Information architecture for effective Workload Control: an insight from a successful implementation

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Abstract

The implementation of Workload Control (WLC), a Production Planning and Control concept uniquely designed for Make-To-Order companies, has been a constant challenge. Scholars argued that WLC is largely developed through simulations of well-defined environments while much more complex circumstances (e.g., information availability) have emerged in field research. A recent trend of WLC research is to improve the practical applicability of the concept, where empirical evidence is essential. However, success in WLC implementation remains impeded. The availability of data has been a significant area that frustrates the implementation process. While there is a tendency to simplify data requirements in recent WLC theory development, it is important to understand and maintain the information that is essential for the concept to be effective. For the first time in the field, this paper details the information architecture for WLC. Key informational entities of relevance to the input/output control functions in WLC as well as performance measurement are discussed based on evidence from a successful implementation. The paper not only sheds light for practitioners on how to construct an information system that facilitates successful WLC implementation but also has implications for future development of WLC mechanisms coping with information uncertainties in practice.

Keywords: workload control; production planning and control; make-to-order; information architecture; implementation;

1. Introduction

Workload Control (WLC) is a Production Planning and Control (PPC) concept uniquely designed for manufacturers of bespoke products, such as Make-to-Order (MTO) companies (Stevenson, Hendry, and Kingsman 2005). Bespoke items are often produced in low volume and high variety, where high levels of complexity and uncertainty are involved in the order fulfilment process. Despite an increasing focus on the development of the WLC concept since the early 1980s, only a handful of successful applications have been reported. When researchers attempted to implement WLC, they often encountered significant difficulties due to the gap between theory and practice. It is argued that WLC has been largely developed through simulations of simple/well-defined systems while field researchers have found more complex/uncertain circumstances in practice.

A recent trend of WLC research is to improve the practical applicability of the concept. Distinctive contributions include investigating the detailed implementation process (see, for example, Hendry, Huang, and Stevenson 2013; Hendry et al. 2008) to identify real-world challenges and developing corresponding solutions in simulation studies (see, for example, Thürer, Silva, and Stevenson 2010; Thürer et al. 2014). The shift of the research focus stresses the importance of WLC empirical research and advocates the need for more implementation cases to examine solutions proposed in simulation studies. However, success in WLC implementation remains hindered, where the lack of complete and real-time information has frequently been reported as a key barrier (Tatsiopoulos 1983; Hendry, Elings, and Pegg 1993; Silva, Roque, and Almeida 2006; Stevenson 2006; Huang, Stevenson, and Hendry 2008; Stevenson et al. 2011).

Intelligent computer systems are playing an increasingly significant role in embedding the WLC concept in practice; although this is subject to information availability (see Silva, Roque, and Almeida 2006; Stevenson 2006; Stevenson, Huang, and Hendry 2009). While a few WLC systems are presented in the literature, information requirements for such systems to be effective have not been explicitly articulated. In addition, previous empirical studies suggest that the inherent information flow in MTO companies is typically fuzzy and incomplete (Silva, Roque, and Almeida 2006; Stevenson 2006; Stevenson et al. 2011), which explains the challenges encountered in WLC implementation and confirms the need for effective information management. In response, this paper is motivated by the following research question:

"*What information is required to support successful implementation of the WLC concept?*"

The WLC concept presented in the literature differs in the account of workload overtime, release mechanisms, workload norms, and levels of PPC decisions (see Land and Gaalman 1996; Thürer, Stevenson, and Silva 2011), whereas the commonality is the use of a pre-shop pool/buffer to regulate shop-floor congestion and reduce work-in-progress (Wisner 1995). This paper mainly considers an aggregate load-oriented approach – originating from the doctoral work of Tatsiopoulos (1983) and Hendry (1989) at the Lancaster University Management School (hereafter referred to as the LUMS approach) – in determining WLC data requirements due to its comprehensive coverage of the PPC decisions and effectiveness in improving shop-floor performance in practice (see Stevenson and Hendry 2006; Thürer, Stevenson, and Silva 2011).

The remainder of the paper is organised as follows. Section 2 provides an overview of the LUMS approach including its key PPC stages followed by the barrier of information availability among a number of commonly encountered WLC implementation challenges. An action research method is detailed in Section 3. Section 4 discusses the specific data required to generate the information of relevance to WLC functions, structured in areas of input control, output control, and performance measurement. In particular, evidence of how such information is structured and managed in a rare, successful case of WLC implementation is provided. A framework of WLC information architecture indicating the flow of information is presented before the paper concludes in Section 5.

2. Literature review

This section introduces the LUMS approach upon which the WLC information architecture is explicated in Section 4. A number of challenges that are frequently encountered in WLC implementation are detailed in the remainder of the section, where information availability is particularly identified as a key barrier.

2.1 The LUMS approach

The fundamental principle underlying the LUMS approach is the balance between the input of incoming orders and the output of manufacturing capacity (Wight 1970). The approach is built around the control of a hierarchy of workloads, which represent the incoming orders, over four PPC stages including Customer Enquiry (CE), Job Entry (JE), Job Release (JR), and Shop-Floor Control (SFC). Details of the input/output control and decision making at each of the PPC stages are outlined below:

(1) The CE stage supports decision making on Due Date (DD) setting when a new customer enquiry arrives. The Total Workload (TW) of existing and future orders is controlled in line with the overall shop capacity to bid competitively while preventing resources from overloading; this is particularly important for MTO companies.

(2) The JE stage aids production planning such as job routing, scheduling and material preparation by controlling Planned Workloads (PWs) of existing orders (i.e. pool buffer and work-in-progress) across shop-floor resources (e.g., work centres), consequently supporting decision making on job acceptance/rejection or renegotiation with customers if needed. Jobs that overload shop-floor resources and have little room for DD negotiation should be rejected.

(3) The JR decision is based on the urgency of the job and the control of Released Workloads (RWs) on the work centres that are involved in the corresponding operations. In other words, a job remains in the pool no later than a Latest Release Date according to the plans (e.g., backward scheduling) drawn up at the Job Entry stage while no shop-floor capacity unit is overloaded (i.e. no workload norms are exceeded).

(4) Simple dispatching rules are sufficient in the SFC stage given a controlled shop-floor (Kingsman 2000). Expectations are that job progress is controlled and updated in a timely manner to identify and address potential delay before it is too late. In addition, longer-than-necessary workload contributions to work centres can be avoided to allow further release options.

2.2 WLC implementation challenges

Among a limited number of WLC empirical studies reported in the literature, the main focus in the 1980s and 1990s was to demonstrate the performance of the concept in practice (see, for example, Bechte 1988 and 1994; Wiendahl 1995; and Park et al. 1999). The attention has shifted to organisational embedding of the concept since the 2000s due to limited successful cases in the last two decades (see, for example, Hendry et al. 2008; Huang, Stevenson, and Hendry 2008; and Stevenson et al. 2011). The challenges encountered in WLC implementation are mainly attributed to the discrepancy between the real-world situations and the simulation experimental settings where the WLC concept was initially designed. Some (e.g., Stevenson et al. 2011) argued that the WLC concept should be refined to be more suitable for the practical environment and organisations need to adapt their practice in line with the fundamental WLC principle. Examples of challenges frequently stressed in the literature include:

- The lack of the awareness of WLC in industry to a great extent affects the motivation and participation of individuals, resulting in misuse of the concept (Hendry, Elings, and Pegg 1993; Silva, Roque, and Almeida 2006; Huang, Stevenson, and Hendry 2008). Some such as Hendry et al. (2008) and Stevensen and Silva (2008) contend that it is important to provide sufficient training to key organisation personnel before full implementation. In particular, an interactive end-user training tool and the training process are presented in the study by Stevenson, Huang, and Hendry (2009).
- An ill-informed end-user who is supposed to be of close relevance to the key functions of WLC may contribute to implementation failure (Hendry, Elings, and Pegg 1993). Multiple users with the involvement of key personnel in the corresponding functional units and production stages are considered more effective but require sophisticated information technology support (Silva, Roque, and Almeida 2006; Hendry, Huang, and Stevenson 2013).
- The availability of data, particularly in Small- and Medium-sized Enterprises (SMEs) that constitute a very important part of the MTO sector (Land and Gaalman 2009), has been a significant area that frustrates the WLC implementation process. The development of WLC software systems can effectively facilitate the embedding of WLC in practice but on condition that sufficient and reliable data are provided in a timely fashion (Silva, Roque, and Almeida 2006; Stevenson 2006).
- Material and information flows in the MTO context are often complex and unregulated, which implies the need for a systematic and detailed implementation strategy (Hendry et al. 2008; Stevenson and Silva 2008). Stevenson et al. (2011) proposed a roadmap towards successful WLC implementation and concluded the need for detailing/building up the elements including the information flow within the roadmap.

The above underlines the need to further develop the WLC implementation roadmap, where information availability is an outstanding issue. Thus, the topic is discussed in more detail as follows.

2.2.1 The barrier of information availability

A comprehensive WLC concept requires detailed job information from the customer enquiry stage in order to construct a competitive quotation. However, empirical evidence has found that historical information such as job routing and processing time for each operation involved in the routing is often not available in MTO SMEs given that their products are typically of high variety, low volume, and low repetition (Stevenson et al. 2011; Hendry, Huang, Stevenson 2013). It is argued that companies are less likely to make a detailed estimation at the stage when the possibility of getting a job is unknown (Stevenson et al. 2011). Land and Gaalman (2009) likewise report that MTO SMEs continuously have inadequate planning information (e.g., order, capacity) for sale decisions.

As one of the few early attempts to implement the WLC concept, Tatsiopoulos (1983) found that the lack of feedback information regarding shop-floor resources and job progress had significantly hindered the application of the job release function in WLC. The incompleteness and inaccuracy of such information is considered typical in SMEs (see Hicks, Culley, and McMahon 2006; Hicks 2007). Accordingly, it is suggested that grouping machines with identical or similar functions into a bigger capacity unit (e.g., work centre) will reduce the burden (e.g., amount) of feedback data (Henrich et al. 2004). However, the trade-off is that errors arise as the number of machines per work centre increases. For example, the processing time of jobs that cannot be split between machines may be erroneously shortened while a benefit of grouping similar machines is to produce items on more than one machine simultaneously (Silva, Roque, and Almeida 2006).

The lack of guidance to set workload norms for shop-floor capacity units (e.g., work centre) has been identified as another obstacle in WLC implementation (see Silva, Roque, and Almeida 2006; and Stevenson and Silva 2008). Appropriate norms for capacity units are critical for WLC performance (see, for example, Hendry, Kingsman, and Cheung 1998; Land and Gaalman 1998; and Perona and Portioli 1998). It is argued that the corrected/adjusted aggregate load approach presented by Land and Gaalman

(1996) and Oosterman, Land, and Gaalman (2000) is the most practically applicable method to ease the difficulties and burden of data requirements in determining the norms through simulation, where a common optimal value can be shared among all the capacity units (Thürer, Silva, and Stevenson 2010). However, the findings are yet to be applied and detailed in practice.

While the availability of information has been frequently stressed as a key challenge of WLC implementation, to the best of the author's knowledge no previous study has attempted to provide a comprehensive view of the information architecture for WLC to be effective. This paper addresses this gap by portraying WLC data requirement and information flow in detail supported by practical evidence.

3. Methodology

While the importance for organisations to construct an information system (IS) that is well aligned with the WLC concept is appreciated, the availability of information in real-world MTO companies should also be considered in refining the WLC concept to make it more effective in practice. Thus, this study employs a two-stage research strategy to address the research question given in the introduction. Firstly, the WLC concept is revisited in order to derive an ideal setting of WLC data requirements. Secondly, a realistic composition of information in practice is illustrated by looking into a rare, successful WLC implementation case where the construction and management of information was a long journey but proved to be a critical success factor.

The implementation project drew on an action research method, where the participation and intervention of the research team played a vital role in embedding the WLC system in the organisation. Action research is distinguished from other similar empirical methods (e.g., case study) by its unique characteristics of research in action, interaction between researchers and practitioners, and cyclical reflection and intervention with the ultimate aim of scientific knowledge-building (Westbrook 1995; Baskerville and Wood-Harper 1996; Eden and Huxham 1996; Coughlan and Coghlan 2002). The WLC information requirement was one of the main implementation areas explored in the project; the action research method is particularly relevant when dealing with the complex social context (e.g., organisational process and human behaviour) into which the IS (e.g., WLC system) is introduced (Warmington 1980; Checkland 1981; Baskerville and Wood-Harper 1996).

Action research attempts to link theory and practice, where knowledge is acquired in iterations of reflection and action (Susman 1983). To assure the rigour of knowledge generation, first, a theoretical framework or framework of ideas must be defined so it can then interact with practice (Warmington 1980; Baskerville and Wood-Harper 1996). As the WLC information requirement has not been comprehensively presented in the literature, a theoretical framework is prototyped in 'stage one' of the study (as specified earlier in the section) through a systematic analysis of the WLC concept before the action research in 'stage two'. As shown in Figure 1, the framework of WLC information requirement, the scientific knowledge explored in the study, lies at the core of the action research and is continuously refined and improved by dealing with all sorts of complexities in reality (indicated by the 'explosion' shape in the figure). The cyclical interventions in action research, such as 'diagnosing', 'action planning', 'action taking' and 'action evaluation' described by Coughlan and Coghlan (2002), enable immediate application and feedback of the refined theories (Baskerville and Wood-Harper 1996). Thus, empirical evidence and opportunities in WLC research are no longer restricted by the success of a full implementation as action research allows continuous "dialogues" between theory and practice (presented as the double arrows in Figure 1) during the journey towards success.

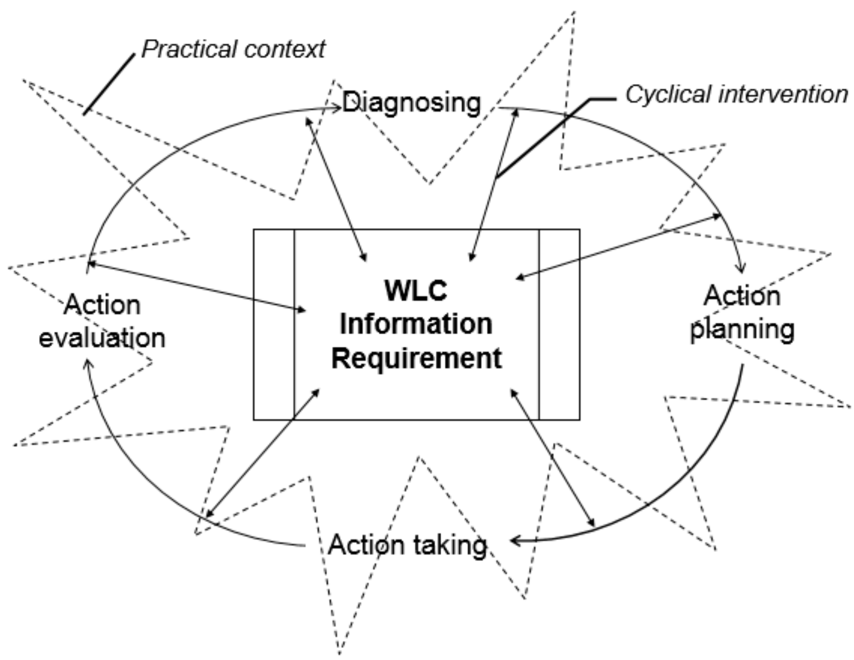

Figure 1. The development of WLC information requirement in action research cycle

Action research is typically criticised for a lack of objectivity and impartiality due to the direct involvement of researchers in shaping and telling the story (Baskerville and Wood-Harper 1996; Eden and Huxham 1996; Coughlan and Coghlan 2002). Coughlan and Coghlan (2002) stress the need to present the story including interventions, actions and reflections in a valid way and suggest journal-keeping as an effective mechanism for rigorous intervention. In response, a research diary was kept in the action research project to capture important events, opinions and behaviours, interventions, and performance over time. In addition, the researcher's feelings and thoughts were noted, which not only facilitates the researcher's reflections from experience but also enhances opportunities of evaluating critical events and maintaining objectivity (Raelin 2000).

3.1 Case description

The company (hereafter referred to as Company Y) that has successfully embedded the WLC concept in their organisation is a small precision-engineering manufacturer supplying bespoke products and components to the aerospace, commercial, and food industries. Before the implementation, an ad-hoc decision-making process was employed; prioritisation was based on social capital and *'who shouts the loudest'*. Information support was limited as described by the Operations Director - *'we don't have great data to compare how long it generally took to make the part'*. Company Y was pushed by their key customer to improve delivery performance. However, there was little knowledge on the availability of shop-floor capacity and the balance with the incoming orders. As the Production Controller explained, *'it doesn't give us the full impact of changes – the effect changes will have on all the orders…when customers make changes, we should be able to go back to them and say, yes we can do that but this is what you will impact'*. The commercial off-the-shelf packages such as Enterprise Resource Planning (ERP) systems were considered inappropriate for their problems – *'some of the others are not what we want and are over complicated* [Operations Director]*'*.

To implement WLC in Company Y, a Decision Support System (DSS) employing the WLC concept was developed at the start of the project in C# programming language with an underling MySQL Server database, followed by iterations of improvements in response to practical requirements identified during the implementation. It took over two years to achieve the performing stage when the impacts of WLC became evident; performance improvements that were observed include shortened lead times, increased delivery dependability, reduced overtime costs, higher quality due to less ‘fire-fighting’, and improved internal and external co-ordination as well as the overall ability to pass customer audits. The development of the DSS played an important role in understanding the information architecture for the WLC concept and how, in practice, data could be obtained and transformed into the required information. In particular, the DSS provides a central platform for information governance and communication which are essential for the success; details are set out with examples in Section 4.

4. Information architecture for WLC

To ensure effective decisions throughout the key control stages outlined in Section 2, it is important to have appropriate information architecture that facilitates the supply of the right information (e.g., job workload, resource capacity) at the right time (e.g., PPC stages) while promoting organisational/operational changes in conformity with the adoption of WLC principles. The rest of the section looks into information that establishes the input control and output control mechanisms including performance measurement in the WLC concept, where detailed data requirements are discussed. Examples from the action research provide a practical insight into how data are managed through a DSS to facilitate a successful WLC implementation. A framework of information architecture for WLC implementation concludes the section.

4.1 Input control: job related

In WLC mechanisms, the input control unit is often built upon a job that is established for the production of a product/component with a *contractual due date* (CDD). A job is different from a product which may be requested more than once to be delivered on different CDDs for the same or different customers. In other words, separate jobs are set off on a MTO basis for the production of a product with different CDDs. The rest of the session discusses job-related informational entities that determine or influence the account of input control.

4.1.1 Workload information

The input of incoming jobs can be measured by either the number of jobs or the actual work content (e.g., processing time in 'hours of work'); the latter is commonly used in WLC methodologies so that high job variability is accurately represented (Bergamaschi et al. 1997). For example, the work content of an incoming job, referred to as workload, on a particular capacity resource (if involved) is measured by the total time spent for the operation including *operation set-up time* and *operation processing time*. Operation set-up time is the time required for the preparation (e.g., machine changeover) before the start of a job on the capacity unit. Operation set-up time may vary across jobs or even depend on the previously processed job; the latter is called sequence-dependent set-up time (Missbauer 1997) and should be job-specific. Operation processing time varies in job complexity and job size; consequently, it can be calculated as the product of *unit processing time* and *job quantity*. The total work content of a job is the sum of workloads of all the involved operations defined by the job routine – i.e. the work centres required to produce the job in the *operational sequence* (Stevenson 2006).

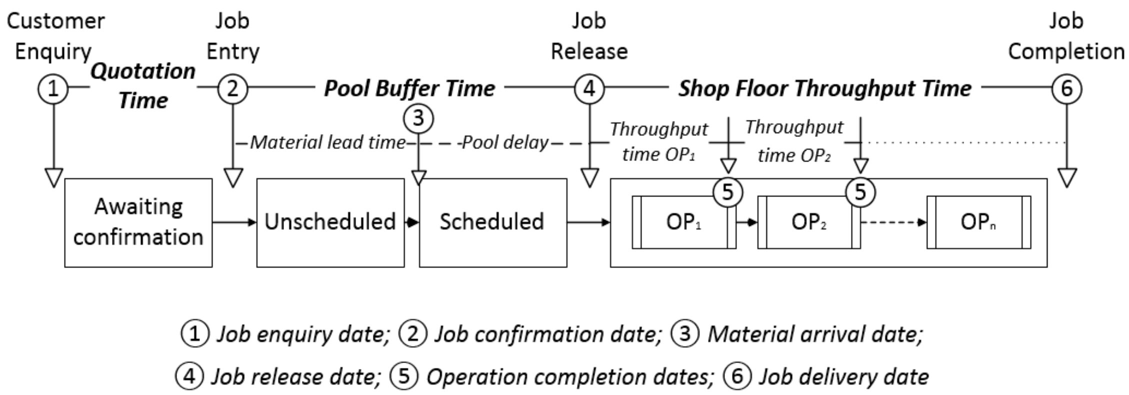

Figure 2. Progress control and key dates along the order fulfilment process in WLC

4.1.2 Progress control

The workload impact of a job on shop capacity units alters as the job goes from one production stage to another, as explained in Section 2.1. Figure 2 denotes the key dates to be monitored during the order fulfilment process. *Job enquiry date* and *job confirmation date* define the quotation period in which only a proportion (referred to as 'strike rate' in the literature and further explained in Section 4.3) of the work content contributes to the TW, as an enquired job may or may not be produced in the future. As soon as a tender result is received, the job status should be updated accordingly as this would either remove the partial workload (for rejection) or reflect the full work content (for confirmation). An accepted job approaches the JE stage, if successfully scheduled, contributing to the PWs of the individual capacity resources involved in its production. The *material arrival date* is key at the JE stage as it determines the earliest start date for forward scheduling; it must be no later than the latest release date by backward scheduling from the *CDD*. The *job release date* is the point when a job starts to have its actual impact - RWs on the corresponding shop capacity units; it tracks the shop-floor throughput time together with the *job delivery date*. When jobs are produced on the shop floor, real-time information regarding the progress (i.e. the operation or work centre) of a job closely affects the accuracy of the workload account and consequently the job release decisions. For example, the *operation completion date* determines when the workload of a job is removed from the work centre. In addition, *operation completion dates* articulate details of job progress on the shop floor, which explains the final delivery performance.

Jobs may have different priorities (e.g., *high*, *normal*) for release decisions and/or dispatching rules, where differing extents of pool delays and shop-floor buffers are expected. Job characteristics that may affect its priority level include the urgency of the job, job size or complexity, current progress of the job, the expected job profit, and the importance of the customer, among others. Some scholars argue that shop and delivery performance can be significantly improved by prioritising rush and/or large jobs (Land 2006; Thürer, Silva, and Stevenson 2010). However, the proportions of jobs taking a high priority should be restricted in line with the manufacturing capabilities, so that the expected accelerations can be achieved while normal jobs can still meet their delivery requirements (Stevenson and Hendry 2006). Table 1 summarises the ideal setting of job information of important relevance to the input control in WLC mechanisms. Detailed data requirements that feed such information for WLC key functions/decisions and the involved PPC stages are also outlined in the table. It is worth noting that some of the job information (e.g., routing, operation workload, and priority) is estimated for planning purposes while progress status is actual information for the update of workload count over time. Section 4.1.3 shows how job information has been managed in Company Y to facilitate effective WLC input control throughput in the key PPC stages. In particular, data that are 'nice-to-have' for advanced WLC impact but difficult to obtain in practice (marked as * in Table 1), or over-simplified in the design of the WLC concept (marked as ** in Table 1) are discussed.

Table 1. WLC input control informational entities

Job information	**Data requirement**	**Description**	**Key WLC function/decision**	**PPC stage**
Routing (Estimated)	*Work centres, operational sequence*	Capacity resources that will be required by the manufacturing of the job in operational sequence	Workload count, DD setting, scheduling	CE
Operation workload (Estimated)	*Operation set-up time**	The time required for the preparation (e.g., machine changeover) before the start of a job at the operation	Workload count, DD setting, scheduling	CE, JE
	*Unit processing time**	The time required for the production of the unit at the operation (e.g., work centre)	Workload count, DD setting, scheduling	CE, JE
	*Job quantity***	Quantity to be produced at the operation	Workload count, DD setting, scheduling	CE, JE, JR, SFC
Progress status (Actual)	*Job enquiry date*	The date that the job is enquired by the customer	Total workload count	CE
	Job confirmation date	The date that the job is confirmed by the customer	Planned workload count	JE
	Material arrival date	The date that all materials are ready for the job	Scheduling (forward)	JE
	Contractual due date	The delivery date agreed with the customer	Scheduling (backward)	JE
	Job release date	The date that the job is released for production	Released workload count	JR
	*Operation completion time**	The time that the job is completed at the operation	Released workload count; progress control	SFC
	Job delivery date	The date that the job is delivered to the customer	Release workload count; progress control	SFC
Job priority (Estimated)	*Normal/high*	The importance of the job defined by its urgency, complexity, size, progress, profit, customer, etc.	DD setting, Scheduling, dispatching rules	CE, JE

*Data that are ‘nice-to-have’ but difficult to obtain in practice (see practical alternatives in Table 2)
**Data that are over-simplified in the design of the WLC concept (see practical concerns in Section 4.1.3)

4.1.3 Job information management in Company Y

Company Y did not have a formal IS before the start of the project. Job information (e.g., quantity, routing, and operation times) was inconsistent, missing, overlapping, and stored in more than one place (e.g., paper documents, spreadsheets). The CE function was significantly hindered at early implementation due to the lack of data. Such a situation is typical in MTO SMEs (Stevenson et al. 2011; Hendry, Huang, and Stevenson 2013). To avoid an overwhelming data burden at the CE stage when the likelihood of securing a job is as yet unknown, *standard work centre throughput times* (see details in Section 4.3.2) were used instead of specific operation set-up times and processing times to simplify the estimation of TWs.

Given that a product (or component) may be produced more than once on a MTO basis, product portfolios including essential marketing and manufacturing information (e.g., price, routing, and materials) could be retained for efficient data management. Such historical data, even for repeat products/components, were not available in Company Y. As a result, a 'master book' that stores portfolios for typical products/components that are likely to be reproduced in the future is incorporated in the WLC DSS. Essential information is built up and archived as a job progresses, and retrieved when similar ones commence. Figure 3 presents an effective quotation process employed in Company Y in the full implementation phase with the support of the 'master book'.

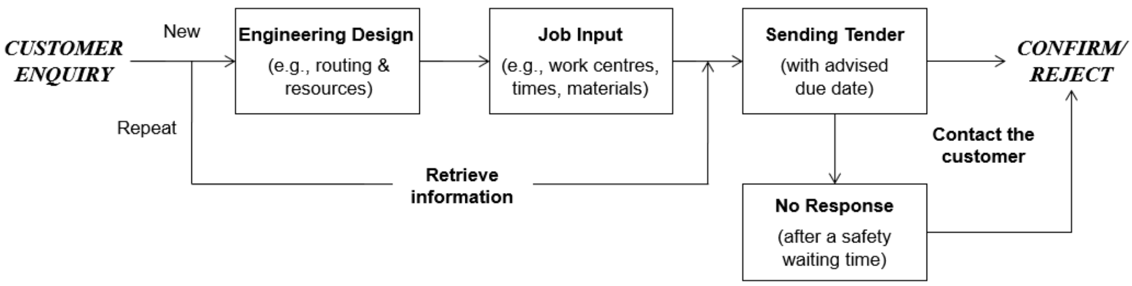

Figure 3. Quotation process in Company Y

An enquiry from a customer could be for a new or a repeat product. As indicated in Figure 3, a new job requires engineering design regarding manufacturing operations, machines, people, and materials before the job is input into the system with its essential information. Any newly designed jobs considered typical in the future are saved in the ‘master book’ for repeat use. Once all necessary information is available, a tender is sent to the customer with a system-advised DD. To avoid an unconfirmed job contributing to the TW for too long, the customer is contacted to be advised of any further implications if an expected confirmation time has passed.

At the JE stage when further information (e.g., operation set-up times and processing times) is meant to be added for detailed planning (Stevenson 2006), two uncertainties to capture the required data were found in Company Y. Firstly, a quantity larger than the customer’s requirements may be produced due to rework or scraps and the quantity may vary (most likely reduce) as production continues. Secondly, sequence-dependent set-up times (if involved) are often unknown until the actual jobs queuing at the front of the capacity unit and the dispatching sequence are determined. To anticipate a ‘*quantity-to-release*’, a successful rate - production yield (further discussed in Section 4.3) of the item could be applied to the quantity required by the customer. In case of sequence-dependent set-up time, the *average operation set-up time* of the capacity unit can be used as a rough estimate for planning purposes at the JE stage.

As mentioned in Section 4.1.2, job progress information (e.g., operation completion times) is important for effective release decisions. Such information was often overlooked in Company Y until problems were flagged. Since a real-time information feedback system (e.g., bar code) was not possible in the short term, a manual update system that corresponds with release decisions was suggested. For MTO companies that generally have tight lead times, the interval of job release (so as to progress update) should be no longer than one working day (Stevenson 2006). Hence, *operation completion dates* were suggested when a more frequent update was not possible.

To address the issues of information shortage and fragmentation in Company Y, a centralised job information management module is incorporated in the WLC DSS. The interface of the module is shown in Figure 4. The order summary component on the top of the interface enables users to specify and track all contract-related information (e.g., quantity, priority), ensuring jobs are confirmed with appropriate DDs at job entry. Production details in the middle provide a quick view of manufacturing-related information, making sure all progress (e.g., material arrival, current PPC stage) concerned with the job is monitored and controlled. The routing design function at the bottom of the interface incorporates alternative input approaches; work centres can be added to the job routing with either specific set-up times and unit processing times, or standard work centre throughput times. The latter is used when detailed data are not available. Such a job information management module, managing all essentials in one place, improved data availability for effective WLC decisions to a great extent in Company Y.

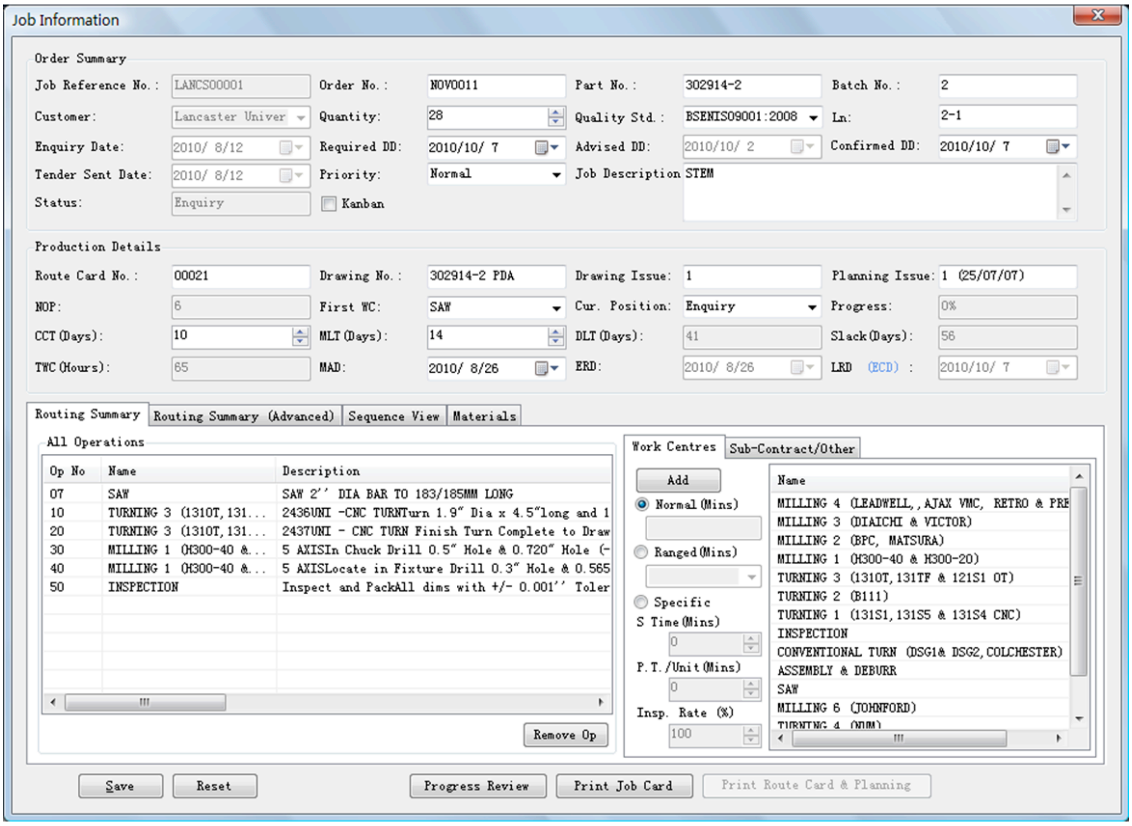

Figure 4. Job information management interface in WLC DSS

To complement the ideal setting (as shown in Table 1) of data requirements for WLC input control, Table 2 spotlights those difficult to achieve in practice, including alternative solutions. Among the identified challenges, Stevenson, Huang and Hendry (2011) have stressed the need for simplified routing information (e.g., operation set-up and processing times) for WLC theory development at the CE and JE stages. However, yield loss, which could cause significant hidden workloads, seems to have been continuously overlooked in WLC research.

Table 2. A practical perspective of WLC input control information

Ideal data	Challenge in practice	Practical solution
Job quantity	A quantity larger than that required by the customer may be produced due to rework/scrap	'*Quantity-to-release*' taking production yield into account
Operation set-up times	Set-up times are often unknown at the JE stage (when confirmation is needed) if they are sequence-dependent	*Average operation set-up times*
Operation processing times	Detailed operation times are often not available for new jobs at the CE stage	*Average operation processing times*
Operation completion time	A real-time information feedback system is often not available in SMEs that have limited financial resources	*Operation completion date*

4.2 Output control: production related

Given the workload (e.g., hours) of a transformation process (e.g., operation), the actual lead time of the process depends on the output rate - capacity of the function unit (Kingsman 2000). For example, a job has a separable workload of 16 hours on grinding machines; it takes two days for a work centre with one grinding machine and one day for two identical grinding machines with each producing half of the quantity simultaneously. As described in these two scenarios (e.g., one machine/work centre, two machines/work centre), the amount of work (e.g., 8 hours, 16 hours) that can be accommodated by a capacity unit (e.g., work centre) in a standard period of time (e.g., day) is called 'capacity'. WLC, like all other production systems, is sensitive to the determination of capacity which directly influences the lead times. In addition, contingent output control measures – e.g., subcontracting, overtime, alternative routing and reallocation of operators – are required to cope with diversities in the input rate (Kingsman 2000). The rest of this section discusses the key contributors of output control measures in the shop environment where WLC applies and how information can be built up to effectively reflect the output rates.

4.2.1 Hierarchical output control

The LUMS WLC uses 'workload length', defined as the number of days it will take for the shop/capacity group to complete its cumulated workload, to control the input of incoming orders and the output of capacity simultaneously (Stevenson 2006). PPC decisions can be affected by both, the account of input and the change to output

(Kingsman, Tatsiopoulos, and Hendry 1989). While the input information is becoming explicit as jobs progress from one production stage to another, the output control evolves from a rough-cut shop-capacity level to a specific concern of individual-capacity resources (see, for example, Park and Bobrowski 1989; Land and Gaalman 1996; and Stevenson 2006). For CE management, TW is shaped at a highly aggregate level in line with the overall shop capacity as strike rate does not specify individual jobs (consequently operations) but rather the total impact of future load. JE is the starting point of capacity commitment to the order book from individual resources (e.g., work centre). The aggregate workload impact of all the relevant jobs on a particular work centre should be balanced by its standard output rate based on the regular work pattern – namely, medium-term capacity control. JR decisions are made in consideration of short-term/immediate capacity including the contingent measures (e.g., overtime, subcontracting) of corresponding capacity resources for a particular job.

4.2.2 Capacity/resource constraint

While the account of workloads has been extensively discussed in the WLC literature, the description of capacity is typically simplified to standard output rates per time period (e.g., machine hours per day) without details of the composition. However, previous attempts to implement WLC have found that real manufacturing environments often entail a much more complex and dynamic capacity system, where more sophisticated mechanisms are needed to measure and control the output rate (Silva, Roque, and Almeida 2006; Stevenson 2006). Among a number of contributions (e.g., Bertrand and Wortmann 1981, Park and Bobrowski 1989, Riezebos, Korte, and Land 2003) that incorporate the impact of dual/multiple resource constraints on WLC performance: Park and Bobrowski (1989) demonstrate significant improvements of shop performance by introducing multi-skilled workers who can operate more than one machine at a time; and Stevenson (2006) presents a case study using work shift pattern (i.e. available man hours) and work centre efficiency (i.e. a machine-hours per man-hour ratio) to capture the dynamics and diversity of capacity in practice.

In order to perform effective output control in WLC mechanisms, it is essential to understand the typical sources (e.g., machine, manpower, outsourcing) of manufacturing capacity and their impacts on the output rate.

- *Machine:* The shop floor consists of a number of machines performing various functions required in the manufacturing of products. Machines with similar function may form a capacity group called *work centre* to simplify planning and control activities such as alternative machines (Henrich, Land, and Gaalman 2006; Stevenson 2006). The capacity of a work centre depends on the composition of machines (e.g., number of machines, sequential/parallel processing, individual machine performance) and their working pattern (e.g., length of factory day). Machines in each work centre may vary in physical conditions and processing capabilities which alter their performance compared with a standard output level. For example, a machine fully working over an eight-hour shift may only be capable of accomplishing the workload of seven hours. Parallel machines which produce more than one job at a time are considered as high-efficiency capacity units. Hence, the performance of an individual machine can be expressed by *machine efficiency rate* which should be evaluated on a regular basis. The overall effectiveness of a machine is measured by the product of *standard working hours* and its efficiency rate. In principle, the standard working hours can be the length of factory day depending on the number of shifts and the length of each shift. Additionally, non-automated or low-automation machines often run under the supervision of shop-floor operators. Thus, their working patterns are constrained by the availability of manpower.
- *Manpower:* A machine-man hour ratio by Stevenson (2006), defined as the capacity of machine hours per man hour, could be applied to represent the interaction between machine and manpower capacity in operations that require a human work component. Individual workers are dissimilar in experience, skills, and flexibilities; consequently, they have different impacts on shop-floor capacities. For example, experienced workers may potentially double capacity rates by running two machines simultaneously while less experienced workers can only operate one at a time. Flexibilities are no doubt required for customised production. While job shop facilitates product flexibility, production flexibility is often enabled by general-function machines and multi-skilled workers (Fryer 1974; Park and Bobrowski 1989). It is argued that reallocation of workers, who are capable of working at a second or third work centre, is an important

contingent output control approach in WLC literature (see, for example, Park and Bobrowski 1989; Kingsman 2000; Kingsman and Hendry 2002; and Stevenson and Silva 2008). In addition, an individual's flexibility for overtime, including willingness, available hours, and length of notice, would determine firms' capacity to cope with unexpected work (e.g., rush orders, excess demands). While the *regular work shift pattern* defines standard capacity rates, occasional events (e.g., *overtime, reallocation*) facilitate contingent capacity.

- *Subcontracting:* Subcontracting happens mainly due to technological concerns or capacity tightness (Bertrand and Sridharan 2001); the WLC literature has reported this as one of the more commonly used output control alternatives. However, subcontracted work is also a classic source of uncertainty in production lead times (see, for example, Kingsman 2000; Stevenson and Hendry 2006; and Stevenson 2008). Subcontracting can apply to the production of an independent product/component as well as a part (e.g., an operation) of the production. In either case, a fixed *lead time* that ensures the overall production scheduling is important; final delivery performance should be agreed with the subcontractor and closely monitored once the job is out for subcontract operations. A shorter lead time is often associated with a higher price. The decision is a trade-off, although it is highly linked with the urgency of the job/operation.

As discussed above, machine hours are often constrained by the availability of manpower. Working pattern of machines as well as manpower determines a standard capacity level. Reallocation of multi-skilled workers, overtime, and subcontracting enables contingent capacity. Table 3 summarises informational entities for output control in WLC mechanisms at both standard and contingent levels. The former is considered as 'essential-to-have' capacity data for WLC to be effective, and the latter, referred to as 'nice-to-have', facilitates an advance use of the concept by providing information of flexible output control.

Table 3. Capacity-related informational entities

Capacity information	Data requirement	Standard capacity	Contingent capacity
Machine	Work centre (operation function)	√	
	Efficiency (0%-100%)	√	
	Standard working hours (working pattern)	√	
Manpower	Main work centre (skill)	√	
	Alternative work centres (skill)*		√
	Machine-man hour ratio (experience)	√	
	Regular shift/working hours	√	
	Overtime availability*		√
Subcontract	Work centre/operation*		√
	Subcontractor*		√
	Lead time*		√

*Data that are 'nice-to-have' for advance use of WLC with contingent capacity management

4.2.3 Capacity management in Company Y

One of the key concerns for WLC implementation in Company Y was knowledge on capacity loading. Their customer described the lack of appropriate capacity monitoring that is common among suppliers like Company Y: '*As a customer, you want a credible delivery date … capacity is key … you need to know what capacity you have in order to sell it! However, it is the missing link. I don't think I've dealt with a supplier yet that knows what capacity they have.*' Hence, it was important to define appropriate capacity units (e.g., work centres) and determine corresponding capacity calculations in Company Y before WLC is fully implemented.

Machine downtime in Company Y was considered a problem with an average efficiency of 50%-60%. New machines should be purchased to replace old ones for long-term capacity improvement, but this can only be achieved gradually and was restricted by the company's financial situation. For an effective capacity management system, Company Y has been encouraged to group similar machines into work centres. Most machines were semi/fully automatic which means it is possible for one operator to run two or more machines at the same time. Some operators were able to work across several work centres; the available working time of each operator at each work centre was estimated by a percentage of the operator's total working hours. The capacity constraints could be either unbalanced machine loading or operators with limited skill levels (machine set-up is a skilled job that not all operators can perform). To avoid capacity calculations becoming overly complex, the ratio of machine hours per operator hour suggested by Stevenson (2006) for each work centre was applied; thus capacity management was simplified to manage available operator hours at each work centre as shown in Figure 5. The maximum operator hours were controlled by the shop-floor engineers to ensure the alignment with the machine constraint.

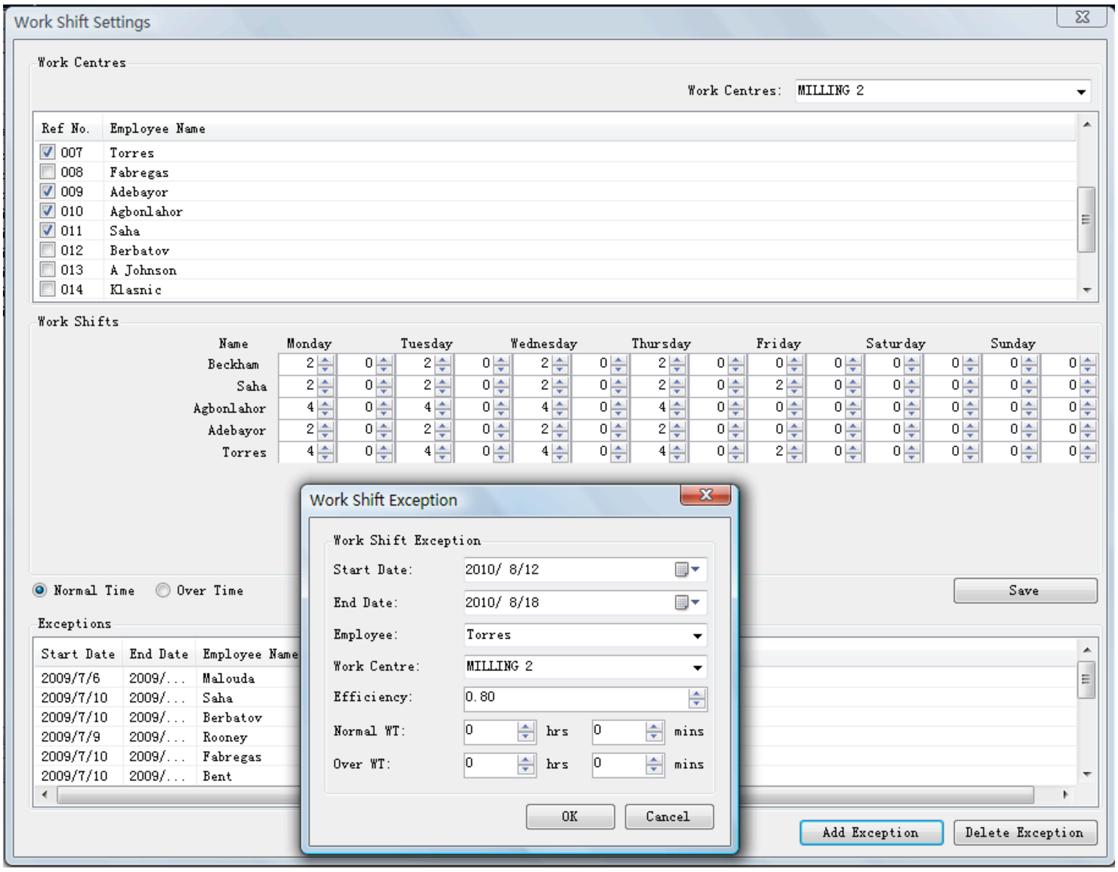

Figure 5. Work shift setting for capacity management in Company Y

To define the capacity for a particular work centre, for example, Milling 2 in Figure 5, the relevant operators are selected from the employee list on the top of the ‘Work Shift Settings’ interface followed by their daily committed hours specified in the regular work shifts table; this contributes to the standard daily capacity for the work centre. Any short-term changes (e.g., reallocation, holidays, and overtime) can be specified using the exception function at the bottom: start and end dates (period of exception), people involved, work centre affected, efficiency, and working hours. In addition, this exception function can also define long-term capacity change (e.g., new machine purchase) in advance by adjusting the work centre efficiency with the presumed start date. The overall work centre capacity is accordingly determined by the total man hours based on an average machine/manpower ratio at the work centre. Capacity management at work-centre level means that jobs do not have to be assigned to a particular machine until the last minute.

4.3 Performance informational entities

WLC-related performance measures identified in the literature are typically used for gauging the impact of WLC in simulations as well as in empirical studies. Recent studies regarding WLC implementation have been responding to the call for contingent applications of knowledge in the fields of operations and production (Sousa and Voss 2008; Tenhiälä 2011). It has been argued that there is no best WLC mechanism, only the one most suitable for the given context (Thürer, Silva, and Stevenson 2011). For example, companies that compete particularly on speed may require a tight setting of the workload boundaries (Hendry, Huang, and Stevenson 2013). Hence, performance measurement plays a greater role than just assessing impact; the control measures also facilitate the diagnosis of areas of improvement and the selection of the right mechanisms in WLC implementation. This section provides understanding of the job/product and production process-related performance entities and their specific roles (e.g., WLC impact indicators, control measures) in supporting WLC implementation.

4.3.1 Job/product related

Job- or product-related performance measures observed in the literature to assess the effectiveness of WLC include delivery, proportion of successful quotations, quality, and cost (see, for example, Cigolini and Portioli-Staudacher 2002; Kingsman and Hendry 2002; Weng 2008; and Hendry, Huang, and Stevenson 2013). Quality and cost improvements have been indirectly attributed to the impact of WLC associated with the reduction of work-in-progress and overwork (Hendry, Huang, and Stevenson 2013); their specific measures are not detailed as a direct performance of WLC.

Tardiness and/or *lateness* are commonly used to measure delivery performance in the WLC literature in various settings, depending on the focus of improvement. For example, tardiness (e.g., % of late deliveries, average length of delays) indicates jobs with actual deliveries later than the promised DDs; it is particularly pertinent when penalties (e.g., extra costs, reputation damages) apply, and consequently, the key concern of improvement is to minimise late deliveries. Lateness is usually taken as the average of delivery variations, where early deliveries are expressed as negative values (e.g., - m days of earliness) and late deliveries contribute to positive values (e.g., + n days of delay). Average lateness sheds light on the general capability of meeting DDs at the shop level or individual capacity unit level: a positive value denotes a tendency of late deliveries; and a negative value might suggest insufficient capacity usage or unnecessary inventory expenses because of earliness. For organisations that employ lean principles or aim for on-time (i.e. neither early nor late) deliveries, lateness distributions would provide a more comprehensive view on performance.

The proportion of successful quotations among total enquiries, referred to as '*strike rate*' by Kingsman et al. (1996) and Kingsman and Mercer (1997), is not only a criterion to assess sales performance but also a vital parameter to take into account concerning the workload impact of future confirmed orders among all the enquiries at the CE stage. In other words, the TW consists of confirmed orders and a proportion (e.g., strike rate) of unconfirmed orders; the latter is particularly relevant when the average strike rate is higher than 10% (Silva, Roque, and Almeida 2006; Stevenson 2006).

Production yield, as a result of 'fall-out' during the manufacturing process, has been typically studied for its economic impacts due to the loss of materials, e.g., rework and scraps (Bohn and Terwiesch 1999); however, it has received little attention in WLC research. Recent WLC empirical studies suggest that rework and/or scraps may cause significant disturbances to the RWs, which should be effectively reflected in WLC mechanisms (Stevenson et al. 2011; Hendry, Huang, and Stevenson 2013). Thus, production yield, referred to as the successful rate of the production of a product, is an important informational entity to scrutinise for workload implementation.

4.3.2 Production process related

Compared with products, it is more likely that the performance of the manufacturing process (e.g., resource-related and lead time-related) will be ignored or unmonitored in practice as it is not of direct concern to, or judged by, customers. However, process determines results and the entailed measures provide important information to support contingent PPC decisions and the best practice of WLC.

Although *queuing time* and *processing time* at each work centre often vary from one job to another in job shops (Henrich, Land, and Gaalman 2004; Land 2006), a *standard throughput time* – an average length of stay at the work centre including average set-up times and processing times – facilitates a quick estimate of workload when detailed data are not available (described in Section 4.1.1). Moreover, a close observation of work centre standard throughput times may assist identification of bottlenecks and how easily they can shift. Hence, the *length-of-stay* – defined as the interval between a job leaving the previous work centre and leaving the current work centre – of individual jobs should be collected and archived for statistics of standard throughput time. For organisations particularly aiming to improve work centre queuing times or processing times, separate observations are necessary.

Shop-floor throughput time (SFTT) and total *manufacturing lead time* (MLT) are performance measures commonly used in WLC studies; the former excludes *pool delay* (the period between job confirmation and job release) from the latter. While a controlled MLT, which is the duration between job confirmation and completion, assures reliable and competitive deliveries, SFTT provides a better view of the pure shop-floor performance. It has been argued that WLC parameter-setting including determining appropriate workload boundaries at various production stages is a complex decision sensitive to WLC mechanisms and practical settings (Perona and Portioli 1998; Land 2006). The average or standard MLT and SFTT could be used as an initial setting for WLC boundaries at JE and JR, and the values can be tailored for specific contexts and situations as the implementation progresses (Stevenson and Hendry 2006).

Work-in-progress is typically measured as the number of jobs or their cumulated hours over a certain period of time (e.g., per day, per week); the latter may have a more accurate point for job shops. Work-in-progress provides not only a consistent view of MLT as a measure of time-related performance but also represents a cost indicator from the inventory perspective.

4.3.3 Performance measurement in Company Y

It was found at the pre-implementation stage that there was a lack of data in Company Y to support performance analysis and parameter setting. For example, there were significant variations in strike rate for customers, products, and even seasons; it was impossible to estimate an average which is important for the calculation of TW. Rework and scraps caused a high level of uncertainty on the shop floor in Company Y, where no yield rates were tracked. Although capacity utilisation is not a typical WLC performance measure, it was found essential for output control decisions. Hence, strike rate, production yield, and capacity utilisation are particularly discussed in this section as examples of performance measurement in Company Y.

To address the issue of lacking statistical support for strike-rate estimation, the DSS monitors the strike rate by tracking the numbers of confirmed orders and total enquired orders on a continuous basis. Since strike rates varied significantly among customers and products in Company Y, it was considered that observations of individual figures or trends would provide a better view on the anticipated workload and sales/market performance with specific customers or products. Figure 6 shows an example of customer-specific strike rates over a certain period (e.g., month average, year average); the same applies to product-specific rates. Monitoring customer-specific strike rates was found particularly appealing for Company Y as it also provided a visual comparison of market share among customers. A high strike rate indicates significant and steady business and a low rate of success calls for investigations and actions of improvement.

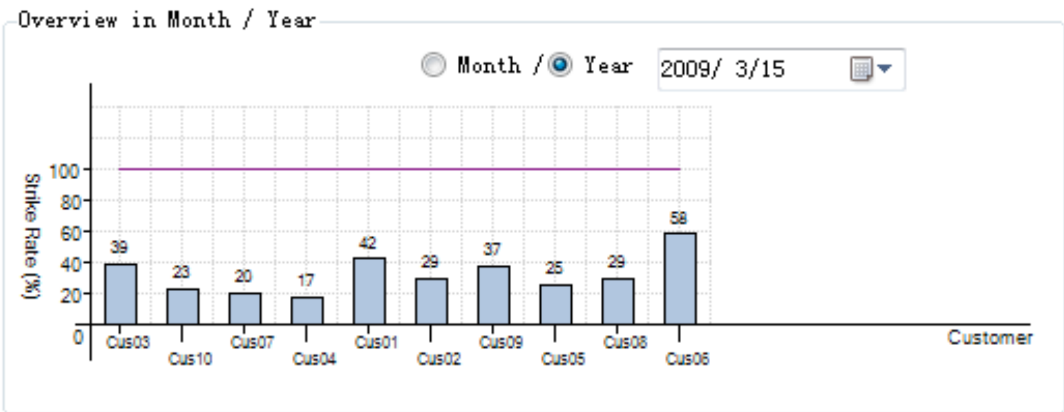

Figure 6. Annual overview of customer strike rates

The production loss (e.g., rework, scraps) observed in Company Y could be addressed either proactively or reactively, such as planning and releasing surplus quantities if production yield of a particular product or operations is known; or considering rework or scraps as rush orders which are prioritised in production. The former indicates additional contribution to the account of workloads based on the rate of production yield which was not available in Company Y at the beginning of the implementation. Thus, the latter strategy was adapted as a start-up setting, but it created uncertainties to shop floor and delivery performance. It was found that the production loss could increase processing times not only in the operation where the loss happens but also in all the upstream operations in the case of scraps where jobs have to start from the beginning of the routing. As a result, it was necessary to observe production yields at various levels (e.g., product, operation). In addition, the fact that production loss could introduce layers of uncertainty into WLC mechanisms must be considered in future theory development.

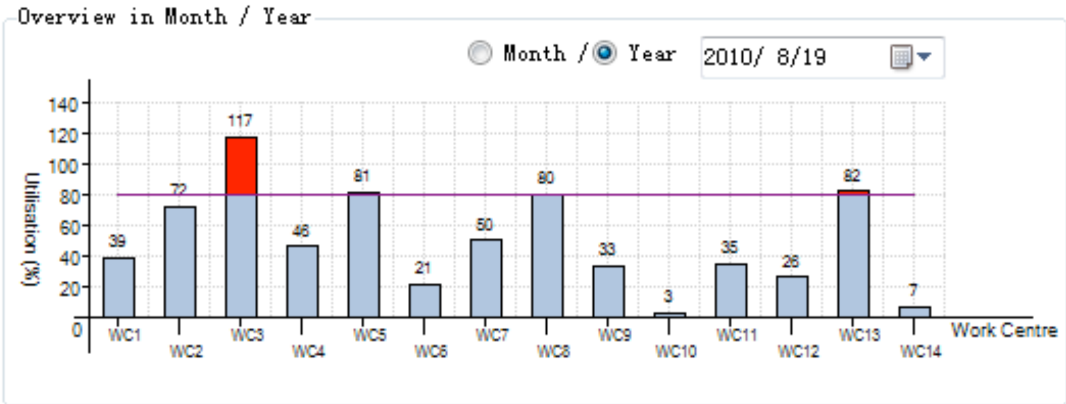

Figure 7. Annual overview of work centre utilisation

The importance of effective capacity management is not only stressed by Company Y's key customer but also explained by the previously mentioned uncertainties (e.g., job variety, rush orders, production loss) involved in the input control. Although subcontracting, overtime, and reallocation provide contingency in output control, their applications are often restricted in availability and create extra costs. If a tendency towards capacity shortage or surplus compared with the input of workloads is appreciated, the need for contingent capacity as well as the extra production costs could be reduced by better planning of standard capacity. An observation of the ratio (hereafter referred to as *capacity utilisation*) between the actual output (including the contribution of contingent capacity) and standard capacity at a work centre on a regular basis (e.g., monthly or yearly) may identify seasonal patterns and requirements for medium- and long-term capacity adjustments. A significant amount of reallocation hours compared with the standard capacity hours signals the need to evaluate the composition of shop-floor capacity. Figure 7 describes an example of the annual overview of capacity utilisation across work centres. A warning level (e.g., 80%), depending on product and production characteristics and capacity management preference, is set for the consideration of long-time capacity improvement. A utilisation rate of 117% indicates that 17% of the capacity hours are addressed by contingent capacity (e.g., overtime, allocation, subcontracting) so that the input of workloads on WC3 can be fully accommodated as required. Since the annual overview reveals a steady capacity shortage in WC3, its standard capacity should be raised to a higher level. On the contrary, a low utilisation rate (e.g., 3%) at WC10 suggests an unnecessary level of standard capacity, probably resulting in machine and/or manpower idleness and consequently leading to a waste of resources.

A full list of performance information entities including the additional insight from practice discussed in this section are presented in Table 4. While it is appreciated that some of the performance information (marked with an asterisk) is less likely to be available at the beginning of the implementation, it is worth gradually building such information up as the implementation progresses for more effective/contingent use of WLC. In addition to the detailed data requirement, purpose of measurement and the relevant PPC stages are also included. It is noted that some of the items listed in the data column are also required for workload account as discussed earlier in the input control section; this reflects the flow of information in supporting different WLC functions.

4.4 An overview of WLC information flows

It may have been evidenced in previous discussion in this paper that individual information entities for input control, output control, and performance measurement do not stand alone to serve WLC functions; they constantly interact with each other in support of the alignment between control activities and performance. A framework of WLC information architecture (see Figure 8) depicts the information flows in addition to the data requirements detailed in Tables 1-4. As shown in the figure:

- WLC input control concerns *job information*, where workload account is the essence. Information entities determining the workloads include job quantity, the required operations and their sequence, set-up time and processing time at each operation, and job progress. Job progress affects the account of workloads which varies at different production stages. Manufacturing capacity and material supply, as well as customer information, are factors that influence job progress. A 'master book' to archive such essential information for typical products would be particularly useful for companies that involve elements of repeat production.

Table 4. WLC performance measurement entities

Performance information	**Data requirement**	**Purpose of measurement**	**PPC Stage**
Job/product related			
Tardiness (e.g., % late jobs, average length of delays)	Contractual DD; job delivery date	Control measure (problem diagnosis), and WLC impact (delivery performance)	SFC
Lateness (e.g., average lateness)	Contractual DD; job delivery date	Control measure (problem diagnosis), and WLC impact (delivery performance)	SFC
Strike rate (e.g., % successful quotations Overall/per customer*/per product*)	Number of successful quotations; number of total enquired jobs	Control measure (parameter setting) and WLC impact (delivery performance)	CE
Production yield* (e.g., % successful production rate per product/per operation)	Input/release quantity; output/dispatch quantity	Control measure (parameter setting) and WLC impact (cost performance)	CE/JE (data input) SFC (data update)
Production process related			
Work centre throughput time (e.g., average throughput time per work centre)	Operation completion times of previous work centre and current work centre	Control measure (parameter setting and problem diagnosis)	SFC
Work centre queuing time* (e.g., the average queuing time in front of each work centre)	Operation completion time of previous work centre; operation start time of current work centre	Control measure (parameter setting and problem diagnosis) and WLC impact (lead time)	SFC
Shop-floor throughput time (e.g., the average shop-floor throughput time)	Job release date; job delivery date	Control measure (parameter setting) and WLC impact (lead time)	JR, SFC
Manufacturing lead time (e.g., the average manufacturing lead time)	Job confirmation date; job delivery date	Control measure (parameter setting) and WLC impact (lead time)	JE,SFC
Pool delay (e.g., the average pool delay time)	Job confirmation date; job release date	Control measure (parameter setting)	JE, JR
Work-in-progress* (e.g., per day, per week)	Number of jobs or released workloads on the shop floor per period time	WLC impact (cost performance)	SFC
Capacity utilisation*(e.g., the actual work compared with the standard capacity)	The aggregate workload completed at the work centre; the regular capacity of the work centre	Control measure (problem diagnosis)	SFC

*Information that is ‘nice-to-have’ for advanced WLC impacts or that needs to be gradually built up as the implementation progresses

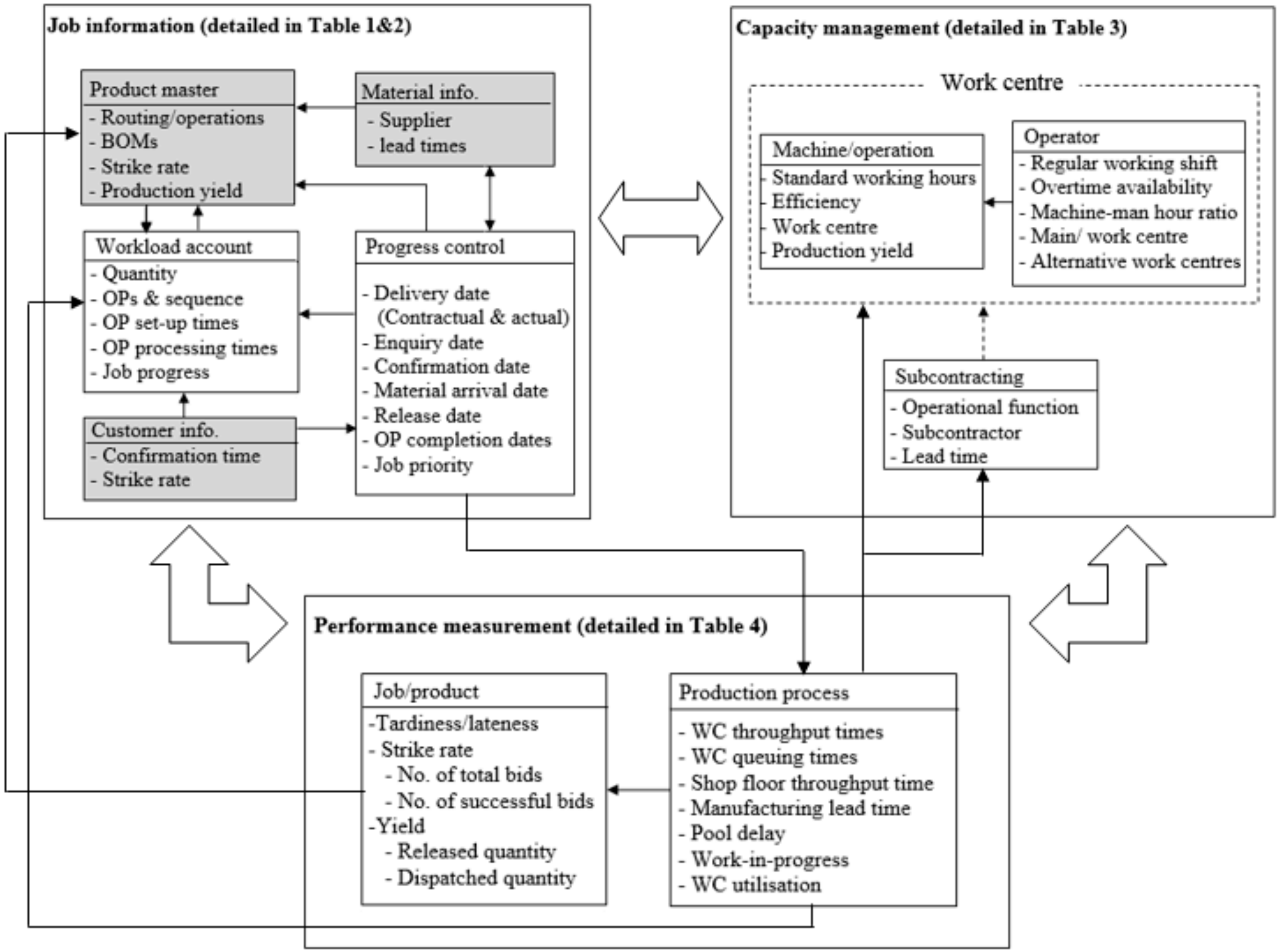

Figure 8. A framework of information architecture for WLC implementation

Product, material, and customer information (as highlighted in grey) could be imported from general enterprise-wide information systems (e.g., ERP, Material Requirement Planning) if these already exist.

- *Capacity management* requires adequate understanding of the standard output rate as well as the contingency to cope with uncertainties. The former is determined by machine and/or operator regular working patterns (e.g., daily working hours) and their individual performance (e.g., efficiency, yield, skills). The latter is often facilitated by overwork, reallocation of multi-skilled operators, and subcontracting. Effective WLC decisions require a real-time communication between capacity and job information. If capacity data are managed in a separate information system, they need to be fully integrated with the WLC system.
- *Performance measurement* not only assesses WLC impacts but also gathers data for problem diagnoses and parameter setting in support of input/output control activities. The progress control data (e.g., operation completion dates) for individual jobs build up the production process performance data (e.g., throughput times) which are then fed back to the workload data (e.g., processing times) as well as the capacity data (e.g., yield rates). The process performance also accumulates information (e.g., job performance) for the product 'master book'.

5. Conclusion

The implementation of WLC has been an enduring challenge, where one of the main obstacles is information availability (Hendry et al. 2008; Stevenson and Silva 2008; Stevenson et al. 2011; Hendry, Huang, and Stevenson 2013). Like many PPC systems, the WLC concept has been developed with an implicit assumption that the information required for key decisions is already in place. However, that is often not the case in MTO SMEs, where WLC operates, according to previous empirical studies (Silva, Roque, and Almeida 2006; Stevenson 2006; Stevenson et al. 2011). While there is a trend of simplifying data requirements in recent WLC theory development, it is important to understand and maintain the information that is essential for the concept to perform its functions effectively.

To facilitate the use of WLC in practice, Stevenson et al. (2011) advocate an implementation roadmap and call for empirical evidence to detail the elements (e.g., information management) contained in the roadmap. In response, this paper contributes to the literature by articulating the information architecture including data requirements and the information flow in support of successful WLC implementation. More specifically, the research question specified in the introduction section is addressed from two perspectives: (1) an ideal setting of data requirements of relevance to WLC key functions including input control, output control, and performance measurement are derived from adoption of a comprehensive LUMS WLC approach; and (2) data that are either typically challenging to obtain in practice or that need to be gradually built up as the implementation progresses (marked as 'nice-to-have' in Table 1, Table 3, and Table 4) are identified in an action research project, where alternative solutions are provided to facilitate the embedding of WLC data requirements in practice and, consequently, ensure the success of the implementation. Worthy of note is that the essential setting where those 'nice-to-have' data are excluded can be a less aggressive start-up for WLC implementation when data availability is poor in an organisation. However, an ideal setting should be aimed for in order to achieve the full advantage of the WLC concept. In addition, the reflective feature of action research reveals data that have been over-simplified in the design of the WLC concept. To narrow the gap between the WLC concept and its practice, a two-way adjustment from both sides is required (Stevenson 2011). Implications for research and practice outlined in the rest of this section conclude the paper.

5.1 Implications for research

This is the first paper to provide an explicit link between WLC key functions and the detailed data requirements. Although the study is built upon a particular WLC method (i.e. the LUMS approach), the information framework is considered of relevance to most of the WLC concepts embracing the input/output control mechanism. However, further research into how such an information framework is tailored for different WLC methods is still needed, given that different PPC stages and accounts of workload might be involved. In addition, any future development of the WLC concept needs to address the following information uncertainties that are typical in MTO companies:

- Production loss (e.g., rework, scraps) is particularly pertinent in a MTO environment where the knowledge of the production system remains at a low level due to the high variety of products. Such loss causes not only extra costs but also unexpected workloads which consequently affect WIP, throughput times, and delivery performance. Information regarding production yield is often not readily available in practice as the rate could vary in product as well as process (e.g., operations). As such, new rules must be suggested at the key decision-making levels (e.g., CE/JE, JR, SFC) of WLC to incorporate the stochastic nature of the yield performance resulting from production loss.
- Job-routing information such as operation set-up times and processing times is another inherent uncertainty in customised production. It is particularly challenging to acquire accurate data for new jobs at CE and/or JE stages while the estimation of workloads is essential for effective PPC decisions. The use of a standard throughput time for each involved work centre or operation is suggested as a compromise solution when detailed set-up and process times are difficult to anticipate. However, the impact on the variation of individual job performance needs to be assessed through simulation results as well as empirical evidence involving different levels of customisation.

5.2 Implications for practice

A computer-based WLC system has no doubt been an effective accelerator to embed the WLC concept in organisational practice (see, for example, Silva, Roque, and Almeida 2006; Stevenson 2006; and Hendry, Huang, and Stevenson 2013). This study provides an information framework to WLC practitioners, detailing how data and the flow of information should be constructed and managed for effective WLC implementation. While the information entities presented in the paper could be interpreted and adopted to suit different practical settings, examples from a successful case provide a valuable insight into how they could support effective WLC functions and embed the corresponding control activities in an organisation's day-to-day practice. Further practical concern may explore the interface with other enterprise-wide systems (e.g., ERP systems) which may already exist in organisations or be used by customers.

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