best compromise between throughput (implying production efficiency), lowering cost and average leadtime, and thus leading to customer satisfaction and cash management.

To take advantage of Table 1 – column 2 (Card Count (CC)/Lot Sizing (LS)), it is important to notice that the literature takes two approaches for card count: the first considers static card count calculations and the second considers an adaptive WIP level methodology. Some typical papers for these two approaches are cited and contextualised in the following lines.

In the first approach, Hopp and Spearman (2011) present a formula whereby throughput is directly related to the number of tickets and the bottleneck rate. This allows for an estimate of the best number of cards but first requires knowing the optimal throughput and the mean bottleneck rate. To complete this calculation, Marek, Elkins, and Smith (2001) propose a card reduction heuristic method to adjust the number of tickets. Pergher and Vaccaro (2014) consider the WIP level definition as a multi-criteria problem driven by flow policies, inventory costs, production shortage, service levels and variability of production processes. These authors propose a combined method – computer simulation and Electre-TRI (multiple criteria sorting method) – to determine the amount of WIP on production lines managed with ConWip.

The second approach is less addressed but provides some original research avenues. Hopp and Roof (1998) propose an automatically adjusted card number method based on real-time data. This method, called Statistical Throughput Control (STC), aims to achieve production rate targets by optimising the number of cards and as a consequence of the WIP level. Variation in demand, inventory and backorder levels are the three parameters that Tardif and Maaseidvaag (2001) use to determine the different number of cards allowed in the system. Their study aims to disseminate the benefits of a pull production system in highly variable manufacturing environments. Belisário and Pierreval (2015) propose deeper research based on the same model as Tardif and Maaseidvaag (2001) but also based on a minimum number of cards that can be completed by an extra set of cards. The decision whether to complete the initial set of cards is made through a decision tree. The initial state of the production system stands for the input data of the tree while the modified number of cards is suggested as the output.

Lot sizing and card count determine the amount of WIP on the production line and, as such, must also be seen as a way of balancing throughput and average leadtime. The setup time, especially concerning the bottleneck stations, can be a relevant lens through which to look at lot sizing. However, adjusting the WIP level through lot sizing has been studied less. To the best of our knowledge, only three papers use this parameter. Two of them consider this topic directly and are highlighted here: Zhang and Chen (2001) define a mathematical programming model to calculate the best lot sizing strategy, while Pergher and Vaccaro (2014) optimise lot sizing with a multi-criteria problem solving methodology.

## 2.2 Performance

As Spearman, Woodruff, and Hopp (1990) explain, ‘WIP is inherently easier to optimise than throughput’. Nevertheless, throughput and average leadtime are part of the most relevant performance metrics of a production line as outlined by Hallihan, Sackett, and Williams (1997). This means that their levels essentially need to be monitored. Furthermore, these two indicators are closely linked, as shown in Section 1, which implies that these are studied jointly. Depending on the strategy of the manufacturer, a practitioner will face several possible situations. Taking into consideration Figure 3, it appears that increasing throughput, reducing WIP and reducing leadtime are the three different strategic challenges directly linked with our topic. All are discussed through a typical example or environment in which they might take place and through a recommendation that is based on our own experiences and discussions with practitioners:

- In a case where the strategic challenge is to increase throughput, which can be in the case of a manufacturer that lacks the volume to absorb fixed costs: the choice is rarely to increase WIP, since this would imply an increasing need for finance. The chosen alternative in this case is to decrease leadtime. This could require some new organisation in the fabrication line, or at least some improvements.
- In a case where the strategic challenge is to reduce WIP, which can be illustrated by a manufacturer that lacks finance or that is looking for an additional footprint: the choice cannot be to reduce throughput, otherwise profitability would be negatively affected. The chosen alternative in this case is also to decrease leadtime.
- In a case in which the strategic challenge is to reduce leadtime, which can be illustrated by a manufacturer who holds a position in a leadtime driven market (for instance, an automotive industry tier 1 supplier): the choice could be either to increase throughput or to decrease the WIP level, both of which create a virtuous circle. A manufacturer would choose the best option depending on the secondary strategic challenge or depending on the respective costs of the two alternatives.

Fewer authors address this topic. To provide the best benefit from Table 1 – column 3 (Throughput (T)/WIP level (W)/Average leadtime (ALT)), one should know that these papers could be divided into two categories since they generally pursue two aims. The following lines give some characteristic illustrations for each of these two categories.

The first consists of demonstrating in a given environment that ConWip would outperform the actual system in terms of flow time and/or throughput. For instance, Eng and Sin (2013) study ConWip applied to a semiconductor end-of-line assembly. Using a discrete event simulation model, they highlight that the ConWip system is able to significantly reduce flow time while maintaining current throughput performance. Proceeding in the same way, Romagnoli (2015) simulates a ‘pull-from-the-bottleneck-ConWip’ in a complex manufacturing system and demonstrates its ability to considerably decrease average leadtime with only a few losses in terms of throughput.

The second aim consists of foreseeing the performance of a ConWip system in a determined production context. Herer and Shalom (2000) attempt to predict the performance of a ConWip system after determining the best amount of WIP by using a non-integral approach. In particular, they focus on mean throughput and mean flowtime to quantify the performance level. Hopp and Spearman (1991) also use their simulation model to predict the output parameters of a production line operating under ConWip while also highlighting throughput and average leadtime. Pergher and Vaccaro (2014) propose giving some weight to several key performance indicators amongst which are average leadtime and throughput. Based on a quantitative data analysis, they determine the best WIP level to optimise the weighted set of indicators.

## 2.3 Research avenues

Two research avenues are identified. The first one is the determination of the card count. This topic is the most frequently suggested by the authors for future research. This is easily understandable since an optimised accuracy in this frame would imply an optimised balance between WIP level and service rate. Indeed, these two performance factors are

key in terms of economical performance, which explains the relevance of this research avenue. For example, the reactive or adaptive card count is opposed to the static card count as a relevant way of optimisation. Belisário, Azouz, and Pierrel (2015) suggest an analysis focused on the latter topic, which helps to measure the pros and cons of the adaptive method. Among the implementation and optimisation research avenues, a number of authors address the challenging question of unbalanced production lines (with related set-up times, bottlenecks and throughput issues) involving constant card count but varying load levels (due to heterogeneous routings). This topic is also a core issue in the specific make-to-order (MTO) and high product mix context, and fundamental given today's industrial economic challenges. More generally, this in turn leads to studying the robustness of CONWIP in a production process characterised by changing routings, moving bottlenecks and variable conditions resulting from lean production.

Taking into consideration the body of literature that is interested in ConWip sizing and taking into account our focus on a decision-making guide, two future research avenues can be stated.

The first one would be an evaluation of the static and variable card count managing processes. Such a study could provide a decision-making scheme for practitioners, depending on their industrial context and on their economic objectives. It would take two factors into account to characterise industrial context: the variability of the production load and the adaptability of the production tool. The financial treasury optimisation and the turnover optimisation would be used as two different economical metrics to evaluate and finally compare both card count managing processes.

The second one could consist of studying the influence of the heterogeneity of routings on ConWip performance and would propose a methodology to define 'mean routings' to represent the mixed model that loads the production line. The 'mean routing' defined would be used to dimension and implement ConWip in a make-to-order context. To finish, the comparison between different potential 'mean routings' would also be helpful to determine the best of them or a 'good' one among them. This research would also provide some additional elements to decision-makers and help answer the dimensioning question of the ConWip loop.

An industrial environment characterised by a high seasonality in terms of the mixed model would be chosen to perform both of these research avenues. This particular choice is relevant since it introduces a changing production line balance (in terms of workload per station, which implies a potential moving bottleneck). This characteristic would provide the opportunity of a variable card count to show its possible benefits.

### 3. The ConWip system in various contexts

This sections aims to answer research question 2: How does ConWip work in different implementation contexts? Even if ConWip were a nimble alternative to former PCSs (Spearman, Woodruff, and Hopp 1990), it is interesting to note that most of the authors mainly consider ConWip in a specific context. This section aims to review the papers that consider ConWip in an industrial environment characterised by the 'make to' model or the shop configuration as illustrated in Figure 5. This classification choice is based on the fundamental study of production planning and control proposed by Stevenson, Hendry, and Kingsman (2005). Their study explains that the Make to Order (MTO) /Make to Stock (MTS) distinction is fundamental since MTS is significantly more sensitive to the accuracy of the PCS choice. On top of that, Stevenson et al. show that shop floor configuration is a major determination for PCS choice. Finally, articles dealing with ConWip in non-manufacturing contexts are proposed (Table 2).

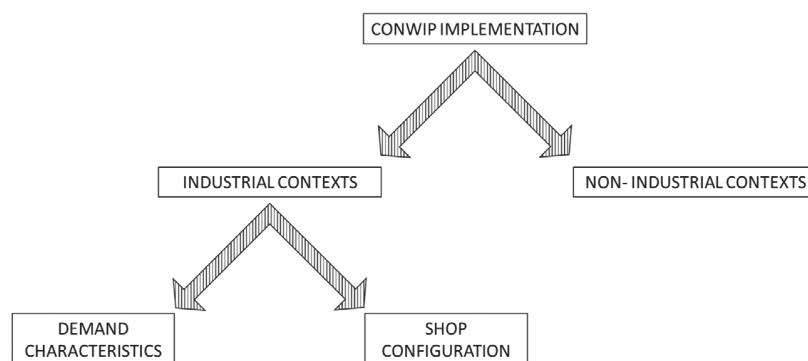


Figure 5. ConWip environment factors.



Table 2. Analysis of the papers that deal with an environmental topic.

Reference	Environment		NI
	Demand	Shop Type	
Aglan and Durmusoglu (2015)		FS/JS	
Bahaji and Kuhl (2008)	MTS	FS	
Belisário, Azouz, and Pierreval (2015)	MTS		
Bertolini, Romagnoli, and Zammori (2015)	MTO	JS	
Bonvik, Dallery, and Gershwin (2000)	MTS	FS	
Crop et al. (2015)			X
Dallasega, Rauch, and Matt (2015)			X
Economopoulos and Kouikoglou (2008)	MTS	FS	
Framinan, Ruiz-Usano, and Leisten (2001)		FS	
Germes and Riezebos (2010)	MTO		
Harrod and Kanet (2013)	MTO	JS	
Helber, Schimmelpfeng, and Stolletz (2011)		FS	
Herer and Shalom (2000)		FS	
Huang et al. (2015)	MTO	JS	
Huang et al. (2017)		FS	
Jodlbauer and Huber (2008)		FS	
Korugan and Gupta (2014)	MTS		
Lavoie, Gharbi, and Kenné (2010)	MTS	FS	
Li (2010)		JS	
Mhada and Malhamé (2011)	MTS	FS	
Olaitan, Yu, and Alfines (2017)	MTO	FS	
Onyeocha, Khoury, and Geraghty (2013)		FS	
Onyeocha et al. (2015)		FS	
Papadopoulou (2013)		JS	
Parvin et al. (2012)		FS	
Pergher and Vaccaro (2014)	MTS	FS	
Prakash and Feng (2011)		FS	
Prakash and Chin (2017)		FS	
Romagnoli (2015)	MTO	JS	
Ryan and Vorasayan (2005)	MTS		
Sastry and Garg (2017)		FS	
Stevenson, Hendry, and Kingsman (2005)	MTO	JS	
Takahashi and Hirotsu (2005)	MTS		
Tardif and Maaseidvaag (2001)	MTS		
Wang, Cao, and Kong (2009)	MTS		
Wang, Wang, and Yue (2013)	MTS	FS	
Zhang and Chen (2001)	MTS	FS	

### 3.1 Demand characteristics

This subsection aims to highlight some typical examples of studies mentioned in Table 2 – column 2 (Demand) in order to provide readers with some contextualised papers dealing with MTS and MTO contexts. Generally speaking, it can be stated that authors show interest for ConWip in both MTS and MTO contexts. Nevertheless, it is noteworthy that ConWip has only been associated with MTO after 2010, except in the paper proposed by Stevenson et al., who opened the way by studying the adaptability of different PCSs to MTO. This illustrates that ConWip was initially designed with a purpose to MTS and that authors recently discovered that its simplicity and efficiency are also meaningful for MTO contexts. This is the first original finding that can be highlighted through these reviews. The second one deals with the more classical use of ConWip in MTS contexts: it can be stated that some authors have become interested in adaptive card count. The present review underlines some of their papers in this section.

A great deal of attention has been paid to ConWip implementation and outcomes in the MTS manufacturing approach. Ryan and Vorasayan (2005) analyse a ConWip-managed MTS multi-product context seeking to reduce the number of lost sales by optimising the number of tickets per product type. This original approach is rooted in the fact that satisfying demand for one product type can lead to the loss of sales of another product. To answer this question, they propose an original model that enables the optimal number of tickets per product type to be defined in order to minimise the loss of sales. They illustrate that the loss can decrease by up to 50 per cent. Tardif and Maaseidvaag

(2001) also consider adjusting the number of tickets and propose a dynamic number of cards in the loop based on inventory and backorder level. The evaluation of this process is undertaken on a single-product in a single-stage system. Takahashi and Hirotsu (2005) study a more complex model, defining a multi-stage assembly line with dedicated lead-times for each stage. Their paper analyses an MTS approach that allows considering the finished product inventory as the last stage of the ConWip loop. In the same vein, Lavoie, Gharbi, and Kenné (2010) demonstrate the efficiency of ConWip in an unreliable MTS manufacturing context. Pergher and Vaccaro (2014) instead propose a ConWip MTS-focused approach consisting of an 18-step methodology to define the best WIP level.

Although the MTO context is generally less studied, three papers are noteworthy. Romagnoli (2015) designs a methodology to integrate and size ConWip in an MTO production line with multiple product families. The focus is on sizing the ConWip loop that starts from the first stage of the line and ends at the bottleneck. Harrod and Kanet (2013) also consider an MTO scheme to compare Kanban, Paired-cell Overlapping Loops of Cards with Authorization (POLCA) and ConWip (discussed in more detail in Section (5.2). Germs and Riezebos (2010) develop the critical issue of the workload balancing capability of a pull system in an MTO production process and demonstrate how POLCA and m-ConWip (a hybrid ConWip system they describe in the same paper) can balance such a workload.

### **3.2 Shop configuration**

According to Stevenson, Hendry, and Kingsman (2005), a shop floor configuration is a major determination for PCS choice. The two main configurations that can be found in the literature are flowshop and jobshop. This subsection will focus on both of them by highlighting some relevant papers mentioned in Table 2 – column 3 (Shop Type). Within the same view angle as MTS/MTO, it appears that Stevenson, Hendry, and Kingsman (2005) proposed the first article that associated ConWip and jobshop in 2005. Before this date, ConWip was usually associated to flowshops. In the past 7 years, authors have given more interest to the use of ConWip in this particular shop configuration.

Flow shop production lines have also been widely studied. Some papers dealing with this have previously been mentioned, particularly in relation to MTS and include Pergher and Vaccaro (2014), Ryan and Vorasayan (2005) and Lavoie, Gharbi, and Kenné (2010). Bonvik, Couch, and Gershwin (1997) and Framinan, Ruiz-Usano, and Leisten (2001) study the case of a 4-machine production line with 1 and 2 product type(s). Bonvik, Couch, and Gershwin (1997)'s approach rests on comparing different PCSs in this particular environment (their results are described in Section 4.1). Framinan, Ruiz-Usano, and Leisten (2001) examine backlog sequencing in a ConWip-managed flow shop, defining an easy-to-use sequencing rule for flow shop-managed orders.

With regard to job shops, aside from the Romagnoli (2015) and Harrod and Kanet (2013) papers previously mentioned in the MTO/MTS subsection, two noteworthy papers should be mentioned. Ryan, Baynat, and Fred Choobineh (2000)'s study attempts to heuristically determine a fixed WIP level (and WIP mix) adapted to a modelled job shop with multiple products and multiple routings using the same production resource. Li (2010) study the impact of layout change, quality improvement and set-up time reduction on ConWip operations. This approach shows that the superiority of ConWip in a jobshop environment depends on the scale of the three considered impacts, which is an original and new finding for this specific context.

### **3.3 Non-manufacturing context**

The ConWip system applied to a non-manufacturing context is also of interest. Two papers in particular illustrate this concept. Dallasega, Rauch, and Matt (2015) study a specific engineer-to-order (ETO) case characterised by on-site installation. They show how ConWip can be used as a project management tool, leading to better synchronisation between engineering, fabrication and installation. Project leadtime reduction is a key result of their approach. In a medical context, Crop et al. (2015) apply ConWip to the radiotherapy treatment process, demonstrating that 'managing WIP instead of scheduling all steps' can optimise leadtimes and increase throughput in a non-manufacturing environment.

### **3.4 Research avenues**

A complete analysis of the questions raised by papers reviewed in this section shows that ConWip has widely been studied for the most simple manufacturing environments. In particular, ConWip in flowshop configurations working under a MTS policy has been quite deeply questioned and analysed. On top of that, it appears that several authors raise the question of high mix environments, which add to the challenge of efficiently implementing a PCS. To synthesise, the key questions concern manufacturing environments and related job shops, MTO policies, high product mix and/or high routings mix.

Two main lines of research could be highlighted according to this review and would contribute to a decision-making guide for a specific manufacturing environment, as explained in this section.

The first one focuses on CONWIP adaptation to a manufacturing environment such as jobshops, interconnected production lines or network lines. This research line would be particularly relevant in the case of an after sales service repair line. Indeed, this kind of environment is generally characterised by a jobshop organisation, since each line uses a lot of different and expensive tools or machines that are only sparsely loaded with low identical volumes and therefore shared between different lines. On top of that, this kind of environment would aim to be developed in the future in the field of reverse logistics.

The second deals with CONWIP adaptation to MTO policy and high standard deviation between product routings. This research avenue would be performed in two different industries. The first one is in an industrial subcontracting of capacity, since it is characterised by MTO and changing products and aims to provide short delivery times. The second one is in the special machines manufacturing industry since it is characterised by MTO and high standard routings deviation and aims to be best in class in terms of timely delivery.

#### **4. ConWip compared to other PCSs**

ConWip was originally developed to overcome some weaknesses of former PCSs (Spearman, Woodruff, and Hopp 1990) and hence (Framinan, González, and Ruiz-Usano 2003) observed that a large number of papers are dedicated to comparing these with ConWip. This section focuses on these studies with the aim of providing an overview of the research conclusions to enlighten manufacturers on the results of the comparison (Table 3) and to answer research question 3: How does ConWip perform compared to other PCSs?

Before going too deeply into detail in these comparison studies, it is relevant to highlight the overview proposed by González-r, Framinan, and Pierreval (2012). This study provides a complete classification of token-based PCSs and shows their main characteristics without comparing them in a specific context. It provides a very relevant overview and stands as an efficient entry point for anyone interested in comparing ConWip with other PCSs.

The two following subsections will provide some clues to readers with the aim of optimising the effectiveness of Table 3. Indeed, they will bring to light part of the cited papers to illustrate the most relevant or original comparisons of the research papers.

The first section is dedicated to comparisons between ConWip and push or pull systems. The second subsection is made to highlight comparisons between ConWip and Hybrid-ConWip and ConWip and POLCA as they all are unit-based pull PCSs with some common points that provide specific interest to their comparisons (Germs and Riezebos 2010).

##### **4.1 ConWip vs. push and pull systems**

Generally speaking, the body of literature shows several different, noteworthy trends. The first is that push systems should only be of interest in very simple environments that are characterised by very low mix and high volume. The second is that ConWip is not systematically the best performer for complex environments, but is easier to implement, to use and to maintain. The third is that ConWip is particularly successful in manufacturing environments characterised by small production series. To go deeper into detail in this section, it is of interest to state that the most common comparison is between ConWip, Kanban and push systems. Kanban is a pull system following the Just In Time (JIT) philosophy. The use of products by downstream workshops authorises the start of the manufacturing process of other products, and then of other semi-finished products and so on. This way of thinking carries on as far as the order for raw materials. The system utilises cards between the different workshops. The number of cards determines the WIP level.

Spearman and Zazanis (1992) proposed the first paper under this framework. Using an analytical model, they show that ConWip outperforms Kanban and MRP in terms of WIP variability, limitation, effectiveness and manageability. Takahashi and Hirotsu (2005) pursue the same goal, focusing on complex supply chains. The additional contribution of this paper is introducing synchronised ConWip in the comparison. The synchronised ConWip has been designed to manage supply chains characterised by assembly stages with different leadtimes. In addition to original ConWip, the order release is conditioned here to the availability of a card, as well as to the adjustment of the considered assembly stage leadtime so that the released and processed orders can be synchronised during their assembly. This study shows in which cases Kanban, ConWip or synchronised ConWip is preferable. To complete the picture, Prakash and Feng (2011) introduce machine breakdown, comparing the push system, ConWip and parallel ConWip under this additional constraint. Here, parallel ConWip is designed to separately manage high runner products and low runner products. To perform this separated management, two sets of ConWip cards are used: the first one is dedicated to high runners and the

Table 3. Overview of the papers involved in a comparison analysis.

Reference	ConWip compared to	Conclusion
Bahaji and Kuhl (2008)	Push	Push outperforms ConWip in all experiments involving low mix and high volume production
Baynat et al. (2001)	Kanban/Hybrid Kanban	The emphasis is put on the comparison method for Kanban, like PCSs, but no performance comparison is performed. The conclusion of this study consists of providing a new comparison method that is faster and more generic
Baynat, Buzacott, and Dallery (2002)	Kanban/Hybrid Kanban	The comparison focuses on shared versus dedicated Kanban. The study shows the cases in which sharing or dedicating Kanban is quite equivalent or strongly discriminating
Eng and Sin (2013)	Push/Modified ConWip	Both ConWip and Modified ConWip outperform push system by controlling WIP level and reducing cycle time and throughput time. Modified ConWip outperforms ConWip in terms of cycle time and robustness
Germs and Riezebos (2010)	Polca/Modified ConWip	Polca, ConWip and Modified-ConWip can all three reduce both the total throughput time and the average time orders spend on the shop floor. The three PCSs show benefits depending on the manufacturing conditions
Gong, Yang, and Wang (2014)	Push/Kanban	ConWip needs the smallest amount of information and has the least time delays
González-r, Framinan, and Pierreval (2012)	An overview of the token-based PCSs	It appears that determining which type of system is the best in which type of environment remains quite difficult and requires more research effort and feedback from a real implantation in industry
Harrod and Kanet (2013)	Kanban/Polca	ConWip is the best choice in a MTO manufacturing context
Jodlbauer and Huber (2008)	Push/Kanban	ConWip outperforms Kb and MRP for service level, WIP and optimisation ease but shows weaknesses in term of stability
Korugan and Gupta (2014)	Hybrid Kanban	Hybrid Kanban is dominant with respect to average work in process and backorders levels
Land (2009)	Cobabacana	Discussion of card based systems for job shop control with no conclusion in terms of outperformance from one or another
Lavoie, Gharbi, and Kenné (2010)	Kanban/Hybrid Kanban	For a single part type production, Hybrid Kanban outperforms ConWip and Kanban when the storage space and inventory costs are considered. ConWip is equivalent to Hybrid if the two costs are aggregated. ConWip is outperformed by Kanban if the number of stations and the storage space costs increase
Lavoie, Gharbi, and Kenné (2010)	Push	In jobshop environment, ConWip outperforms Kanban
Marek, Elkins, and Smith (2001)	Push/Kanban	ConWip systems are easier to implement and adjust than Kanban
Onyeocha, Khoury, and Geraghty (2013)	Modified ConWip	In a multiproduct manufacturing environment Modified ConWip outperforms Kanban
Onyeocha et al. (2015)	Hybrid Kanban	Comparison of two Modified ConWip in a multiproduct manufacturing environment. One of them is shown as the overall best strategy when minimisation of the average total WIP for targeted service levels is a concern
Prakash and Chin (2015)	Modified ConWip	ConWip is compared to 15 Modified ConWip through a classification scheme which offers insight into how these systems alter dominant system characteristics to influence performance
Prakash and Feng (2011)	Push/Kanban/Modified ConWip	Push is superior in term of throughput, Modified ConWip (parallel) is superior in terms of flow time per part and bottleneck utilisation and ConWip is superior in terms of service level
Sastry and Garg (2017)	Kanban/Hybrid Kanban	The performance of Hybrid Kanban is optimal compared to Kanban and ConWip. Hybrid Kanban was implemented for one month and the production increased by 54%
Stevenson, Hendry, and Kingsman (2005)	Push/Kanban/Polca	This paper provides a PCSs selection matrix depending on the manufacturing conditions
Suri (1998)	Polca	Advantage of Polca over other PCSs are shown in terms of operations effectiveness and employee satisfaction
Takahashi and Hirotani (2005)	Push/Kanban/Modified ConWip	Modified ConWip outperforms Kanban and ConWip in terms of inventories when higher priority has to be given to several inventory stations but Kanban and ConWip are better than Modified ConWip when higher priority is given to the last inventory station
Takahashi and Nakamura (2002)	Kanban/Modified ConWip	Reactive ConWip system is less effective to react to unstable changes in demand than reactive Kanban

(Continued)

Table 3. (Continued)

Reference	ConWip compared to	Conclusion
Thürer et al. (2017)	Cobacabana	No performance comparison but discussion around ability of Copacabana to control the release of orders through cards only better than ConWip does
Wang, Cao, and Kong (2009)	Hybrid ConWip	Hybrid ConWip provides improved productivity and reduced delay time compared to ConWip
Ziengs, Riezebos, and Germs (2012)	Polca	POLCA ability to balance the workload at a later stage outperforms balancing the workload at the moment of release for ConWip

second one to low runners. In this way, two ConWips run at the same time on the production line. Their chosen performance metrics are WIP level, average leadtime, throughput and bottleneck utilisation rate, showing the relevance of selecting one PCS over another. Two original contributions in this sphere include Marek, Elkins, and Smith (2001)'s modelling and comparison tool as a tutorial to compare Kanban and ConWip, prompting some questions on push and pull systems. Second, Gong, Yang, and Wang (2014) consider PCS as 'information-processing organisation (IPO)' and compare ConWip, Kanban and MRP in this context. This paper concludes with the superiority of ConWip - followed by Kanban - over MRP in terms of information entropy, amount of information and decision-making time.

The second type of comparison involves Hybrid-Kanban PCS and ConWip. Baynat et al. (2001) propose a queuing network modelling order to analyse and evaluate the performance of the Kanban-like PCS. Baynat, Buzacott, and Dallery (2002) highlight the pros and cons of PCS in a multi-product context using shared or dedicated tickets. Bonvik, Couch, and Gershwin (1997) consider the relevant question of type of demand, comparing Kanban, Hybrid-Kanban and ConWip in terms of service level and inventory. Their study is conducted in a specific environment and under two types of demand policies: under constant demand, Kanban is expected to deliver the best results while ConWip and hybrid-Kanban outperform under changing demand policies. Korugan and Gupta (2014) also take into account the nature of demand, comparing static Kanban with adaptive Kanban. Lavoie, Gharbi, and Kenné (2010) follow an original methodology, optimising the PCSs they deal with (Kanban, Hybrid-Kanban, ConWip) before comparing these and thereby addressing the limitations of Framinan, González, and Ruiz-Usano (2003)'s comparison studies. To conclude this subsection, it is interesting to note that Onyeocha, Khoury, and Geraghty (2013) employ the same optimisation-comparison approach with a shared or dedicated ticket characterisation similar to Baynat, Buzacott, and Dallery (2002).

#### 4.2 ConWip vs. modified-ConWip and POLCA

In the past decade, some modified-ConWip systems have been developed and compared to the original concept. As previously discussed in Section 4.1, Takahashi and Hirotsu (2005) define synchronised ConWip (SPW), which is expected to outperform ConWip when required to manage complicated supply chains. Prakash and Feng (2011) introduce the additional Parallel ConWip (PCW). Their paper shows the superiority of PCW for high-mix production, applying the concept of high-runner and low-runner products. Onyeocha, Khoury, and Geraghty (2013) also developed a modified ConWip system called Basestock-Kanban-ConWip (BKCW) based on three control parameters: each step of the production line is controlled by two parameters while the entire system is controlled by a third. Their paper demonstrates the superiority of BKCW over other ConWip-like PCSs. Important to note is the review that Prakash and Chin (2015) execute with the aim of classifying 15 modified-ConWip systems based on the main attributes of the original ConWip system.

Also relevant is Suri (1998)'s suggested PCS called POLCA. POLCA means Paired cell Overlapping Loops Cards with Authorization. It is a hybrid push-pull card-based system following the Quick Response Manufacturing (QRM) philosophy. A workshop is divided into work cells. The Kanban cards are used, but they circulate between the work cells. The aim is to manage high variety or custom-engineered productions. Harrod and Kanet (2013) provide a comparison between ConWip, POLCA and Kanban. They demonstrate that all three reduce shop inventory with an original contribution, showing that queuing discipline choice is more relevant than PCS choice. In the same vein, Germs and Riezebos (2010) compare ConWip, POLCA and m-ConWip in relation to workload balancing control.

#### 4.3 Research avenues

Regarding comparison between PCSs, the main research avenue deals with comparison methodology and comparison framework. For instance, any comparison between two PCSs should be performed using an optimal configuration of

each. How is it possible to ensure that this condition is fulfilled? To complete this concept, identifying which parameters influence the PCS's level of adaptation to its context and distinguishing this from the level of performance represents another research line. The level of adaptation is determined by structural parameters, including the type of shop (job-shop/flowshop) the product mix or standard deviation between product routings. These must be differentiated from elements that affect sizing, such as card count or lot sizing, albeit this is not helpful in choosing between one PCS and another. A specific study can also be conducted to determine which intrinsic factory or shop characteristics (setups, bottlenecks, department structure, assembly requirements, etc.) affect the choice of PCS. Any answer to this research avenue would allow an unskewed comparison methodology to be built, which still has not emerged in the existing literature. In a case where such research would become available, it would no doubt take a central place in a practitioner's decision-making process, since it would provide a novel framework in which to compare PCSs.

## 5. Approaches and models in ConWip studies

This section is devoted to answering research question 4: Which methodologies are used in the different ConWip studies? From the papers cited in this article (Table 4), simulation appears to be the most frequently used research approach, mathematical models comes in second, three papers describe new methodologies, six papers use industrial experience returns while three papers focus on the state-of-the-art.

Table 4. Overview of the referenced papers using simulation.

References	Research approach	Simulation variables	Experimental results
Bahaji and Kuhl (2008)	Simulation	Due date tightness level – Machine utilisation rate – Processing time	Push outperforms ConWip in all experiments involving low mix and high volume production
Belisário, Azouz, and Pierreval (2015)	Simulation	Idem Tardif and Maaseidvaag (2001)	The reduction of costs is achieved through a tremendous amount of number of card changes, which can lead to system instability. This illustrates that, when implementing an adaptive ConWIP system, practitioners should carefully take into consideration the consequences of modifying the number of cards
Belisário and Pierreval (2015)	Simulation (+Genetic Programming)	Idem Tardif and Maaseidvaag (2001)	The proposed simulation-based genetic programming approach generates a decision logic that specifies under which circumstances it is worth modifying the number of cards
Bertolini, Romagnoli, and Zammori (2015)	Simulation	Inter-arrival times – Processing times – Setup times – Expected utilisation rates of each workcenter – Average product mix	The simulations of three work load control systems including ConWip show very good results compared to a push system in term of WIP minimisation and due date compliance, especially in highly constrained productive environments
Eng and Sin (2013)	Simulation	Process times – Set-up times – Breakdown times	Both ConWip and Modified ConWip outperform a push system by controlling WIP level and reducing cycle time and throughput time. Modified ConWip outperforms ConWip in terms of cycle time and robustness
Germes and Riezebos (2010)	Simulation	Workstation processing time – Arrival rate – Distribution of inter-arrival times – Batch size	Polca, ConWip and Modified-ConWip can all reduce both the total throughput time and the average time orders spend on the shop floor. The three PCSs show benefits depending on the manufacturing conditions

(Continued)

Table 4. (Continued)

References	Research approach	Simulation variables	Experimental results
Harrod and Kanet (2013)	Simulation	Total card count	ConWip is the best choice in a MTO manufacturing context
Helber, Schimmelpfeng, and Stolletz (2011)	Simulation	Bottleneck factor – base processing rate - Processing time variability - Buffer space per buffer	Optimisation of the configuration to maximise production rate and/or short-term profit
Herer and Shalom (2000)	Simulation	Machine processing time - Number of cards	This paper shows that a methodology with a non-integral number of cards allows models to be used in a more natural way to obtain results that are more economical and were previously considered infeasible
Huang et al. (2015)	Simulation	Assembly proportion – Assembly batch – Set-up time	The simulation shows that multi-loop is better than single loop in a ConWip assembly system, but a greater loop amount is not necessarily better. The loop amount should be adjusted on the actual shop floor
Huang et al. (2017)	Simulation	ConWip policies	The simulation result implies that (i) the CONWIP alternative policy with robustness has the potential to cope with more fluctuations in high-variety production environment; (ii) a better design for CONWIP policy will be able to enhance the system performance in practice; and (iii) the loop structure can serve as a parameter of CONWIP.
Jodlbauer and Huber (2008)	Simulation	Mean Time To Repair – Set-up time – Machine availability – Scrap rate – Demand Coefficient of variation	ConWip outperforms Kb and MRP for service level, WIP and optimisation ease but shows weaknesses in terms of stability
Lavoie, Gharbi, and Kenné (2010)	Simulation	Mean Time to failure – Mean time to repair – production rate per machine – Unit cost for backlog – Unit inventory cost	For a single part type production, Hybrid Kanban outperforms ConWip and Kanban when the storage space and inventory costs are considered. ConWip is equivalent to Hybrid if the two costs are aggregated. ConWip is outperformed by Kanban if the number of stations and the storage space costs increase
Li (2010)	Simulation	Set-up time – Processing time – Reworking time – Reset time – Inspection time	In a jobshop environment, ConWip outperforms Kanban
Marek, Elkins, and Smith (2001)	Simulation	Card allocation – Card number	ConWip systems are easier to implement and adjust than Kanban
Onyeocha, Khoury, and Geraghty (2013)	Simulation	Processing Time – Mean time between failure – Mean Time to Repair – Changes in product mix	In a multiproduct manufacturing environment Modified ConWip outperforms Kanban
Onyeocha et al. (2015)	Simulation	Processing time – Mean time between failure – Mean time to repair	A documented comparison of two Modified ConWip in a multiproduct manufacturing environment
Pierreval et al. (2013)	Simulation	Idem Tardif and Maaseidvaag (2001)	The presented simulation approach based on simulation optimisation allows setting the parameters, which influence the system performance in the design of a reactive pull system
Prakash and Chin (2017)	Simulation	Batch size – Ratio of High Runner (HR) and Low Runner (LR) products – Breakdown frequency – Numbers of cards for HR and for LR	Push is superior in term of throughput, Modified ConWip (parallel) is superior in terms of flow time per part and bottleneck utilisation and ConWip is superior in terms of service level.

(Continued)

Table 4. (Continued)

References	Research approach	Simulation variables	Experimental results
Ryan and Vorasayan (2005)	Simulation	Number of products – Total number of cards – Mean processing rate – Mean demand rate	Determine the card allocation (within a fixed total number of cards) to product types in order to minimise lost sales equitability
Sastry and Garg (2017)	Simulation	Demand Rate – Breakdown rate	The performance of Hybrid Kanban is optimal compared to Kanban and ConWip. Hybrid Kanban was implemented for one month and the production increased by 54%
Takahashi and Hirotani (2005)	Simulation	On-hand inventories for each part – Order quantities for each part – Production quantities for each part – Amount of backorders for each part – Amount of demand for the final product – Amount of satisfied demand for the final product – Amount of backlog of demand for the final product – Weighted total WIP	Modified ConWip outperforms Kanban and ConWip in terms of inventories when higher priority has to be given to several inventory stations, but Kanban and ConWip are better than Modified ConWip when higher priority is given to the last inventory station
Takahashi and Nakamura (2002)	Simulation	Mean inter-arrival time of demand	Reactive ConWip system is less effective to react to unstable changes in demand than the reactive Kanban
Tardif and Maaseidvaag (2001)	Simulation	Number of cards – Number of available extra cards – Cards release threshold – Cards capture threshold	Evaluation of an adaptive system (number of cards is allowed to change) compared to a traditional system with a fixed number of cards
Wang, Cao, and Kong (2009)	Simulation	Number of cards	Hybrid ConWip provides improved productivity and reduced delay time compared to ConWip
Wang, Wang, and Yue (2013)	Simulation	Demand quantities – Buffer sizes limitation	Simulation results show that the problem of bottleneck or hunger of the production line can be solved by setting a bottleneck area Kanban number and buffer size
Ziengs, Riezebos, and Germs (2012)	Simulation	Batch size – Utilisation level – Inter-arrival and processing times distributions	POLCA ability to balance the workload at a later stage outperforms balancing the workload at the moment of release for ConWip

### 5.1 Simulation

Table 4 provides a synthesis of the referenced papers that are based on simulation. The simulation-based papers are synthesised through their simulation variables and their experimental results.

### 5.2 Mathematical models

Table 5 provides a synthesis of the referenced papers that are based on mathematical models. The mathematical method-based papers are synthesised through their parameters and their aims.

### 5.3 Rex and literature review

Table 6 provides a synthesis of the referenced papers that execute a literature review or a return of experience.

The literature review executed by Stevenson et al. is not focused on ConWip but more generally on PCSs, the one proposed by Prakash and Chin is focused on modified ConWip and the one proposed by Framinan, González, and Ruiz-Usano (2003) is fully focused on ConWip.



Table 5. Overview of the referenced papers using mathematical models.

References	Research approach	Aims	Parameters
Aglan and Durmusoglu (2015)	Mathematical model	Applying lot splitting and ConWip simultaneously through a mathematical model which is compared with lot production under push control.	Maximum number of sublots – Number of ConWip cards – Lot size – Removal times – Fixed and variable transfer times – Processing times – Sequence dependant set-up times -
Baynat et al. (2001)	Mathematical model	Refinement of an original algorithm to provide a general framework for the analysis of more general Kanban systems	Number of stages – Number of Kanban – Arrival rate
Baynat, Buzacott, and Dallery (2002)	Mathematical model	Provide an in-depth analysis of the resulting control mechanisms of both dedicated card and shared card configurations	Type of cards: dedicated or shared
Bonvik, Dallery, and Gershwin (2000)	Mathematical model	Construct an iterative algorithm to determine the values of the used building block parameters and to estimate the performance measures of the system	Repair rates – Failure rates – Buffer capacities – ConWip limit – Machine efficiencies
Cao and Chen (2005)	Mathematical model	Determine optimal part assignment, production sequence and lot sizes simultaneously by solving a two travelling salesman problem.	Weighted cost associated with line idle time - Weighted cost associated with total set-up time - Forecasted product delivery time - Processing times - Set-up times
Economopoulos and Kouikoglou (2008)	Mathematical model	The objective is to determine the CONWIP level and the base backlog that maximise the mean profit rate of the system.	Demand rate - Mean relative deadline - Unit product holding cost rate - Raw item holding cost rate
Gong, Yang, and Wang (2014)	Mathematical model	ConWip needs the smallest amount of information and has the least time delays	Probability of any product in any workstation – the quantity of products in the PCS – The number of workstations
Korugan and Gupta (2014)	Mathematical model	Compare adaptive cards control to the best static cards control	Unit time backorder cost of a demand – Unit time holding costs of a product in new product manufacturing system, in remanufacturing system and in finished goods inventory – Average processing rate of a new part by a machine – Average remanufacturing rate of a part by a machine
Mhada and Malhamé (2011)	Mathematical model/ simulation	Determine the performance estimates of interest (mean total wip, probability of parts availability at the end buffer in the loop) for unreliable non homogeneous transfer lines	Maximum production rate – Repair rate – Failure rate – Maximum storage parameter
Parvin et al. (2012)	Mathematical model	Develop a methodology to use the proposed canonical model of worker cross-training in U-shaped ConWip lines	Mean processing times – Number of shared stations for which a given worker is trained - Number of fixed stations for which a given worker is trained – Number of stations in a line – Number of workers in a line
Satyam and Obtain estimates of key performance measures such as throughput and mean queue lengths for a multi-product system under ConWip control	Number of cards – Service rate – Mean raw material inter-arrival time	Krishnamurthy (2013)	Mathematical model/simulation
Zhang and Chen (2001)	Mathematical model	Determine an optimal production sequence and lot sizes in a ConWip production line	Cost associated with set-up times – Cost for unbalanced workload between production batches – Capacity of the bottleneck machine – Demand – Processing times – Set-up times on bottleneck machine

#### 5.4 Research avenues

It is unsurprising that the majority of studies undertake simulations, since this enables a comparison of two systems under the same conditions, while mathematical models are apt to define a new concept. The study of ConWip in various contexts should also entail industrial applications, yet studies based on industrial feedback in relation to ConWip are scarce and thus constitute a future and relevant research avenue. They could provide an operational validation of the simulation or mathematical models' results. In addition, such studies could also allow authors to refine their models according to the experimental results. Furthermore, they could help check whether variable card count management (which was covered in Section 2) is too complex to apply on a shop floor.

### 6. Decision and implementation scheme

SECTIONS 2 to 5 have provided some answers to the four research questions that this paper was interested in through a systematic review and classification of the literature body dealing with the ConWip PCS:

- Research question 1: How can ConWip be sized?
- Research question 2: How does ConWip work in different implementation contexts?
- Research question 3: How does ConWip perform compared to other PCSs?
- Research question 4: Which methodologies are used in the different ConWip studies?

These four questions, and their answers provided by the literature, can be linked together to build a ConWip implementation guide. In this context, Section 6 proposes a decision and implementation process: what should a practitioner do if he were to consider implementing ConWip? It discusses the managerial implications of the present state of the art.

This section sets a dual objective. The first is to help practitioners who aim to implement ConWip. The second is to provide an operating manual that will best take advantage of this literature review by linking this process to the different sections of this article, and by extension, to all of the papers that have been reviewed in this work. In any case, this decision and implementation scheme provides a synthesis of the managerial relevance that can be found in the present paper (Figure 6).

The first step of the proposed decision-making process is to analyse a production environment. A non-exhaustive list of characteristics to perform this analysis would contain the mixed-model (routings, standard deviation), the demand typology (stability, predictability, MTO, MTS), the type of workshop (jobshop, flowshop) and the hazards that occur in the studied environment (type, frequency). Since this question is not part of the aim of the present literature review, it will not be discussed here. To our knowledge, this specific topic would be worthy of dedicated research connected with the general comparison framework that (Framinan, González, and Ruiz-Usano 2003) highlight as a real need.

Considering the result of this analysis, the second step of the process consists of checking the compatibility level of ConWip with this production environment: Is ConWip adapted to the environment? Practitioners may refer to Sections 4 and 5 in this step. Indeed, Section 4 provides hints and references about the compatibility of ConWip to a given context and Section 5 provides indications and references about a comparison of ConWip and other PCSs. In other words, Section 4 helps build an opinion in absolute terms and Section 5 helps build an opinion in relative terms.

If the second step prompts a positive conclusion for the adaptation of ConWip to the given environment, the next step consists of determining the best parameters for ConWip. Section 3 may help practitioners solve this issue by using its content or by referring to the papers that it mentions.

Table 6. Overview of the referenced papers focused on Rex and Literature Review.

References	Research approach
Crop et al. (2015)	Non manufacturing Rex
Dallasega, Rauch, and Matt (2015)	Method description/non manufacturing Rex
Framinan, González, and Ruiz-Usano (2003)	Literature review
Gastermann et al. (2014)	Industrial Rex
Ip et al. (2007)	Industrial Rex/simulation
Pergher and Vaccaro (2014)	Industrial Rex/simulation
Prakash and Chin (2015)	Literature review
Romagnoli (2015)	Industrial Rex/simulation
Srinivasan, Ebbing, and Swearingen (2003)	Industrial Rex
Stevenson, Hendry, and Kingsman (2005)	Literature review
Suri (1998)	Method description/industrial Rex

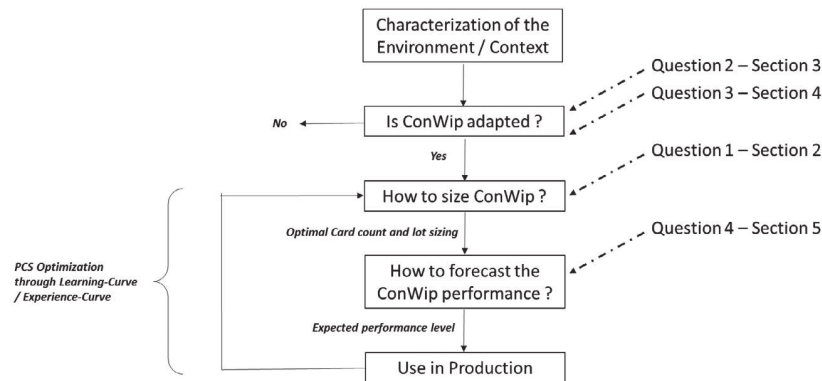


Figure 6. Proposed decision making scheme.

Once the best parameters are determined, the process goes on with a performance forecasting step. This step is made necessary by the strategic nature of the decision to implement a PCS (Jodlbauer and Huber 2008). Section 6 provides some clues to finding the right way to forecast the future performance. Indeed, the simulation tools and the mathematical models usually attempt to predict the behaviour of a given PCS in a given environment as accurately as possible. As a practitioner, one can find some interesting and operable papers to solve this question in Section 5.

The last step is about operating ConWip in production and is extended by a continuous improvement loop, which develops itself around a learning curve. The growing experience acquired by using the implemented PCS in the field will provide some internal Rex curve that can be used to refine the design of the PCS and/or the sizing and the implementation of the PCS.

To conclude this section, it is worth briefly stating the advantages of ConWip that appear in the entire body of literature to encourage practitioners to select it as their PCS. Huang et al. (2017) provides a complete overview of these advantages:

- CONWIP has a simple structure and is easy to understand and to use,
- Compared to other PCSs, ConWip has, generally speaking, acceptable performance and is even better in some aspects (e.g. high throughput, short cycle time and low WIP),
- The ConWip system is more suitable for MTO production than a Kanban system (Prakash and Chin 2015),
- ConWip has the fewest time delays for decision-making,
- ConWip has lower mean and variance of tardiness than Kanban and POLCA (paired-cell overlapping loops of cards with authorisation) in MTO (Harrod and Kanet 2013).

## 7. Conclusion

This review aimed to go through the body of literature on ConWip and to analyse it with an original view angle. This view angle was inspired by Stevenson, Hendry, and Kingsman (2005) and brought up four research questions. A specific section has been dedicated to each, with a special focus on their related perspectives. One more section has been included to propose a decision and implementation scheme connected with the four research questions. This conclusion highlights our perspectives of key research avenues that can be drawn from this literature review.

### (1) How can ConWip be sized?

Considering the current globalised market and related consumer behaviours, manufacturers must meet and even anticipate customers' expectations. In view of this trend, Stevenson, Hendry, and Kingsman (2005) indicate that MTO can be considered the future of industrial production. When considering the body of literature, the issue of sizing ConWip for an unbalanced MTO production line appears as a core issue and stands for one of the most relevant research avenues to help answer this first question. Additionally, the opposition between static card count and adaptive card count also needs to be explored further, since no clear decision can be made because of the balance of perspectives in the literature.

(2) How does ConWip work in different implementation contexts?

Ounnar and Pujo (2012) illustrate that efficient and customised job shop organisations are tailored to the growing demand for customised and even specific products. Nevertheless, the majority of the ConWip literature is dedicated to shop flow production and to the MTS context. Prakash and Chin (2015) explain that ConWip was ‘originally designed for manufacturing with constant product routings, similar processing times, minimal set-ups and linear process flow.’ However, as indicated here, few papers attempt to demonstrate ConWip’s ability to manage MTO with plants designed as job shops. Considering the scarce attention paid to this specific topic, ConWip processing in a job shop and the MTO industry is a relevant research avenue.

(3) How does ConWip perform compared to other PCSs?

Decision tools for better PCS choice in a given context constitute a real operational need. However, ConWip has been widely compared to all existing PCSs and these studies provide a relevant and complete database for choosing between existing PCSs. This is the reason why these comparisons do not constitute a main research avenue.

(4) Which methodologies are used in the different ConWip studies?

The final section of this paper highlights the lack of studies in the ConWip industrial return experience. Therefore, studying ConWip in an applied production context could be a research avenue of interest.

Through the four research questions raised by the present review, it appears that the research on ConWip remains relevant and has not been fully explored. Furthermore, some research avenues could bring about the conclusion that ConWip is the best PCS to manage certain typical industrial environments in the future. We hope this paper will provide some appropriate perspectives for researchers.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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