Cite as: Sayyed Shoaib-ul-Hasan, Marco Macchi, Alessandro Pozzetti, Ruth Carrasco-Gallego. A routine-based framework implementing workload control to address recurring disturbances. Production Planning & Control: The Management of Operations, vol. 29, issue 11, 2018, 943-957.

POST-PRINT Version

A routine-based framework implementing workload control to address recurring disturbances

Sayyed Shoaib-ul-Hasan[a, b], Marco Macchi[a], Alessandro Pozzetti[a], Ruth Carrasco-Gallego[b]

[a]*Dipartimento di Ingegneria Gestionale, Politecnico di Milano. Piazza Leonardo da Vinci 32, 20133 Milano, Italy.*

[b]*Escuela Tecnica Superior de Ingenieros Industriales, Universidad Politecnica de Madrid. C/Jose Gutierrez Abascal 2, 28006 Madrid, Spain.*

sayyed.shoaibulhasan@polimi.it; marco.macchi@polimi.it; alessandro.pozzetti@polimi.it; ruth.carrasco@upm.es

Abstract. This research focuses on responsiveness in high variety manufacturing environments. To achieve it, the paper proposes to develop Dynamic Response Capabilities (DRCs) of the manufacturing system defined as the abilities to readjust the planned operating parameters of workload, capacity, and lead time, in the wake of disturbances. To inform their development, built on the Workload Control theory, a routine-based framework is proposed. The framework supports an integrated approach for the implementation of adaptive decision-making routines for workload, capacity, and lead time readjustments at different stages in the order fulfilment process. Findings from two empirical cases show the appropriateness of the framework to develop and utilize DRCs in different settings of disturbances. Results of a simulation study, with one of the case companies, also shows the effectiveness of the framework to drive performance improvements in presence of recurring disturbances leading to demand variability.

Keywords: High product variety, Order fulfilment process, Disturbances, Manufacturing Responsiveness, Routines, Operations capabilities, Workload control.

1. Introduction

Manufacturing industry is evolving from a mass production to a mass customization paradigm that is characterized by increasing customer demand for high product variety (Hu 2013). This paradigm shift has brought new challenges. The major challenge is the complexity induced by high product variety (Hu et al. 2008; Abdelkafi 2008): this makes it difficult to properly plan and control production, due to incomplete and insecure data (Henrich, Land, and Gaalman 2004). The complexity increases further due to the unpredictable changes in internal/external environments of the manufacturing companies (Bozarth et al. 2009). The unpredictability is, indeed, a consequence of events beyond control of the manufacturing manager (Hopp and Spearman 2011). This research focuses on the sources of unpredictable changes that occur repetitively, hereinafter referred to as ‘recurring disturbances’. For example, the arrival of customer orders is a highly stochastic event leading to unexpected changes in order priorities, quantities, and product specifications (Zhong, Li, et al. 2013; Zhong, Dai, et al. 2013). Besides, the companies usually face random variations in their normal plans and schedules owing to the stochastic operations times of customized product models, that are difficult to estimate, and the unplanned outages (e.g. machine breakdown) affecting capacity, that are difficult to predict (Hopp and Spearman 2004; Zhong, Dai, et al. 2013). Eventually, unreliable component supply is another source of unpredictable change, leading to instability on the production shop floor with a negative impact on the schedule attainment (Bozarth et al. 2009; Pujawan and Smart 2012).

The disturbances induce variability in a manufacturing system, and ‘increasing variability always degrades the performance’ of the system (Hopp and Spearman 2011). Nonetheless, responsiveness to disturbances – i.e. ‘the ability of a manufacturing system to achieve its operational goals in the presence of customer, supplier, and internal disturbances' (Matson and McFarlane 1999) – is required for competitiveness. To this end, different buffering strategies can be adopted to cope with variabilities induced by disturbances beyond control (or, at least, under a partial control) of manufacturing managers. Hopp and Spearman (2011) identified three types of buffer – i) inventory buffer (e.g. safety stocks); ii) capacity buffer (e.g. excess capacity); and time buffer (e.g. safety lead times) – also remarking the importance of flexibility to mitigate the buffering needs. The existence of decision making structures is claimed to use or deploy basic technical abilities, such as flexibility and buffers and, according to Kritchanchai and MacCarthy (1999), such structures should be specific for each type of disturbance. Likewise, Matson and McFarlane (1999) emphasizes that, to achieve responsiveness, disturbances must be recognised and evaluated and, subsequently, appropriate decisions should be made to properly use the available flexibility and buffers. Several other authors have investigated responsiveness in relation to disturbances, with a particular focus on decision making; see, e.g., Ramirez-campos et al. (2006); Chan, Bhagwat, and Chan (2014); and Michalos et al. (2016). These studies remark the need to use specific algorithm and control logic for decision-making, to determine the readjustments on the shop floor that conserve or improve performance when a disturbance occurs. In particular, the authors Michalos et al. (2016) argued that control logic-based decision-making allows a better exploitation of the flexibility potential of the manufacturing resources, leading to their better utilization and improved performance.

Although all these studies provide interesting insights, further investigation is required regarding how decision-making processes can be structured to provide an integrated approach with coherent response capabilities to address recurring disturbances along the order fulfilment process. Thus, the following question is guiding the research: '*how can response capabilities be developed and utilized to cope with different types of recurring disturbances arising along the order fulfilment process in high variety manufacturing environments?*'

To answer the question, the research proposes to develop Dynamic Response Capabilities (DRCs) of the manufacturing system defined as the abilities to readjust its planned parameters in the wake of disturbances ('dynamic' capabilities, as they should enable to cope with the dynamics of recurring disturbances). For example, the planned operating parameters of capacity may require to be readjusted in order to fit the current operating conditions affected by the disturbances. To inform the development of the DRCs, this paper proposes a routine-based framework, inspired by the routine-based approach to build the operations capabilities; see, e.g., Peng, Schroeder, and Shah (2008) on this subject. Moreover, the research posits that, to achieve responsiveness, adaptive decision-making routines should be implemented at different stages in the order fulfilment process, in order to readjust the planned operating parameters of the manufacturing system in the wake of disturbances. To this end, the framework implements Workload Control (WLC) theory as a consolidated Production Planning and Control (PPC) concept. WLC aims at decisions based on the control of lead times, capacity, and the work-in-process (WIP) (Thürer et al. 2012) at different stages in the order fulfilment process (considered as 'stages in the order flow' in literature concerning WLC theory, see, e.g. Breithaupt, Land, and Nyhuis (2002), and Fernandes and Carmo-Silva (2011). Thus, the framework aims at supporting an integrated approach to develop and utilize different DRCs inspired by WLC theory, in order to address different types of recurring disturbances along the order fulfilment process. Doing so, the integrated approach is usable for the implementation of adaptive decision-making routines for workload, capacity, and lead time readjustments at different stages in the order fulfilment process.

Two case studies aim at testing the appropriateness of the routine-based framework to develop and utilize DRCs in different settings of disturbances. Results of a simulation study, with one of the case companies, also aims at showing the effectiveness of the framework to drive performance improvements in the presence of recurring disturbances leading to demand variability.

The remainder of this paper is organized as follows. Section 2 provides the theoretical background wherein WLC theory is discussed. Section 3 illustrates the routine-based framework. The methodology to test the framework is presented in Section 4. Section 5 provides findings from the case study analysis and the simulation study. Section 6 provides discussion on the contributions of the paper, while section 7 concludes with final remarks and future research directions.

2. Theoretical background

2.1 Overview on Workload Control theory

WLC is considered as a leading PPC solution that aims to simultaneously control the WIP in the system, plan capacity, and meet the due dates (Thürer et al. 2012). WLC was originally developed for make-to-order companies with job shop configuration (Stevenson, Hendry, and Kingsman 2005). Because of its simple and easy use, it is particularly relevant for SMEs with limited financial and technological resources (Stevenson, Hendry, and Kingsman 2005; Land and Gaalman 2009). Indeed, researchers have been investigating WLC from different perspectives for more than three decades and different approaches to WLC have emerged.

The unifying theme in all WLC approaches is that the order entry is decoupled from release; orders are held back in a pre-shop pool and the input to the shop floor is regulated in accordance with the workload limits or norms (Thürer, Stevenson, and Silva 2011). Limits are typically set on the released workload length (RWL), which refers to the time required to process the current workload based on planned capacity (Hendry, Huang, and Stevenson 2013). RWLs are defined and monitored for each workstation to ensure the limits are not exceeded as each order is released. For this purpose, appropriate release methods and dispatching rules are applied to balance the workstation's utilization and to meet the due dates (Land and Gaalman 1996; Stevenson, Hendry, and Kingsman 2005; Thürer, Stevenson, and Silva 2011).

Over the last years, many research efforts have been made to advance the WLC concept leading to a more comprehensive approach. In particular, the simple principle of input/output control (I/OC), i.e. the actual output determines the input, has been the focus of many research works; see, e.g., Kingsman (2000), Kingsman and Hendry (2002), Fredendall, Ojha, and Patterson (2010), and Thürer, Stevenson, and Land (2016). To achieve the balance between the input and the output rates, two control mechanisms are currently discussed in WLC literature: i) the input control mechanism, to regulate the inflow of work to the system; and (ii) the output control mechanism, to regulate the outflow of work from the system (Thürer, Stevenson, and Land 2016). On the whole, several approaches to operationalize I/OC mechanisms have been proposed at different stages in the order fulfilment process. The stages and the operationalization of control mechanisms are discussed in next section.

2.2 Input and output control at different stages in the order fulfilment process

Four main stages in the order fulfilment process are discussed in literature for implementing WLC: customer enquiry, order entry, order release, and order dispatch stage.

- Customer enquiry stage takes place between a customer making a request for quotation and a manufacturer receiving the request. The main aim at this stage is to determine whether to accept or reject the customer order, and to decide the due date and price (Kingsman et al. 1996). Typically, the required and available capacities are matched such that the total workload can be produced profitably and on time (Hendry, Kingsman, and Cheung 1998). Besides, the proportion of the workload of unconfirmed orders in the total workload of the system, based on the probability of winning an order, may be considered (Kingsman and Hendry 2002).
- Order entry stage begins with order acceptance and includes pre-production preparations for confirmed orders, e.g. material arrangement (Thürer, Stevenson, and Silva 2011). Once accepted, the orders wait for release in the pre-shop pool, i.e. usually a database consisting of all the orders already accepted but not yet released to the shop floor. The presence of pre-shop pool gives certain advantages as it allows all jobs to compete against each other for release (Hendry, Kingsman, and Cheung 1998) and absorbs the unexpected changes in the incoming customer orders as well as in the orders already present in the pool (Oosterman, Land, and Gaalman 2000). Overall, it is worth remarking that many papers consider order entry together with customer enquiry stage (Fredendall,

Ojha, and Patterson 2010; Thürer, Stevenson, and Silva 2011; Thürer, Stevenson, and Land 2016).

- Order release stage, perhaps the most important one for WLC, aims at controlled release of orders from pre-shop pool to the shop floor (Ragatz and Mabert 1988). In this regard, two distinct approaches for order release have emerged in literature: i) the probabilistic load oriented manufacturing control (LOMC) approach; and ii) the aggregate load oriented Lancaster University Management School (LUMS) approach. In LOMC approach the total load of a workstation is computed as the sum of its direct load and the weighted contribution of the indirect load (Bechte 1988, 1994; Breithaupt, Land, and Nyhuis 2002), while in LUMS approach the direct and indirect loads of a workstation are aggregated together (Kingsman, Tatsiopoulos, and Hendry 1989; Hendry and Kingsman 1991). The LUMS approach was later extended to consider the corrected aggregate load due to the position of a workstation in the routing of a job (Land and Gaalman 1996). A further refinement to the LUMS approach regards the order release method made by combining periodic release approach with continuous release approach to avoid starvation at workstations (Thürer et al. 2012).
- The order dispatch stage relates to the way jobs – part of the WIP of the shop until it is completed (Stevenson and Hendry 2006) – should be scheduled at workstations on the shop floor. Although dispatching rules play significant role if practiced alone, they become less significant when combined with the other stages and related methods and rules, e.g. release rules (Ragatz and Mabert 1988). Thus, in the presence of entry and release rules, simple dispatching rules are considered as sufficient to meet the due dates

mainly because of small order queues on the shop floor (Thürer, Stevenson, and Silva 2011; Land and Gaalman 1996).

Table 1 provides a summary built on some representative papers with the aim to illustrate the I/OC mechanisms – workload adjustments, lead time adjustments, and capacity adjustments (Kingsman 2000) – used to operationalize the input and output control at different stages in the order fulfilment process.

Table 1 Operationalization of I/OC at different stages in the order fulfilment process

Stages in the order fulfilment process	**Operationalization of input control**	**References**	**Operationalization of output control**	**References**
Order enquiry/ entry stage	*Workload adjustments:* order rejection or acceptance (after negotiations with customers) using pre-established maximum planned workload limits or norms	(Philipoom and Fry 1992), (Hendry, Kingsman, and Cheung 1998),(Kingsman and Hendry 2002), (Riezebos, Korte, and Land 2003), (Moreira and Alves 2009)	*Capacity adjustments:* re-allocation of workers between workstations or allocation of overtime or both options	(Hendry, Kingsman, and Cheung 1998), (Kingsman 2000) (Kingsman and Hendry 2002)
			Lead time adjustments: due date setting, based on pre-established rules	(Thürer et al. 2013)
			Capacity adjustments: subcontracting when demand exceeds the capacity, based on pre-established rules	(Thürer et al. 2014), (Thürer, Stevenson, and Qu 2015)
Order release stage	*Workload adjustments*: workload is adjusted considering the condition that the sum of deviations from aggregate balance of each workstation is reduced	(Bergamaschi et al. 1997)	*Capacity adjustments*: avoiding / reducing queues, based on capacity flexibility	(Henrich, Land, and Gaalman 2004)
	Workload adjustments: workload is adjusted considering prioritisation according to job size, routing length, converted priority	(Thürer, Silva, and Stevenson 2010)	*Capacity adjustments*: capacity is adjusted as soon as the planned load to a workstation violates a predefined trigger threshold	(Land et al. 2015), (Thurer et al., 2016)
	Workload adjustments: workload is adjusted considering pre-shop pool sequencing and selection of orders	(Thürer et al. 2015)		

	Workload adjustments: workload is adjusted considering load balancing and timing function	(Land 2004), (Yan et al. 2016)		
Order dispatch/ execution stage	*Workload adjustments*: order selection considering priority dispatching rules	(Land and Gaalman 1996), (Stevenson 2006), (Thürer et al. 2012), (Yan et al. 2016)	*Capacity adjustments:* reallocation of workers and allocation of overtime as needed (only mentioned)	(Breithaupt, Land, and Nyhuis 2002), (Fredendall, Ojha, and Patterson 2010)

3. Routine-based framework implementing Workload Control

The framework consists of a routine-based approach proposed to develop and utilize different DRCs inspired by WLC theory, to address different types of recurring disturbances. Routine-based approach considers capability as a ‘bundle of routines’, being routines described as the way things are done, or patterns of activities (Teece, Pisano, and Shuen 1997). According to Peng, Schroeder, and Shah (2008), routines are a critical source of higher order operations capabilities. In this work, the DRCs, as the higher order operational capabilities, primarily rely on adaptive decision-making routines, at different stages in the order fulfilment process, to be responsiveness in the wake of recurring disturbances. It requires companies to:

- sense the manufacturing environment in order to recognize and evaluate the current operating conditions due to the disturbances (Huang, Zhang, and Jiang 2008; Zhong, Li, et al. 2013; Zhong, Dai, et al. 2013; Matson and McFarlane 1999);
- adopt appropriate decision-making logic and rules to define the readjustment(s), if needed, of the planned operating parameters of the manufacturing system (Kritchanchai and MacCarthy 1999; Ramirez-campos et al. 2006; Chan, Bhagwat, and Chan 2014; Michalos et al. 2016);

- readjust the planned operating parameters, relying on different types of buffers and flexibilities (Hopp and Spearman 2004, 2011; Matson and McFarlane 1999).

The framework adopts WLC-based input and output control (Figure 1) to build adaptive decision-making routines with the purpose to fit the current operating conditions due to the disturbances recognized and evaluated by sensing routines. Input and output control aim to readjust the planned operating parameters – of workload, lead time, capacity – exploiting different types of buffers and flexibilities of the manufacturing system. The framework is illustrated in the remainder.

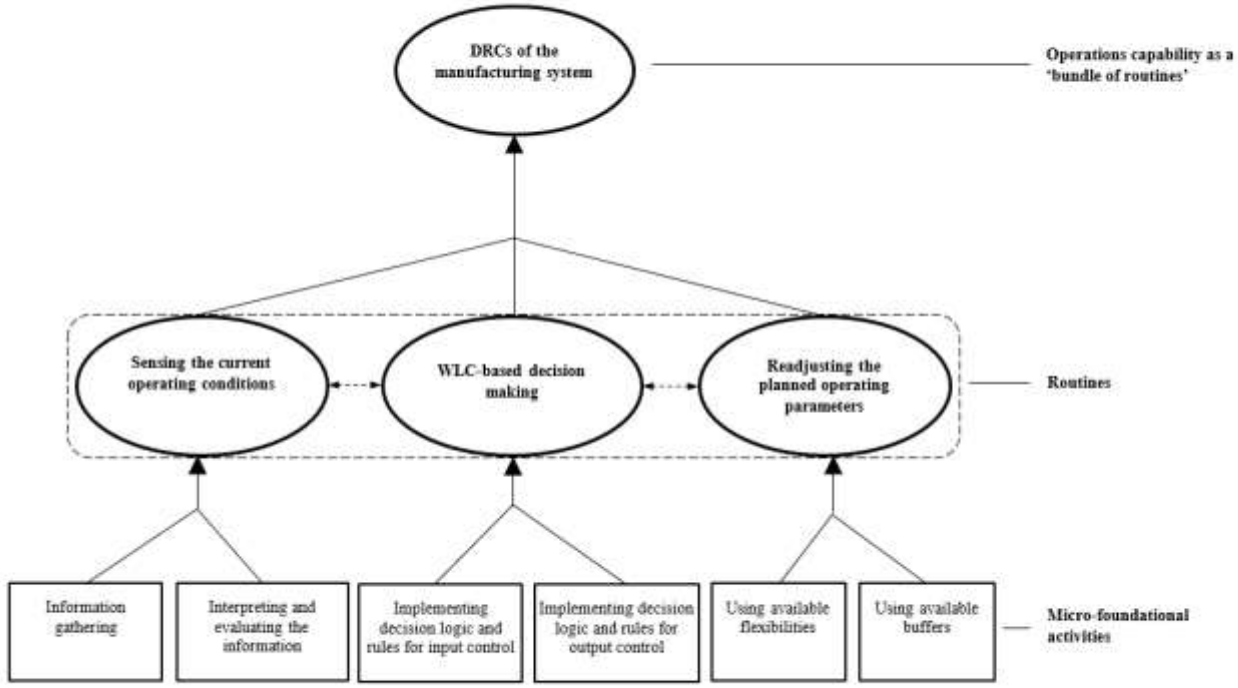

Figure 1 Framework to develop and utilize Dynamic Response Capabilities by implementing WLC-based adaptive decision-making routines

3.1 Sensing the current operating conditions

The main goal of sensing is to recognise and evaluate any deviation in the current operating conditions due to the disturbances arising from customers, suppliers, and internal manufacturing operations. Sensing routines are then concerned with the information gathering, interpretation, and evaluation in regard to the system variables of interest (e.g., WIP, capacity, incoming orders, etc. …) affected by recurring disturbances. The purpose is to check, either based on events or based on fixed intervals, if they are within norms and limits defined in accordance with the operational goals of the manufacturing system. Majorly inspired by WLC theory, while backed up by fundamental theories of factory physics (Hopp and Spearman 2011), norms and limits can be expressed in terms of planned operating parameters of workload (the typical measure subject to norms and limits in WLC theory), capacity, and lead time, with the aim to trigger proper readjustment decisions in the wake of disturbances.

Today, information systems are enabling high sensing capabilities. For example, automatic identification (Auto-ID) technologies with barcode and radio-frequency identification (RFID) technologies are important enablers of sensing capabilities for logistics in industrial environments (Gwon et al. 2011; Makris, Michalos, and Chryssolouris 2012; Wang, Luo, and Wong 2010; Zhang et al. 2015; Zhong, Li, et al. 2013). Another example regards the use of Manufacturing Execution System (MES) where, due to the objective of coordination of production operations, timely information regarding the tracking of equipment status, material delivery and consumption as well as production progress is required (Blanc, Demongodin, and Castagna 2008; Saenz de Ugarte, Artiba, and Pellerin 2009). To sense what is happening in the supply chain, recently the application of the Internet of Things (IoT) is becoming increasingly important (Ben-Daya, Hassini, and Bahroun 2017). It enhances supply chain visibility to cope with uncertain changes in the operating environment (Ellis, Morris, and Santagate 2015). Indeed, in the current and future trends envisioned by the paradigm of Industry 4.0 (see, e.g., Xu, Xu, and Li 2018), sensing plays a significant role in collecting real-time and accurate data, which provides the basis to promptly generate adaptive decisions in the wake of disturbances.

3.2 WLC-based decision-making

To be responsive to disturbances, the readjustment decisions should be taken such that they either conserve the overall production performance or enhance it (Ramirez-campos et al. 2006). Indeed, the readjustments result from adaptive decision-making routines implemented based on the major inspiration of WLC theory, and occurs when norms and limits of the planned operating parameters of interest are exceeded. According to the WLC theory, the key idea is to implement different I/OC mechanisms along the order fulfilment process: as disturbances arise, the I/OC mechanisms are operated at its stages (i.e. order enquiry/entry, release, and dispatch/execution) based on an adequate frequency (daily, weekly, event based). Proper decision methods and rules for I/OC are adopted.

3.3 Readjusting the planned operating parameters

Readjusting routines refer to the adaptive use of the available flexibilities and buffers to readjust the planned operating parameters of workload, capacity, and lead time, in order to accommodate the disturbances.

Different types of buffers can be used in the manufacturing system to provide protection against the demand and/or production variabilities induced by disturbances beyond control (or, at least, under a partial control) of manufacturing managers (Hopp and Spearman 2004, 2011). These are: i) *inventory buffer*, by holding stock of intermediate or finished products; ii) *capacity buffer*, by having more production capacity than actually required and/or by having flexible resources (e.g. flexible workers and shops), enabling a *flexible capacity buffer*; iii) *time buffer*, by increasing the lead-time from the absolute minimum to an extra-amount of time. Time buffer is particularly relevant to address disturbances leading to volume and mix demand variability (Raturi and Jack 2004; Kampen, van Donk, and van der Zee 2010).

The simultaneous readjustments in workload, capacity, and/or lead-time can be operated through a joint use of buffers and resource flexibility (see, e.g., Ruiz-Torres and Mahmoodi (2007) for a discussion on worker and shop flexibility) to accommodate the requirements arising from disturbances sensed at different stages in the order fulfilment process. It requires a careful analysis of the constraints due to the design choices of resource flexibility and buffer size.

4. Methodology to test the framework

This research employs two methodologies to test the routine-based framework: i) case study (Barratt, Choi, and Li 2011); and ii) simulation study (Shafer and Smunt 2004).

The main purpose of using qualitative case studies is that of confirmation (or falsification) of the appropriateness of a theory in a particular context (Bonoma 1985; Johnston, Leach, and Liu 1999; Ross and Staw 1993; Yin 2009). The context addressed in this paper is that of manufacturing environments featuring high product variety while needing responsiveness in order to sustain their competitiveness. Two cases were selected to represent the context: both the cases are operating catalogue mode of mass customization, which leads to high product variety; besides, considering the contingency of their respective markets, they are particularly challenged by responsiveness to the market as competitive priority of the last years. Another common feature is that they are SMEs, which is useful to test the framework also in this context. As they are two cases, this enables to let emerge also different contingencies, the most notable is that one case is more oriented to customer service as demand fulfilment rate (order fulfilment in the same period when orders are requested), the second more oriented to customer service as short delivery time.

Based on these two case companies, the main hypothesis that the research intends to test is that the *routine-based framework is appropriate to develop and utilize DRCs in different settings of disturbances*. The main evaluation criterion to this end is that case companies should demonstrate, in their current pattern of activities, the utilization of DRCs to cope with different types of recurring disturbances arising along the order fulfilment process. In particular, they should demonstrate the use of adaptive decision-making routines featuring methods and rules assimilated to WLC while being defined in an integrated scheme together with proper sensing and readjusting routines, with the aim to manage disturbances at different stages of the order fulfilment process. Table 2 provides the main characteristics of company A and B. Both the case studies were conducted through plant visits and interviews having as main target the production manager, the supervisor, and the operators on the shop floor.

Table 2 Main characteristics of case companies

	Company A	**Company B**

Nature of business	Manufacturer	Manufacturer
Product Sector	Food processing machines (Slicers)	Wheels and castors
Main product models (external variety)	55	More than 3500
Annual turnover (EURO) (approx.)	35 Million	23 Million
Markets Served	Europe, North America, China	Global
Number of employees	200	145

To show the *effectiveness* of the routine-based framework, the case of company A was further developed as collaborative research, deploying a simulation study wherein the application of the framework was used to drive the performance improvements. Indeed, the main evaluation criterion to this end is that the case company should be guided, through the framework, into a focused reflection helping in the identification of the recurring disturbances to be prioritized within the improvement plan and of the correspondent improvement potentials of the DRCs of the manufacturing system. The potentials should then be analysed by means of simulation to evaluate the most relevant DRCs for the effective implementation. This required further work to collect the data regarding variables and constraints affecting the decisions in the order fulfilment process (e.g. demand for different types of product models, lead time requirements, number of workers on the shop floor, …). Moreover, a simulation model was built and used in order to evaluate different DRCs implementing different I/OC mechanisms for adaptive decision-making.

5. Case description and findings

5.1 Case study analysis in company A

Company A is considered as a global leader for manufacturing of meat slicers. Currently, the company offers more than 55 different models of slicers on the catalogue and fulfills the needs of over 500 dealers nationally and different markets worldwide, being the products entirely made in

Italy. The product models are divided into different Product Families (PFs) produced mainly through an Assemble-to-Order (ATO) fulfilment strategy, with the final assembly organized in a number of assembly cells where one or more cells are dedicated to a particular PF.

Company A considers relevant for customer service the respect of the demand according to what negotiated based on the customer needs (i.e. respect of due date setting). Company A faces two types of recurring disturbances that may lead not to reach the goal. The customer-side disturbances (due to the wide spread of global customers with varying needs) lead to volume and mix demand variability, while the internal disturbances (arisen due to stochastic operations times of different product models and workers' performance variation) may cause random variations in the normal production schedules. To address these disturbances and to achieve responsiveness in the order fulfilment process, the company A has implemented different routines and I/OC mechanisms at different stages (summarised in Table 3 in accordance with their use in the current pattern of activities).

Table 3 Findings from case company A

Order fulfilment stages	**Type of disturbance and variability**	**Sensing Routine**	**WLC-based decision making routine**		**Readjusting routine (using buffers and flexibilities)**
			Input control	**Output control**	
Order enquiry/ entry stage	(Disturbance) Customer disturbance (Variability) Volume demand variability	Barcode technology supported information system enables to evaluate the total WIP in the system of assembly cells and the production progress on the shop floor which then enables to check, adding the workload due to the incoming orders, if the total workload is within the defined limits or not	*Workload adjustment:* order acceptance / rejection based on a planned aggregate workload limit (limit due to planned aggregate capacity and lead time constraints) and subsequent negotiations with the customers on lead time when the total workload exceeds the limit	*Lead time adjustment*: due date setting, based on pre-established rules that adopt standardized lead-time buffer settings to accommodate the extra demand	Time buffer enables readjustments in the planned lead time and planned aggregate workload: when the load for the current planning period is full, the orders are accepted with longer lead time to be produced during the next planning period

Order release stage	(Disturbance) Customer disturbance (Variability) Mix demand variability among different PFs	Barcode technology supported information system enables weekly evaluation of the total WIP of each PF on the shop floor. Then, the total workload of each PF, due to the WIP and to the pool of orders waiting to be produced during the current week, is calculated, enabling then to check, with released orders, if the total workload is within the defined limits or not	*Workload adjustment*: order selection and release based on due dates and the available cell capacities during the week: the workload of each PF, with due date set in the current week, is compared with the capacities available during the week; when the total workload exceeds the limit, a capacity readjustment is activated	*Capacity adjustment*: Capacity is adjusted by means of the dynamic allocation of capacities of the different assembly cells to different PFs	Shop and worker flexibilities enable readjustments in the planned weekly capacities of different PFs: under normal circumstances assembly cells' capacities are allocated to dedicated PFs; otherwise, one or more cells are selected to host PFs (other than the dedicated ones) featuring a peak demand
Order dispatch/ execution stage	(Disturbance) Internal disturbance due to stochastic operations times and workers' performance variation (Variability) Random variation in the production schedule	Barcode technology supported information system enables daily evaluation of the accumulated output of each assembly cell, thus checking if capacity is within the defined limits or not	*Workload adjustment*: order selection and dispatch based on early due date	*Capacity adjustment*: Capacity is adjusted by means of the dynamic allocation of workers among different assembly cells, when the capacity exceeds the limit	Worker flexibility enables readjustments in planned daily cell capacities by dynamically re-allocating workers to assembly cells lagging behind schedule

At order enquiry/entry stage, every time a customer is making a request for quotation, the company adopts a planned aggregate workload limit to evaluate any deviation in the current operating conditions due to customer-side disturbances. In particular, having visibility on the total WIP in the whole system of assembly cells and the production progress as current workload on the shop floor, the company evaluates the effect of adding the incoming demand to the existing workload. When the workload is beyond the limits, an adaptive decision-making is taken leading to utilize time buffer for output control and, in exceptional cases, when the time buffer is not enough, order rejection for input control. Overall, the adaptive decision-making is used to manage, in aggregated terms, the volume demand variability induced by customer-side disturbances.

At order release stage, a weekly adaptive decision-making routine is operated. Each week, the existing WIP along with the workload of *each* PF on the shop floor that needs to be produced during current week (according to due date) is evaluated. When the released workloads of PFs exceed the limit, an adaptive decision is taken where the capacities for PFs are readjusted for the week. In particular, as assembly cells are designed to host different types of PFs, a dynamic allocation of capacity among different PFs is possible. This enables to use excess capacity from assembly cells with low demand (of their own PF) to host PFs featuring a 'peak' demand (i.e. PFs for which the workload exceeds the capacity solely available from the cell(s) normally dedicated to them). Overall, the worker and shop flexibilities enable such readjustments in planned capacities to address mix demand variability.

Finally, at order dispatch stage, the company has implemented a daily adaptive decision-making routine where the daily output of each assembly cell is evaluated to check if the production is progressing according to the schedule or not. If the schedule is showing accumulated output / capacity below the limit, for the next day the planned cell capacities are readjusted by moving workers to assembly cells lagging behind schedule to speed-up the production. Thus, the worker flexibility is used to address the random variation in the production schedule.

5.2 Case study analysis in company B

Company B has a wide product range and currently offers more than 3500 different product models on the catalogue. The products are related to movement and handling needs for industry and home applications, i.e. wheels, rollers, brackets, and locking devices. The company mainly operates through an ATO fulfilment strategy, while only few product models are produced using a make-to-stock (MTS) strategy and some special orders using make-to-order and purchase-to-order strategies. For product models utilizing ATO and MTS fulfilment strategy, the manufacturing of components is managed by a Kanban system and roughly five days stock of components is held to meet the final assembly and delivery needs. Overall, the company processes on average 200 customer orders per day, whereas each order varies in terms of product mix: on average a single order has more than 10 product models, with several pieces of each model. This mix variability, within the single order, requires that different types of material flows are coordinated at the shop floor, due to: i) picking components for assembly; ii) assembly operations; iii) picking final products/components from stocks; and iv) packaging operations. In addition, material flows related to the workload that is being outsourced, in case of special components, need to be coordinated when the materials are entering into the factory. Eventually, it is worth remarking that the final assembly is organized with several fixed position assembly stations, in the remainder shortly referred to as workstations.

Company B considers relevant for customer service the short delivery time (having, on average, very challenging needs in terms of short times to order), while facing different types of recurring disturbances, mainly from customer- and supply-side, that may prevent to reach the goal. The customer-side disturbances (due to the wide product range and the mix of requirements between and within orders) lead to demand variability, including also the presence of rush orders, while the supply-side disturbances (arisen due to unreliable component supply at the workstations) may cause instability on the production shop floor and the schedule attainment. To address these disturbances and to achieve responsiveness in the order fulfilment process, the company B has implemented different routines and I/OC mechanisms at different stages (summarised in Table 4 in accordance with their use in the current pattern of activities).

Table 4 Findings from case company B

Order fulfilment stages	**Type of disturbance and variability**	**Sensing routine**	**WLC-based decision making routine**		**Readjusting routines (using buffers and flexibilities)**
			Input control	**Output control**	
Order enquiry/ entry	(Disturbance) Customer disturbance (Variability) Volume demand variability	When incoming orders are issued, the information system may generate four types of alerts as a result of different checks on the induced workload: i) when the aggregate workload for five days' time frame exceeds the pre-defined limit; ii) when the workload of a certain product model exceeds the pre-defined limit; iii) when the workload of a single customer order exceeds the predefined limit; iv) when the workload of products that use supplier components exceeds the predefined limit. If no alert is generated, the orders are sent directly to the pre-shop pool in the system	*Workload adjustment*: order acceptance/ rejection based on different workload limits (limits due to planned component inventory, capacity and lead time constraints) and subsequent negotiations with the customers on lead time when the total workload exceeds at least one of the predefined limits	*Lead time adjustment*: due date setting, based on pre-established rules that adopt standardized lead-time buffer settings to accommodate the excess demand	Time buffer enables readjustments in planned workload and lead time: when the load for the current planning period is full, the orders are accepted with longer lead time to be produced during the next planning period
	(Disturbance) Customer disturbance (with specific concern to rush orders) (Variability) Volume demand variability	When rush orders are issued, they are directly recognized as critical events by the commercial office who assign a colour code to them. As a 'shortcut', the information system triggers the workload adjustment to assign the rush orders directly to the workstations, that see the newly released orders	*Workload adjustment*: workload is adjusted adopting maximum order quantity limit for rush orders + making order acceptance decision for rush orders only for a subset of preferred customers	*Lead time adjustment*: lead time is adjusted due to change in the sequence of existing orders, putting rush orders in front of the queue at workstations (with the objective to decrease assembly lead time for rush orders)	Available lead-time buffer, combined with shop and worker flexibility, enables readjustments in daily schedule to produce rush orders with short lead times
Order release stage	(Disturbance) Customer disturbance (Variability) Day-to-day aggregate volume demand variability	The pre-shop pool is continuously updated as the new orders are accepted and entered in the information system, then allowing to recognize all the orders for next five days.	*Workload adjustment*: order selection and release based on due date and available daily capacity	*Capacity adjustment*: Capacity is adjusted by means of the dynamic allocation of capacity to the workload across five days	Available lead-time buffer, combined with shop and worker flexibility, enables readjustments in capacity and daily schedules to balance the

		This allows to evaluate the existing and new workload (due to existent WIP and new released orders): if there is a deviation in the norm for workload balance among workstations for each day, an adjustment is required to rebalance it			daily workload of each workstation
Order dispatch/ execution stage	(Disturbance) Customer disturbance (with specific concern to rush orders) (Variability) Volume demand variability	When it recognizes the need, the commercial office calls the production supervisor to change the status of a (previously) normal order to (now) rush order; the MES allows this change by a simple click (controlled by supervisor); the pickers and assembly workers are informed automatically using radio frequency terminals	*Workload adjustment:* order selection and dispatch based on early due date	*Lead time / capacity adjustment*: lead time is adjusted due to change in the sequence of already released orders based on a simple rule (i.e. MES dynamically assigns rush order with priority to a workstation where there is already a rush order being processed). Capacity is adjusted based on a simple rule (i.e. if there is no existing rush order being processed, the new rush order is assigned with priority to a workstation with less load)	Available lead-time buffer, combined with shop and worker flexibility, enables readjustments in capacity and daily schedule to produce rush orders with short lead times
	(Disturbance) Supply disturbance (with unreliable component supply) (Variability) Random variation in the production schedule	When orders are dispatched, the MES automatically knows if some components are missing as inventory record is updated automatically with material handlings. The MES then sends the information to pickers and to the assembly stations about missing components. The product model for which the components are missing is shown on the screen at workstation and is kept on stand-by, waiting for the components. As soon as the components arrive, the system sends information to pickers through radio frequency terminals	*Workload adjustment:* order/task selection and execution based on urgency and component availability (the system doesn't allow to work on product models with missing components)	*Lead time adjustment*: lead time is adjusted due to change in the sequence of orders/tasks at assembly station by workers (to increase production lead time when the components for certain product models are late)	Available lead-time buffer enables readjustments in planned order/task sequence to produce product models (with missing components) with long production lead times

Concentrating on the shop floor, company B has implemented a RFID enabled MES for order management. It enables coordinated scheduling of production and logistics, aiming at synchronization of the logistics and assembly operations at the workstations for final assembly, according to a short-term production plan. Based on the sequence of orders scheduled at each workstation, the MES communicates with pickers, through radio-frequency terminals, to pick the components according to each order requirements. Besides, production supervisor and assembly operators work based on the visibility of the scheduled orders at the workstations, achieved through a Gantt chart regularly updated by the MES at their terminals.

Owing to the MES, at order enquiry/entry stage, the company uses different types of alerts in order to keep under control customer disturbances leading to volume demand variability: when the workload generated by the order entries exceeds the defined limits, the system generates an alert. Based on the alert, readjustments follow: the commercial office and the planning department then readjust lead-time buffer to accommodate the extra workload. This is combined with the order release stage: to manage the day-to-day demand variability where available lead-time buffer, combined with shop and worker flexibility, enables readjustments in capacity and daily schedules to balance the daily workload of each workstation. Indeed, a five days standard lead-time creates a time buffer used to manage the day-to-day demand variability as an aggregate demand (i.e. over five days), to be spread equally on each day to stabilize the daily workload on the shop floor. Thus, when releasing orders, the MES enables to evaluate the available capacity and the aggregate workload for next five days and then, based on the due dates, to spread the workload equally across each day. The calculated workload for the current day is then released to the workstations and a queue of orders in front of each workstation is shown on a Gantt chart.

Similarly, the rush orders are managed at different stages in the order fulfilment process. At order entry stage, based on the preferred customers and maximum order quantity constraints, the rush orders are colour-coded. The MES is then used to release them directly to the workstations without involving the planning department: thanks to the available lead-time buffer and the shop and worker flexibility, the rush orders are assigned to the workstations with priority. Moreover, many orders may become rush orders when waiting in the pre-shop pool that contains aggregate workload of five days, or when already released. To manage these other rush orders, the commercial department calls – at order dispatch/execution stage – the production supervisor to change the status of these orders. The MES allows this change (controlled by production supervisor), and the orders are typically put at the start of the queue in front of the workstations. Overall, according to the adopted rules, two options exist. Firstly, the rush orders are dynamically allocated giving priority to the workstations where other rush orders have been already assigned; in this case, lead-time buffers are used for readjustments in the released order sequence. Alternatively, the rush orders are assigned to new workstations, not already loaded with rush orders, thus relying on a capacity adjustment to give priority to less loaded workstations.

Based on the sequence of released orders, the system dispatches the orders. The picker then pick the components in trolleys and bring them next to the workstation, creating a small pool of orders in front of a workstation. Due to the presence of this pool, the operator at the workstation has the means to eventually decide adaptively different order sequencings at the dispatch/execution stage. For example, whenever some components are not arriving according to the scheduled order sequence or there is change in sequence of orders due to rush orders, workers make adaptive decisions for on-field readjustments of assembly tasks. Thanks to the available lead-time buffer, such on-field readjustments in planned order/task sequence by workers have little effect on the existing delivery schedules.

5.3 Collaborative research in company A

The scope and purpose of the collaborative research in company A were defined based upon the DRCs of the manufacturing system in accordance with the current pattern of activities (see table 3). It was, in fact, the starting point to stimulate a focused reflection to identify the disturbances to be prioritized in the improvement plan and the correspondent improvement potentials of the DRCs.

While carrying out the collaborative research, firstly, the scope was limited to responsiveness to address the customer-side disturbances, identified, with the production manager, as main recurring disturbances to be prioritized as they lead to relevant variabilities to cope with, both volume and mix demand variability. Then, the goal of the company was identified: to enhance its performance in terms of *customer service* and *productivity*, regardless of the disturbances. To achieve this goal, the framework implemented for the company case (table 3) was helpful in order to focus where to introduce the performance improvements and, thus, to formulate the objective of the simulation study, aimed at analysing the impact on the production performance of company A of DRCs utilizing different WLC-based adaptive decision-making routines.

For simulation purposes 'Plant Simulation' software is used (Bangsow 2016). The simulation model considers eight assembly cells where each cell is dedicated to a particular PF and has its own dedicated worker(s) trained to perform the operations on all the product models belonging to the dedicated PF. Table 5 provides the input data for the simulation.

Table 5 Input data setting for simulation experiments

	PF1	**PF2**	**PF3**	**PF4**	**PF5**	**PF6**	**PF7**	**PF8**

Average weekly demand (items)	72	60	14	19	42	51	18	26
Coefficient of variation of demand	0.15	0.42	0.21	0.26	0.33	0.49	0.22	0.23
Dedicated capacity (hours/week)	40	40	40	40	40	40	40	40
Average assembly time (hours/item)	0.56	0.67	2.86	2.11	0.95	0.78	2.22	1.54
Coefficient of variation of assembly time	0.11	0.22	0.12	0.13	0.16	0.05	0.15	0.09

Experimental factors

The simulation study considers the following I/OC logics as experimental factors to evaluate the performance improvements:

- *lead-time buffer based output control* combined with *order rejection based input control* at order enquiry/entry stage, with three alternative levels, that is (planned lead-time + order rejection), (one week lead-time buffer + order rejection), (two weeks lead-time buffer + order rejection);
- *capacity adjustment based output control* combined with *workload adjustment based input control* at order release stage with two alternative levels, that is (planned dedicated capacity + workload adjustment), (flexible capacity adjustment + workload adjustment).

The I/OC mechanisms correspondingly used to operationalize the input and output control in the simulation experiments are summarized in the flow chart of Figure 2.

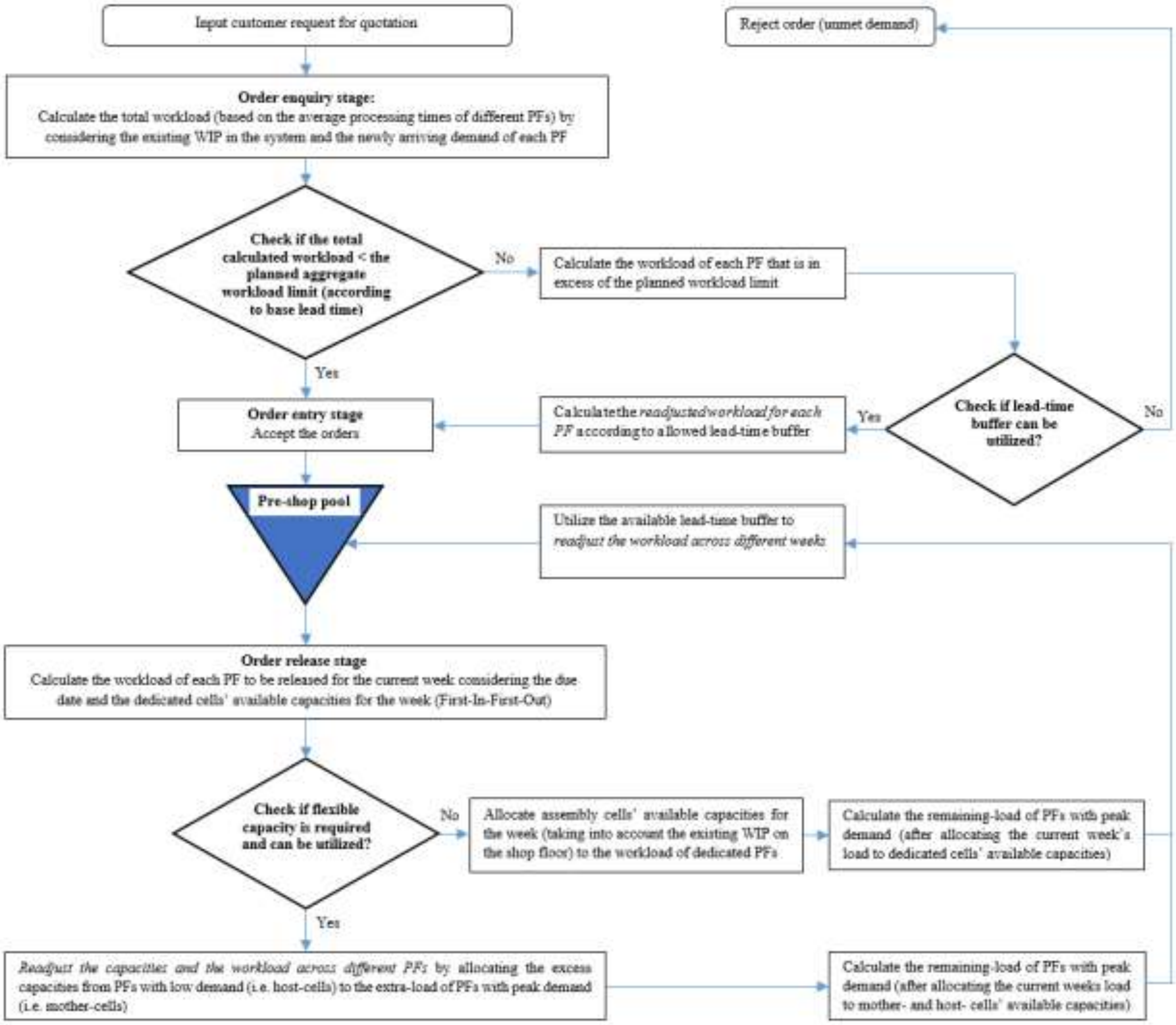

Figure 2 Adaptive decision-making routines implemented inside the simulation model to address recurring customer-side disturbances

The I/OC at order enquiry/entry stage are implemented based on the planned aggregate workload limit. The calculation of the planned aggregate workload limit (Workload_p) is defined in accordance with the well-known Little's law (see following equation 1 for the calculation):

$$\text{Workload}_p = \text{Capacity}_p \times \text{LeadTime}_p \quad (1)$$

Where:

Workload_p is the planned aggregate workload that can be accepted by the shop capacity, which is the system of assembly cells [hours];

Capacity_p is the planned aggregate shop capacity, i.e. aggregate capacity of the system of assembly cells [hours/week];

LeadTime_p is the planned lead-time to meet the demand [week(s)].

The Workload_p is calculated for one week lead time, taken as planned lead-time, and the weekly planned aggregate shop capacity due to all assembly cells, i.e. 320 hours. When the aggregate workload required by the demand and the WIP already present in the shop exceeds the Workload_p, an adaptive decision is made to utilize the lead-time buffer in order to accommodate the excess demand. The excess workload of each PF is then accepted/rejected based on the readjusted lead-time buffer. In particular, the due date is considered according to lead-time buffer option from the date of order acceptance (i.e. one, two, or three weeks' time period from the date of acceptance of an order, correspondingly with the planned lead-time or the additional lead-time buffer options). Overall, this adaptive decision-making routine utilizes time buffer and order rejection for readjustments in the wake of customer-side disturbances leading to aggregate volume demand variability, thus enabling to change the planned operating parameters (i.e. planned lead-time and planned aggregate workload) at order enquiry/entry stage.

Afterwards, the orders are released from the pre-shop pool to the shop floor, implementing I/OC at order release stage based on planned weekly capacity of assembly cells for different PFs. When the workload of a PF that need to be released for the current week exceeds the planned capacity of its dedicated assembly cell, an adaptive decision is made to utilize the capacity flexibility of the shop. With capacity flexibility, the cell with excess workload (i.e. workload of the PF more than the planned capacity of its dedicated cell) become a ‘mother-cell’ looking for a cell with excess capacity that can become the ‘host-cell’. More specifically, the excess workloads from ‘mother-cells’ are allocated to ‘host-cells’ by ranking and matching the excess workloads and available capacities from highest to lowest (i.e. the host-cell with highest available capacity is allocated to the PF with highest extra load). It is also important to mention that, to maintain quality in assembly and to avoid complexity in assembly cells, two operational rules are used to limit the capacity allocation. Firstly, one cell can host maximum one additional PF at a time. Secondly, with flexible capacity adjustment, the planned worker efficiency is reduced when the worker performs assembly operations on other PFs (i.e. 80% efficiency is considered to this regard). After allocating the current week’s load to the mother and the host cells, if some load is left, based on the available time buffer (i.e. decided at order entry stage), it is kept waiting in the pre-shop pool till next week, and is released during the next week as a new planning period together with next week’s load. Overall, this adaptive decision-making routine utilizes capacity flexibility and available time buffer for readjustments in the wake of disturbances at PF level, leading to mix demand variability; it enables to change the planned parameters (i.e. planned weekly capacities and workload for different PFs) at order release stage.

Performance assessment

To evaluate the impact of the experimental factors on performance, four measures are used: i) demand fulfilment rate and ii) assembly lead time (corresponding to the goal of *customer* *service*); iii) capacity utilization; and iv) throughput (corresponding to the goal of *productivity*).

- Demand fulfilment rate is the probability of satisfying the products demand in the same period (i.e. week) of their arrival. It is calculated based on the actual number of orders produced within their period of arrival.
- Assembly lead time is calculated by measuring the average life-span (i.e. time from order acceptance till completion) of orders completed during each period.
- Capacity utilization is calculated for each period by comparing the total actual working time with the total available working time during that period.
- The throughput is the total number of items produced by the system in each period.

All the four measures are used to test the significance of adaptive decision-making routines implemented within the simulation model. The main choices for the analysis of simulation results are herein summarized:

- the performance measures are reported on a weekly basis of operation;
- a run length of 500 weeks is used in each experiment and the desired statistics are collected starting with week 151; it is done to nullify the impact of initial conditions and to ensure steady state results;
- each experiment is replicated 10 times and the averages of the 10 replications are used for results and analysis.

Based on the statistics for the throughput, an ANOVA test is performed with a significance level of 0.05. ANOVA results show that both lead-time buffer based output control and flexible capacity adjustment based output control have a significant effect on the throughput, with a significant interaction between them. It justifies the current practice of the company that does not consider, as possible DRC, the joined use of planned lead-time and planned dedicated capacity based output control that, in fact, demonstrated, in past practices, very low performance levels. The next table 6 summarizes the improvement potentials of the DRCs still under discussion (after excluding the joined use of planned lead-time and planned dedicated capacity based output control).

Table 6 Simulation Results [95% Confidence Interval]

DRCs implementing different I/OC mechanisms	**Demand fulfilment rate (%)**	**Capacity utilization (%)**	**Assembly lead time (days)**
DRCs 1: (planned lead-time based output control + order rejection based input control) at order enquiry/entry stage **+** (flexible capacity adjustment based output control + workload adjustment based input control) at order release stage	[90.76 , 92.51]	[93.94 , 93.97]	[4.91 , 4.91]
DRCs 2: (one week lead-time buffer based output control + order rejection based input control) at order enquiry/entry stage **+** (planned dedicated capacity based output control + workload adjustment based input control) at order release stage	[89.91 , 91.15]	[91.04 , 91.07]	[11.74 , 11.75]
DRCs 3: (one week lead-time buffer based output control + order rejection based input control) at order enquiry/entry stage + (flexible capacity adjustment based output control + workload adjustment based input control) at order release stage	[93.80 , 94. 89]	[96.75 , 96.76]	[9.68 , 9.71]
DRCs 4: (two weeks lead-time buffer based output control + order rejection based input control) at order enquiry/entry stage **+** (planned dedicated capacity based output control + workload adjustment based input control) at order release stage	[96.03 , 96.93]	[96.03, 96.07]	[15.44 , 15.46]
DRCs 5: (two weeks lead-time buffer based output control + order rejection based input control) at order enquiry/entry stage **+** (flexible capacity adjustment based output control + workload adjustment based input control) at order release stage	[97.71 , 98.42]	[98.56 , 98.59]	[13.71 , 13.78]

The company has two alternatives to improve its performance.

- The company can improve its performance in terms of *delivery service* (i.e. with 4.91 days assembly lead time) by operationalizing adaptive decision-making routines that utilize order rejection based input control at order enquiry/entry stage and flexible capacity adjustment based output control at order release stage (i.e. see table 6, DRCs 1).

- The company can improve its performance in terms of *demand fulfilment rate* and *capacity utilization* by operationalizing adaptive decision-making routines that utilize lead-time buffer (one or two weeks) based output control at order enquiry/entry stage, and flexible capacity adjustment based output control at order release stage (i.e. see table 6, DRCs 3 and DRCs 5). Besides, it is worth pointing out a specific remark. Even when some orders are accepted with two weeks lead-time buffer on top of planned lead time, the simulation results show that the company can manage to complete orders within 2 weeks' time period (i.e. [13.71 , 13.78 assembly lead time] days) by implementing flexible capacity adjustment based output control at order release stage. This could be an adequate performance if the customers accepts, after negotiation, such extra weeks.

Thus, depending on its goals, the company can choose to implement either of the two alternatives. As company A nowadays considers relevant for customer service the respect of the demand according to what negotiated based on the customer needs (i.e. respect of due date setting), and judges feasible the use of one or two weeks lead-time buffer to accommodate extra workload, DRCs 3 or 5 are preferable. As the current demand patterns may change in the future, the company should re-evaluate the I/OC logic and rules to better fit its responsiveness needs.

Overall, the simulation study shows that the proposed routine-based framework is effective to drive the performance improvement based on different DRCs to address a particular recurring disturbance. Furthermore, as different DRCs may have different impact on the performance, it is important that the selected DRCs are aligned with the overall goals of the company.

6. Discussion

This research aims to investigate how response capabilities can be developed and utilized to cope with different types of recurring disturbances arising along the order fulfilment process in high variety manufacturing environments. This paper contributes towards this direction, arguing that the development of DRCs of the manufacturing system is required. In particular, the paper shows the applicability of the routine-based approach for the development of the DRCs, thus extending the work of Peng, Schroeder, and Shah (2008) on operations capabilities.

DRCs are conceived by integrating sensing, decision-making, and readjusting routines at different stages in the order fulfilment process. Building on the integrated approach, the paper adopts the notion of capabilities as ‘bundle of routines’, eventually leading to adaptive decision-making routines in order to enable higher responsiveness.

The integrated approach proposed by the paper is inspired by WLC theory, while dynamic adaptiveness results from explicitly linking the WLC-based routines with sensing and readjusting routines. Doing so, the approach is usable for the implementation of adaptive decision-making routines for workload, capacity, and lead time readjustments to address different types of recurring disturbances at different stages in the order fulfilment process.

This proposal is aligned with the increasing interest to investigate on an integrated view of I/OC mechanisms in the order fulfilment process (Thurer et al. 2014; Thurer, Stevenson, and Qu 2015; Thurer, Stevenson, and Land 2016). This is also consistent with the enhanced supports from technology enablers within the current evolutionary trends envisioned by the paradigm of Industry 4.0, where sensing plays a significant role in collecting real-time and accurate data. Having an integrated scheme where sensing routines are leading to promptly generate adaptive decisions is a relevant means to guarantee the exploitation of flexibility and buffers within the manufacturing systems whenever needed by unexpected changes due to disturbances.

Concluding, the proposed routine-based framework is an aid and a guiding tool as it supports outlining different activities needed to implement each type of routine and, overall, the resulting DRCs. The framework also enables a holistic analysis of the I/OC mechanisms: it could be useful to focus on specific stages of the order fulfilment process for eventual improvements according to the needs of disturbances.

7. Conclusions

Achieving production goals in the presence of disturbances is a challenge as well as a key to competitiveness in high variety manufacturing environments. This research argues that, in these contexts, an effective response to recurring disturbances is required and can be achieved by means of DRCs that adopt WLC-based adaptive decision-making routines along the order fulfilment process. The I/OC mechanisms of the WLC facilitate the deployment of available buffers and flexibilities to readjust the planned operating parameters of workload, capacity, and lead time. To be effective and on time, the I/OC mechanisms should be supported with proper sensing routines to have visibility into the current operating conditions, and to subsequently activate the adaptation of the planned operating parameters. To inform the development of DRCs built on WLC, a routine-based framework is proposed. This is also tested through a case study analysis and a simulation study.

The findings from the case studies show that high variety manufacturing environments, being even SMEs, are already developing different DRCs to cope with recurring disturbances; moreover, WLC-based adaptive decision-making routines are evident at different stages in their order fulfilment processes. Furthermore, a simulation study shows that implementing DRCs that utilize WLC-based adaptive decision-making routines lead to improved production performance in the presence of recurring disturbances leading to demand variability. Thus, it can be concluded that the proposed routine-based framework is appropriate and effective to develop and utilize DRCs with high variety manufacturing.

In future researches, it will be interesting to see how the routine-based framework can be applied to develop DRCs with different settings of disturbances, order fulfilment strategies, shop configuration types, buffering strategies, and flexibilities.

Acknowledgements

This paper is produced as part of the EMJD Programme European Doctorate in Industrial Management (EDIM) funded by the European Commission, Erasmus Mundus Action 1.

8. References

Abdelkafi, Nizar. 2008. *Variety Induced Complexity in Mass Customization: Concepts and Management*. Berlin: Erich Schmidt Verlag GmbH & Co KG.

Bangsow, Steffen. 2016. *Tecnomatix Plant Simulation*. Cham: Springer International Publishing. doi:10.1007/978-3-319-19503-2.

Barratt, Mark, Thomas Y. Choi, and Mei Li. 2011. “Qualitative Case Studies in Operations

Management: Trends, Research Outcomes, and Future Research Implications." *Journal of Operations Management* 29 (4): 329–42. doi:10.1016/j.jom.2010.06.002.

Bechte, Wolfgang. 1988. "Theory and Practice of Load-Oriented Manufacturing Control." *International Journal of Production Research* 26 (3): 375–95. doi:10.1080/00207548808947871.

Bechte, Wolfgang. 1994. "Load-Oriented Manufacturing Control Just-in-Time Production for Job Shops." *Production Planning & Control* 5 (3): 292–307. doi:10.1080/09537289408919499.

Ben-Daya, Mohamed, Elkafi Hassini, and Zied Bahroun. 2017. "Internet of Things and Supply Chain Management: A Literature Review." *International Journal of Production Research*, Advance online publication. doi:10.1080/00207543.2017.1402140.

Bergamaschi, D., R. Cigolini, M. Perona, and A. Portioli. 1997. "Order Review and Release Strategies in a Job Shop Environment: A Review and a Classification." *International Journal of Production Research* 35 (2): 399–420. doi:10.1080/002075497195821.

Blanc, Pascal, Isabel Demongodin, and Pierre Castagna. 2008. "A Holonic Approach for Manufacturing Execution System Design: An Industrial Application." *Engineering Applications of Artificial Intelligence* 21 (3): 315–30. doi:10.1016/j.engappai.2008.01.007.

Bonoma, Thomas V. 1985. "Case Research in Marketing: Opportunities, Problems, and a Process." *Journal of Marketing Research* 22 (2): 199–208. doi:10.2307/3151365.

Bozarth, Cecil C., Donald P. Warsing, Barbara B. Flynn, and E. James Flynn. 2009. "The Impact of Supply Chain Complexity on Manufacturing Plant Performance." *Journal of Operations Management* 27 (1): 78–93. doi:10.1016/j.jom.2008.07.003.

Breithaupt, Jan-Wilhelm, Martin J. Land, and Peter Nyhuis. 2002. "The Workload Control Concept: Theory and Practical Extensions of Load Oriented Order Release." *Production Planning & Control* 13 (7): 625–38. doi:10.1080/0953728021000026230.

Chan, Felix T.S., Rajat Bhagwat, and Hing Kai Chan. 2014. "The Effect of Responsiveness of the Control-Decision System to the Performance of FMS." *Computers & Industrial Engineering* 72: 32–42. doi:10.1016/j.cie.2014.03.003.

Ellis, Simon, Henry D. Morris, and John Santagate. 2015. "IoT-Enabled Analytic Applications Revolutionize Supply Chain Planning and Execution." International Data Corporation (IDC) White Paper. https://www.savi.com/wp-content/uploads/IDC-IoT-enabled-analytics-applications_final.pdf

Fernandes, Nuno O., and S. Carmo-Silva. 2011. "Workload Control under Continuous Order Release." *International Journal of Production Economics* 131 (1): 257–62. doi:10.1016/j.ijpe.2010.09.026.

Fredendall, Lawrence D., Divesh Ojha, and J. Wayne Patterson. 2010. "Concerning the Theory of Workload Control." *European Journal of Operational Research* 201 (1): 99–111. doi:10.1016/j.ejor.2009.02.003.

Gwon, Seong-hoon, Seog-Chan Oh, Ningjian Huang, and Soon-ki Hong. 2011. “Advanced RFID Application for a Mixed-Product Assembly Line.” *The International Journal of Advanced Manufacturing Technology* 56 (1–4): 377–86. doi:10.1007/s00170-011-3155-3.

Hendry, Linda C., Yuan Huang, and Mark Stevenson. 2013. “Workload Control: Successful Implementation Taking a Contingency-Based View of Production Planning and Control.” *International Journal of Operations & Production Management* 33 (1): 69–103. doi:10.1108/01443571311288057.

Hendry, Linda C., and Brian G. Kingsman. 1991. “A Decision Support System for Job Release in Make-to-order Companies.” *International Journal of Operations & Production Management* 11 (6): 6–16. doi:10.1108/01443579110144655.

Hendry, Linda C., Brian G. Kingsman, and P Cheung. 1998. “The Effect of Workload Control (WLC) on Performance in Make-to-Order Companies.” *Journal of Operations Management* 16 (1): 63–75. doi:http://dx.doi.org/10.1016/S0272-6963(97)00011-9.

Henrich, Peter, Martin J. Land, and Gerard J.C. Gaalman. 2004. “Exploring Applicability of the Workload Control Concept.” *International Journal of Production Economics* 90 (2): 187–98. doi:10.1016/S0925-5273(03)00126-9.

Hopp, Wallace J., and Mark L. Spearman. 2004. “To Pull or Not to Pull: What Is the Question?” *Manufacturing & Service Operations Management* 6 (2): 133–48. doi:10.1287/msom.1030.0028.

Hopp, Wallace J., and Mark L. Spearman. 2011. *Factory Physics*. 3rd ed. Illinois: Waveland Press.

Hu, S. J. 2013. "Evolving Paradigms of Manufacturing: From Mass Production to Mass Customization and Personalization." *Procedia CIRP* 7: 3–8. doi:10.1016/j.procir.2013.05.002.

Hu, S.J., X. Zhu, H. Wang, and Y. Koren. 2008. "Product Variety and Manufacturing Complexity in Assembly Systems and Supply Chains." *CIRP Annals* 57 (1): 45–48. doi:10.1016/j.cirp.2008.03.138.

Huang, George Q., YF Zhang, and PY Jiang. 2008. "RFID-Based Wireless Manufacturing for Real-Time Management of Job Shop WIP Inventories." *The International Journal of Advanced Manufacturing Technology* 36 (7–8): 752–64. doi:10.1007/s00170-006-0897-4.

Johnston, Wesley J., Mark P. Leach, and Annie H. Liu. 1999. "Theory Testing Using Case Studies in Business-to-Business Research." *Industrial Marketing Management* 28 (3): 201–13. doi:10.1016/S0019-8501(98)00040-6.

Kampen, Tim J. van, Dirk Pieter van Donk, and Durk-Jouke van der Zee. 2010. "Safety Stock or Safety Lead Time: Coping with Unreliability in Demand and Supply." *International Journal of Production Research* 48 (24): 7463–81. doi:10.1080/00207540903348346.

Kingsman, Brian G. 2000. "Modelling Input-Output Workload Control for Dynamic Capacity Planning in Production Planning Systems." *International Journal of Production Economics*

68 (1): 73–93. doi:10.1016/S0925-5273(00)00037-2.

Kingsman, Brian G., and Linda C. Hendry. 2002. “The Relative Contributions of Input and Output Controls on the Performance of a Workload Control System in Make-To-Order Companies.” *Production Planning & Control* 13 (7): 579–90. doi:10.1080/0953728021000026285.

Kingsman, Brian G., Linda C. Hendry, Alan Mercer, and Antonio De Souza. 1996. “Responding to Customer Enquiries in Make-to-Order Companies Problems and Solutions.” *International Journal of Production Economics* 46–47: 219–31. doi:10.1016/0925-5273(95)00199-9.

Kingsman, Brian G., I. P. Tatsiopoulos, and Linda C. Hendry. 1989. “A Structural Methodology for Managing Manufacturing Lead Times in Make-to-Order Companies.” *European Journal of Operational Research* 40 (2): 196–209. doi:10.1016/0377-2217(89)90330-5.

Kritchanchai, Duangpun, and B.L. MacCarthy. 1999. “Responsiveness of the Order Fulfilment Process.” *International Journal of Operations & Production Management* 19 (8): 812–33. doi:10.1108/01443579910274419.

Land, Martin J. 2004. “Workload Control in Job Shops: Grasping the Tap.” PhD diss., University of Groningen.

Land, Martin J., and Gerard Gaalman. 1996. “Workload Control Concepts in Job Shops A Critical Assessment.” *International Journal of Production Economics* 46–47: 535–48.

doi:10.1016/S0925-5273(96)00088-6.

Land, Martin J., and Gerard J.C. Gaalman. 2009. “Production Planning and Control in SMEs: Time for Change.” *Production Planning & Control* 20 (7): 548–58. doi:10.1080/09537280903034230.

Land, Martin J., Mark Stevenson, Matthias Thürer, and Gerard J.C. Gaalman. 2015. “Job Shop Control: In Search of the Key to Delivery Improvements.” *International Journal of Production Economics* 168: 257–66. doi:10.1016/j.ijpe.2015.07.007.

Makris, Sotiris, George Michalos, and George Chryssolouris. 2012. “RFID Driven Robotic Assembly for Random Mix Manufacturing.” *Robotics and Computer-Integrated Manufacturing* 28 (3): 359–65. doi:10.1016/j.rcim.2011.10.007.

Matson, Jeremy B., and Duncan C. McFarlane. 1999. “Assessing the Responsiveness of Existing Production Operations.” *International Journal of Operations & Production Management* 19 (8): 765–84. doi:10.1108/01443579910274374.

Michalos, George, Platon Sipsas, Sotiris Makris, and George Chryssolouris. 2016. “Decision Making Logic for Flexible Assembly Lines Reconfiguration.” *Robotics and Computer-Integrated Manufacturing* 37: 233–50. doi:10.1016/j.rcim.2015.04.006.

Moreira, M.R.A., and R.a.F.S. Alves. 2009. “A Methodology for Planning and Controlling Workload in a Job-Shop: A Four-Way Decision-Making Problem.” *International Journal of Production Research* 47 (10): 2805–21. doi:10.1080/00207540701725083.

Oosterman, Bas, Martin J. Land, and Gerard J.C. Gaalman. 2000. “The Influence of Shop Characteristics on Workload Control.” *International Journal of Production Economics* 68 (1): 107–19. doi:10.1016/S0925-5273(99)00141-3.

Peng, David Xiaosong, Roger G. Schroeder, and Rachna Shah. 2008. “Linking Routines to Operations Capabilities: A New Perspective.” *Journal of Operations Management* 26 (6): 730–48. doi:10.1016/J.JOM.2007.11.001.

Philipoom, P. R., and T. D. Fry. 1992. “Capacity-Based Order Review/Release Strategies to Improve Manufacturing Performance.” *International Journal of Production Research* 30 (11): 2559–72. doi:10.1080/00207549208948176.

Pujawan, I Nyoman, and Alison U. Smart. 2012. “Factors Affecting Schedule Instability in Manufacturing Companies.” *International Journal of Production Research* 50 (8): 2252–66. doi:10.1080/00207543.2011.575095.

Ragatz, Gary L., and Vincent A. Mabert. 1988. “An Evaluation of Order Release Mechanisms in a Job-Shop Environment.” *Decision Sciences* 19 (1): 167–89. doi:10.1111/j.1540-5915.1988.tb00260.x.

Ramirez-campos, Sergio, Luis Torres Trevino, M. Cedillo Campos, and Joge Leza. 2006. “Assembly Line Reconfiguration Under Disturbances: An Evolutionary Approach to Decision Making.” In *15th International Conference on Computing*, 24–32. Mexico City: IEEE. doi:10.1109/CIC.2006.27.

Raturi, Amitabh S., and Eric P. Jack. 2004. “Creating a Volume-Flexible Firm.” *Business Horizons* 47 (6): 69–78. doi:10.1016/j.bushor.2004.09.010.

Riezebos, J., G. J. Korte, and Martin J. Land. 2003. “Improving a Practical DBR Buffering Approach Using Workload Control.” *International Journal of Production Research* 41 (4): 699–712. doi:10.1080/0020754031000065485.

Ross, Jerry, and Barry M. Staw. 1993. “Organizational Escalation and Exit: Lessons From the Shoreham Nuclear Power Plant.” *Academy of Management Journal* 36 (4): 701–32. doi:10.5465/256756.

Ruiz-Torres, A. J., and F. Mahmoodi. 2007. “Impact of Worker and Shop Flexibility on Assembly Cells.” *International Journal of Production Research* 45 (6): 1369–88. doi:10.1080/00207540600690727.

Saenz de Ugarte, B., A. Artiba, and R. Pellerin. 2009. “Manufacturing Execution System – a Literature Review.” *Production Planning & Control* 20 (6): 525–39. doi:10.1080/09537280902938613.

Shafer, Scott M., and Timothy L. Smunt. 2004. “Empirical Simulation Studies in Operations Management: Context, Trends, and Research Opportunities.” *Journal of Operations Management* 22 (4): 345–54. doi:10.1016/j.jom.2004.05.002.

Stevenson, Mark. 2006. “Refining a Workload Control (WLC) Concept: A Case Study.” *International Journal of Production Research* 44 (4): 767–90.

doi:10.1080/00207540500338070.

Stevenson, Mark, and Linda C. Hendry. 2006. "Aggregate Load-Oriented Workload Control: A Review and a Re-Classification of a Key Approach." *International Journal of Production Economics* 104 (2): 676–93. doi:10.1016/j.ijpe.2005.05.022.

Stevenson, Mark, Linda C. Hendry, and Brian G. Kingsman. 2005. "A Review of Production Planning and Control: The Applicability of Key Concepts to the Make-to-Order Industry." *International Journal of Production Research* 43 (5): 869–98. doi:10.1080/0020754042000298520.

Teece, David J., Gary Pisano, and Amy Shuen. 1997. "Dynamic Capabilities and Strategic Management." *Strategic Management Journal* 18 (7): 509–33.

Thürer, Matthias, Martin J. Land, Mark Stevenson, Lawrence D. Fredendall, and Moacir Godinho Filho. 2015. "Concerning Workload Control and Order Release: The Pre-Shop Pool Sequencing Decision." *Production and Operations Management* 24 (7): 1179–92. doi:10.1111/poms.12304.

Thürer, Matthias, Cristovao Silva, and Mark Stevenson. 2010. "Workload Control Release Mechanisms: From Practice Back to Theory Building." *International Journal of Production Research* 48 (12): 3593–3617. doi:10.1080/00207540902922810.

Thürer, Matthias, Mark Stevenson, and Martin J. Land. 2016. "On the Integration of Input and Output Control: Workload Control Order Release." *International Journal of Production*

Economics 174 (April): 43–53. doi:10.1016/j.ijpe.2016.01.005.

Thürer, Matthias, Mark Stevenson, and Ting Qu. 2015. “Simple Subcontracting Rules for Make-to-Order Shops with Limited Subcontractor Capacity: An Assessment by Simulation.” *Production Planning & Control* 26 (13): 1145–61. doi:10.1080/09537287.2015.1019590.

Thürer, Matthias, Mark Stevenson, Ting Qu, and Godinho Filho Moacir. 2014. “The Design of Simple Subcontracting Rules for Make-to-Order Shops: An Assessment by Simulation.” *European Journal of Operational Research* 239 (3): 854–64. doi:10.1016/j.ejor.2014.06.018.

Thürer, Matthias, Mark Stevenson, and Cristovao Silva. 2011. “Three Decades of Workload Control Research: A Systematic Review of the Literature.” *International Journal of Production Research* 49 (23): 6905–35. doi:10.1080/00207543.2010.519000.

Thürer, Matthias, Mark Stevenson, Cristovao Silva, and Martin Land. 2013. “Towards an Integrated Workload Control (WLC) Concept: The Performance of Due Date Setting Rules in Job Shops with Contingent Orders.” *International Journal of Production Research* 51 (15): 4502–16. doi:10.1080/00207543.2013.774485.

Thürer, Matthias, Mark Stevenson, Cristovao Silva, Martin J. Land, and Lawrence D. Fredendall. 2012. “Workload Control and Order Release: A Lean Solution for Make-to-Order Companies.” *Production and Operations Management* 21 (5): 939–53. doi:10.1111/j.1937-5956.2011.01307.x.

Wang, Jiahao, Zongwei Luo, and Edward C. Wong. 2010. “RFID-Enabled Tracking in Flexible Assembly Line.” *The International Journal of Advanced Manufacturing Technology* 46 (1–4): 351–60. doi:10.1007/s00170-009-2102-z.

Xu, Li Da, Eric L. Xu, and Ling Li. 2018. “Industry 4.0: State of the Art and Future Trends.” *International Journal of Production Research* 56 (8): 2941–62. doi:10.1080/00207543.2018.1444806.

Yan, Haoyun, Mark Stevenson, Linda C. Hendry, and Martin J. Land. 2016. “Load-Oriented Order Release (LOOR) Revisited: Bringing It Back to the State of the Art.” *Production Planning & Control* 27 (13): 1078–91. doi:10.1080/09537287.2016.1183831.

Yin, Robert K. 2009. *Case Study Research: Design and Methods*. 4th ed. Sage Publications.

Zhang, Yingfeng, Geng Zhang, Junqiang Wang, Shudong Sun, Shubin Si, and Teng Yang. 2015. “Real-Time Information Capturing and Integration Framework of the Internet of Manufacturing Things.” *International Journal of Computer Integrated Manufacturing* 28 (8): 811–22. doi:10.1080/0951192X.2014.900874.

Zhong, Ray Y., Q.Y. Dai, T. Qu, G.J. Hu, and George Q. Huang. 2013. “RFID-Enabled Real-Time Manufacturing Execution System for Mass-Customization Production.” *Robotics and Computer-Integrated Manufacturing* 29 (2): 283–92. doi:10.1016/j.rcim.2012.08.001.

Zhong, Ray Y., Z. Li, L.Y. Pang, Y. Pan, T. Qu, and George Q. Huang. 2013. “RFID-Enabled Real-Time Advanced Planning and Scheduling Shell for Production Decision Making.”

International Journal of Computer Integrated Manufacturing 26 (7): 649–62. doi:10.1080/0951192X.2012.749532.