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Three decades of workload control research: a systematic review of the literature

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The workload control (WLC) concept has received much attention in the past three decades; however, a comprehensive literature review has not been presented. In response, this article provides a systematic review of the conceptual, analytical, empirical and simulation-based WLC literature. It explores the evolution of WLC research, determines the current state-of-the-art and identifies key areas for further study. The research finds that the field has evolved substantially. Early research focused on theoretical development and experimental testing of order release strategies; order release was then integrated with other planning stages, e.g., the customer enquiry stage, making the concept more suitable for customised manufacturing and leading to a comprehensive concept which combines input and output control effectively; recent attention has focused on implementing the resulting concept in practice and refining theory. While WLC is well placed to meet the needs of producers of customised products, future research should include: conducting further action research into how WLC can be effectively implemented in practice; studying human factors that affect WLC; and feeding back empirical findings to simulation-based WLC research to improve the applicability of WLC theory to real-life job shops.

Keywords: workload control (WLC); order review and release (ORR); production planning and control (PPC); systematic literature review

1. Introduction

The workload control (WLC) concept was developed to overcome the 'lead time syndrome' (Mather and Plossl 1978). Job entry is decoupled from release; orders are held back in a pre-shop pool and input to the shop floor is regulated in accordance with workload limits or norms. The objective is to maintain WIP at an optimal level and keep queue lengths in front of work centres short. The output rate is manipulated by adjusting capacity and it has been shown that the two control mechanisms complement each other, i.e. input should be regulated in accordance with the output rate (Hendry and Kingsman 2002). WLC stabilises WIP and lead times, enabling production and inventory costs to be reduced and both competitive prices and reliable due dates (DDs) to be quoted.

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It is considered a leading production planning and control (PPC) solution for make-to-order (MTO) companies, where pricing and DDs have to be determined for each job and are crucial order winning factors (Kingsman and Hendry 2002, Stevenson *et al.* 2005), and particularly appropriate for small and medium sized enterprises (SMEs) with limited financial resources (Stevenson *et al.* 2005, Land and Gaalman 2009).

WLC research has been conducted throughout the past three decades; however, it was not until Zäpfel and Missbauer (1993b) that the term 'WLC' was first used to refer to a group of PPC methods. The authors referred to 'PPC system[s] including WLC', grouping together three streams of research which seek to control workloads: order review and release (ORR) methods, largely developed in North America (e.g. Melnyk and Ragatz 1989, Melnyk *et al.* 1991, Ahmed and Fisher 1992); workload controlling methods building on input/output control (I/OC, from Plossl and Wight 1971), largely developed in the UK at Lancaster University (e.g. Tatsiopoulos and Kingsman 1983, Hendry and Kingsman 1991a, Hendry and Kingsman 1993); and load oriented manufacturing control (LOMC), largely developed at Hanover University in Germany (e.g. Bechte 1988, Wiendahl *et al.* 1992, Bechte 1994). More recently, Land and Gaalman (1996a) reviewed order release rules that seek to control workloads and integrated these into a comprehensive PPC system, hereafter referred to as 'ORR WLC'. Finally, Hendry *et al.* (1998) consolidated the four streams of research (i.e. ORR, I/OC, LOMC and ORR WLC) under the 'umbrella term' of 'WLC', designating it a new group of PPC concepts to control queues in job shops. Nowadays, all four of the concepts referred to above are generally accepted as being part of WLC research.

Elements of WLC research have been referred to in several reviews of a range of PPC concepts (e.g. Hendry and Kingsman 1989, Zäpfel and Missbauer 1993b, Stevenson *et al.* 2005); however, these studies are too broad to go into sufficient depth on each concept. Other studies have attempted to provide an overview of WLC research but have tended to focus on describing the various ORR mechanisms (e.g. Melnyk and Ragatz 1988, Wisner 1995, Bergamaschi *et al.* 1997) or comparing them through simulation (e.g. Philipoom *et al.* 1993, Sabuncuoglu and Karapinar 1999) and hence do not incorporate all PPC stages within the scope of WLC. Moreover, few recent reviews of the PPC literature have been presented – most of the aforementioned studies were published in the 1980s and 1990s, thus recent developments (e.g. since 2000) have not been considered. It follows that a comprehensive contemporary review is required which focuses only on WLC and covers all of the PPC stages within its scope.

In response, this article provides a systematic review of the conceptual-, analytical-, empirical- and simulation-based WLC literature published between 1980 and 2009, with a particular focus on the last decade. It consolidates the WLC literature to date, explores the evolution of WLC research, and identifies outstanding gaps for future research. Research relating to all of the concepts above (ORR, I/OC, etc.) are included in the review provided that the objective is to control the workload directly. On the other hand, constant work-in-process (ConWIP) is not included in the review as it only controls workload indirectly (based on the number of jobs in the system).

The remainder of this article is organised as follows. Section 2 outlines the systematic method behind the review – including how the literature was categorised. Section 3 briefly defines WLC. The literature review is presented in Section 4, which includes identifying key research gaps. The final conclusions follow in Section 5.

2. Methodology

This review began by considering the following research questions (RQ1 and RQ2):

RQ1: What have been the main contributions to the field of WLC? And has the focus of WLC research shifted over the past three decades? In other words, how is the field evolving?

RQ2: What are the most important future research directions in the field of WLC? In other words, how should the field of WLC evolve in the future?

A WLC database was built for systematic review through a four-stage process. First, papers published in international Business and Management Journals were analysed (www.b-on.pt) and all those appearing potentially relevant to WLC (including ORR, I/OC, etc.) were shortlisted. Second, the shortlisted articles were carefully read to assess the true relevance; if relevant, the papers passed into a preliminary database. Third, papers cited in the articles identified during the second stage were also read carefully to determine relevance to WLC; this ensured that relevant articles not identified during the first step were not overlooked. Fourth, all articles in the database related to WLC and cited more than once were chosen for the final WLC database. The final database contained 107 articles (27 from the 1980s, 42 from the 1990s and 38 since 2000). All articles in the final database have been included in the systematic review which is presented in what follows. Note that the reference list at the end of this paper has been split into two: (i) the papers contained in the WLC database and used in this review process; and (ii) additional references used in this paper but which are not contained in the database.

2.1 *Categorisation of literature*

In his review of order release policies, Wisner (1995) divided research into: descriptive, analytical and simulation-based research. Descriptive research contained general discussion papers, case study research and survey research. Only two empirical studies were included (Igel 1981, Bechte 1982) but, in this review, there are a further nine. The above categorisation is therefore adapted to: conceptual, analytical, empirical and simulation-based (conceptual corresponds to the descriptive category from Wisner (1995) excluding empirical research). Almost all articles could be categorised as conceptual but only those which do not fall under one of the other categories are included.

3. Workload control: an introduction

Many WLC methods are described in the literature; the unifying theme is use of a pre-shop pool and order release mechanism. All regulate release by considering the current load (e.g. at each work centre), workload limits and job characteristics (e.g. DD and workload). WLC methods emerging from the classical ORR concept and viewing WLC as the interface between the planning system and the shop floor have three control levels: job entry, job release and priority dispatch. Land and Gaalman (1996a) combined these into a comprehensive hierarchical concept referred to here as the ORR WLC concept. The WLC methods based on I/OC, largely developed at the Lancaster University and hereafter referred to as the LUMS Approach, added the customer enquiry stage to create a

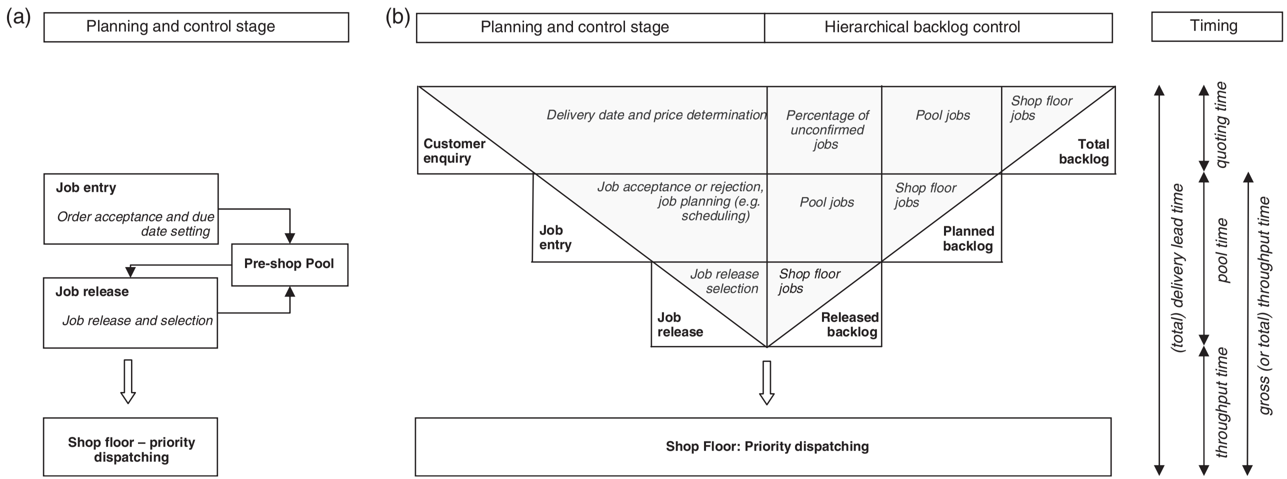

Figure 1 (a) ORR and ORR WLC (Land and Gaalman 1996a); (b) LUMS Approach to WLC.

four-tiered system. Figure 1 illustrates the control levels of the ORR WLC concept and the LUMS Approach; each control level is briefly described below.

3.1 *Customer enquiry and job entry stages*

Much research was conducted in the 1980s into setting adequate DDs (e.g. Bertrand 1983b, Ragatz and Mabert 1984) and throughout the 1990s many ORR researchers sought to find the best fit between DD assignment, order release and dispatching rules (e.g. Ahmed and Fisher 1992). A key finding was that DD rules which consider shop and job information perform better than those which do not (Ragatz and Mabert 1984).

The customer enquiry stage, as included in the LUMS Approach, takes place between a customer making a request for quotation and an order being accepted/rejected (Kingsman *et al*. 1996). It includes determining whether to bid for an order and, if so, what the DD and price should be. The LUMS Approach considers both shop and job information and incorporates a proportion of the workload of unconfirmed jobs in the total workload of the shop based on the probability of winning a tender (Kingsman and Mercer 1997). Much recent research has focused on this stage; for example, Kingsman (2000) proposed an analytical model for dynamic capacity planning at the customer enquiry stage and Kingsman and Hendry (2002) highlighted the importance of I/OC at this stage. Order entry begins with order acceptance/rejection and includes pre-production preparations for confirmed orders (e.g. checking material availability).

3.2 *Job release stage*

Two order release methods have dominated WLC research: the probabilistic and aggregate approaches. The release procedure is similar in both (Land and Gaalman 1998): jobs are held in a pre-shop pool where they are considered for release, e.g. according to shortest slack, latest release date or first-come-first-served. The load of a job is compared with the current load and limits of work centres and, if one or more limits would be exceeded by releasing the job, it is retained in the pool until the next release date. If the limits are not exceeded, the job is released and its load contributes to that of the work centres. The norms can be upper bound, lower bound or upper and lower bound and either rigid or flexible.

The main difference between the approaches is how they treat the indirect load, i.e. how the workload of a job that is still upstream of a given work centre is handled:

- The probabilistic approach estimates the input from jobs upstream to the direct load of a work centre using a depreciation factor based on historical data. When a job is released, its processing time partly contributes to the input estimation; the contribution increases as the job progresses downstream. The whole of the direct load and the estimated input is indicated as the converted load (Bechte 1994, Wiendahl 1995). The approach was introduced by Bechte (1980, 1982) and known as load oriented order release (LOOR); LOOR formed the basis of the LOMC concept (Bechte 1988, Bechte 1994, Wiendahl 1995).
- The classical aggregate load approach, introduced by Bertrand and Wortmann (1981) and Tatsiopoulos (1983), does not consider the position of a work centre in the routing of a job. The direct and indirect workloads of a resource are simply aggregated together. Tatsiopoulos (1983) developed a variant of this called the extended approach which controls the shop load rather than the load of each

individual work centre to overcome problems caused by a lack of feedback from the shop floor; but this has since been shown to perform poorly in simulation (Oosterman *et al.* 2000). Land and Gaalman (1996b) proposed a further extension, the corrected aggregate load approach, which divides the load by the position of a work centre in the routing of a job thereby converting the load (like the probabilistic approach) but without requiring statistical data. This approach arguably performs the best of the above, especially if a dominant flow exists (Oosterman *et al.* 2000).

3.3 *Dispatching stage*

Much research into dispatching took place in the 1980s and 1990s, with many authors underlining the importance of an appropriate dispatching rule (e.g. Melnyk and Ragatz 1989, Ahmed and Fisher 1992). However, the choice of dispatching rule becomes less significant when combined with other control levels. For example, Ragatz and Mabert (1988) stated that order release rules reduce differences between dispatching rules as the number of shop floor jobs is reduced. Most contemporary WLC research applies only simple dispatching rules; however, there are exceptions. For example, Stevenson (2006) applied a special dispatching policy for priority jobs.

4. Literature review and future research directions

This section is structured as follows. First, for each research category (conceptual-, analytical-, empirical- and simulation-based research; see Sections 4.1–4.4, respectively), key WLC research from the 1980s and 1990s is reviewed in order to explore how the field has evolved and build the backdrop for the analysis of the literature since 2000. Second, recent literature published since 2000 is reviewed in light of the research from the 1980s and 1990s in order to identify changes in the focus of research and outstanding research gaps. Third, future research directions for each category are outlined.

4.1 *Conceptual research*

4.1.1 *Conceptual research (1980–1999)*

Four types of conceptual research were conducted in the 1980s and 1990s: (1) the categorisation of WLC; (2) reviewing different PPC concepts and WLC; (3) developing the theory of the LUMS Approach; and, (4) developing the theory of LOMC. The first group mainly consists of Wisner (1995) and Bergamaschi *et al.* (1997) who categorised order release policies. The second group consists of the reviews by Hendry and Kingsman (1989), Zäpfel and Missbauer (1993b) and Land and Gaalman (1996a). For example, Hendry and Kingsman (1989) assessed the relevance of PPC concepts to MTO companies, concluding that LOMC and what later became known as the LUMS Approach were most appropriate. Researchers in the third group focused on developing the LUMS Approach. Tatsiopoulos and Kingsman (1983) and Kingsman *et al.* (1989) outlined the concept before it was further developed, for example, by Hendry and Kingsman (1991a) and Hendry and Kingsman (1991b). Hendry and Kingsman (1993) presented theory for controlling the total and planned backlog lengths (TBL and PBL) simultaneously; Kingsman *et al.* (1993) outlined the importance of integrating production and sales, introducing the use of the strike rate; and, Kingsman *et al*. (1996) presented an approach for determining prices and DDs. Researchers in the fourth group developed the LOMC concept. These papers (e.g. Bechte 1988, 1994) made important conceptual contributions but theory was typically developed through empirical insight and hence the papers are also included in Section 4.3 (empirical research).

At the end of the 1990s, two decades of conceptual research had contributed to the development of two mature WLC systems: the LUMS Approach, a comprehensive PPC system; and, LOMC, a widely implemented solution for integrating a planning system with the shop floor.

4.1.2 *Conceptual research (2000–2009)*

Four conceptual research directions were identified in the 1980s and 1990s. Research continued in all four areas but with most attention on Group 3: developing the theory of the LUMS Approach. The only contribution to Group 1 was Henrich *et al*. (2004a) who introduced a framework for analysing the characteristics of a company and assessing WLC applicability. This is an important contribution but more research is needed to delimit WLC from other PPC concepts (e.g. ConWIP) especially if it is to be compared with these concepts, as by researchers in Group 2. The main contribution to Group 2 was Stevenson *et al*. (2005) who assessed the applicability of several PPC concepts to different shop characteristics. As in previous reviews, WLC was found to be one of the best solutions for MTO companies. The other contribution was made by Fowler *et al*. (2002) who assessed the applicability of different PPC systems to the semi-conductor industry considering starvation avoidance (SA), developed especially for wafer fabrication by Glassey and Resende (1988). The remainder of this subsection focuses on groups 3 and 4 where the emphasis has shifted from theory development to theory refinement.

Since 2000, the LUMS Approach has been refined according to theoretical advances and contextual changes (Stevenson and Hendry 2006) and in response to issues encountered whilst implementing WLC, including human factors (e.g. Silva *et al*. 2006, Hendry *et al*. 2008, Huang *et al*. 2008, Stevenson and Silva 2008). Refinements in response to theoretical advances included removing the lower bounding of workloads introduced by Hendry and Kingsman (1991a) following the simulation results of Cigolini and Portioli-Staudacher (2002); refinements in response to contextual changes included controlling daily rather than weekly total and planned workload lengths to cope with shorter lead time demands. Implementation issues encountered included a lack of familiarity in practice with WLC, hindering progress during the early stages of a project (Silva *et al*. 2006, Hendry *et al*. 2008, Stevenson and Silva 2008). In response, Stevenson *et al*. (2009) developed an interactive end-user training tool which coupled a DSS based on the LUMS Approach with a simulated shop floor and demonstrated its positive impact in practice. In other cases, refinements were made without validation. For example, Stevenson (2006) introduced the option of releasing part of a job from the pool but did not evaluate the impact on overall release performance, while Stevenson and Silva (2008) compared refinements made during two implementations of the LUMS Approach conducted independently but in parallel and found that few refinements were valid for both cases.

A need for web-functionality within a WLC DSS was also identified, either to improve accessibility for multiple users or to integrate supply chain partners. Stevenson and Hendry (2007a, b) explored the implications of web-functionality for WLC while Silva and Magalhaes (2003) and Silva *et al*. (2006) developed a system that incorporated this technology. Web-functionality can be considered a step towards integration into the wider supply chain and integration with other systems, e.g. enterprise resource planning (ERP) systems but previous studies had not explicitly considered this. A further conceptual extension is provided by Soepenberg *et al.* (2008) who introduced a diagram which allows order progress to be tracked in a simple graphical way, helping to diagnose the causes of, and control, lateness. The tool was applied by Land and Gaalman (2009) to identify the causes of PPC implementation problems in seven cases. The main contribution to Group 4 was by Breithaupt *et al.* (2002) who made several refinements to LOOR and LOMC; for example, a dialogue-oriented extension to overcome balancing problems described by Wiendahl (1991) and a logistic operating curve to define optimal parameters (Nyhuis and Wiendahl 1999).

Finally, Table 1 summarises the most important conceptual WLC studies from the past three decades according to the categorisation introduced at the beginning of Section 4.1.1.

4.1.3 *Conceptual research: future research directions*

After 30 years, WLC is now a mature concept suitable as either a comprehensive PPC approach (e.g. Land and Gaalman 1996a, Stevenson 2006) or an interface between a higher level planning system and the shop floor (e.g. Bechte 1994, Breithaupt *et al.* 2002). But to remain at the forefront, the concept has to evolve with contextual changes and new technologies. Future research directions include:

- Developing a comprehensive framework to clearly outline the characteristics of WLC and delimit it from other PPC systems, such as ConWIP.
- Exploring how WLC can be incorporated into (more) ERP systems. While Fandel *et al.* (1998) reported that LOOR is included in 28% of commercially available PPC and ERP systems, up-to-date statistics are not available. Nor is it clear whether recent advances in the WLC literature have been incorporated. However, convincing more ERP vendors to adopt WLC may rely on establishing further empirical evidence of its positive effect on performance.
- Developing WLC to integrate the concept further into the management of supply chains (e.g. through more sophisticated web-functionality).

4.2 *Analytical research*

4.2.1 *Analytical research (1980–1999)*

Few analytical research contributions were made in the 1980s and 1990s because an adequate approach for modelling WLC was missing; all of the contributions that did emerge were based on queuing theory. The first attempt was by Kanet (1988) who used a single-machine model to analyse the influence of load limited order release on shop performance. The author found that it may negatively influence performance but this could be due to the simplicity of the release method applied. A second contribution was made as part of the conceptual study by Hendry and Kingsman (1991b), who analysed the relationship between the released backlog length (RBL) and throughput time and the influence of the percentage of priority orders on the performance of non-priority orders. The work is similar to a simulation study by Malhotra *et al.* (1994) – the same results were obtained but much quicker and without building a complex simulation model; this demonstrated the potential of analytical modelling. Finally, Missbauer (1997) studied the

Table 1. Summary of conceptual WLC research (1980–2009).

Group	1980s	1990s	2000s
Group 1: Categorisation of WLC	None	Bergamaschi *et al.* (1997) and Wisner (1995)	Henrich *et al.* (2004a)
Group 2: Reviewing different PPC concepts and WLC	Hendry and Kingsman (1989)	Land and Gaalman (1996a) and Zäpfel and Missbauer (1993b)	Stevenson *et al.* (2005) and Fowler *et al.* (2002)
Group 3: Developing the theory of the LUMS Approach	Kingsman *et al.* (1989) and Tatsiopoulos and Kingsman (1983)	Kingsman *et al.* (1996), Hendry and Kingsman (1993), Kingsman *et al.* (1993) and Hendry and Kingsman (1991a,b)	Stevenson *et al.* (2009), Hendry *et al.* (2008), Soepenberg *et al.* (2008), Stevenson and Silva (2008), Stevenson and Hendry (2007a,b), Stevenson (2006) and Stevenson and Hendry (2006)
Group 4: Developing the theory of LOMC	Bechte (1988)[a]	Bechte (1994)[a]	Breithaupt *et al.* (2002)

Note: [a]Conceptual and empirical research.

influence of sequence-dependent set-up times on the relationship between WIP and throughput showing that when sequence-dependent set-up times exist, throughput may be improved by increasing WIP because the number of set-ups decreases if more jobs are waiting in front of a work centre and can be grouped together.

4.2.2 *Analytical research (2000–2009)*

Few analytical research contributions were made in the 1980s or 1990s but there have been several recent attempts. Contributions are divided into three groups: (1) analytical models applying queuing theory; (2) mathematical analysis of new release methods; and, (3) analytical tools to facilitate management decisions. In Group 1, Haskose *et al.* (2002) developed a tandem queuing network with buffer constraints corresponding to a pure flow shop (PFS). This was extended by Haskose *et al.* (2004) to an arbitrary queuing network with buffer constraints corresponding to a general flow shop (GFS) and a pure job shop (PJS); however, only an approximate solution for the arbitrary queuing network could be provided. While this work is important to analytical model building in WLC research, it remains unclear whether applying buffer constraints is appropriate as most WLC policies do not restrict the buffer (or queue length) in front of work centres; work centre buffers are usually considered infinite as the buffering happens in the pre-shop pool to avoid blocking on the shop floor. An alternative was provided by Missbauer (2002a, 2009) who used the theory of transient queuing networks to build aggregate order release planning models, introducing a clearing function model with more than one independent variable. This appears more appropriate, but clearing function models are based on steady-state assumptions and hence still only provide approximation solutions. An additional contribution was made by Missbauer (2002b), where a single-stage model based on open queuing networks was introduced to explore the influence of lot sizes on WLC.

Enns (2000) made the main contribution to Group 2 by proposing minimum release time interval (MRTI), a method which releases jobs from the input buffer at equal time intervals corresponding to the expected processing time of a job at the bottleneck. MRTI is analysed using rapid modelling which provides an insight into performance without building a simulation model; the drawback is that feedback cannot be modelled. Therefore, an additional simulation model was built to validate the results and compare MRTI with alternatives. Further tests showed that MRTI did not perform as well as some sophisticated traditional order release methods. Hence, it remains unclear whether effective new release methods can be developed using analytical modelling in isolation. The main contributions to Group 3 are Kingsman (2000), who proposed a mathematical model to facilitate dynamic capacity planning at the customer enquiry stage, and Corti *et al.* (2006) who presented a heuristic to verify the feasibility of DDs requested by customers. However, while Corti *et al.* (2006) provided a first step towards providing managers with an effective tool for making fast and appropriate decisions, the focus was purely on checking the feasibility of proposed DDs and capacity planning at the customer enquiry stage; other important issues, such as the process of actually proposing a DD and parameter setting at the order release stage (e.g. workload norms), were neglected.

Finally, Table 2 summarises the most important analytical WLC research contributions from the past three decades demonstrating the increased interest in this approach in the last decade.

Table 2. Summary of analytical WLC Research (1980–2009).

Group	1980s	1990s	2000s
Group 1: Analytical models applying queuing theory	Kanet (1988)	Missbauer (1997)	Missbauer (2009), Haskose *et al*. (2004), Haskose *et al*. (2002) and Missbauer. (2002a,b)[a]
Group 2: Mathematical analysis of new release methods	None	None	Enns (2000)
Group 3: Analytical tools to facilitate management decisions	None	None	Corti *et al*. (2006) and Kingsman (2000)

Note: [a]Analytical- and simulation-based research.

4.2.3 *Analytical research: future research directions*

Analytical research has grown substantially and positive progress has been made in modelling WLC; future research directions include:

- Going beyond the approximate analytical modelling solutions presented to date.
- Developing simpler, yet effective, heuristics and models to support managers in making faster decisions in practice, including tools to support the process of setting appropriate WLC parameters.

4.3 ***Empirical research***

4.3.1 *Empirical research (1980–1999)*

Three types of empirical research were conducted in the 1980s and 1990s: (1) research based on single cases; (2) research based on multiple cases; and, (3) single case study accounts of hybrid PPC systems. Successful implementations of LOMC and LOOR were reported in Group 1 by Bechte (1988) and Bechte (1994) and in Group 2 by Wiendahl *et al*. (1992). All three report on implementations in small and medium sized MTO companies (from plastic and textile processing (Bechte 1988) to mechanical engineering (Wiendahl 1992, Bechte 1994), reporting reductions in lead times and WIP. Further empirical studies categorised in Group 1, where implementation success was less conclusive, were presented by Bertrand and Wortman (1981), Tatsiopoulos (1983), Fry and Smith (1987), Hendry (1989), and Hendry *et al*. (1993). Finally, research in Group 3 emerged at the end of the 1990s when Park *et al*. (1999) implemented customer enquiry management theory from the LUMS Approach but without the order release rule. A hybrid system was built that retained the company's existing releasing policy. The authors developed a decision support system (DSS) incorporating a heuristic delivery date decision algorithm (HDDDA) that revised the capacity planning model within the LUMS Approach. The system helped managers set feasible DDs but only considered the current load of the bottleneck machine and hence may be susceptible over time to the 'wandering bottleneck' problem (Lawrence and Buss 1994). The work demonstrated the flexibility of the LUMS

Approach (elements of the theory could be combined with existing business processes) and the hybrid system improved the performance of the company.

By the end of the 1990s, the body of empirical research was limited and papers tended to focus on reporting the before and after situation in the cases without describing the process of implementation itself. The exception to this was Fry and Smith (1987) who provided a framework for the implementation of a simple I/OC system and Wiendahl (1995) who included a 6-stage implementation framework.

4.3.2 *Empirical research (2000–2009)*

While empirical research in the 1980s and 1990s focused on comparing performance before and after implementation with the researcher as an external observer, recent contributions have focused more on the process of implementation with the researcher participating in organisational change. Hence, the scope of empirical WLC research has extended to action research; like in the 1980s and 1990s, research is divided into three groups: (1) research based on single cases; (2) research based on multiple cases; and, (3) single case study accounts of hybrid PPC systems.

Group 1 consists of Stevenson (2006) and Silva *et al*. (2006); both include a WLC DSS based on the LUMS Approach. The former was implemented in a small MTO company in the UK and the latter in a medium sized mould-producing MTO company in Portugal. Stevenson and Silva (2008) then collaborated to compare the two cases, while research questions raised by the implementation in the UK (and an additional case in the Netherlands) were summarised in Hendry *et al*. (2008). One of these concerned how assembly and rush orders could be accommodated; this has since been partially addressed by Thürer *et al*. (2009) who used simulation to find that prioritising rush orders at the release stage is the best solution. This group of research has outlined implementation problems (not just results) and outstanding research questions. In time, additional responses to that provided by Thürer *et al*. (2009) are expected. Finally, none of the authors in Group 1 and 2 who presented positive empirical results in the 1980s and 1990s have presented follow-up results since 2000 which demonstrate whether or not success was sustained over a long period of time.

In Group 2, Land and Gaalman (2009) explored why PPC concepts regularly fail by analysing data from seven companies, so future research can use the insight to implement WLC principles in practice. Key problems were uncontrolled delays in engineering and inadequate capacity planning overviews to support sales decisions. The former could be accounted for within the order entry/pre-production stage of WLC, while the latter can be overcome by applying WLC principles as shown in the work of Park *et al*. (1999) and Riezebos *et al*. (2003) below.

In Group 3, Riezebos *et al*. (2003) demonstrated that WLC can be successfully implemented when it is part of a hybrid system. Like Park *et al*. (1999), Riezebos *et al*. (2003) maintained the order release rule already used in the company (Drum-Buffer-Rope) and restructured order acceptance from a procedure where the sales department was allowed to accept orders freely up to a maximum financial daily turnover limit to a capacity-based approach considering two semi-interchangeable bottleneck machines. The authors also introduced LOMC principles, rather than the LUMS Approach favoured by Park *et al*. (1999), with a positive impact on performance.

Finally, Table 3 summarises the most important empirical WLC research contributions of the past three decades.

Table 3. Summary of empirical WLC research (1980–2009).

Group	1980s	1990s	2000s
Group 1: Research based on single cases	Bechte (1988)[a] and Fry and Smith (1987)	Bechte (1994)[a] and Hendry *et al*. (1993)	Silva *et al*. (2006) and Stevenson (2006)
Group 2: Research based on multiple cases	None	Wiendahl (1992)	Land and Gaalman (2009)
Group 3: Single case study accounts of hybrid PPC systems	None	Park *et al*. (1999)	Riezebos *et al*. (2003)

[a]Conceptual and empirical research.

4.3.3 *Empirical research: future research directions*

Recent empirical research has provided an insight into the implementation problems encountered in practice and raised questions regarding how they can be overcome, potentially leading to new conceptual advances. The future of WLC appears to lie in a comprehensive PPC system based on the LUMS and LOMC approaches but in which independent order release rules may be embedded. Future research directions include:

- Continuing to focus on implementation challenges and the process of implementation itself so future research can identify solutions to problems identified. This may also lead to developing a clear implementation strategy or roadmap for WLC.
- Considering the sustainability of implementation success over time. WLC implementations should be revisited several years after implementation to observe if the concept is still being used (or how it has been adapted over time) and determine how any positive effects can be sustained.

4.4 *Simulation-based research*

4.4.1 *Simulation-based research (1980–1999)*

Simulation was the dominant approach in the WLC literature in the 1980s and 1990s. Four groups of simulation-based research can be identified: (1) testing the influence of WLC (mostly ORR) on performance to find the best fit between control stages; (2) developing new release methods and comparing performance; (3) studying the influence of environmental (external) parameters on performance; and, (4) analysing the influence of WLC characteristics (internal parameters) on performance.

Research in Group 1 was concerned with evaluating different combinations of DD, order release and dispatching rules to determine the best combination. Bertrand (1983a) and Baker (1984) tested the influence of controlled order release on performance, while Ragatz and Mabert (1988) sought to find the best fit between dispatching and job release rules. This research continued throughout the 1990s (e.g. Ahmed and Fisher 1992, Wein and Chevalier 1992, Fredendall *et al*. 1996) but a combination of rules which clearly performs best under all conditions could not be determined. In an attempt to make the different control stages work together, authors such as Melnyk *et al*. (1991), Park and Salegna (1995) and Salegna (1996) introduced 'load smoothing' to control the entry of jobs into the pool. A ceiling (upper bound) and floor (lower bound) limit for the pool was introduced and the load was either pulled forward or pushed backward to smooth the overall pool load and improve order release performance. Melnyk *et al*. (1994b) later found that this adversely affected dispatching performance; hence, no conclusive results emerged and this research stagnated towards the end of the 1990s.

Researchers in Group 2 compared and developed new order release rules, such as: load balancing and load limiting (Shimoyashiro *et al*. 1984); SA (Glassey and Resende 1988); superfluous load avoidance release (SLAR: Land and Gaalman 1998); and, the Path-based bottleneck (PPB) approach (Philipoom *et al*. 1993). In addition, the conceptual work by Tatsiopoulos and Kingsman (1983) led to a control system presented by Onur and Fabrycky (1987), while Hendry and Wong (1994) tested the order release policy introduced by Hendry and Kingsman (1991a). Simulation was also used to compare WLC release policies against each other (e.g. Sabuncuoglu and Karapinar 1999) or against the release policies of other PPC systems, such as ConWIP (Roderick *et al*. 1992, Lingayat *et al*. 1995). However, none of these studies were able to establish one universal rule which performed best under all performance measures. By the end of the 1990s, an extensive set of alternative order release mechanisms had been developed and research in this group began to stagnate.

Researchers in Group 3 studied the influence of environmental (external) parameters, e.g. worker flexibility or sequence-dependent set-up times, on the performance of combinations of DD, order release and dispatching rules. For example, Park and Bobrowski (1989) and Bobrowski and Park (1989) showed that flexible workers have a positive effect on shop floor performance, Philipoom and Fry (1992) demonstrated that rejecting a small proportion of orders can improve performance, while Malhotra *et al*. (1994) found that the number of orders given priority should not exceed 30% or the performance of non-priority orders will deteriorate significantly. Finally, Philipoom and Fry (1999) showed that order release can offset performance losses that occur when operators refuse to follow dispatching rules. Each of these studies focused on an individual environmental parameter but, in practice, researchers encounter complex combinations of factors.

Research in Group 4 emerged towards the end of the 1990s. Cigolini *et al*. (1998) underlined the importance of testing the characteristics of release rules (internal parameters) iteratively, i.e. gradually changing them to determine applicability to different contexts. The authors analysed the influence of workload accounting over time approaches on performance and emphasised the importance of robustness in dynamic and uncertain job shop environments; probabilistic approaches performed the best. Perona and Portioli (1998) investigated the influence of the time between two releases (check period) and the planning period on the performance of LOOR. The authors suggested that the check period should be smaller than the planning period but exact values depend on the average processing time. The authors did not present a definitive answer as to how all of the internal parameters relevant to WLC should be set – an important issue for research in the 2000s.

4.4.2 *Simulation-based research (2000–2009)*

Simulation remains the dominant method adopted in WLC research. The same four groups of research noted in the 1980s and 1990s are evident since 2000 but with changing importance and objectives. The only studies which continue research in Group 1 are Weng *et al.* (2008) and Moreira and Alves (2009). Weng *et al.* (2008) presented a multi-agent WLC methodology consisting of a network of four independent agents, one for each of the three ORR control stages and one for information feedback. Previous research had struggled to cope with interaction between the different control levels but the network allows all levels to be controlled simultaneously. The results suggested that dynamic control might be a better solution than trying to find a best-fit combination of rules. Like many authors in the 1980s and 1990s, Moreira and Alves (2009) struggled to find one best-fit combination for the different control stages.

The previous two decades had provided an almost exhaustive set of release methods; as a result, few attempts to add to this list have been made since 2000 and the number of contributions to research in Group 2 has significantly decreased. Sabuncuoglu and Karapinar (2000) developed the DD and load-oriented release (DLR) method to minimise the mean absolute deviation (MAD) of lateness by considering both DDs and shop load. DLR outperformed several alternatives, e.g. the periodic aggregate loading (PAGG) and PBB methods including in terms of MAD and throughput time. Enns and Prongue Costa (2002) developed the aggregate load oriented release (ALOR) and bottleneck load oriented release (BLOR) methods. ALOR performs best in a flow shop but is outperformed if the flow characteristics are less structured. But none of these new rules have been applied by other authors, arguably because they are only slight variants on previously existing, and adequately performing, rules. Finally, Fredendall *et al.* (2009) compared WLC order release rules, and rules from other PPC systems, concluding that no single rule performs best under all conditions; the findings supported those made by authors in the 1980s and 1990s.

Within Group 3, Oosterman *et al.* (2000) and Land (2004) studied the influence of routing direction on the performance of WLC. The studies investigated four particular shop configurations (pure and restricted job shops and pure and GFSs) showing the superior performance of the corrected aggregate load approach if a dominant routing direction exists. Thürer *et al.* (2009) explored the influence of job size on performance, addressing a research question raised by Silva *et al.* (2006) and Stevenson and Silva (2008). Giving priority to large jobs at the release stage significantly improved the performance of large jobs with only a small performance loss for small jobs. A further implementation issue experienced by Silva *et al.* (2006) was how to group machines into work centres. This had been partly addressed earlier by Henrich *et al.* (2004b); the authors sought to reduce feedback requirements from the shop floor (a significant problem in practice) and found that this could be achieved by grouping machines with similar processing capabilities into work centres and controlling the load of the work centre rather than each individual machine. While information feedback was reduced, results indicated that the smaller the work centre (approaching one machine per centre) the better the performance. Hence, a trade-off has to be made between the cost of investing in efficient data collection tools and the performance loss of intermittent feedback.

Grouping interchangeable machines allows the allocation of jobs to a particular machine to be delayed until the last possible moment; however, machines are often semi-interchangeable, restricting flexibility. Henrich *et al.* (2006, 2007) found that the routing decision between two semi-interchangeable machines has to be made as late as possible if optimum performance is to be achieved. This is consistent with Kim and Bobrowski (1995) who studied the influence of sequence-dependent set-up times. If jobs have to wait for a free machine, or set-up times depend on short-term sequencing decisions, then the dispatching rule determines shop floor performance. This is contrary to the many authors who had earlier suggested that if order release is controlled, only a simple dispatching rule is necessary.

Further research into handling sequence-dependent setup times and routing decisions for semi-interchangeable machines at the order release stage is required, as is research into handling assembly orders. When considering the parts which make up an assembly order, should all parts be released together or treated independently? Precedence rules within the product structure also influence how the job flows through the shop floor, further complicating how workload might be accounted for over time. Bertrand and Van de Wakker (2002) provided a starting point for integrating assembly orders into WLC by testing several order release policies. Results suggested that performance is not affected by releasing all the work orders of an assembly order at the same time compared to treating them independently. Moreover, average lateness for assembly orders can be reduced to zero by planning all work orders of an assembly order with a flow time allowance (used to forward or backward schedule the orders) equal to the average operation waiting time. However, the authors did not apply any workload limit thereby avoiding the workload accounting problem and meaning that their contribution cannot strictly be considered part of the WLC literature.

Another important factor missing in WLC simulation research is the 'human factor'; the only study considering this was Bertrand and Van Ooijen (2002). The authors concluded that the level of WIP influences worker productivity and thus processing times. The authors argued that an optimum WIP level can be found and that WLC can be an appropriate means of maintaining WIP at the optimal level. Incorporating human factors like this within WLC research is important but can only be achieved by combining simulation models with empirical experience.

Finally, in Group 4, Cigolini and Portioli-Staudacher (2002) continued the work of Cigolini *et al*. (1998) and Perona and Portioli (1998) by investigating the influence of different workload bounding policies on performance. The authors found that an upper and a lower bound might conflict each other and negatively affect release performance, leading to one of the conceptual refinements made by Stevenson and Hendry (2006). Hendry and Kingsman (2002) studied the influence of input and output control on the performance of the LUMS Approach. A first simulation applied only input control, while a second applied input and output control; results suggested that the two control mechanisms complement each other. Finally, Land (2004) explored the influence of the check period, shop floor characteristics and flow time allowance on the performance of order release rules, summarising the results in Land (2006). No further contributions have been made since Land (2004, 2006), arguably because most key parameters have now been studied. Findings should assist practitioners in setting WLC parameters but empirical evidence which verifies this is required.

Finally, Table 4 summarises the most important simulation-based WLC studies from the past three decades. The table highlights the clear shift away from research in Group 1 and 2 and the increase in research in Group 3 and 4, as discussed earlier in this section.

Table 5 summarises simulation properties from papers since 2000, including the way jobs are ordered in the pool, the order release rule, performance criteria and approach

Table 4. Summary of simulation-based WLC research (1980–2009).

Group	1980s	1990s	2000s
Group 1: Testing the influence of WLC on performance to find the best fit between control stages	Ragatz and Mabert (1988), Baker (1984) and Bertrand (1983a)	Fredendall *et al*. (1996), Salegna (1996), Park and Salegna (1995), Melnyk *et al*. (1994), Ahmed and Fisher (1992), Wein and Chevalier (1992) and Melnyk *et al*. (1991)	Moreira and Alves (2009) and Weng *et al*. (2008)
Group 2: Developing new release methods and comparing performance	Glassey and Resende (1988), Onur and Fabrycky (1987) and Shimoyashiro (1984)	Sabucuoglu and Karapinar (1999), Land and Gaalman (1998), Lingayat *et al*. (1995), Hendry and Wong (1994), Philipoom *et al*. (1993) and Roderick *et al*. (1992)	Fredendall *et al*. (2009), Enns and Prongue Costa (2002) and Sabuncuoglu and Karapinar (2000)
Group 3: The influence of environmental (external) parameters on performance	Bobrowski and Park (1989) and Park and Bobrowski (1989)	Philipoom and Fry (1999), Malhotra *et al*. (1994) and Philipoom and Fry (1992)	Thürer *et al*. (2009), Henrich *et al*. (2004b, 2006, 2007), Bertrand and Van Ooijen (2002) and Missbauer (2002a)[a] Oosterman *et al*. (2000)
Group 4: The influence of WLC characteristics (internal parameters) on performance	None	Cigolini *et al*. (1998) and Perona and Portioli (1998)	Land (2006), Cigolini and Portioli-Staudacher (2002) and Hendry and Kingsman (2002)

Note: [a]Analytical- and simulation-based research.

Table 5. Summary of simulation properties.

Author	Pre-shop pool rule	Job release rules	Performance criteria	Statistical analysis
Bertrand and Van Ooijen (2002)	First in first out (FIFO)	Jobs are either immediately released to the shop floor if the load is above a threshold or wait until the load falls below a threshold and immediate release (IMR)	Total throughput time, (shop floor) throughput time and pool time	Wilcoxon
Cigolini and Portioli-Staudacher (2002)	Earliest due date (EDD)	Probabilistic, classical aggregate and time bucketing approach	Total throughput time, throughput time, shop utilisation, conditional tardiness, lateness, proportion of tardy jobs and WIP	Analysis of variance (ANOVA), *t*-test
Enns and Prongue-Costa (2002)	FIFO	ALOR and BLOR	Total throughput time, throughput time, mean time at machine, mean number of jobs in system and shop queue	No information
Fredendall *et al.* (2009)	No information	Modified infinite loading (MIL), CONWIP, DBR and (DLR)	Total throughput time, throughput time, standard deviation of throughput times, percentage tardy, number of jobs in the shop and bottleneck 'shiftiness'	Hierarchical regression
Henrich *et al.* (2007)	Planned release date (PRD)	Corrected aggregate load approach and routing decision according to largest load gap first (LLGF)	Total throughput time and throughput time	No information

		for the two interchangeable machines		
Henrich *et al.* (2006)	PRD	Classical and corrected aggregate load approach and special routing policy for interchangeable machines (50–50% or A/B/A/B and LLGF)	Total throughput time and throughput time	No information
Henrich *et al.* (2004b)	PRD	Classical and corrected aggregate load approach adapted to production units	Total throughput time and throughput time	No information
Kingsman and Hendry (2002)	No information	Classical aggregate load approach (LUMS Approach)	Total throughput time, reallocation time, overtime, WIP, mean queuing time and capacity utilisation	Regression analysis
Land (2006)	PRD	Probabilistic and classical aggregate load approach	Total throughput time, throughput time, percentage of tardy jobs, standard deviation of lateness and direct load	No information
Missbauer (2002a)	PRD	Aggregate order release planning method, LOOR (according to Zäpfel 1991)	Total throughput time, mean earliness, tardiness, WIP at bottlenecks and percentage of orders late and early	No information
Moreira and Alves (2009)	No information	IMR, backward infinite loading (BIL), MIL and planned input/output control (PIOC) which is similar to BLOR Enns	Mean tardiness, percent tardy, proportion of rejected orders, mean pool time, throughput time and gross throughput time	No information

(*continued*)

Table 5. Continued.

Author	Pre-shop pool rule	Job release rules	Performance criteria	Statistical analysis
		and Prongue Costa (2002)		
Oosterman *et al.* (2000)	PRD	Probabilistic, classical aggregate, extended aggregate, corrected aggregate and extended corrected aggregate load approach	Total throughput time and throughput time	No information
Sabuncuoglu and Karapinar (2000)	FIFO	DLR, interval release (IR), PAGG, PBB, period infinite loading (PIL) and forward finite loading (FFIN)	Total throughput time, throughput time, tardiness, lateness and absolute deviation of lateness	ANOVA, paired *t*-test, Bonferroni
Thürer *et al.* (2009)	Special policy	Classical, extended and corrected aggregate load approach	Total throughput time and throughput time	No information
Weng *et al.* (2008)	EDD	IMR, continuous aggregate loading (CAGG) and multi-agent job routing and sequencing method Wu and Weng (2005)	Total throughput time, throughput time, weighted earliness and tardiness and WIP	No information

to statistically validating results. Almost all use a special time-related policy to consider jobs for release, generally either backward or forward scheduled release or by considering the job with the earliest (planned) release date or earliest DD first. Many release rules have been simulated; however, in the last decade, the approaches outlined in Section 3.2 have prevailed (probabilistic and aggregate load approaches). The performance measures are either time-related (e.g. throughput times or lateness) or according to the number of jobs. Cost measures are less common in recent studies, perhaps because of the subjective nature of cost estimates in simulations; future research should consider how cost measures can be incorporated in an objective manner. Finally, the statistical analysis of results is uncommon and should be developed in the future.

Table 6 summarises the shop floor characteristics from papers since 2000, including routing sequence and length, processing times, arrival time of jobs, number of work centres, whether the shop floor is hypothetical or a real-life shop, and the simulation software used. Most studies are based on similar shop floor configurations to those presented by Melnyk and Ragatz (1989), simulating a PJS with uniformly distributed routing lengths, a fixed mean processing time which follows a certain distribution, and an arrival time adapted to achieve a certain utilisation level. Few studies base shop floor configuration on a real-life shop floor; although these would arguably provide the more realistic insight, a hypothetical configuration allows individual parameters to be studied while other parameters are controlled. Several simulation software packages have been used; authors do not routinely provide information about the logic underpinning the models developed, making it hard to compare results across researchers reliably.

4.4.3 *Simulation-based research: future research directions*

Recent research has shifted the focus from testing release mechanisms to addressing practical questions emerging from implementation experience; only 5 of the 15 simulation studies published since 2000 focused on release method development and comparison. Future research directions should include the following:

- Determining how to best handle assembly orders; while Bertrand and Van de Wakker (2002) provided a starting point, more research is required.
- Developing more realistic simulation models; most are hypothetical and, in many ways, do not reflect reality (Perona and Miragliotta 2000) leading to problems when researchers attempt to implement the results in practice. This should include incorporating more human factors within the design of simulation experiments.
- Validating refinements to the WLC concept (Section 4.1.2). This would combine empirical and simulation-based research to improve the conceptual basis of WLC.
- Providing an open-source WLC model. If all researchers used the same simulation model, results could be compared across research groups more reliably and the time spent on model building would be reduced. This could apply to code for order release or dispatching rules and for shop and job characteristics.

5. Conclusion

This review began by considering how the field of WLC has evolved towards identifying how it should evolve in the future. A comprehensive systematic review of the conceptual, analytical, empirical and simulation-based WLC literature published since 1980 has

Table 6. Summary of simulated shop floor characteristics.

Author	Routing: Sequence	Routing: Length	Processing time	Arrival time	Number of work centres	Buffer constraints	Type	Software
Bertrand and Van Ooijen (2002)	Random, equal for all (PJS), re-entrant loops	Mean routing length 5	Negative exponential [1][b]	Negative exponential (utilisation 90%)[c]	10	Infinite	Hypothetical	No information
Cigolini and Portioli-Staudacher (2002)	Random, equal for all (PJS), re-entrant loops	Uniform [1–12][a]	Constant + variable (normal [0], var. 0.1)	According to MRPII	11	Infinite	Hypothetical	SIMAN, Fortran
Enns and Prongue Costa (2002)	Job Shop (re-entrant), flow shop (no re-entrant loops)	Uniform [4–6]	Constant + variable (2-Erlang [0], var. 0.5)	Negative exponential [0.9]	6	Infinite	Hypothetical	Arena 3.0
Fredendall *et al*. (2009)	According to Lawrence and Buss (1994), 10 different products with unique routing and arrival times, and 13 different work centres with unique processing times				13	Infinite	Real	AWE-SIM
Henrich *et al*. (2007)	Random, equal for all (PJS), no re-entrant loops	Uniform [1–6]	2-Erlang [1] and [2] for 2 semi-interchangeable machines	Negative exponential (utilisation 90%)	$5 + 2^4$	Infinite	Hypothetical	EM-Plant
Henrich *et al*. (2006)	Random, equal for all (PJS), no re-entrant loops	Uniform [1–6]	2-Gamma [1] and [2] for 2 semi-interchangeable machines	Negative exponential (utilisation 90%)	5 + 2	Infinite	Hypothetical	EM-Plant
					12	Infinite	Hypothetical	EM-Plant

Henrich *et al.* (2004b)	General flow shop, 2 PJS with six machines each	Uniform [1–12]	2-Gamma [1], var. 0.5	Negative exponential (utilisation 90%)				
Kingsman and Hendry (2002)	According to a sample of 85 orders			Negative exponential	11 + 4 (18)[e]	Infinite	Real	No information
Land (2006)	Random, equal for all (PJS), no re-entrant loops	Uniform [1–6]	2-Erlang [1]	Exponential (utilisation 90%)	6	Infinite	Hypothetical	No information
Missbauer (2002a)	25 different products with unique job characteristics			No information (three levels of utilisation)	15	Infinite	Hypothetical	No information
Moreira and Alves (2009)	Random, equal for all (PJS), no re-entrant loops	Uniform [1–6]	Exponential [1.5]	Poisson process, 1 job per hour	6	Infinite	Hypothetical	Arena 7.1
Oosterman *et al.* (2000)	Random (PJS, GFS, RJS, PFJ)[f]	Uniform [1–6]	2-Erlang [1]	Negative exponential (utilisation 90%)	6	Infinite	Hypothetical	No information
Sabuncuoglu and Karapinar (2000)	Random, equal for all (PJS)	Uniform [1–6]	2-Erlang + special travel time	Negative exponential (utilisation 63–90%)[7]	6	Four jobs	Hypothetical	SIMAN
Thürer *et al.* (2009)	Random, equal for all (PJS), no re-	Uniform [1–6]	2-Erlang [1], negative exponential [1]	Negative exponential (utilisation 90%)	6	Infinite	Hypothetical	Simul8

(*continued*)

Table 6. Continued.

Author	Routing: Sequence	Routing: Length	Processing time	Arrival time	Number of work centres	Buffer constraints	Type	Software
	entrant loops							
Weng *et al.* (2008)	Random, no re-entrant loops	5	Truncated exponential [15] between 1 and 30	Negative exponential (utilisation 80–90%)	5	Infinite	Hypothetical	C++

Notes: [a]$[a–b]$ = between a and b.
[b]$[a]$ = mean a.
[c]Arrival time such that utilisation at this level.
[d]$a+b$ = a number of normal work centres and b number of interchangeable work centres.
[e]18 operators which can be allocated.
[f]PJS, GFS, restricted jobs shop (RJS), PFS.
[g]Different levels of utilisation have been simulated.

been conducted. In response to Research Question 1, regarding the evolution of the field of WLC, the following conclusions could be drawn:

- By the end of the 1990s, the conceptual development of the LUMS Approach and LOMC had reached maturity; the focus since 2000 has shifted towards conceptual refinement, e.g. in light of empirical evidence.
- There has been a substantial increase in analytical modelling since 2000, while the focus of field research has shifted from observation, and reporting before/after implementation, to focusing on *how* WLC can be implemented through participation.
- While it remains the most commonly adopted method, simulation has somewhat declined in use and its focus has shifted from finding the best fit between DD setting, release and dispatching rules to internal parameter setting and the influence of external parameters on the performance of order release rules, in many cases addressing issues encountered during empirical research.

Many valuable contributions to the development of WLC have been presented in the past three decades; however, there are many opportunities for further research. To conclude this article, and in response to Research Question 2, outstanding WLC research gaps identified include:

- Conceptual research: The need to give far greater consideration to human factors in the design of PPC systems based on WLC; and, the need to integrate WLC with ERP systems and the wider supply chain.
- Analytical research: The need to develop tools that support managers in making fast and appropriate decisions, e.g. during the process of setting appropriate (internal) WLC parameters.
- Empirical research: The need to conduct further action research into how WLC can be effectively implemented in practice; and, to investigate whether improvements can be sustained over time.
- Simulation-based research: The need to further improve simulation models, including studying human factors that affect WLC; and, feeding back empirical findings to simulation-based WLC research to improve the applicability of WLC theory to real-life job shops.

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