# The pursuit of responsiveness in high variety manufacturing environments
## Towards building the Dynamic Response Capabilities

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# Abstract

Mass customization is considered as a viable business strategy for Small and Medium-Sized Enterprises (SMEs) to increase their growth and profitability. However, in operations management literature, most of the research on mass customization is geared towards large enterprises while there is little guidance for SMEs in its implementation. Without proper guidance, implementing mass customization in SMEs poses many challenges. The product variety increases which increases complexity in products and production. Besides, due to high variety the manufacturing systems face different types of recurring disturbances from multiple sources that affect the planned production operations with adverse effect on performance. Nonetheless, successful implementation of mass customization requires an appropriate and responsive order fulfilment process capable not only to meet the differentiated customer needs but also to cope with different types of recurring disturbances that may arise at different times, different places in relation to stages in the order fulfilment process, and with different intensity. How such process is developed and maintained may differ among large enterprises and SMEs mainly due SME specific factors such as low sales volume, limited organizational and technological resources, close customer interaction and high demand variability. Therefore, this research aims to understand and explain how responsiveness in the order fulfilment process can be achieved for successful implementation of mass customization in SMEs. For this purpose, the thesis investigates two key aspects: i) designing an appropriate order fulfilment process for mass customization in SMEs; ii) developing the Dynamic Response Capabilities (DRCs) to cope with different types of recurring disturbances arising along the order fulfilment process.

The first aspect, designing an appropriate order fulfilment process for mass customization in SMEs, aims at setting the scope of the research work. For this purpose, the research particularly focuses on Assemble-to-Order (ATO) fulfilment strategy for catalogue mode of mass customization in SMEs. To design the order fulfilment process under ATO fulfilment strategy two key elements are identified from literature: i) Workload Control (WLC) is considered as a relevant PPC method for SMEs to plan, prioritize, and coordinate order fulfilment activities starting from the order enquiry/entry stage; ii) similarly, based on the volume-variety requirements within SME context, six shop configuration types have been considered as relevant for SMEs to structure the order fulfilment activities.

The second aspect – developing the DRCs to address recurring disturbances arising along the order fulfilment process, which is the core contribution of this thesis –, aims to formalize a framework that can be used as a guiding tool to develop the DRCs of the manufacturing system in SME context. This research defines DRCs as the ability of a manufacturing system to (re)adjust its planned operating routines (i.e. planned capacity, lead time, and workload) in the wake of customer, supplier, and internal disturbances to achieve its operational goals. Based on the reviewed literature, the research employs a routine-based approach to build DRCs as higher order operational capabilities of the manufacturing system by implementing adaptive decision-making routines at different stages in the order fulfilment process. This research argues that in SME context DRCs can be developed by implementing WLC-based decision-making routines at different stages in the order fulfilment process. The I/OC mechanisms of WLC utilize different types of buffer and flexibilities (i.e. lower level capabilities) to readjust the planned workload, capacity, and/or lead-time in the wake of disturbances from customers, suppliers, and internal manufacturing operations. For I/OC mechanisms to be effective, they should be supported with proper sensing routines and mechanisms to have visibility into the current operating conditions in order to recognize the disturbances as they arise along the order fulfilment process and to adapt the planned capacity, lead time, and workload by using available buffer and flexibilities. Thus, to develop DRCs a routine-based framework is proposed which implements WLC-based adaptive decision-making routines at different stages in the order fulfilment process to readjust the planned operating routines in the wake of recurring disturbances.

The routine-based framework of the DRCs is tested for its relevance, feasibility, and effectiveness using two case studies from the SME sector and a simulation study performed in collaboration with one of the case companies. Findings from case studies show that mass customization SMEs are already developing different types of DRCs by implementing WLC-based adaptive decision-making routines at different stages of their order fulfilment processes. The findings from case studies

provide evidence for DRCs by identifying the adaptive decision-making routines and mechanisms implemented by the case companies to address multiple types of recurring disturbances. In particular, the DRCs to cope with recurring disturbances due to volume demand variability, mix demand variability, rush orders, internal performance variation, and unreliable component supply have been identified. Based on the findings from case studies it is concluded that the routine-based framework is relevant and feasible for mass customization SMEs to build DRCs and to achieve responsiveness in the order fulfilment process. Furthermore, simulation results show that performance in terms of order fulfilment rate and capacity utilization is improved in the presence of recurring disturbances due to volume and mix demand variability by implementing DRCs that utilize WLC-based adaptive-decision making routines at order enquiry/entry and release stages of the order fulfilment process. Based on the findings from the case studies and the collaborative simulation study, it is concluded that the proposed routine-based framework and the I/OC mechanisms can be effectively used to identify, analyze, and develop different DRCs to cope with multiple types of recurring disturbances and to achieve responsiveness in the order fulfilment process for successful implementation of mass customization in SMEs.

# Estratto

La mass customization è considerata una valida strategia aziendale per le piccole e medie imprese (PMI) per aumentarne la crescita e la redditività. Tuttavia, nella letteratura sulla gestione operativa, la maggior parte della ricerca sulla mass customization è orientata verso le grandi imprese, mentre sulla sua messa in opera nelle PMI vi sono poche indicazioni. Senza una guida adeguata, l'implementazione della mass customization nelle PMI pone molte sfide. La varietà dei prodotti aumenta e aumenta la complessità della produzione. Inoltre, a causa dell'elevata varietà, i sistemi di produzione devono affrontare diversi tipi di disturbi ricorrenti da più fonti che influiscono sulle operazioni di produzione pianificate, con effetti negativi sulle prestazioni. Tuttavia, l'implementazione di successo della mass customization richiede un processo di evasione degli ordini adeguato e reattivo in grado non solo di soddisfare le esigenze differenziate dei clienti, ma anche di far fronte a diversi tipi di disturbi ricorrenti che possono sorgere in tempi diversi, momenti diversi, e con diversa intensità, in relazione alle fasi nel processo di evasione dell'ordine. Il modo in cui tale processo viene sviluppato e mantenuto può differire tra le grandi imprese e le PMI, principalmente a causa di fattori specifici delle PMI quali i bassi volumi di vendita, le risorse organizzative e tecnologiche limitate, la stretta interazione con i clienti e l'elevata variabilità della domanda. Pertanto, questa ricerca ha lo scopo di comprendere e spiegare in che modo è possibile conseguire la reattività nel processo di evasione degli ordini per l'implementazione di successo della mass customization nelle PMI. A tal fine, la tesi indaga su due aspetti chiave: i) la progettazione di un adeguato processo di evasione degli ordini per la mass customization nelle PMI; ii) la sviluppo delle capacità di risposta dinamica (DRC) per far fronte a diversi tipi di disturbi ricorrenti durante il processo di evasione degli ordini.

Il primo aspetto, la progettazione di un adeguato processo di evasione degli ordini per la mass customization nelle PMI, mira a stabilire l'ambito del lavoro di ricerca. A tal fine, la ricerca si concentra in particolare sulla strategia di Assemble-to-Order (ATO) con la modalità a catalogo di mass customization. Per progettare il processo di evasione degli ordini secondo la strategia ATO, dalla letteratura vengono identificati due elementi chiave: i) Workload Control (WLC) è considerato un metodo di Production Planning & Control (PPC) rilevante per le PMI per pianificare, stabilire le priorità e coordinare le attività di evasione degli ordini a partire dalla fase di richiesta / ingresso dell'ordine; ii) analogamente, sulla base dell'analisi della letteratura, e considerando le caratteristiche del volume-varietà all'interno del contesto delle PMI, sei tipi di configurazione di sistema produttivo sono stati considerati rilevanti per le PMI per strutturare le attività di evasione degli ordini.

Secondo aspetto riguarda lo sviluppo delle capacità di risposta dinamica (DRC) per affrontare i disturbi ricorrenti che si verificano durante il processo di evasione degli ordini, ciò che è il contributo principale di questa tesi. Tale contributo mira a formalizzare una struttura che può essere utilizzata come strumento di guida per lo sviluppo delle DRC del sistema produttivo in un contesto delle PMI. Questa ricerca definisce i DRC come la capacità di un sistema di produzione di (ri)-regolare le sue routine operative pianificate (vale a dire capacità pianificata, tempi di consegna e carico di lavoro) a seguito dei disturbi insorti da clienti, fornitori e disturbi interni, per raggiungere i propri obiettivi operativi. Sulla base della letteratura revisionata, la ricerca utilizza un approccio basato sulla routine per creare DRC come capacità operative superiori del sistema di produzione, implementando routine di decisione adattiva in diverse fasi del processo di evasione degli ordini. Questa ricerca sostiene che nel contesto delle PMI i DRC possono essere sviluppati implementando routine decisionali basate su WLC in diverse fasi del processo di evasione degli ordini. I meccanismi I / OC (controllo input / output) del WLC utilizzano diversi tipi di buffer e flessibilità per regolare il carico di lavoro pianificato, la capacità e / o il lead time in seguito a disturbi da parte di clienti, fornitori e operazioni di produzione interne. Affinché i meccanismi I / OC siano efficaci, devono essere supportati con procedure e meccanismi di rilevamento adeguati per avere visibilità sulle attuali condizioni operative, al fine di riconoscere i disturbi che si presentano durante il processo di evasione degli ordini e per adattare la capacità pianificata, il tempo di consegna e il carico di lavoro, utilizzando il buffer e le flessibilità disponibili. Pertanto, per sviluppare

i DRC viene proposta una struttura basata su routine di decisione adattive basate su WLC in diverse fasi del processo di evasione degli ordini, per riadattare le routine operative pianificate a seguito di disturbi ricorrenti.

La struttura basata sulle routine dei DRC viene testata per la sua rilevanza, fattibilità ed efficacia utilizzando due studi di caso nel settore delle PMI e uno studio di simulazione condotto in collaborazione con una delle aziende oggetto degli studi di caso. I risultati degli studi di caso dimostrano che le PMI con la mass customization stanno già sviluppando diversi tipi di DRC mediante l'implementazione di routine di decisione adattiva basate su WLC in diverse fasi dei loro processi di evasione degli ordini. I risultati degli studio di caso forniscono prove per i DRC, perché permettono di identificare le procedure decisionali adattative e i meccanismi già implementati, nelle aziende dei casi, per affrontare diversi tipi di disturbi ricorrenti. In particolare, i DRC sono stati identificati per far fronte a ricorrenti disturbi dovuti alla variabilità della domanda di volume, alla variabilità della domanda, agli ordini urgenti, alla variazione delle prestazioni interne e alla fornitura di componenti inaffidabili. Sulla base dei risultati degli studi di caso si è concluso che il framework basato sulla routine, proposto nella tesi, è pertinente e fattibile per costruire DRC e per ottenere reattività nel processo di evasione degli ordini in PMI che operano con mass customization. Inoltre, i risultati della simulazione mostrano che le prestazioni in termini di velocità di evasione degli ordini e utilizzo della capacità sono migliorate in presenza di disturbi ricorrenti dovuti alla variabilità della domanda di volume e mix, implementando DRC che utilizzano routine di decisione adattativa basate su WLC su richiesta / ingresso e fasi di rilascio del processo di evasione degli ordini. Sulla base dei risultati degli studi di caso e dello studio di simulazione collaborativa, si conclude che il framework basato su routine proposto e i meccanismi I / OC possono essere utilizzati efficacemente per identificare, analizzare e sviluppare diversi DRC per far fronte a più tipi di perturbazioni ricorrenti e per raggiungere la reattività nel processo di evasione degli ordini per l'implementazione di successo della mass customization nelle PMI.


**Parole chiave**

Personalizzazione di massa, alta varietà, PMI, processo di evasione ordini, perturbazioni, reattività, controllo del carico di lavoro, capacità di risposta dinamica

*"Be halfway in the fire and you will get burned.*

*Be fully in the fire and you become one with it*

*to light up the entire world"*

*-Brian Piergrossi-*

## <u>Dedication</u>

Dedicated to the ones who burn their souls to create light.

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# Acknowledgements

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# CONTENTS

## Summary of the Chapters and Thesis Structure

The thesis is structured into 8 chapters. A short summary of each chapter is provided in this section.

**Chapter 1** provides the background and the context in which the research is being conducted. It describes the evolution of manufacturing from craft production to the most recent mass customization paradigm. It discusses customer involvement and modularity as the two key dimensions of mass customization. Then a literature review on mass customization in SMEs has been performed to identify different challenges that manufacturing SMEs face when they embark on this journey. To address those challenges, the need and the pursuit of responsiveness have been discussed. In particular, the thesis focuses on responsiveness in relation to recurring disturbances arising along the order fulfilment process and identifies the research gap. Based on the research gap different research questions have been identified: they will be guiding the research throughout this thesis.

**Chapter 2** starts with the discussion on mass customization from an operations perspective with the objective to identify the key elements that are needed to design an appropriate order fulfilment process for mass customization in SMEs. It provides an overview on different operational modes, order fulfilment models, and order fulfilment strategies for mass customization. The research focuses on the catalogue mode of mass customization. To implement catalogue mode of mass customization in SMEs, the suitability of different order fulfilment models and strategies has been discussed. The research particularly focuses on the design of the order fulfilment process under ATO fulfilment strategy for catalogue mode of mass customization in SMEs. To design the detailed order fulfilment process under ATO fulfilment strategy, the suitability of the production planning methods and the production processing technologies for mass customization SMEs has been discussed. The main purpose is to evaluate their appropriateness for SMEs to *plan, control, and structure* the order fulfilment activities starting from the order entry stage. Chapter 2 concludes with the main findings from the literature review.

**Chapter 3** provides the overall research design and methodologies used during different phases of this research. It discusses the three main research objectives and their motivation. The research objectives are: i) to formalize a framework of the DRCs for mass customization SMEs; ii) to verify the relevance and the feasibility of the DRCs framework for mass customization SMEs; and iii) to test the effectiveness of the DRCs for mass customization SMEs. To achieve

the research objectives, it discusses three methodologies that are used in this research: i) a routine-based approach to operations capabilities; ii) deductive case study approach; and iii) simulation study. It provides the justification for the choice of research methodologies and discusses how they are actually operationalized during different phases of the research to achieve the objectives.

**Chapter 4** starts with an overview on the DRCs of the manufacturing systems. It reviews the relevant literature and proposes the routine-based framework of DRCs by identifying the routines and mechanisms that are essential to generate dynamic and adaptive responses in the wake of recurring disturbances. In particular three routines are identified: i) sensing the current operating routines and disturbances; ii) WLC-based decision making; and iii) readjusting planned operating routines. The chapter explicates different mechanisms that are required to implement the identified routines in a structured way, i.e. mechanisms fulfilling the requirements to effectively operationalize the identified routines. The chapter concludes with the remarks on how the routine-based framework is developed based on the knowledge in three different streams of research.

**Chapter 5** provides the case studies. It starts with the discussion on the scope of case studies for this research and develops two hypotheses regarding the relevance and the feasibility of the routine-based framework for mass customization SMEs to develop DRCs. It provides the main evaluation criteria to test the hypotheses through case studies. To analyse the case studies, the chapter provides an overview of the case companies and the context in which they operate, the mode of operation and the number of product models they offer to their customers, order fulfilment models, and the main order fulfilment strategies they operate to fulfil different customer orders. A particular attention has been paid to the configuration type they have implemented and the way they organize their production. For each case company, the complete order fulfilment process has been analysed to identify the recurring disturbances and the adaptive decision-making routines and mechanisms they have implemented to address them. The key findings from both case studies are discussed in detail and are summarised in tables. The findings are then assessed against their evaluation criteria. At the end, the chapter provides concluding remarks on how the case companies have designed an appropriate order fulfilment process to implement mass customization and how they have developed different DRCs to address multiple types of recurring disturbances arising along their order fulfilment processes.

**Chapter 6** starts with the discussion on the main objectives of the collaborative project and the simulation study performed with one of the case companies in real settings. Three main

objectives are discussed: i) to evaluate the impact of DRCs on production performance; ii) to verify if the routine-based framework can be used as a guiding tool to improve the performance of existing production operations; and iii) to compare the proposed routine-based approach with a traditional PPC method. To achieve these objectives, the simulation study is implemented in collaboration with the case company where the routine-based framework guided the design of the experiments. Different DRCs are identified which are then operationalized inside the simulation model as experimental factors. The results of the simulation experiments are then analysed to evaluate the impact of different DRCs (i.e. as experimental factors) on different performance measures. The results are also compared with those of a traditional PPC method. The simulation results show that implementing DRCs that utilize adaptive decision-making routines and mechanisms at different stages in the order fulfilment process lead to improved production performance. At the end, the chapter provides concluding remarks on the lessons learnt from the collaborative project as well as from the simulation study.

**Chapter 7** synthesizes the thesis findings by explaining how each research question introduced in chapter 1 is answered and how the research objectives are achieved. It provides some of the findings' most significant implications for theory and practice. It discusses findings from literature review, case studies, and collaborative simulation study. It also provides implications of developing DRCs on a company's long term objectives and stresses the need to identify and analyse alternative adaptive decision-making routines and mechanisms to achieve both operational as well as strategic objectives.

**Chapter 8** concludes the thesis by explaining the two key actions that are needed for successful implementation of mass customization in SMEs: i) designing an appropriate order fulfilment process; and iii) developing DRCs to address recurring disturbances arising along the order fulfilment process. It remarks how the emprical evidences have provided support for routine-based framework to develop DRCs and how implmenting DRCs that utilize WLC-based adaptive decision-making routines lead to improved production performance in mass customization SMEs. Finally, the thesis concludes by outlining different future reseach directions.
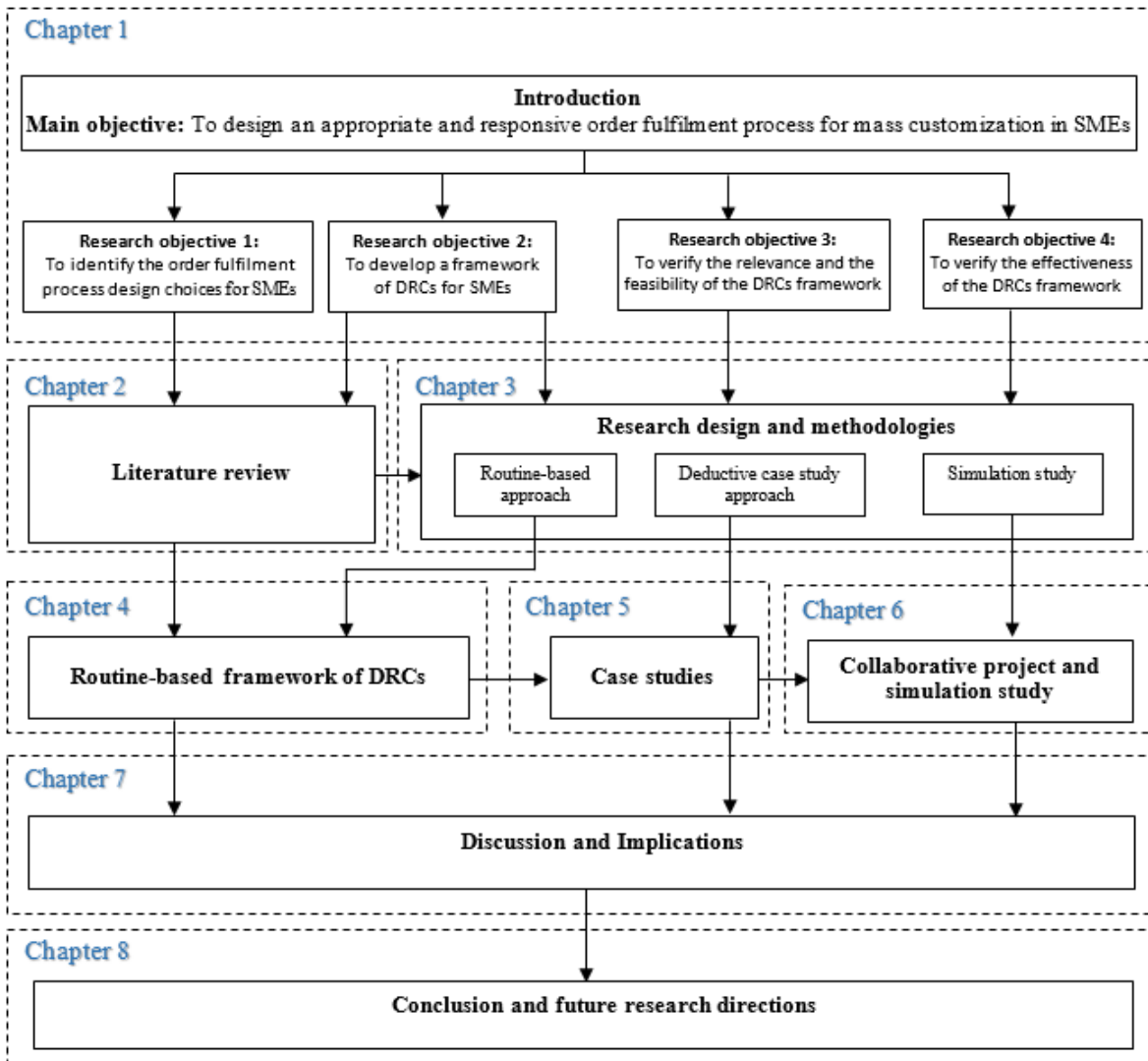
Figure 1 Thesis Structure

# 1 INTRODUCTION

## 1.1 EVOLUTION OF MANUFACTURING

Manufacturing sector is considered as a key enabler of sustainable economic growth as it plays a crucial role in the creation and distribution of wealth in a society. Since its birth two centuries ago, manufacturing has evolved through several paradigms that can be explained based on a volume-variety relationship (Yoram Koren 2010; Hu et al. 2011).
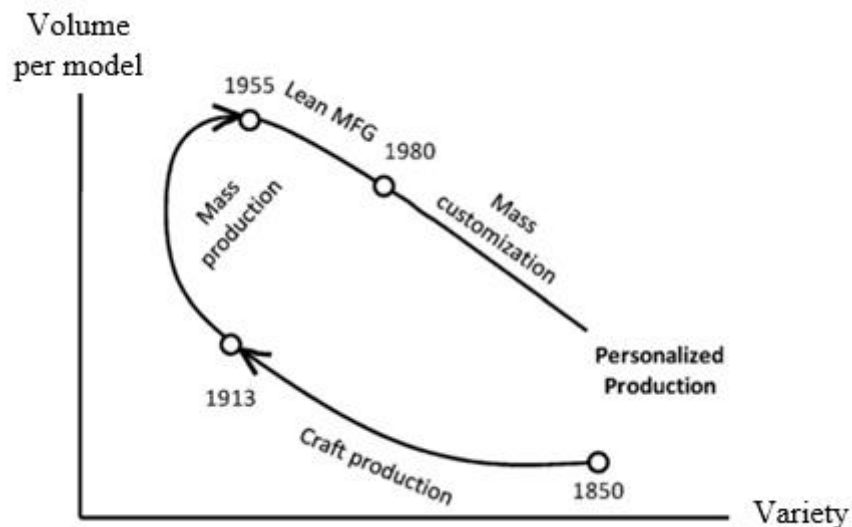


Figure 2 Evolution of manufacturing adapted from (Koren 2010; Hu et al. 2011)

As shown in figure 2, the first paradigm was 'craft production', where the products were created according to the exact customer requests but at a high cost and long lead time. There were no standardized manufacturing systems available and each customer request was handled uniquely. Manufacturing was usually carried out by a single skilled artisan with assistants and craftsmanship was considered as the key success factor. Although, customer satisfaction was high but the outreach of craft vendors was limited to their localized geographical regions hence such production was not scalable.

The advancements in science and technology, leading to efficient machines supported with interchangeable parts and scientific management, paved the way for low-cost manufacturing of large volumes of products. In particularly, the invention of moving assembly line by Henry Ford in 1913 shifted manufacturing focus from 'craft production' to 'mass production'. In mass production, economic efficiency and labour productivity were considered as key success factors. To this end, different organizational and management approaches emerged along the way to improve the efficiency and the productivity. Division of labour into

individual tasks, where each worker focus on some specialized repetitive tasks, led to increase in productivity. This became particularly relevant with moving assembly lines where work was divided among different work stations each specializing in particular set of tasks. To further improve the economic efficiency and labour productivity the theory of scientific management was introduced (Taylor 1911). The time and motion studies, method studies, and training of workers were the key focus areas for scientific management.

Although mass production enabled to produce large volumes of products at low cost, there were many limitations of these production systems. The sole focus on productivity led to deteriorating quality. Manufacturers were pushing their products to customers with little input from them, as evidenced by the famous statement from Henry Ford, "any customer can have a car painted any color he wants as long as it's black." In fact, manufacturers were designing and producing products without realizing that customers were becoming more aware of their needs and they were looking for options to better satisfy those needs. The Japanese manufacturers were the first to realize this changing manufacturing landscape and they started offering product options which were cheaper and better as compared to products manufactured in the West. This forced manufacturers in the West to rethink their approach towards manufacturing and they started inquiring the Japanese manufacturing methods and techniques. These inquiries led to the discovery of 'lean manufacturing'(Womack, Jones, and Roos 1990). Lean manufacturing is a management philosophy that seeks to maximize value to the customer while minimize waste along the 'process' flow. It is based on the lessons learned and follow-ups of the Toyota Production System and in fact it is a reflection of the West on Japanese way of doing work. It comprises various principles and methods for manufacturing management. The key focus of lean manufacturing is to standardize the procedures and processes and to reduce *variability* in manufacturing. In this paradigm, the cost, quality, and delivery were considered as key success factors and manufacturers across the globe started embracing lean philosophy to achieve these objectives.

Although discovery of lean led to several improvements in manufacturing, the product variety offered by such production systems was limited. On the other hand, the incoming globalization and more self-aware customers brought new opportunities and challenges for manufacturers. In particular, to gain greater market share and to satisfy customer's needs and wants globally, manufacturers needed to produce highly customized products with quick response and at a reasonable price. This situation put manufacturing companies under tremendous pressure to meet apparently conflicting goals of efficiency and providing

customers exactly what they want. To this end, 'mass customization' has emerged as a new business strategy (Davis 1987; Pine 1993; Pine, Peppers, and Rogers 1995). Mass Customization aims to provide product variety and customization at prices comparable to mass-produced products. The shift from mass production to mass customization is not an easy task and manufacturing companies face many challenges in its implementation and execution (Åhlström and Westbrook 1999). Mass Customization presents a paradox by combining customization and mass production. In practice, it does not fit the conventional mind-set of manufacturing and management methods mostly developed to support the production of either customized crafted products or standardized mass-produced products (Duray et al. 2000; Duray 2002). Traditionally, customized products usually are made using low volume production processes (i.e. craft production) with major focus on product variety and customer involvement in the design process while standardized products are made using high volume production processes (i.e. mass production) with major focus on efficiency and capturing scale economies (in mass production customer involvement is generally limited to market research for capturing standard product design attributes).

## 1.2 KEY DIMENSIONS OF MASS CUSTOMIZATION

The essence of mass customization lies in two key dimensions: i) customer involvement; and ii) modularity (Duray et al. 2000; Duray 2002). Customer involvement regards the means to include each customer's specifications in the product design to achieve customization, while modularity regards the utilization of modular design to gain scale volume and manufacturing efficiencies that approximate those of standard mass produced products.

**Customer involvement**

The level of customer involvement in the production cycle plays a critical role in determining the degree of customization (Lampel and Mintzberg 1996). The point, or stage, of customer involvement in the production cycle (i.e. design, fabrication, assembly, delivery/use) is a key variable in the process choice decision (McCutcheon, Raturi, and Meredith 1994). It is also a key indicator of the degree or type of customization provided (customer involvement in the early design stages of the production cycle means high degree of customization and vice versa) (Duray 2002). Previously, it has been also referred to as Customer Order Decoupling Point (CODP) (Wortmann 1983; Wemmerlöv 1984; Giesberts and van der Tang 1992) and order penetration point (Olhager 2003, 2010). It is defined as 'the point in the manufacturing value chain where the product is linked to a specific customer order' (Olhager 2003). It separates

decisions made under uncertainty from decisions made under certainty concerning customer demand (Rudberg and Wikner 2004). It serves as a reference to decide where to implement efficiency-related and flexibility-related production techniques in order to achieve both volume scale (i.e. mass) and customization (van Donk and van Doorne 2016).

Based on CODP, different order fulfilment strategies can be considered. These strategies include deliver-to-order (DTO), assemble-to-order (ATO), make-to-order (MTO), design-to-order (DeTO), and engineer-to-order (ETO) (Britton and Torvinen 2013). This classification is in line with the ones proposed by Wortmann (1983), and later, by Mather (1988) who distinguish between make-to-stock (MTS), ATO, MTO, and ETO. As shown in figure 3, these strategies differ with respect to where the stock is held in the system and where the production process is decoupled from the customer order (i.e. customer involvement point).
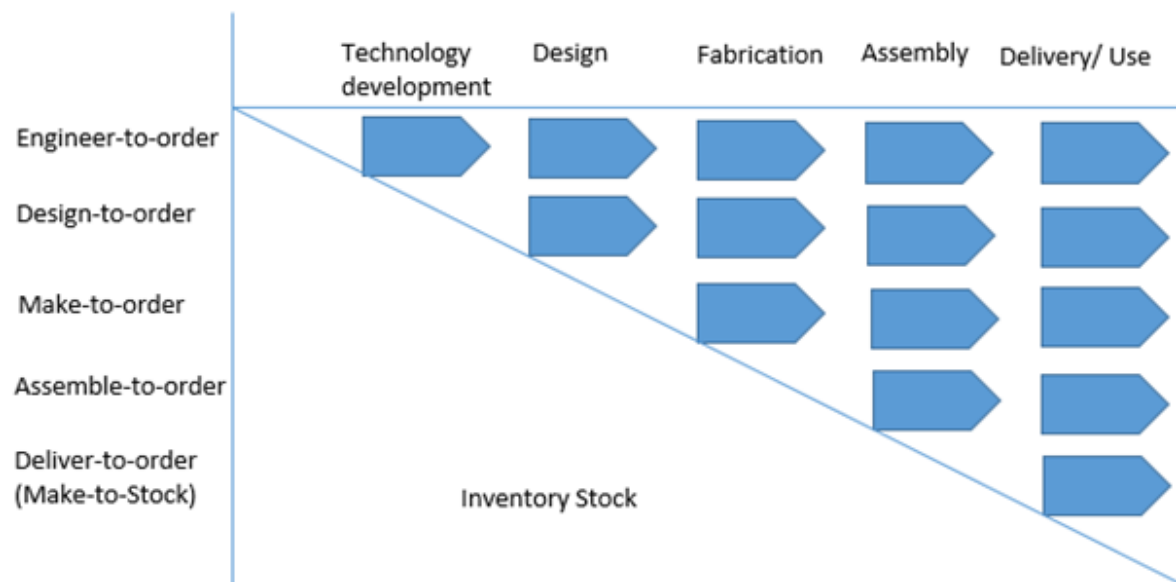


Figure 3 CODP and order fulfilment strategies adapted from (Britton and Torvinen 2013)

Each order fulfilment strategy enables to achieve different degree of customization and delivery cycle time. On one end, MTS, equivalently DTO, fulfilment strategy characterizes immediate delivery but virtually no product customization; while on the other end, ETO enables high customization but with longer delivery cycle times.

ETO and DeTO fulfilment strategies enable high customization; to this end, technology development and design are included in the order life cycle. Under ETO and DeTO fulfilment strategies, the delivery cycle time is quite long as the time is required both to custom design the product and to develop the technology to build it. Furthermore, the significant

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customization makes ETO and DeTO fulfilment strategies more suitable for one-off projects (e.g. huge ships) that require unique engineering design, set of part numbers, bill of materials, and routings, etc. Under MTO fulfilment strategy the production activities (i.e. component fabrication and/or assembly) are performed only after the complete requirements and specifications are known from the customers. Raw material is either stocked in advance or purchased according to customer's specifications. The final product usually is a combination of standardized and custom items to meet the customer's specific needs. Although MTO enables high customization and eliminates finished goods' inventories, it usually exhibits long delivery cycle times and large order backlogs (Gupta and Benjaafar 2004). Under an ATO fulfilment strategy a large number of products are assembled according to individual customer's orders from a set of standard components and subassemblies from the stock. The components and subassemblies are produced based on a forecast, while finished products are assembled only after the actual orders arrive (Wemmerlöv 1984; van Hoek 2001; Pil and Holweg 2004). Previously, it has been also referred to as delayed product differentiation, a form of postponement (van Hoek 2001), implemented in assembly systems to defer the differentiation of final product configurations. ATO enables customization with quick delivery (ElMaraghy et al. 2013). Furthermore, by delaying the final assembly of the end products until the arrival of customer demand, the companies can benefit from pooling component inventories to offer multiple end products (Atan et al. 2017). Under DTO/MTS strategy the standard products are made according to forecast before any committed orders come in, thus product customization is not possible as the products are already produced and stored in inventory. Consequently, DTO/MTS fulfilment strategy is more suitable for standard products with stable demand.

Usually a company employs one dominant CODP (Olhager 2010) leading to one dominant order fulfilment strategy but it is also possible to have multiple CODPs resulting in a hybrid strategy to satisfy diverse customer demands (Wei et al. 2010). For example, MTO and ATO can be used to satisfy the demand for customized products; while MTS, or equivalently DTO, can be used for standard products with stable demand.

The order fulfillment strategies are a background of the order fulfilment models for mass customization, as will be cleared out in section 2.1.

**Modularity**

Much like customer involvement, modularity plays a critical role in effective implementation of mass customization (Pine 1993; Pine, Peppers, and Rogers 1995). It provides the basis for repetitiveness in production and is considered as a key identifier for the choice of manufacturing and management methods to produce mass customized goods (Duray et al. 2000; Duray 2002). According to (Blecker and Abdelkafi 2006c) product modularity is 'an attribute of the product system that characterizes the ability to mix and match independent and interchangeable product building blocks with standardized interfaces in order to create product variants'. Previously, in literature, several benefits of modularity have been discussed from different perspectives. Table 1 provides different benefits of modularity as discussed in literature.

Table 1 Benefits of modularity

| Benefits of modularity | References |
|---|---|
| Modularity in product design enables to achieve both variety and delivery speed | McCutcheon, Raturi, and Meredith (1994), Ulrich (1995) |
| Product modularity makes it easier to implement mass customization as it separates the composition of end products into parts and/or subassemblies that are common and those that are not | (H. Lee 1998) |
| Modularity allows to reduce the manufacturing lead times as long manufacturing lines can be split into parallel production of modules | (Ericsson and Erixon 1999) |
| Modularity can facilitate increasing the number of product features available while also decreasing costs by decreasing the variety of components and allowing for repetitive manufactruing | (Duray et al. 2000) |
| Product modularity helps to mitigate complexity as it allows to achieve the desired functionality with minimum physical changes | (Ulrich and Eppinger 1995) |
| Product modularity enables the production of variety while facilitating the achievement of the economies of scale and the economies of scope | (Blecker and Abdelkafi 2006d) |

Different modularity types have been discussed in literature in relation to mass customization: component-sharing modularity, component-swapping modularity, cut-to-fit or fabricate-to-fit modularity, mix modularity, bus modularity, and sectional modularity (Ulrich and Tung 1991; Pine 1993; Duray et al. 2000). From a variety management perspective, component-sharing and component-swapping modularity types have been particularly emphasized as important enablers of mass customization (Fisher, Ramdas, and Ulrich 1999; Salvador, Rungtusanatham, and Forza 2004; Abdelkafi 2008).

- Component-sharing modularity refers to a situation in which one component is common to more than one end items. Products are uniquely designed around a base unit of common components. The aim is to reduce the internal variety by using as few components in as many end products as possible. The example of component-sharing modularity can be found in computer industry where the same power cord can be used in different product families (i.e. different computers). Several benefits of component commonality have been discussed in literature. Mohebbi and Choobineh (2005) found that component commonality significantly interacts with existence of demand and supply uncertainties, and its benefits are most pronounced when both uncertainties exist. Similarly, Eynan and Fouque (2005) note that the use of common components reduces variability leading to better control and utilization of inventory. One of the major benefit of component commonality is that companies can offer high end product variety by pooling component inventories and reduce the cost of offering multiple end products (Atan et al. 2017). Other benefits of component commonality include easier engineering design process, fewer setups on the shop floor, fewer changeovers, and shorter manufacturing lead times (Blecker and Abdelkafi 2006d).

- Component-swapping modularity refers to a situation where a standard product can have several module options (i.e., module switching). It is identical to component-sharing modularity except that, in component-swapping modularity, a basic common module, also referred as product platform, is paired with two or more alternative types of components to create several variants of a product family. "Swapping" involves different components of the same basic products and "sharing" involves different basic products using the same components (Ulrich and Tung 1991; Robertson and Ulrich 1998). The example of component-swapping modularity can also be found in computer industry where different hard disk types, monitor types, and keyboards can be matched with the same basic CPU to create several variants. The use of common basic module offers several benefits. It facilitates implementation of delayed differentiation and helps to reduce complexity as several variants within a product family share the same basic module (Blecker and Abdelkafi 2006a). Furthermore, with basic modules in place, the new product development time and cost are significantly reduced; thus, new variants can be easily added to a product family (Halman, Hofer, and Van Vuuren 2003). With product platforms, high efficiency can be achieved as product platforms are expected to exhibit large demand volumes and low demand variability due to their high level of commonality among product variants.

This further leads to reduced number of setups on the shop floor and helps to achieve short lead times (Blecker and Abdelkafi 2006d).

In addition, several other approaches have also been proposed for effective implementation of mass customization. According to Tersine and Tersine (2005), to effectively manage the variety and customization, in-house reengineering should be initiated, with the purpose to flatten bills of material, simplify designs, standardize components, and grouping components into families. Overall, the product modularity influence the way in which customer orders are processed and completed: it facilitates the customer involvement and provides the background to implement order fulfilment strategies for mass customization.

## 1.3 MASS CUSTOMIZATION IN SMEs

Mass customization has been emphasized as a viable business strategy for SMEs to increase their growth and profitability (Ismail et al. 2007). However, in operations management literature, the research on mass customization has been mostly geared towards large enterprises where different generic classifications, order fulfilment models, and capabilities have been discussed for its implementation (see, e.g., Lampel and Mintzberg 1996; Duray et al. 2000; Duray 2002; MacCarthy, Brabazon, and Bramham 2003; Salvador, De Holan, and Piller 2009). In particular, Salvador, De Holan, and Piller (2009) identified three fundamental capabilities for successful implementation of mass customization:

i) *solution space development:* identifying the attributes along which customer needs diverge;

ii) *robust process design:* reusing or readjusting existing organizational and value chain resources to fulfil a stream of differentiated customer needs;

iii) *choice navigation:* supporting customers in identifying their own solutions while minimizing complexity and the burden of choice.

For successful implementation of mass customization, these generic capabilities are essential for both large enterprises and SMEs but they may differ in the way these capabilities are developed and maintained (Taps, Ditlev, and Nielsen 2017). With low sales volume and limited organizational resources (i.e., factors that are relevant for SMEs), implementing mass customization poses many challenges (Brunoe and Nielsen 2016). In particular, without proper guidance, SMEs often embark on a strategy of offering customers more choice without considering its impact on their operational performance (Ismail et al. 2007). It is then inevitable that product variety increases which in turn increases the complexity in products and

production process. This variety-induced complexity could be detrimental to a company (for both SMEs and large enterprises) if not dealt with appropriately (Piller et al. 2003). To this end, Brunoe and Nielsen (2016) emphasized the need to develop methods and capabilities for complexity management which can be easily applied in the specific context of SMEs where the volume-variety relationship is much different than large organizations. Notwithstanding the clear interest as well as the different characteristics among large enterprises and SMEs, implementation of mass customization in SMEs is still partially covered: in their literature review, Taps, Ditlev, and Nielsen (2017) found that only a small portion of research (less than 40 publications) directly or indirectly focused on mass customization in SMEs. Although mass customization has been investigated mostly for large enterprises, some generic difficulties and challenges of mass customization can be identified that are relevant both for large enterprises and SMEs. Next section provides some of the difficulties and challenges that companies face due to high variety in mass customization production environments.

## 1.4 CHALLENGES OF HIGH VARIETY

Mass customization brings many challenges both for large enterprises and SMEs. The major challenge is the increase in product variety which induces complexity (Hu et al. 2008; Zhu et al. 2008; Brunoe and Nielsen 2016). In particular, with increasing product variety, complexity is brought into operations and at the shop floor level. In fact, the complexity of the scheduling function increases due to frequent product changeovers (i.e. due to reduction in the volume of production lots), more routing alternatives on the shop floor, larger volumes of work-in-process (WIP) inventories etc. (Blecker and Abdelkafi 2006b). Besides, the complexity increases further due to the predictable and unpredictable changes occurring in the internal and external environment of the manufacturing systems. A change can be considered predictable if it can be identified before its occurrence and a plan can be prepared in advance to cope with it at the time of occurrence. An unpredictable change arises due to the lack of knowledge regarding some characteristics of the source of change prior to occurrence (e.g. time and place of occurrence, extent of resulting change etc.), hence it cannot be fully planned: a situational response is required to address it effectively.

High variety manufacturing system are prone to different kinds and sources of unpredictable change. The sources of unpredictable change could be related to upstream (i.e. supply-side), internal operations including control processes, or downstream (i.e. customer side) (Frizelle, McFarlane, and Bongaerts 1998; Leitao and Francisco 2004). The unpredictable

changes induce further complexity in the manufacturing system and affect its usual operation and stability leading to poor performance (Leitao and Francisco 2004; Bozarth et al. 2009; Dewa et al. 2014) and are mainly referred as disturbances. Indeed, the manufacturing systems of the companies operating in high variety manufacturing environments – such as mass customization production – face many unexpected changes and disturbances at shop floor level leading to a deviation from the usual operations and stability (Barroso, Machado, and Cruz Machado 2008). The arrival of customer orders is highly stochastic leading to unexpected changes in order priority (i.e. rush orders), quantities, and product specifications (Zhong, Li, et al. 2013; Zhong, Dai, et al. 2013). In particular, the introduction of rush orders implies re-scheduling which sometimes leads to temporal conflicts with other already allocated work orders (Leitao and Francisco 2004). Moreover, in high variety manufacturing environments, the customer orders may vary in terms of their composition of different product models that need to be produced and coordinated for final delivery. Apart from demand-side disturbances, internally companies face variations in their plans and schedules owing to the stochastic operations times of different product models that are difficult to estimate (Zhong, Dai, et al. 2013; Dietrich, Kirn, and Sugumaran 2007) and the disturbances in planned capacity (e.g. unavailability of labour and machine breakdown) that are difficult to predict. In particular, the machine breakdown and unavailability of labour lead to decrease in production capacity with adverse impact on throughput (Leitao and Francisco 2004). Last but not least, late component deliveries due to unreliable suppliers create instability on the production shop floor with a negative impact on schedule attainment as the delay causes the need to re-schedule all production orders related to the delayed purchased order (Bozarth et al. 2009; Pujawan and Smart 2012).

Depending on the frequency of occurrence, the sources of unpredictable changes can be categorized as: i) those that occur repetitively, as part of the business routine, but with largely unknown parameters; and ii) those that occur randomly without any specific pattern (Birkie 2015). Figure 4 provides the categorization of all sources of change based on their frequency of occurrence and predictability of change.

Frequency of occurrence

| | Recurring/repetitive | Random/non-repetitive |
|---|---|---|
| **Predictable** | I | IV |
| **Unpredictable** | II | III |

Figure 4 Categorization of sources of change in manufacturing environments developed from (Birkie 2015)

As depicted in figure 4, each quadrant represents a different type of change and uncertainty.

- In Quadrant I, those sources of change are considered which occur repetitively as part of business routine and their probabilities of occurrence and parameters (i.e. time, place, and extent, etc.) can be estimated. These changes can be planned in advance e.g. advanced planning to address day-to-day and seasonal demand in mass production environments (Birkie 2015).

- Quadrant II represents those sources of change and uncertainty which occur repetitively as part of business routine but with largely unknown parameters (e.g., time and place of occurrence, intensity of change etc.). These changes cannot be fully planned in advance and they mostly require situational knowledge and response depending on their time and place of occurrence and intensity of change. An example of unpredictable but repetitive change is the rush orders that require response based on the current conditions (at the time of occurrence) of the manufacturing system as well as the characteristics (i.e. intensity) of the rush order (e.g. quantity etc.).

- Quadrant III represents those sources of change and uncertainty which occur randomly without any specific pattern and thus cannot be predicted. Unavailability of components at a manufacturing plant due to supply chain disruptions caused by random event such as a strike, earth quake or flood, a typical example of an unpredictable change that seldom occurs.

- Quadrant IV represents those sources of change which occur randomly but can be predicted (i.e. assessed) and planned in advance for proper management. An example of a source of

predictable but random change could be a workplace accident (e.g. slips, trips, or falls) that can be addressed by established risk management processes.

Different streams of literature have provided different solutions. Predictable and repetitive changes (quadrant I) have been mostly addressed in lean manufacturing literature where focus has been on implementing lean practice bundles to reduce variability and to improve performance in relatively stable business environments (Shah and Ward 2003, 2007). Risk management literature addresses non-repetitive but predictable changes (quadrant IV), where a proper risk management process can be established for each potential source of change (Amandus et al. 2012). The unpredictable and non-repetitive changes (quadrant III) have been mostly addressed in operational resilience literature (Ponis and Koronis 2012; Bhamra, Dani, and Burnard 2011; Ponomarov and Holcomb 2009).

This research focuses on the sources of unpredictable changes which occur repetitively (Quadrant II). The unpredictable and repetitive changes are hereinafter referred to as 'recurring disturbances'. In fact, based on the definition proposed by Matson and McFarlane (1999), this research considers recurring disturbance as an unpredictable change occurring repetitively in the internal or external environment of a manufacturing system, which can affect its operational performance, and is either outside its control or has not been fully planned by the system. Building on the work of Matson and McFarlane (1999), following recurring disturbances can be found in high variety manufacturing systems:

- recurring disturbances outside the control of a manufacturing system such as variations in customer demand (i.e. volume, mix, rush orders, and cancelled orders etc.) (Zhong, Dai, et al. 2013; Zhong, Li, et al. 2013; Leitao and Francisco 2004), unreliable supplier delivery (Bozarth et al. 2009; Pujawan and Smart 2012), power failures (Matson and McFarlane 1999);

- recurring disturbances within the control of a manufacturing system (i.e. changes which have not been planned, yet manufacturing system has some degree of control over them) such as schedule instability (Bozarth et al. 2009; Zhong, Dai, et al. 2013; Dietrich, Kirn, and Sugumaran 2007), operator, planning and communication errors (Matson and McFarlane 1999; Leitao and Francisco 2004), unavailability of labour and equipment/machine breakdown (Saad and Gindy 1998; Matson and McFarlane 1999; Leitao and Francisco 2004).

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These recurring disturbances induce complexity in the production and, if not properly managed, adversely affect the overall performance of the manufacturing systems. Nevertheless, in order to compete and to achieve responsiveness, high variety manufacturing companies, particularly mass customization SMEs, need methods and capabilities to make balanced and rapid responses, while considering the dynamics of recurring disturbances (i.e. same type of disturbance can occur at different times, different places, and with different intensity). Next section provides literature on responsiveness specifically in relation to disturbances.

## 1.5  THE NEED AND THE PURSUIT OF RESPONSIVENESS

The new manufacturing paradigm (i.e. mass customization) brought new challenges, while companies were not fully prepared for the uncertain context that was being shaped by highly demanding customers and global competition (Monckza and Morgan 2000; Pagell 2004). The existing manufacturing systems were designed for stable environment as in the case of mass production and most of them worked on efficiency and productivity. With new dynamic requirements, the management of manufacturing operations became difficult as companies were required to produce large number of customer-chosen products in small quantities with little time and cost penalty (Åhlström and Westbrook 1999). In this new scenario, responsiveness emerged as an important requirement to achieve competitive advantage (Matson and McFarlane 1999; Holweg 2005; Reichhart and Holweg 2007)

The early debate about responsiveness was focused on the concept of "time-based competition" (George Stalk 1988; Bower and Hout 1988; Stalk Jr. and Hout 1990) that underlined the necessity to quickly react to customer needs, speeding up both the new product development process and the order fulfilment process (Hum and Sim 1996). Later on, the debate enlarged the scope, considering competitiveness based on the capabilities to react to all kinds of changes rapidly and cost-effectively (Koren et al. 1999). In particular, changing demand and market needs have been emerging as relevant issues, as remarked by Holweg (2005) in his definition of responsiveness: "the ability to react purposefully and within an appropriate time-scale to customer demands or changes in the marketplace, to bring about or maintain competitive advantage." Reichhart & Holweg (2007) emphasized that responsiveness should be considered as a concept which is solely customer focused. Accordingly, they define responsiveness as "the speed with which the system can adjust its output within the available range of the four external flexibility types: product, mix, volume, and delivery, in response to an external stimulus". Here, product flexibility describes the ability to introduce new products

or changes to existing products. Mix flexibility is the ability to alter the product mix (within the existing product range) that the system delivers. Volume flexibility is the ability to change the system's output and delivery flexibility is the ability to alter delivery dates e.g. shortening manufacturing lead times. These four external flexibility types were originally conceived by Slack (1987), whereas Reichhart & Holweg (2007) maintained that these are the only external flexibility types that a customer might be interested in.

Previously, in operations management literature, much of the research on responsiveness was focused on defining responsiveness as a concept and the potential benefits it can yield; while little attention has been paid to the operational requirements for responsiveness. Only few studies can be found that explained how responsiveness can be actually achieved at operational level, particularly in relation to disturbances. In this regard, one important contribution is by Matson and McFarlane (1999) where the authors developed an audit tool to assess the responsiveness of existing production operations. The authors emphasized that the concept of responsiveness is relevant to disturbances as they affect the operational performance. Responsiveness is required both to guard against the negative effects of disturbances and to exploit the opportunities created by disturbances. They define production responsiveness as 'the ability of a production system to achieve its operational goals in the presence of supplier, customer, and internal disturbances.' To achieve responsiveness, Matson and McFarlane (1999) identified three types of capabilities: recognition capabilities, flexibility and buffer based plant capabilities, and decision making capabilities. More specifically, they emphasized that, to achieve responsiveness, disturbances and operating conditions must be recognized and evaluated effectively; and appropriate decisions should be made regarding the use of the available flexibilities and buffers in the face of disturbances. The use of buffers and flexibilities has also been discussed in relation to variability in general by Hopp and Spearman (2004). The authors identified three types of buffers: i) inventory buffer (e.g. safety stocks); ii) capacity buffer (e.g. excess capacity); and time buffer (e.g. safety lead times). Although these buffers provide protection against disturbances caused by different kinds of variations, proper decision-making capabilities, joined with recognition capabilities, are required to use the proper mix of buffers when needed, where needed.

Similarly, while focusing on the *order fulfilment process*, Kritchanchai and MacCarthy (1999) argued that companies need specific capabilities to achieve responsiveness, i.e. specific to each type of disturbance. The authors noted that capability in this context is not just a technical ability to respond; instead, it requires the existence of decision making structures that are necessary to use or deploy basic technical abilities (e.g. flexibilities and buffers) for each

type of disturbance. Furthermore, to achieve responsiveness, they emphasized the need to focus on the full order management cycle, including all stages of planning and processing up to receipt of an order by the customer.

Later on, several authors have investigated responsiveness, with a particular focus on decision making mechanisms (see, e.g., Ramirez-campos et al. [2006]; Michalos et al. [2016]). These studies emphasized the need to use specific algorithm and control logic for decision-making regarding disturbances. The use of algorithm and control logic help to determine the adjustments 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 for a better exploitation of the flexibility potential of the manufacturing resources leading to their better utilization and improved performance.

Although these studies provide interesting insights, further investigation is required. In-depth insights are needed regarding how order fulfilment process is designed and how decision-making processes can be structured along the order fulfilment process while considering the specific requirements of mass customization SMEs. Then, it is required to investigate, in the context of SMEs, how response capabilities can be developed and utilized to make balanced and rapid responses, while considering the dynamics of recurring disturbances – i.e. disturbances may occur at different times, places in relation to the stages in the order fulfilment process, and with different intensity – arising from multiple sources, e.g. customers, suppliers, manufacturing operations. Therefore, based on the background and the identified research gap, the overall question guiding this research is **"how responsiveness in the order fulfilment process can be achieved for successful implementation of mass customization in SMEs?"** The main question is answered by investigating following research questions:

> *RQ1: how an appropriate order fulfilment process for mass customization is designed in SME context?*
>
> *RQ2: how dynamic response capabilities can be developed and utilized to cope with different types of recurring disturbances arising along the order fulfilment process for mass customization in SMEs?*
>
> *RQ3: what is the impact of dynamic response capabilities on the production performance of mass customization SMEs?*

Response capabilities are termed as 'dynamic' ones as they should be capable to cope with the dynamics of recurring disturbances i.e. disturbances can occur at different times, different

places in relation to the stages in the order fulfilment process, and with different intensity. The responses should be dynamic to match with the recurring disturbances as they arise along the order fulfilment process.

RQ1 is answered based on the literature review on mass customization from an operations perspective while considering the SMEs requirements. It leads to the identification of the key elements that are needed to design an appropriate order fulfilment process for mass customization in SMEs.

RQ2 leads to sketch out a framework that can be used to guide the development of the Dynamic Response Capabilities (DRCs). To develop the framework, this research employs a routine-based approach. This research argues that implementing adaptive decision-making routines at different stages in the order fulfilment process lead to higher responsiveness in the wake of recurring disturbances. Thus, based on the reviewed literature, a framework has been proposed that implements Workload Control (WLC) based decision-making routines at different stages in the order fulfilment process for (re)adjustments in workload, capacity, and/or lead time thanks to the exploitation of different flexibilities and buffers existent in the manufacturing system. WLC provides a structured approach to implement adaptive decision-making routines based on proper input and output control logic and rules at different stages in the order fulfilment process. For decision making routines to be effective, it is further argued that they should be supported with proper sensing and readjusting routines. This helps to develop different DRCs, specific to different types of recurring disturbances emerging along the order fulfilment process. The routine-based framework is then tested for its relevance and feasibility with real world case studies.

RQ3 leads to the evaluation of the impact of different DRCs and their underlying adaptive decision-making routines and mechanisms on performance of the manufacturing system in the presence of recurring disturbances. To evaluate the impact on performance, a simulation study is designed in collaboration with a case company. The simulation study replicates the real world scenario into the simulation environment. Different experiments are designed that utilize WLC-based adaptive decision-making routines to generate dynamic/adaptive responses in the wake of recurring disturbances. The results of the simulation experiments are then analyzed and compared to evaluate the impact on the overall production performance.

More insights on the research design and methodologies are provided in Chapter 3.

## 2 LITERATURE REVIEW

### 2.1 ORDER FULFILMENT MODELS AND STRATEGIES FOR MASS CUSTOMIZATION IN SMEs

Mass customization is still evolving as a business strategy, and a range of classification schemes, operational modes, and order fulfilment models have been discussed in literature (see, e.g., Lampel and Mintzberg 1996; Duray et al. 2000; Duray 2002; MacCarthy, Brabazon, and Bramham 2003; Brabazon and MacCarthy 2006; Salvador, De Holan, and Piller 2009).

From an operations perspective, MacCarthy, Brabazon, and Bramham (2003) identified five fundamental modes of operation for mass customization which consider how a firm's operational resources are used, whether or not the design envelope is predetermined, and whether or not repeat orders are anticipated. The modes of operation include: i) catalogue; ii) fixed resource design-per-order; iii) flexible resource design-per-order; iv) fixed resource call-off; and v) flexible resource call-off. Among these, catalogue mode of mass customization is considered as the most common in practice with a particular relevance for companies operating in consumer product markets and Business-to-Business engineered products (Brabazon and MacCarthy 2006). In catalogue mode of mass customization '…*a customer order is fulfilled from a pre-engineered catalogue of variants, produced using standard order fulfilment processes. In this mode the engineering of products is not linked to orders, but completed before orders are received. Customers select from a pre-specified range and the products are manufactured by the order fulfilment activities that are in place. Likewise the order fulfilment activities are engineered ahead of an order being taken'* (MacCarthy, Brabazon, and Bramham 2003).

Within the catalogue mode of mass customization, several order fulfilment models can be considered. Based on the literature review, Brabazon and MacCarthy (2006) identified four order fulfilment models: i) fulfilment from stock; ii) fulfilment from a single fixed decoupling point; iii) fulfilment from one of several fixed decoupling points; iv) fulfilment from several locations, with floating decoupling points.

- *Fulfilment from stock model* resembles closely to postponement where end consumer is not involved in the process but customization is required for a particular region or stock location. The key focus in this model is on stock replenishment to cope with variety without suffering high costs.

- *Fulfilment from a single fixed decoupling point model* is considered as the most common form of catalogue mass customization. In this model, the producer holds stocks of raw

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materials or part-finished products and once an order is received these are taken forward to be completed and delivered to the customer. This model takes the form of traditional order fulfilment strategies such as ETO, MTO or ATO, etc. (discussed in chapter 1 section 1.2.1). Many companies pursuing mass customization opt for ATO fulfilment strategy as it enables to achieve high variety with quick delivery (ElMaraghy et al. 2013).

- *Fulfilment from one of several fixed decoupling points model* considers more than one fixed decoupling points in the production cycle where the stock of raw material or part-finished products is held. Once an order is received it can be allocated to one of the decoupling points where the material from the stock at that point is made available and taken forward to be completed and delivered to the customer. This model takes the form of using hybrid order fulfilment strategies such as MTS/ATO, MTS/MTO, ATO/MTO, or MTS /ATO/ MTO etc.

- *Fulfilment from several locations, with floating decoupling points model* considers allocation of products to orders at any point along the production process. The customizable products are continuously released to production based on forecasts of what customers will order. When the orders are received, the units at different stages in the production are matched to specific customer orders, they are then completed according to specific customer requirements. This type of order fulfilment models are mostly suitable for products with relatively long production lead times (where the requested delivery lead time is less than the sum of purchasing, fabrication and assembly lead times) such as in capital goods sector, machine tools, and automotive industry. The main rational behind the development of this kind of order fulfilment model is to achieve high variety with short delivery lead times by completing some production activities before the order arrives. Different strategies to operationalize this order fulfilment model have been discussed such as build-to-forecast (BTF) (Raturi et al. 1990); virtual build-to-order (VBTO) (Agrawal, Kumaresh, and Mercer 2001; Brabazon and MacCarthy 2004) and make-to-forecast (MTF) (Meredith and Akinc 2007; Akinc and Meredith 2015).

Previously, the suitability of the order fulfilment models for SMEs has not been discussed explicitly in literature. However, a deduction can be made by analysing the structure of the order fulfilment models discussed by Brabazon and MacCarthy (2006), few case studies found in literature that focus on mass customization in SMEs (see, e.g., Svensson and Barfod 2002; Orsila and Aho 2006), and SMEs specific issues such as limited technological resources and close customer interaction (Suzic et al. 2012). From all these sources, it seems the suitable

order fulfilment models for SMEs could be '*fulfilment from a single fixed decoupling point*' and '*fulfilment from one of several fixed decoupling points*'; instead, the '*fulfilment from stock*' and '*fulfilment from several locations, with floating decoupling points*' have their limitations for SMEs. The former doesn't include the end consumer in the process – and with mass customization in SMEs, a higher customer involvement is expected (Suzic et al. 2012; Stojanova, Suzic, and Orcik 2012). The latter requires use of sophisticated technologies to track and match the products with specific customer order – and it is well known that SMEs face difficulties to develop specific competence for low to medium technology (Suzic et al. 2012). Therefore, this thesis considers only two order fulfilment models to operationalize mass customization in SMEs: i) fulfilment from a single fixed decoupling point; and ii) fulfilment from one of several fixed decoupling points.

With '*fulfilment from a single fixed decoupling point*' and '*fulfilment from one of several fixed decoupling points*' models a number of order fulfilment strategies could be considered. Each order fulfilment strategy has its own pros and cons for mass customization.

- As discussed in chapter 1 (section 1.2), the essence of mass customization lies in two key dimensions: i) customer involvement; and ii) modularity (Duray et al. 2000; Duray 2002). Relying on customer involvement and modularity, the ATO fulfilment strategy enables to offer high variety with quick delivery (ElMaraghy et al. 2013). Therefore, for '*fulfilment from a single fixed decoupling point*' model, ATO is a relevant fulfilment strategy to implement mass customization in SMEs. On the other hand, other strategies could be operated as well, but with lower performances with respect to the delivery time, e.g. MTO enables high customization, but it usually exhibits long delivery cycle times and large order backlogs (Gupta and Benjaafar 2004).

- For '*fulfilment from one of several fixed decoupling points*' model, although some cases of a *hybrid strategy* have been discussed in literature in relation to SMEs (see, e.g., Perona, Saccani, and Zanoni 2009), the research in this area is still limited. Most of the research on hybrid strategies is focused on large enterprises with examples such as food processing industry (Chetan Anil Soman, Van Donk, and Gaalman 2004; C. A. Soman, van Donk, and Gaalman 2007), electronics manufacturer (Wei et al. 2010), global manufacturer of agricultural machinery (Köber and Heinecke 2012), and others. As an example in a SME context, the authors, Perona, Saccani, and Zanoni (2009) investigated the inventory planning issues for a hybrid MTO/MTS strategy. The study shows the potential of a hybrid fulfilment strategy for SMEs. However, the research on hybrid fulfilment strategies is still

fragmented and several issues such as factory design, organization of work, production and capacity planning etc. require further investigation to draw any conclusion regarding their implications for mass customization in SMEs. This thesis assumes that a hybrid strategy could be used for mass customization in SMEs; nonetheless, for the sake of research focus, the ATO fulfilment strategy is specifically addressed, considering its high potential for customization with reduced delivery times.

Summarizing, figure 5 provides ATO as the main fulfilment strategy for catalogue mode of mass customization in SMEs, with the use of several hybrid strategies which could be investigated in a separate study for their potential and implications for mass customization in SMEs.
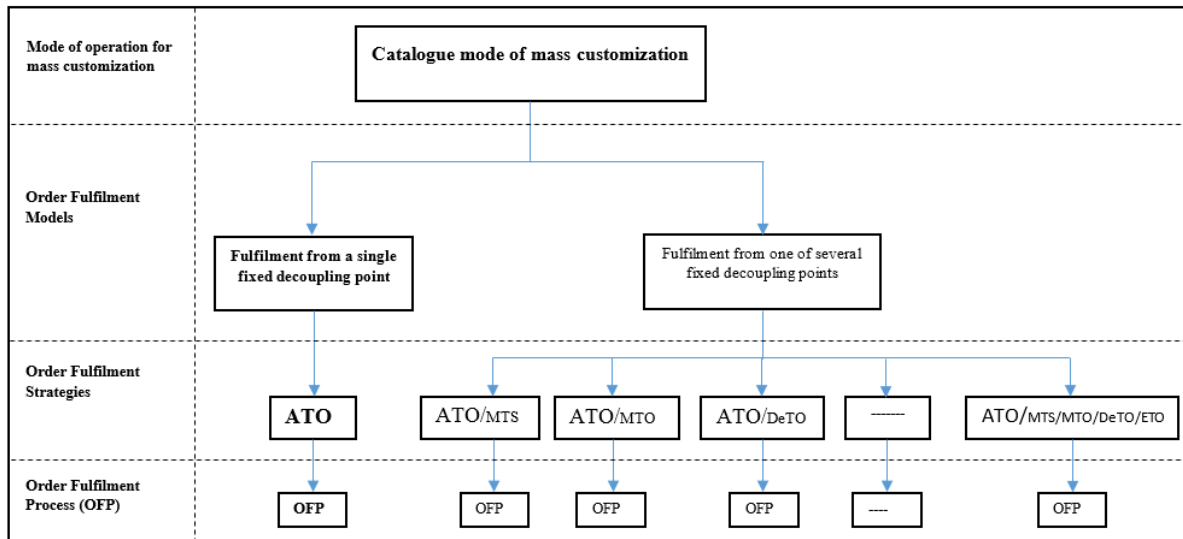


Figure 5 Order fulfilment models and strategies for catalogue mode of mass customization in SMEs developed from (MacCarthy, Brabazon, and Bramham 2003; Brabazon and MacCarthy 2006)

Next section provides discussion on the design of the order fulfilment process for mass customization SMEs considering ATO as the main fulfilment strategy.

## 2.2 DESIGN OF THE ORDER FULFILMENT PROCESS FOR MASS CUSTOMIZATION IN SMEs

For successful implementation of mass customization with ATO fulfilment strategy, an appropriate order fulfilment process needs to be designed in detail. However, from literature it appears that there is no consolidated understanding of what activities should be treated as forming part of the order fulfilment process: in fact, as noted by Brabazon and MacCarthy (2006), 'there is no standard definition of order fulfilment and no common understanding of what activities it involves.' While delineating the order fulfilment process, Brabazon and

MacCarthy (2006) argued that it should encompass not only the *order fulfilment activities* (i.e. material processing/transportation) but also the key elements of *control logic* to plan and prioritize as well as coordinate activities starting from the *order entry stage*. Figure 6 provides the key elements to structure the order fulfilment process.

```
                    ┌─────────────────────────────┐
                    │   Order Fulfilment Process   │
                    └─────────────────────────────┘
                         │                    │
              ┌──────────┘                    └──────────┐
              ▼                                           ▼
   ┌──────────────────────┐       ┌──────────────────────────────────────────┐
   │                      │       │      Order Fulfilment Activities          │
   │    Control Logic     │       │ (e.g. material processing, transportation etc.) │
   │                      │       │                                          │
   └──────────────────────┘       └──────────────────────────────────────────┘
```
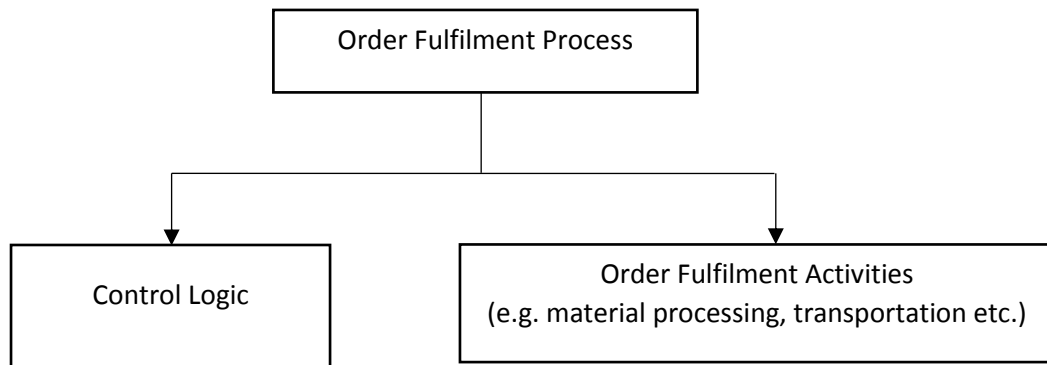
Figure 6 Structure of the order fulfilment process adapted from Brabazon and MacCarthy (2006)

Brabazon and MacCarthy (2006) further argued that one must not confuse CODP with order fulfilment process. With CODP, the upstream activities are usually controlled based on a forecast while the downstream activities are controlled according to the customer orders. However, as the upstream activities can influence the future performance of the downstream activities (e.g. component stock-out in an ATO fulfilment strategy can influence the assembly activities), the order fulfilment process 'cannot be blind to the upstream activities'. Therefore, it is important that the order fulfilment process should have good situational awareness and *control* of both the upstream activities (if the downstream activities are dependent on their performance) and the downstream activities (Brabazon and MacCarthy 2006).

Based on the work of Brabazon and MacCarthy (2006), this research assumes that, to design an order fulfilment process, the production planning method(s) provides the *logic* to plan and control the order fulfilment activities and the production processing technologies dictate how the order fulfilment activities are *structured*. Therefore, they should be configured according to the needs of high variety in the specific context of mass customization SMEs. Next sections provide discussion on the production planning methods and production processing technologies as two key elements (see figure 7) that are relevant to design an appropriate order fulfilment process for mass customization in SME context.
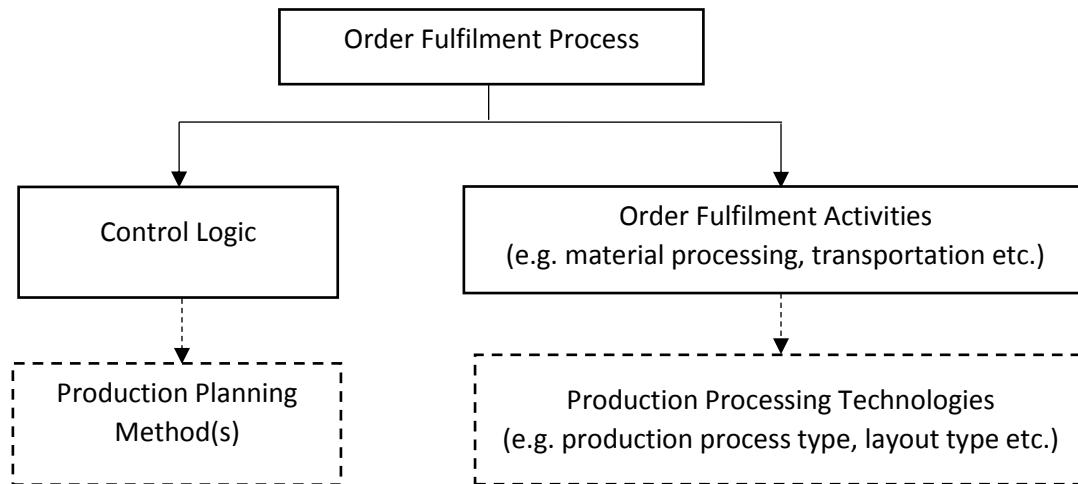
Figure 7 Key elements to design an order fulfilment process developed from Brabazon and MacCarthy (2006)

### 2.2.1 Production planning and control methods

Different production planning and control (PPC) methods have been discussed in literature. The purpose, here in this thesis, is not to perform a comprehensive review on PPC methods as such reviews have been done previously (for details on different PPC methods see e.g. Stevenson, Hendry, and Kingsman (2005)). The main purpose is to identify and elaborate PPC method(s) which can provide the functionality to manage high variety in the specific context of mass customization SMEs. Specifically, considering the definition of order fulfillment process, the PPC methods which provide *logic* to plan, prioritize, and coordinate the *order fulfilment activities* starting from the *order entry stage*.

Based on the literature review of PPC methods, Stevenson, Hendry, and Kingsman (2005) found WLC method as the most effective PPC solution for SMEs operating order-driven strategies (e.g. MTO and/or ATO), mainly due to the following reasons:

i)     it includes the customer enquiry/order entry stage for delivery date determinations and capacity planning;

ii)    it includes job release stages, focusing on due date adherence;

iii)   it provides functionality to cope with non-repeat production, i.e. highly customized products;

iv)    it provides ability to plan and control in the face of variability;

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v)      it is less costly and more practical to implement in SMEs having limited resources.

For a wide overview of PPC methods, the reader should refer to different surveys found in literature such as by Gelders and Van Wassenhove (1981); Zäpfel and Missbauer (1993); and Riezebos, Shambu, and Suresh (1998). These surveys describe different PPC methods and their control logic; however, further guidance is required regarding how the underlying control logic of PPC methods can be embedded in the order fulfilment process to plan, prioritize, and coordinate order fulfilment activities starting from the order entry stage. As WLC method includes customer enquiry/order entry stage, this research further explores its applicability to design an appropriate order fulfilment process for mass customization in SMEs.

### 2.2.1.1   *General overview of Workload control method*

The key idea behind the development of the WLC method is to control the lead time, capacity, and WIP by implementing different input and output control (I/OC) mechanisms at different stages in the order flow, i.e. planning stages within the order fulfilment process also considered as 'stages in the order flow' in some part of the literature.

Little's law (Little 1961) provides the theoretical background to motivate the implementation of different I/OC mechanisms. It is, in fact, well-known that Little's law states that the average number of items either in queue or in service in a system (L) is equal to their arrival rate ($\lambda$) multiplied by the average time spent by items in the system (W) (i.e. $L = \lambda \times W$). The equivalent of Little's law in operations management can be expressed by means of equivalent terms, as capacity, workload, and lead time, e.g. see the expression taken from (Kingsman 2000): Lead time = Workload/Capacity, where Workload is measured as amount of transformation work [items], Capacity is measured as amount of transformation work per time period [items/time], and Lead time is measured in units of time [time]. Other similar expressions, derivable from the Little's law, and assimilated to the one of (Kingsman 2000), can be found in literature, the reader can see, for example, in (W. J. Hopp and Spearman 2011; Nyhuis and Wiendahl 2009). Therein, while the formulation is related to the Little's law, the units of measurement are fitting the specific application of operations management under concern. For example: shop calendar hours (or minutes) are used for lead time related measures such as flow time, throughput time,….; hours or minutes are adopted for WIP; hours/shop calendar hours (or minutes) are used to express the throughput rate as equivalent expression of capacity.

Based on such formulations well established in literature, three I/OC mechanisms can be justified to control the input and output: i) workload adjustment; ii) lead time adjustment; and iii) capacity adjustment. In the remainder, the purpose is not to provide an exhaustive review on specific rules and methods for I/OC, rather an attempt has been made to understand the general concept of WLC approach for simultaneous use of different I/OC mechanisms at different stages in the order flow. Thus, I/OC mechanisms are presented in relationship to the different stages where they are used.

### 2.2.1.2  Input and Output control mechanisms at different stages in the order flow

Three planning stages are typically considered within the Workload control theory: i) order enquiry/entry stage; ii) order release stage; and iii) order dispatch stage.

Each stage is illustrated below together with the I/OC mechanisms proposed within it.

***I/OC at order enquiry/entry stage.*** This stage can be divided in two sub-stages: order enquiry and order entry. *Order enquiry* takes place between a customer making a request for quotation and an order being accepted or rejected. The main aim is to determine whether to accept or reject an order, and if accepted, when to deliver that order (Kingsman et al. 1996). *Order entry* begins with the order acceptance and includes pre-production preparations for confirmed orders, e.g. material arrangements (Thürer, Stevenson, and Silva 2011).

Most of the previous research considers *order entry* stage together with *order enquiry* stage as a single control level that establishes the first important connection between the sales and the production departments. Accordingly, once accepted, the orders wait for release in the pre-shop pool that is usually a database consisting of all the orders already accepted but not yet released to the shop floor. The presence of the pre-shop pool gives certain advantages as it allows to stabilize the WIP on the shop floor and absorbs the unexpected changes and the fluctuations in the incoming customer orders as well as changes in the orders already present in the pool (Oosterman, Land, and Gaalman 2000).

Within the *order enquiry/entry* stage, *workload adjustment* is considered as the key input control mechanism. The main purpose of input control at this stage is to match the demand with the available/planned capacity of the system for a given time period. To regulate the inflow of the work to the system, *workload adjustment* based input control can be operationalized by implementing different limits and norms (such as e.g. maximum limit for the total planned workload) (Hendry, Kingsman, and Cheung 1998; Kingsman and Hendry 2002; Philipoom and Fry 1992; Moreira and Alves 2009). If an order quantity exceeds the limit,

the input workload can be controlled either by rejecting the new orders or by further negotiating with the customers to reduce the order quantity.

Although *workload adjustment* based input control can help to normalize the total workload of the system when demand exceeds the limits, it is less likely that a company will reject an order or part of the order; instead, it is more probable to use mechanisms that increase the outflow of the work from the system. In this regard, *lead time adjustment* and *capacity adjustment* have been emphasized as two important mechanisms for output control at *order enquiry* stage (Kingsman and Hendry 2002; Moreira and Alves 2009; Fredendall, Ojha, and Patterson 2010; Thürer, Stevenson, and Silva 2011). *Lead time adjustment* based output control concerns the due date setting rules to level the demand with available capacity over time (Matthias Thurer et al. 2013). On the other hand, *capacity adjustment* based output control aims to match the required and available capacities in a given time period such that the total workload can be produced profitably and on time (Hendry, Kingsman, and Cheung 1998). Different options for *capacity adjustment* based output control can be considered such as subcontracting the extra load to a third party vendor (Thürer et al. 2014; Thürer, Stevenson, and Qu 2015), using overtime and re-allocating operators between work centers (Kingsman 2000).

*I/OC at order release stage.* Traditionally, this stage is considered as perhaps the most important stage for WLC. It uses different rules and methods to release work orders from pre-shop pool to the shop floor.

To control the input to the shop floor, three types of decisions are considered at *order release* stage: when to release orders from the pre-shop pool; how many orders to release; which orders to release (Fredendall, Ojha, and Patterson 2010). In this regard, two distinct approaches to conceptualize WLC have emerged in literature based on order release methods in job shop environments. The two approaches are the background to develop *workload adjustment* based input control, and they are: i) the probabilistic load oriented manufacturing control (LOMC) approach; and ii) the corrected aggregate load oriented Lancaster University Management School (LUMS) approach. In LOMC approach the total load of a work center 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). In the LUMS approach, the direct and indirect loads of a work center are simply aggregated together (Kingsman, Tatsiopoulos, and Hendry 1989; Hendry and Kingsman 1991). Land and Gaalman (1996) proposed a further extension of aggregate load approach, the corrected aggregate load approach, which divides the load by the

position of a work center in the routing of a job. Thürer et al. (2012) made a further refinement to LUMS order release method. They combined periodic release (based on corrected aggregate load) approach with continuous release approach to avoid starvation at work centers. The new method, as authors call it LUMS COR (Lancaster University Management School Corrected Order Release), is claimed to perform better than purely periodic release and Constant WIP methods in job shop environments.

For output control at this stage, only recently research has emerged which uses *capacity adjustment* based output control among work centers (see, e.g. Thurer et al. 2016). The authors used a method developed by Land et al. (2015) for selective capacity adjustments based on the total planned workload to a certain work center: capacity is adjusted as soon as the total planned load to a center violates a predefined trigger threshold. The authors found that *capacity adjustment* at order release stage significantly improves the performance.

***I/OC at order dispatch stage.*** It is the final stage where the order remains part of the WIP of the shop until it is completed (Stevenson and Hendry 2006). The input control at this stage relates to the workload adjustment in the work centers, done by changing the sequence of scheduled orders. Different priority dispatching rules can be considered to select an order from the queue for processing  (Wein and Chevalier 1992; Ragatz and Mabert 1988). Although dispatching rules play significant role if practiced alone (Melnyk and Ragatz 1989; Ahmed and Fisher 1992), they become less significant when combined with other control levels, e.g. release rules (Ragatz and Mabert 1988). This is mainly because WLC at order release stage keeps the order queues small (Land and Gaalman 1996). Therefore, in the presence of rules at order entry and release stages, simple dispatching rules are considered as sufficient to meet the due dates (Thürer, Stevenson, and Silva 2011). The output control at this stage aims to make small daily capacity adjustments by reallocating workers and allocating overtime as needed (Fredendall, Ojha, and Patterson 2010).

Table 2 provides a summary of the representative papers discussing the operationalization of the I/OC mechanisms, classified according to the stages in the order flow. The table aims to make explicit the mechanisms – i.e. workload adjustments, lead time adjustments, and capacity adjustments (Kingsman 2000) – used to operationalize the input and output control at different stages in the order flow.

Table 2 Operationalization of I/OC at different stages in the order flow

| Stages in the order flow | Operationalization of input control | References | Operationalization of output control | References |
|---|---|---|---|---|
| Order enquiry/ entry stage | Workload adjustments: order rejection or negotiations with customers using pre-established maximum planned workload limit | (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-allocating operators between workstations or allowing overtime to be worked or allowing both options | (Hendry, Kingsman, and Cheung 1998), (Kingsman 2000) (Kingsman and Hendry 2002) (Thürer et al. 2013) |
| | | | Lead time adjustments: pre-established rules for due date setting | |
| | | | Capacity adjustments: pre-established rules for subcontracting when demand exceeds the capacity | (Thürer et al. 2014), (Thürer, Stevenson, and Qu 2015) |
| Order release stage* | Workload adjustments: considering the condition that the sum of deviations from aggregate balance of each machine centre is reduced | (Bergamaschi et al. 1997) | Capacity adjustments: capacity flexibility to avoid / reduce queues (only mentioned) | (Henrich, Land, and Gaalman 2004) |
| | Workload adjustments: 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: considering pre-shop pool sequencing and selection of orders | (Thürer et al. 2015) | | |
| | Workload adjustments: 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: reallocating workers and allocating overtime as needed (only mentioned) | (Breithaupt, Land, and Nyhuis 2002), (Fredendall, Ojha, and Patterson 2010) |

*For more detail on workload adjustment based input control at order release stage see the excellent reviews by (Wisner 1995); (Land and Gaalman 1996); (Bergamaschi et al. 1997); (Sabuncuoglu and Karapınar 1999) and (Fredendall, Ojha, and Patterson 2010)

As it can be seen in Table 2, at order entry stage workload adjustment is used for input control, while lead time and capacity adjustments are used for output control. At order release stage, the major research focus has been on workload adjustment based input control and different methods and rules have been proposed to support three types of input control decisions: when to release orders from the pre-shop pool; how many orders to release; and which orders to

release (Fredendall, Ojha, and Patterson 2010). It is only recently that Thurer, Stevenson, and Land (2016) studied the impact of integrated input and output control at this stage. The authors operationalized output control through selective capacity adjustments where the capacity is adjusted as soon as the planned load to a workstation violates a predefined trigger threshold. The authors found that capacity adjustments at order release stage significantly improve the performance. Similarly, at order dispatch stage, some authors propose to use capacity adjustment based output control by reallocating workers and allocating overtime as needed.

On the whole, the developments in WLC literture show the potentials of I/OC mechanisms, implemented along the order flow, to enable adaptive decision-making, i.e. to (re)adjust planned workloads, capacities and/or lead times, which finally fits to the need of desiging and developing a responsive order fulfilment process in mass customization SMEs facing recurring disturbances. As it is also practical to implement in SMEs having limited resources (Stevenson, Hendry, and Kingsman 2005), WLC appears a relevant solution to design a responsive order fulfilment process in such enterprise context.

### 2.2.2 Production processing technologies

Production processing technologies concern the way in which the order fulfilment activities are carried to process and complete the customer orders. From a volume-variety perspective, it mainly relates to two choices: i) production process type; and ii) layout type (Britton and Torvinen 2013). Although equipment type may also influence the way in which customer orders are processed and completed, their discussion is beyond the scope of this chapter. This study focuses on ATO fulfilment strategy for mass customization in SMEs where the *assembly activities* are usually performed manually by highly skilled workers (Spena et al. 2016). Therefore, the discussion in this section is limited to the choice of the production process type and layout type and their link to product variety and volume in the specific context of mass customization SMEs (with high variety and low sales volume as the key distinguishing factors for SMEs). In this regard, based on the literature review, different possible configurations of production process and layout that are suitable to structure the order fulfilment activities under ATO fulfilment strategy for mass customization in SMEs are considered.

#### 2.2.2.1 Production process types

In general, the design of the order fulfilment process requires a careful selection of the production process type to carry out order fulfilment activities. A production process is considered as a sequence of activities that transform the inputs into useful outputs. With ATO fulfilment strategy for mass customization (as the main scope of this thesis), the customer

orders are fulfilled by carrying out the assembly activities according to each customer's specific requirements. Thus, a careful selection and design of the production process, as *assembly*, is important to design an appropriate order fulfilment process under ATO fulfilment strategy.

Different production process types have been discussed in literature. Production processes are defined by the volume and variety of products they process and are classified into five major types: i) project processes; ii) jobbing processes; iii) batch processes; iv) mass processes; and v) continuous processes (Miltenburg 2005; Britton and Torvinen 2013; Slack, Alistair, and Johnston 2013). Figure 8 provides different production process types and their relationship with volume and variety.
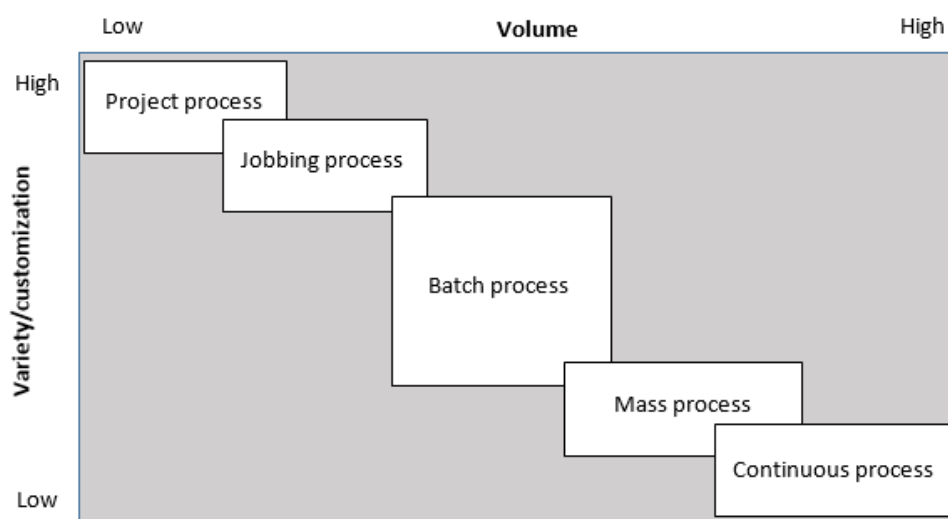


Figure 8 Production process types based on volume-variety characteristics adapted from (Miltenburg 2005; Slack, Alistair, and Johnston 2013; Britton and Torvinen 2013)

- Project process is used to produce one-off, complex, and large-sized products with high work content. Every product is produced as a unique project with predefined quality, cost, and time objectives. Because of high customization many different types of skills have to be coordinated. Manufacturers of large-sized products, such as ships, generally use project process to carry out their production activities. Although project process enables high customization, it is not feasible to produce products in low to medium volume as each product need to be handled as a unique project with long production time. Project process is suitable with ETO fulfilment strategy to produce one-off products (Yang 2013).

- Jobbing process is used when a high variety of products need to be produced in very small quantities (i.e. low volume). Products are highly customized and almost every product require different set of tasks with low repetition (Porter et al. 1999). The main concern in jobbing processes is that each product has to share the operation's resources with many others. Although each product require similar attention, they may differ in their exact needs

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(Slack, Alistair, and Johnston 2013). Jobbing process works best for customized orders where resources can be allocated to complete different orders sequentially. Each work order or job visits the allocated work center(s) where the skilled jobber, or team, complete the required operations. Jobbing process is suitable with MTO and/or ATO fulfilment strategies where different customer orders require different products and different set of tasks with low repetition (Britton and Torvinen 2013).

- Batch process is used to produce products in medium to high volume and relatively low variety (lower than for jobbing process). The main concern in batch process is that each time it produces more than one item at a time. This implies that, when processing a batch, each part of the process has periods when it is repeating itself (Slack, Alistair, and Johnston 2013). Each batch has to share the operations resources with many other batches, thus on surface it may look like jobbing process (especially with small size batches). However, if the batches are large, batch processes can be fairly repetitive (more than jobbing process). Because of this, batch production processes are more suitable for high variety manufacturing environments with repeating demand requiring specialized and narrow skills, i.e. limited to a product family. The application of batch production processes have been particularly emphasized for manufacturing SMEs operating MTO and/or ATO fulfilment strategy (Britton and Torvinen 2013).

- Mass processes, also considered as line processes, are suitable for products with high volume and relatively narrow variety. The variety is limited to only few product models that are fundamentally different than each other requiring significant changes in the basic process of production (Slack, Alistair, and Johnston 2013). Products are usually standard with repeating demand that can be easily predicted. This kind of production process requires a narrow skill set and specialized equipment. Although, setup and change over times are large but they become almost negligible compared to the production run time as few setups are planned. Mass production process is suitable for DTO fulfilment strategy with standard products (Britton and Torvinen 2013). The most prominent example of this type of production process can be found in automobile plants where a single assembly line produces several product variants in large volumes.

- Continuous flow processes are suitable for products with extremely high volume and low variety (often limited to one product). These kind of processes require specialized skills and technology and often come with high initial capital investment. There are only few

change overs but due to high automation it is difficult and expensive to start and stop the process.

As the scope of the thesis is related to mass customization SMEs operating an ATO fulfilment strategy, the relevant production process types for *assembly activities* are jobbing process and batch process as they both enable to produce product variety in low to medium volume. Although project process enables high customization, its application in high variety manufacturing environments is limited: the project process enables small scale production of one-off products (Yang 2013); while under ATO fulfilment strategy for mass customization – which is the focus of this thesis work – several product variants need to be produced in small volumes with repeat demand. Similarly, mass processes and continuous flow processes are not considered due to the reason that they are meant for low variety and high volume production environments where production is mostly driven by a forecast.

### 2.2.2.2 Layout types

Depending on the production process type, different layout types can be considered to carry out the order fulfilment activities. Layout considers the relative positioning and physical arrangement of all resources within a facility and the allocation of tasks to the resources, which together dictate the flow of information and materials through the operation (Slack, Alistair, and Johnston 2013). Previously, four basic layout types have been discussed in manufacturing and operations management literature: i) fixed position layout; ii) functional or process layout; iii) cell layout; and iv) product or line layout (Slack, Alistair, and Johnston 2013; Britton and Torvinen 2013). Much like production process type, the choice of layout type also depends on the volume and variety characteristics of the product (or group of products). Figure 9 provides different layout types and their relationship with volume and variety.
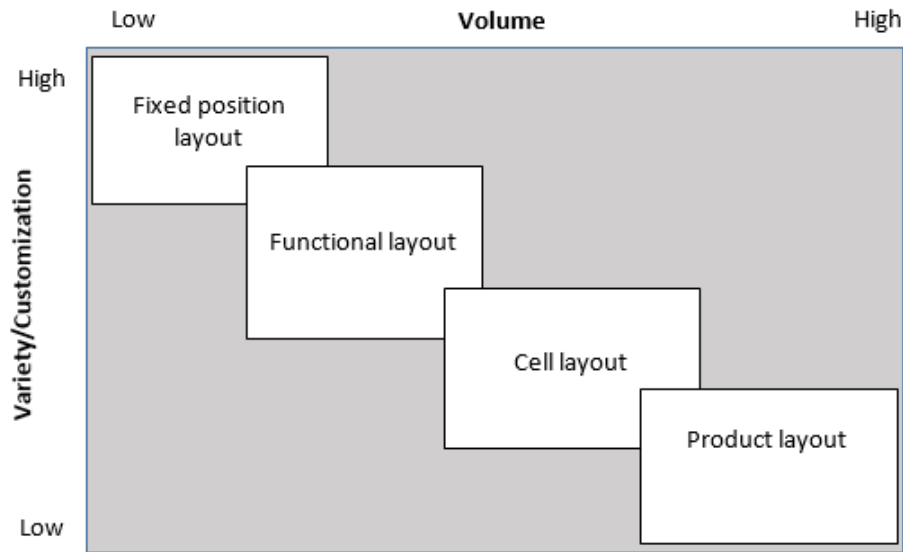
Figure 9 Layout types based on volume-variety characteristics adapted from (Britton and Torvinen 2013; Slack, Alistair, and Johnston 2013)

- Fixed position layout is appropriate for high variety and very low volume production with intermittent flow. In a fixed position layout, products remain at a fixed place while operators move to perform the required operations (in some cases even the operators don't move e.g. fixed position assembly stations with dedicated workers). This type of layout demands high flexibility of resources/operators as they should be able to perform a high variety of tasks on different products. Because many products share the same place/position and resources, it becomes difficult to schedule the space and assembly tasks. Although fixed position layout is more suitable for project processes, it can also be implemented to carry out jobbing and batch production processes (Britton and Torvinen 2013)

- Functional layout is appropriate for high variety and low to medium volume production. In a functional layout, also considered as process layout, all machines performing similar type of operations are grouped at one location i.e. resources are grouped based on similar processes or functions. This type of layout is more suitable for intermittent processing systems and is particularly relevant for batch and jobbing processes (Britton and Torvinen 2013) due to the high variety of products with low production volumes. Depending on the processing needs, different products may follow different flow paths from one functional area to another with the possibility of backtracking. The key objective in a process layout is to maximize efficiency of resources and minimize the movement of material.

- Cell layout is appropriate for medium to high variety (lower than functional layout, limited to several products) and medium volume production. In a cellular layout, also considered

as group layout, different machines are grouped based on the processing needs of a particular product family. In this regard, Group Technology (Burbidge 1996; Lee-Post 2000) enables grouping of products/parts into families based on similar characteristics and provision of resources/machines that can process an entire product family. In this type of layouts, grouping of machines to perform a sequence of operations on a family of similar components or products enables flexibility, i.e. within cell flexibility to perform all the operations on all the product models belonging to that family. In addition, it reduces the production planning time and set-up times for jobs/work orders as, generally, similar products use dedicated cells and resources. Since cellular layouts use dedicated resources for production activities, they can also potentially yield higher productivity (Kannan and Palocsay 1999).

- In a product layout, resources are located according to the processing sequence of the product. The product layout is suitable for high volume production where each product has dedicated machines (i.e. usually machines are not shared by different products) or, in general, resources. Referring to the fabrication phase of the production process, this type of layout typically requires special purpose machines to perform the product specific functions/operations quickly and reliably. Referring to the assembly phase, assembly lines layout were firstly designed for single-models; afterwards there was a trend towards including different product variants, thus leading to the management of multi-models and mixed-models (Bukchin, Dar-El, and Rubinovitz 2002; Zhu et al. 2008), which are solutions that partially increases the variety. In this specific scope, it is worth citing that the product layout has been mostly addressed in relation to automobile industry where one or few fundamentally different car models are produced using an assembly line.

Based on the scope of this thesis, the relevant layout types to carry out *assembly activities* are: fixed position layout, functional layout, and cellular layout. Line or product layout is not considered due to the reason that lines are meant for low variety and high volume production. Although some part of literature discusses assembly lines in relation to product variety (see, e.g. Hu et al. 2011), they are mostly driven by a forecast to produce mindset (i.e. '*fulfilment from stock*' model using an assembly line, see section 2.1) or for large enterprises (e.g., automobile industry) where the volume-variety relationship is much different than SMEs. With ATO fulfilment strategy for mass customization in SMEs, where many different products need to be produced in small volumes according to exact customer requirements, the applicability and the usefulness of the assembly lines appears to be limited.

### 2.2.2.3 Different configuration types to structure order fulfilment activities under ATO fulfilment strategy

Depending on the volume and variety characteristics, different *configuration types* (achievable by linking production process types with layout types) can be considered that are practically viable to structure the order fulfilment activities under ATO fulfilment strategy for mass customization in SMEs.

Based on the discussion in section 2.2.2.1 and section 2.2.2.2, and mainly based on the work of Britton and Torvinen (2013) and Slack, Alistair, and Johnston (2013), six types of configurations can be considered: i) jobbing process with fixed position layout; ii) jobbing process with functional layout; iii) jobbing process with cellular layout; iv) batch process with fixed position layout; v) batch process with functional layout; and vi) batch process with cellular layout. Figure 10 provides different configuration types suitable to structure the order fulfilment activities under ATO fulfilment strategy for mass customization in SMEs.
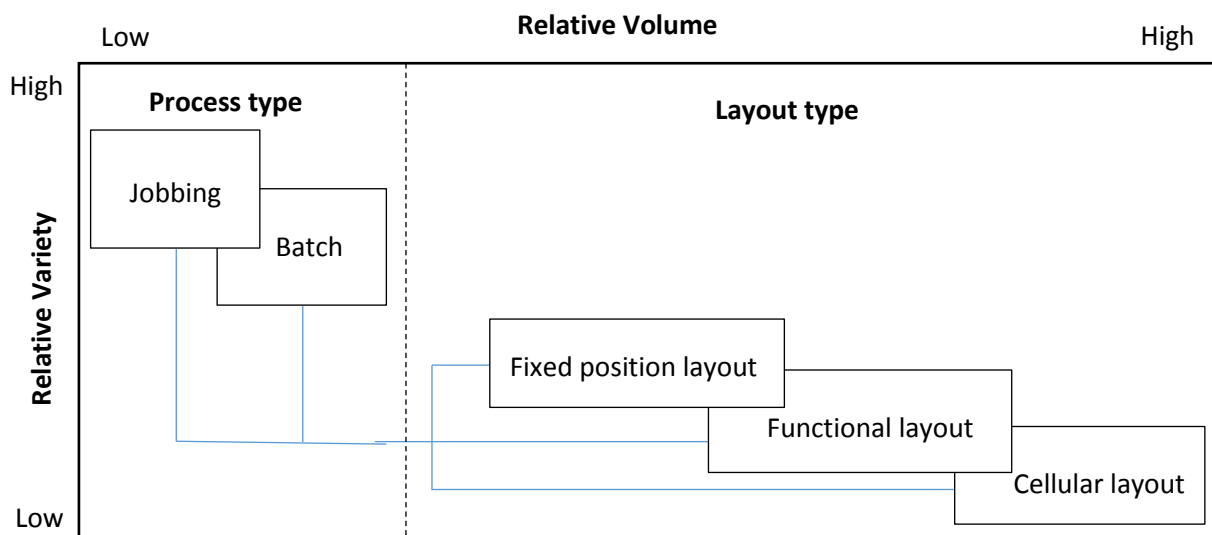


Figure 10 Configuration types relevant to structure the order fulfilment activities under ATO fulfilment strategy for mass customization in SMEs adapted from (Britton and Torvinen 2013; Slack, Alistair, and Johnston 2013)

Manufacturing companies, particularly SMEs operating ATO fulfilment strategy for mass customization, can then implement an appropriate configuration type depending on their relative volume and variety requirements. Indeed, the possible choices in terms of configuration are clearly related to the design of the order fulfilment process as they dictate how the order fulfilment activities are *structured* and carried out.

## 2.3 CONCLUDING REMARKS

Successful implementation of mass customization requires an appropriate order fulfillment process design to meet the differentiated customer needs. How such process is developed and maintained may differ among large enterprises and SMEs. However, previously in operations management literature, most of the research on mass customization is geared towards large enterprises while there is little guidance for SMEs wishing to embark on this journey. With limited resources and low sales volume, implementing mass customization in SMEs poses particular challenges. Without proper guidance, SMEs often embark on a strategy of offering high variety without considering its impact on their operational performance. High variety increases the complexity in products and production. In particular, due to high variety, the manufacturing systems frequently face different types of unexpected changes from multiple sources (i.e. recurring disturbances) which induce complexity in production with adverse effect on their performance. Thus, to support SMEs on their journey towards mass customization, there is a strong need to develop methods and capabilities for complexity management which can be easily applied in the specific context of SMEs.

In this regard, firstly, there is a need to design an appropriate order fulfilment process for mass customization considering the SME specific requirements such as close customer interaction, low sales volume, and limited resources. Second, the order fulfilment process should be designed to cope with recurring disturbances that may arise from multiple sources (e.g. customers, suppliers, internal manufacturing operations) at different times, places in relation to the stages in the order fulfilment process, and with different intensity.

To design order fulfilment process considering SME specific factors, two order fulfilment models with catalogue mode of mass customization are considered as relevant and suitable: i) *fulfilment from a single fixed decoupling point*; and ii) *fulfilment from one of several fixed decoupling points*. These models can be implemented using different order fulfilment strategies. Among all, ATO fulfilment strategy is considered as a relevant and appropriate option as it encompass both the key dimensions of mass customization i.e. customer involvement and modularity. Furthermore, ATO fulfilment strategy enables to offer high variety with quick delivery which makes it more suitable to characterize mass customization in SMEs. Although the potential of a hybrid strategy (with ATO as the dominant strategy) could also be considered to implement mass customization in SMEs, such avenues have not been thoroughly investigated in literature for their implications for SMEs. Therefore, this research focuses on ATO as the main fulfilment strategy and investigates how an appropriate

and responsive order fulfilment process can be designed to implement mass customization in SMEs operating ATO fulfilment strategy. The previous research recognizes that the order fulfilment process should encompass both the *order fulfilment activities* (i.e. material processing/transportation) and the *control logic* to plan, prioritize, and coordinate activities starting from the order entry stage; this research builds on the assumption that the production planning method provides the *control logic* and the production processing technologies dictate how the *order fulfilment activities* are structured and carried out. Therefore, to design an appropriate order fulfilment process, they should be configured according to the needs of high variety in the specific context of mass customization SMEs. Based on the literature review, the production planning method and the production processing technologies have been discussed for their suitability to design an appropriate order fulfilment process while considering the SME specific factors such as limited resources (when selecting the PPC method, it is considered that it should be less costly and more practical to implement in SMEs and it should enable planning of activities starting from the order entry stage) and low sales volume (when selecting the production processing technologies, it is considered that they should enable to produce high variety in low to medium volume). In this regard, firstly, based on the existing surveys on PPC methods found in literature, WLC has been considered as the most suitable PPC solution to design order fulfilment process for mass customization in SMEs. To further understand how the underlying control logic of WLC method can be embedded in the order fulfilment process to plan, prioritize, and coordinate *order fulfilment activities*, a focused literature review has been performed on WLC as a PPC method. Literature shows that WLC method has great potentials for mass customization SMEs as it provides input and output *control logic* at different stages in the order fulfilment process, including the order enquiry/entry stage. Furthermore, it is also practical to implement in SMEs having limited resources. Later on, a literature review has been performed regarding production processing technologies with a particular attention to production process types and layout types. Although equipment type also plays an important role, it has not been discussed in this thesis mainly due to the reason that this study focuses on ATO fulfilment strategy for mass customization in SMEs where *assembly activities* are usually performed *manually* by highly skilled and cross-trained workers. Thus, the research focused on production process type and layout type to evaluate their appropriateness for SMEs to *structure* the order fulfilment activities. Based on the reviewed literature, different configuration types have been considered by linking production process types with the layout types that are relevant for mass customization SMEs to structure the order fulfilment activities.

The choice of the WLC as a PPC method combined with the proper configuration type can then lead to design an appropriate order fulfilment process for mass customization in SMEs. However, even when properly designed, different types of recurring disturbances arising from multiple sources can affect the usual operations and stability of the order fulfilment process leading to poor operational performance. To address recurring disturbances and to achieve responsiveness in the order fulfilment process, this thesis proposes to develop DRCs of the manufacturing system.

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# 3 RESEARCH DESIGN AND METHODOLOGIES

## 3.1 OVERVIEW ON RESEARCH DESIGN AND METHODOLOGIES

Based on the research questions 2 and 3 (see chapter 1, section 1.5), this research has three main objectives: i) to formalize a framework of the DRCs for mass customization SMEs; ii) to verify the relevance and the feasibility of the DRCs framework for mass customization SMEs; and iii) to test the effectiveness of the DRCs for mass customization SMEs. To achieve these research objectives different types of methodological approaches are used during the research phases. Figure 11 provides the overall research framework adopted in this thesis.



**Research Objective 1:** To formalize a framework of the DRCs

| **Methodology**: Routine-based approach to develop operations capabilities | **Outcome**: A routine-based framework of DRCs |

**Research Objective 2:** To verify the relevance and the feasibility of the DRCs framework

| **Methodology:** Deductive case study approach | **Outcome:** Routine-based framework is relevant and feasible for mass customization SMEs to develop DRCs |

**Research Objective 3:** To test the effectiveness of the DRCs

| **Methodology:** Simulation study in collaboration with a case company | **Outcome:** Implementing routine-based framework guided DRCs lead to improved production performance in mass customization SMEs |

Figure 11 Overall research framework

As it can be seen in figure 11, three main research methodologies have been used to achieve the said research objectives. The methodologies include: i) routine-based approach to operations capabilities; ii) deductive case study approach; and iii) simulation study in collaboration with a case company. The justification for the choice of methodologies and their operationalization is discussed in next sections.

## 3.2 Routine-based approach to operations capabilities

The first objective of this research is to formalize a framework that can be used to guide the development of the DRCs in mass customization SMEs. The need to develop the framework arises from the fact that, to achieve responsiveness in the face of disturbances, the operations management literature has long recognized the need to develop specific response capabilities (see chapter 1, section 1.5). However, it requires in-depth investigation regarding how such capabilities can be developed and utilized in a structured way to address recurring disturbances that may arise at different times, places, and with different intensity in the specific context of SMEs where the volume-variety relationship and the amount of available resources is much different than large enterprises.

Capabilities in operations management are mostly studied by assessing the intended or realized competitive operational performance or operational strengths (Boyer and Lewis 2002; Flynn and Flynn 2004; Noble 1995) and different measures such as cost, quality, flexibility, and delivery are used for this purpose. Nonetheless, performance-based approach to operationalizing capabilities is conceptually too aggregated to clearly direct the proper use of manufacturing resources at the shop floor (Swink and Harvey Hegarty 1998). While management scholars have long recognized the importance of operations capabilities in achieving competitive advantage (Hayes and Wheelwright 1984), it is only recently that there is an increasing interest in studying capabilities at plant level where manufacturing capabilities are actually realized (Peng, Schroeder, and Shah 2008). In this regard, recently, the use of Resource-Based Theory (RBT) (Corbett and Claridge 2002) has become increasingly popular in operations management (Hitt, Xu, and Carnes 2016; Hitt, Carnes, and Xu 2016) and different variants of RBT have been proposed, such as routine-based approach (Peng, Schroeder, and Shah 2008) and practice-based view (Bromiley and Rau 2016), to study operations capabilities and performances.

Practice-based view considers the adoption or utilization of specific practices to achieve intermediate or final performance outcomes where practices are 'a defined activity or set of activities that a variety of firms might execute' (Bromiley and Rau 2014). Although practice-based view provides the theoretical basis to study operational performance, it does not concern much with the modelling and the development of the capabilities. In fact, the underlying assumption of practice-based view is that the knowledge about practices is publicly available and all firms can use practices that could benefit them. It does not provide guidance regarding implementation and use of practices to build operations capabilities.

On the other hand, routine-based approach provides theoretical basis to study and model capabilities both at operations as well as strategic level. The routine-based approach to capability originally stemmed from management literature (Amit and Schoemaker 1993; Henderson and Cockburn 1994; Hult, Ketchen, and Nichols 2003; Prahalad and Hamel 1990; G. Stalk, Evans, and Shulman 1992), where capability is considered as a 'bundle of routines' and routines are defined as 'the way things are done or patterns of activities' (Teece, Pisano, and Shuen 1997).

According to Peng et al. (2008) routines are a critical source of operations capabilities. The authors Peng et al. (2008) argued that operations capabilities can be developed by identifying their underlying routines. As shown in figure 12, different micro-foundations provide basis to carry out certain routines and different routines work as a bundle to build the capability. In Fig. 12, 'Routine $n_i$' indicates routine 'n' in capability 'i'. The micro-foundations represent micro-level, observable activities laying the foundations for each routine to be carried out. The micro-level activities can be intentionally implemented to shape certain routines, and different routines can be then integrated to develop the desired operations capability.
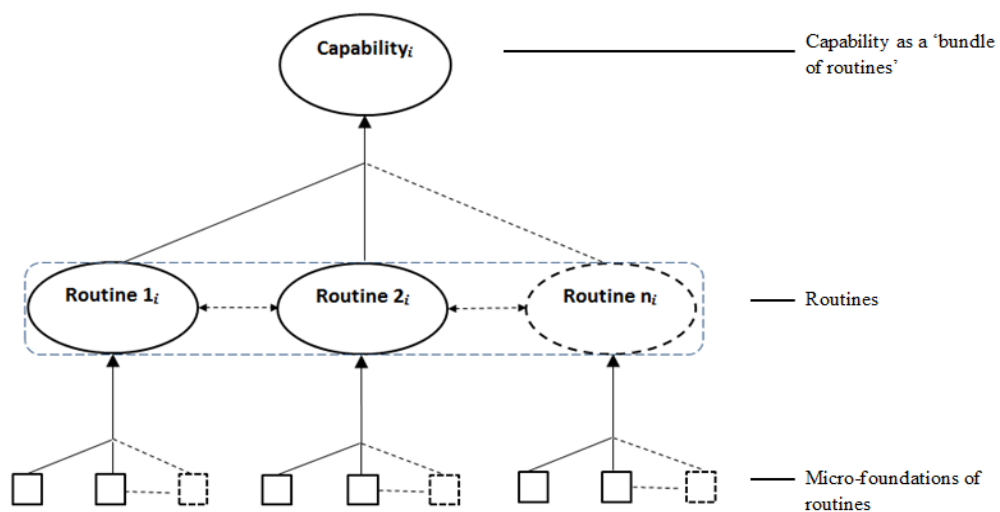


Figure 12 Routine-based approach to build operations capabilities adapted from Peng et al. (2008)

Building on the work of Peng et al. (2008), this research uses the routine-based approach to formalize the framework of the DRCs. Based on the literature review, different routines and their underlying micro-foundational activities are identified that are relevant to generate dynamic responses in the wake of recurring disturbances. The routines and the micro-foundational activities are then formalized in the form of a framework to guide the development of the DRCs.

## 3.3 DEDUCTIVE CASE STUDY APPROACH

After formalizing the routine-based framework of the DRCs, the second research objective is to verify its relevance and feasibility for mass customization SMEs to develop DRCs. This is considered important due to the reason that previously, in literature, there is a lack of understanding regarding how responsiveness can be achieved in practice, particularly in competitive SMEs (Belvedere, Grando, and Papadimitriou 2010). Although literature has provided several definitions of the responsiveness concept and the potential benefits it can yield, there are limited guidelines for manufacturing companies, particularly SMEs, to implement a responsiveness strategy and to build response capabilities (see what already discussed in chapter 1, section 1.5). Furthermore, people in industry may have different meanings and different understandings of the responsiveness concept and the approaches taken to achieve it. Therefore, to verify the relevance and the feasibility of the proposed routine-based framework of DRCs in real world context, a deductive case study approach (Barratt, Choi, and Li 2011) is considered as the appropriate research methodology.

The main purpose of the deductive use of 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 1994). The specific context addressed in this research is that of SMEs operating mass customization strategy and the main hypothesis that this research intends to verify using a qualitative case study approach is that *routine-based framework is relevant and feasible for mass customization SMEs to develop DRCs.* More specifically, the proposed routine-based framework is deemed appropriate if: i) it is relevant for mass customization SMEs to build DRCs; and ii) it is practically feasible for mass customization SMEs to build DRCs by implementing framework specified routines.

In this regard, two SMEs, namely company A and company B, are selected for investigation. While single case could have been enough to confirm or falsify the said hypothesis (Johnston, Leach, and Liu 1999), the choice of two case studies is made to make the research more robust (Barratt, Choi, and Li 2011). Furthermore, in line with the recommendations provided by (Johnston, Leach, and Liu 1999) the cases are selected based on their contextual similarities (i.e. complementary logic). Both the selected SMEs belong to machinery and mechanical equipment sector in discrete manufacturing. Both SMEs operate catalogue mode of mass customization and are particularly challenged by short delivery lead-time (i.e. short according to the contingency of their respective markets). In both cases, the unit

of analysis is the *order fulfilment process* for the main product models produced using an ATO fulfilment strategy. Table 3 provides the main characteristics of company A and company B.

Table 3 Main characteristics of the 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 |

The case studies are carried out by performing several on-site visits of the plants and by using both unstructured and structured interviews with the Plant Managers (operational managers). The interviews were focused on understanding the challenges and difficulties that both the SMEs face in fulfilling customer orders and how they cope with those challenges and difficulties. The literature identifies recurring disturbances as a major challenge that come with high variety in mass customization production environments; thus, the interviews were particularly focused on understanding different kinds of recurring disturbances that both SMEs face in their order fulfilment processes and how they make decisions to adapt in the face of such recurring disturbances. Furthermore, in order to observe the actual working of the plants, the interviews were followed by a visit to different functions of the plants. The observations were particularly focused on the shop floor, where final assembly is performed, in order to understand how supervisors and workers make adaptive decisions when faced with unexpected changes and disturbances. During the visits, the researcher had informal conversations with the personnel on the shop floor and took field notes accordingly. The interviews were transcribed for analysis. Based on the transcribed data and the field notes, the actual process flow was created for each company to identify the recurring disturbances faced within it; moreover, the adaptive decision-making routines implemented at different stages in the order fulfilment process were also identified and studied to understand their operationalization.

## 3.4 COLLABORATIVE PROJECT AND SIMULATION STUDY

After verifying the relevance and the feasibility of the routine-based framework of DRCs with case studies, the next research objective is to test the effectiveness of the DRCs for their impact on production performance of mass customization SMEs. Although both literature and case studies provided support for the development of the DRCs, their usefulness could only be claimed if they lead to improved performance. In other words, developing DRCs is useful and beneficial for mass customization SMEs only if it leads to improved production performance. Thus, to test the effectiveness of the DRCs, the research scope is further expanded into a collaboration with case company A with the purpose to implement a simulation study, thus extending, through simulation experiments, the empirical evidence in the real context.

The main hypothesis that this research intends to test with simulation is that *framework specified routines, implemented to address recurring disturbances arising along the order fulfilment process, lead to higher responsiveness, and overall improved production performance*. Another hypothesis under testing regards the fact that *routine-based framework of DRCs enables guiding the improvement of existing production operations and, subsequently, of production performance in mass customization SMEs.*

The flexibility of the simulation methodology allows modelling real world scenarios (Shafer and Smunt 2004). It essentially requires the active involvement and collaboration of the company personnel to collect the data regarding system variables, information on key management processes, and the constraints of the production system under study. The person from the company who collaborated in this research is currently serving as the Product Manager and looks after the overall plant and the improvement initiatives in the company (in SMEs one person usually have several roles). Besides, he has served for several departments before assuming his current position.

To this end, complete production data for one year is collected from the company in the form of an excel sheet. Production data include number of different product models produced in each month, the number of hours spent, and the number of workers used on the shop floor. Furthermore, the company documents such as production plan and bill of materials are also collected for analysis.

After the initial data collection, a simulation model is developed to represent the actual working of the assembly plant. For simulation purposes 'Plant Simulation' software is used (Bangsow 2016). Different experiments are then designed that consider different WLC-based

adaptive decision-making routines to generate dynamic responses in the wake of recurring disturbances due to demand variability. The data from the simulation experiments is collected in a spread sheet for analysis. Furthermore, to show the usefulness of the proposed approach (i.e. WLC-based adaptive decision-making routines), the results are compared with those of Period Batch Control (PBC) method (Steele 1998). The PBC method has been traditionally advocated as a simple and effective solution for cellular manufacturing. Its characteristics are then aligned with the general need for simple methods in SMEs, as well as with the specific context of company A, where assembly is configured according to cellular layout.

Lastly, during the collaborative project with company A, the routine-based framework of DRCs is used as a guiding tool to verify if it enables improvement of the existing production operations of the company. In this regard, simulation study considers alternative operationalization of WLC-based adaptive decision-making routines in the company. Based on the collected data, an ANOVA is then performed to test the statistical significance of simulation results. Based on the analysis of results, recommendations are then made to improve the existing routines and, subsequently, the responsiveness of the existing order fulfilment process in the company.

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# 4 ROUTINE-BASED FRAMEWORK TO DEVELOP DYNAMIC RESPONSE CAPABILITIES OF THE MANUFACTURING SYSTEM

## 4.1 OVERVIEW ON DYNAMIC RESPONSE CAPABILITIES OF THE MANUFACTURING SYSTEM

To achieve responsiveness in the face of recurring disturbances, it is essential that appropriate decisions are made regarding the use of the available flexibilities and buffers (see chapter 1, section 1.5). These decisions, according to the scope of the thesis (see chapter 2, section 2.1), are made along the order fulfilment process, being them enacted to operate within an ATO fulfilment strategy. Under ATO fulfilment strategy for mass customization, the recurring disturbances can arise from multiple sources, at different times, with different intensity, and at different places in relation to stages in the order fulfilment process: every time a disturbance that significantly affects the existing (planned) production operations arises, effective decision-making regarding the use of the available flexibilities and buffers is then required.

To be effective, decision-making requires implementation of different mechanisms such that every time a recurring disturbance arises it is recognized and (quickly) evaluated for its potential impact on the planned production operations as well as the overall production performance (Matson and McFarlane 1999). More specifically, the mechanisms to recognize, evaluate, and adapt (by using available flexibilities and buffers) contribute to build up the adaptive decision-making (Holm et al. 2014). Indeed, the mechanisms for adaptive decision-making need to be developed for each recurring disturbance according to their frequency, place of occurrence in relation to stages in the order fulfilment process, and the types of flexibilities and buffers that are available in case there is a need to adapt. It requires knowledge (Kritchanchai and MacCarthy 1999) about the recurring disturbance and about the available flexibilities and buffers that can be used to address it. By knowledge it is meant that the recurring disturbance is known to the company as it affects or has the potential to affect the planned production operations while, at the same time, is unknown in regard to when exactly it will affect or how much will be the effect. Furthermore, as recurring disturbances can arise from multiple sources (such as customers, internal operations, and suppliers), multiple recurring disturbances may be known as well, i.e. practically speaking, the most important ones due the contingency of a business context. Such multiple recurring disturbances, regardless of their partial knowledge to a company, have the potential to affect the planned production operations at different stages in the order fulfilment process as intensity, time, and place of occurrence are not exactly controlled.

Two examples are helpful both to reflect on (obvious) challenges induced by recurring disturbances and their partial knowledge, as well as to consider the need for adaptive decision-making according to the specific moment in time when the disturbance(s) arise(s).

- The first example could be rush orders in MTO or ATO production environments. Within an MTO or ATO fulfilment strategy, companies know that a rush order will occur at some point in time but, clearly, it is not known when exactly the individual rush order will occur and how much urgent it will be (i.e. delivery lead time). Forecasting is not enough to characterize such specific type of event for the time being, i.e. at the stage of the order fulfilment process when the rush order arises. Moreover, apart from being difficult to forecast a rush order exactly in time, the reader should remember that SMEs are the target of this study: in practice, forecasting will not be applicable at this stage, as such a "tool" will be hardly available at hands of the SME manager. Henceforth, there is a need of other types of "tools" – i.e. set of mechanisms – to adapt to the current circumstances, thus quickly deciding and readjusting the planned production operations to accommodate the rush order and to achieve the delivery flexibility.

- Another example is the combination of events, which make the situation even more challenging. The demand variability affects at the planning stage while a sudden machine breakdown affects at the processing/execution stage. Such simultaneous occurrence of unexpected events is hard to predict while it can have a multiplicative effect. A response taken at the processing stage will affect the planning stage and vice versa. Although companies know that such unexpected events can occur at different stages in the order fulfilment process but where and when exactly the next unexpected event will occur is not known (i.e. will it be the demand variability, or machine breakdown, or both?). Adaptive decision-making – and related mechanisms – can then be relevant also to contrast the multiplicative effect of different unexpected events (i.e. disturbances).

Overall, it is clear that there is also a lack of knowledge regarding where and when (i.e. the place and time of occurrence in relation to stages in the order fulfilment process) the next recurring disturbance will arise and how much will its effect be on planned production operations. In order to deal with this uncertainty, this research proposes to develop DRCs of the manufacturing system defined as *the ability of a manufacturing system to (re)adjust its planned operating routines (i.e. planned capacity, lead time, and workload) in the wake of customer, supplier, and internal disturbances to achieve its operational goals*. DRCs are then developed by implementing adaptive decision-making routines.

## 4.2 THE ROUTINE-BASED FRAMEWORK OF DYNAMIC RESPONSE CAPABILITIES

This research employs a routine-based approach to develop the DRCs of the manufacturing system. In this regard, a routine-based framework of the DRCs is proposed. Indeed, the thesis postulates the DRCs framework based on the, previously recognized, need to develop specific response capabilities to address disturbances (discussed in chapter 1, section 1.5) while adopting a routine-based approach to build operations capabilities (discussed in chapter 3, section 3.1). Thus, the framework results from two main actions:

i)      identification of the routines essential to generate dynamic and adaptive responses in the wake of recurring disturbances

ii)     identification of the mechanisms required to implement the routines in a structured way, i.e. mechanisms fulfilling the requirements to effectively operationalize such routines and, thus, the dynamic and adaptive responses in the wake of recurring disturbances

Based on the previous general discussion (and, as a methodological background, the routine-based approach to operations capabilities), this research builds on the following concepts and their correspondent meanings:

- *Routine* is an activity or set of activities that are performed after every certain period of time i.e. repeatedly;

- *Planned operating routines* are the activities or set of activities that a company plans to carry out its production in the short term; in particular, it is a short term plan for capacity, lead-time, and workload to achieve the production objectives (e.g. a weekly production plan where the capacity, time, and workload are specified to guide the production activities);

- *Adaptive-decision making routine* is an activity or set of activities to recognize and evaluate the disturbances in planned operating routines and to readjust the planned operating routines by using buffers and flexibilities to achieve the production objectives.

An example of an adaptive decision-making routine could be a daily end-of-the-day review of the production progress in a manufacturing plant to *recognize* any deviation from what was actually planned for the day and to *evaluate* its impact on the delivery schedules. In case the recognized deviation affects the planned operating routines (i.e. delivery schedules cannot be achieved due to the recognized deviation), *readjusting* the planned operating routines is required. Based on the intensity of the deviation, the readjustment would require the use of different available flexibilities and buffers, e.g., allowing overtime (i.e. extra capacity) that was

previously not considered when the actual delivery schedule was created.

That being said, the primary hypothesis of this research is that *adaptive decision-making routines, implemented at different stages in the order fulfilment process, lead to higher responsiveness in the wake of recurring disturbances*. It requires companies to:

1) sense the manufacturing environment to recognize and evaluate the disturbances and current operating conditions (Huang, Zhang, and Jiang 2008; Zhong, Li, et al. 2013; Zhong, Dai, et al. 2013; Matson and McFarlane 1999);

2) adopt appropriate decision-making logic and rules to define the readjustment(s), if needed, of the planned operating routines (Kritchanchai and MacCarthy 1999; Ramirez-campos et al. 2006; Chan, Bhagwat, and Chan 2014; Michalos et al. 2016);

3) (re)adjust the planned operating routines, relying on different types of buffers and flexibilities (W. J. Hopp and Spearman 2011; Wallace J. Hopp and Spearman 2004; Matson and McFarlane 1999).

Although responsiveness literature has long recognized the need to develop decision making structures (Kritchanchai and MacCarthy 1999) to effectively react to disturbances, it is not deeply investigated how such structures can be developed to support decision making. Similarly, few papers, such as (Ramirez-campos et al. 2006) and (Michalos et al. 2016), recognized the need to develop specific decision logic and algorithms to support decision making. Nonetheless, they didn't explain how such logic and algorithms can be embedded in the order fulfilment process in a structured way to generate dynamic and adaptive responses in the wake of recurring disturbances arising from multiple sources. Besides, to achieve responsiveness in the order fulfilment process, the decision making structures need to be developed along the order fulfilment process including also the order entry stage (Brabazon and MacCarthy 2006). Last but not least, the other challenge regards the context target of this study, i.e. SMEs: a method to develop such decision-making structures should fit to this context, thus enabling a practical implementation of adaptive decision-making routines to achieve responsiveness in the wake of recurring disturbances arising along the order fulfilment process.

The literature review regarding WLC is a good source, as already discussed (see section 2.2.1.1 and section 2.2.1.2) for many reasons, and, in particular, in relationship to its potentials of application in SMEs. Indeed, the literature shows that WLC method can help overcome this limitation to develop control logic-based structured decision-making routines. This is in fact the main assumption introduced in this work, deducing from the WLC theory and from the main features of WLC as a production planning and control method. In particular, the I/OC mechanisms of WLC provide a structured approach to implement adaptive decision-making routines that adopt proper rules and logic (sometimes also referred as norms in WLC literature) for (re)adjustments. Moreover, WLC theory explains what to actually adapt and readjust starting from the order entry stage while considering the shop floor conditions; hence it enables to cover the order fulfilment process at large. Specifically, three control mechanisms can be identified in WLC literature to control the input and output: i) workload adjustment; ii) lead time adjustment; and iii) capacity adjustment. When properly implemented, the I/OC mechanisms of WLC enable (re)adjustments in planned workloads, capacities, and/or lead-times, which can then help to address recurring disturbances as they arise along the order fulfilment process. Thus, this research proposes to implement WLC-based decision-making routines, operationalized through the I/OC mechanisms at different stages in the order flow (i.e. planning stages with the order fulfilment process) with the purpose to enable dynamic and adaptive responses in the wake of recurring disturbances.

Figure 13 shows the routine-based framework to develop DRCs of the manufacturing system. As depicted therein, to operationalize decision-making routines, the framework implements WLC-based input and output control: the I/OC mechanisms, when implemented at different stages in the order flow, provide a decision-making structure that adopts proper logic and rules to use the flexibilities and buffers existent in the manufacturing system. It is important to mention that, at each stage in the order flow, the decision-making routines should be supported with proper sensing routines as well as different types of buffers and flexibilities to enable quick and effective (re)adjustments on the shop floor. In next section, the routines and their underlying micro-foundational activities that are needed to develop DRCs discussed.
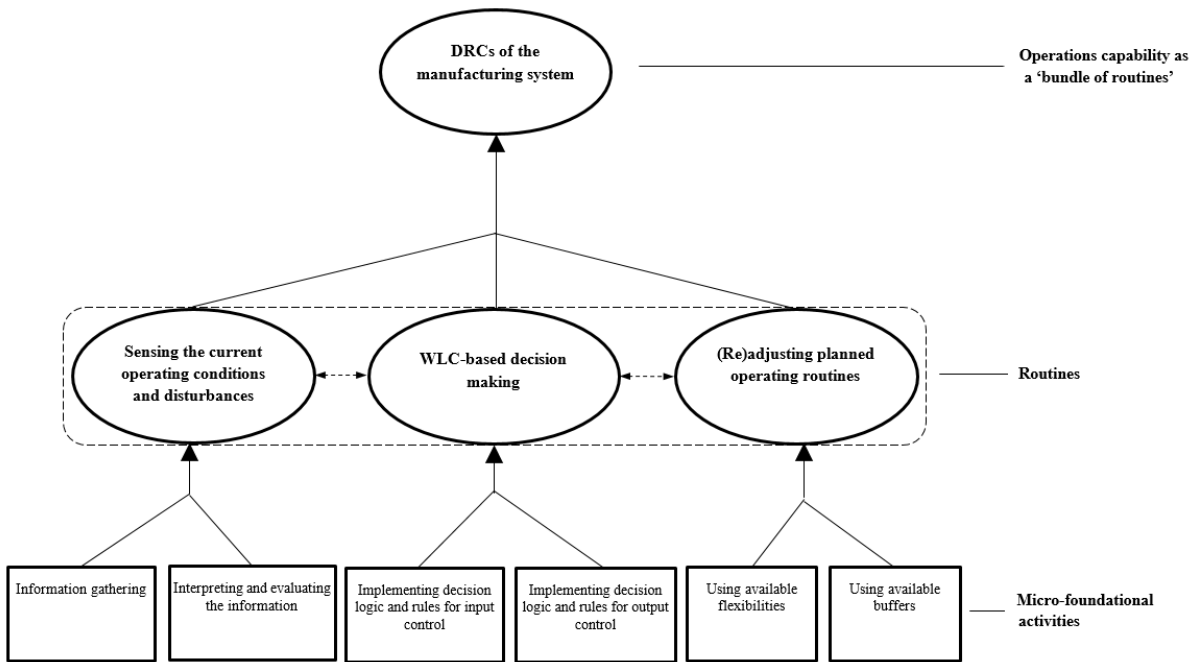
Figure 13 Framework to develop Dynamic Response Capabilities by implementing WLC-based adaptive decision-making routines at different stages in the order flow

### 4.2.1 Sensing the current operating conditions and the disturbances

Sensing routines are concerned with the information gathering, interpretation, and evaluation in regard to the system variables (e.g. material status, resource availability, WIP etc.) that get affected due to a recurring disturbance. Thus, the main goal of sensing routine is to have visibility into the operating conditions to recognise and evaluate the disturbances as they arise from different sources.

Depending on the type of recurring disturbance and its source (i.e. customer, internal, supplier), different routines can be established to track and evaluate the related variables: tracking can be performed either real-time or based on fixed intervals, and can be achieved manually (with paper sheets) or based on the computerization of shop floor operations. A simple example of sensing routine could be the tracking of daily production output at a manufacturing plant to recognize the internal performance variations (i.e. to check if the actual daily output is according to what was planned for the day or there are deviations from the plan). The main purpose here is to recognize internal performance variation as it arises and to evaluate its impact on planned operating routines (e.g. on delivery schedules).

Regarding computerization of shop floor operations, it is worth remarking:

i) the advancements in automatic identification (Auto-ID) technologies with the Barcode and RFID technologies as two important enablers in industrial environments (Baudin and Rao 2005; Gwon et al. 2011; Makris, Michalos, and Chryssolouris 2012; Vyas et al. 2009; Wang, Luo, and Wong 2010; Zhang et al. 2014; Zhong, Li, et al. 2013);

ii) the use of Manufacturing Execution System (MES), to support production operations with detailed scheduling, execution and control, timely information regarding equipment status, material delivery and consumption as well as production progress (Blanc et al. 2008; Saenz de Ugarte, Artiba, and Pellerin 2009).

Indeed, nowadays, and in future trends envisioned also owing to the paradigm of Industry 4.0 (see, e.g., Lee, Bagheri, and Kao (2015); Reinhard, Jesper, and Stefan (2016); Lu (2017)), computerization of shop floor operations plays a significant role in collecting real-time and accurate data. The real-time data capture can provide basis to sense the current operating conditions in order to promptly recognize the disturbances and to evaluate them for their impact on planned operating routines.

### 4.2.2 WLC-based decision making

Once the disturbances are recognized and evaluated to have an impact on planned operating routines, decisions need to be taken to adapt the operating routines according to the newly emerged situation. The decisions should be taken such that they either conserve the overall production performance or enhance it (Ramirez-campos et al. 2006).

The research argues that different decision-making routines, to adapt/readjust the planned operating routines, can be established based on WLC theory. The key idea of WLC theory is to implement different I/OC mechanisms (see section 2.2.1.2) at different stages in the order flow (i.e. order fulfilment process). The I/OC mechanisms use different rules and limits: their main objective is to drive the (re)adjustment decisions in the wake of recurring disturbances. An example of I/OC control could be setting a limit for the maximum amount of total workload that can be accepted by the manufacturing system for a given lead time period. Every time an order quantity exceeds that limit, two options could be utilized for readjustments: i) *input* to the system can be controlled either by rejecting the order or by further negotiating with the customer to reduce the order quantity (i.e. workload adjustment); or ii) *output* from the system can be controlled either by negotiating with the customer to increase the lead time (i.e. lead time adjustment) or by arranging extra capacity to accommodate the extra demand with the given lead time (i.e. capacity adjustment).

Although implementing limits and rules for I/OC enables quick decision making, they should be carefully evaluated for their impact on the overall production performance. Different limits and rules may have different impact on the overall production performance. To better understand it, let's recall the example given at the start of this chapter and in section 4.1. Suppose the company plans production on weekly basis but tracks daily production output to recognize and evaluate internal performance variations. In case there is high internal performance variation and the daily planned/targeted output is not achieved, the company has option to use overtime in order to be on time with planned delivery schedules. Now the question is: when is it profitable to use overtime? In other words, what should be the threshold limit for the daily output to trigger overtime decision? In this case, the limit for daily output control should be carefully evaluated such that it should either improve the overall performance or simply conserve it.

Moreover, as the recurring disturbances can arise at different stages in the order fulfilment process and at different times, the I/OC mechanisms should be operated according to such stages (i.e. enquiry/entry, release, dispatch/execution) and the adequate frequency.

Regarding different stages, it is also worth remarking that recurring disturbances can arise from multiple sources such as customers (e.g. rush orders), internal operations (e.g. performance variation), suppliers (e.g. unreliable supplier lead time) that can affect the planned operating routines at different stages in the order fulfilment process. For example, late component delivery affects at dispatch/execution stage in a just-in-time manufacturing environment where a production plan has already been generated assuming that components will be available for production. In these environments, if late component delivery occurs repetitively (i.e. more often), different rules can be established to drive readjustments on the shop floor, i.e. operators don't have to be idle if components to complete some scheduled orders are not available for a short time period. At the same time, some rush order may arise in the day-by-day operations. It means the decisions are due to an effect of combined events (i.e. late component deliveries and rush orders) arising at different stages in the order fulfilment process. Therefore, simultaneous decision making should have a proper logic and be adequately quick to achieve an adjustment of planned operating routines which is relevant, at least, in order to conserve performances. WLC provides logic and rules for I/OC that can be implemented to manage such disturbances at different stages.

Regarding frequency to operate I/OC mechanisms, it is also worth remarking that recurring disturbances can arise at different times. To address this uncertainty regarding time,

the I/OC mechanisms should be operated as routines (e.g. event based, daily, weekly) based on the frequency of the recurring disturbances that affect the planned operating routines.

### 4.2.3 Readjusting planned operating routines

Readjusting routines refer to the adaptive use of the available buffers and flexibilities to readjust the capacity, workload, and/or lead-time in the short term. As discussed in section 2.2.1.1, Little's law provides the theoretical basis to carry out such (re)adjustments.

Different types of buffer can be used in the manufacturing system to absorb the immediate negative effects of disturbances arising due to different variations in the manufacturing system (Hopp and Spearman 2004):

i) *inventory buffer*, by holding stock of intermediate or finished products, to address disturbances due to variability in demand and/or production;

ii) *capacity buffer*, by having more production capacity than actually required (e.g. by extra machines) and/or by having flexible resources, enabling a *flexible capacity buffer,* to address disturbances due to variability in demand and/or production;

iii) *time buffer*, by increasing the lead-time from the absolute minimum required to an amount of time sufficient to accommodate disturbances in demand and production (i.e. safety lead times). Time buffer is particularly relevant to address disturbances due to volume and mix demand variability (Raturi 2004; Van Kampen, Van Donk, and Van Der Zee 2010).

To better understand it, let's recall the example already discussed in section 4.1 and 4.2. Based on the tracking of daily production output, the company has recognized that they face high internal performance variation which has the potential to affect their weekly production plans with adverse impact on the delivery performance. In order to achieve responsiveness, company has to evaluate different options regarding flexibilities and buffers that can be used to readjust the planned operating routines (i.e. planned capacity, workload, and/or lead-time) in the wake of disturbances due to internal performance variation. Different options can be considered to enable readjustments, e.g. by providing some products from the stock (i.e. inventory buffer), by allowing overtime (i.e. capacity buffer), or by increasing the delivery lead-time (i.e. time buffer) etc. If products cannot be provided from the stock and the customers are not ready to accept long lead-times then the only option company has to enable readjustments in the wake of disturbances due to internal performance variation is by using a capacity buffer.

In general, the more options a company have regarding flexibilities and buffers, the easier it be to readjust the planned operating routines. Moreover, to address recurring disturbances arising at different stages in the order fulfilment process, the simultaneous (re)adjustments in workload, capacity, and/or lead-time can be considered through a joint use of buffers and flexibilities (e.g. worker and shop flexibility (Ruiz-Torres and Mahmoodi [2007]). The simultaneous (re)adjustments lead to operating routines fitting the requirements arising from different disturbances. An example for such simultaneous (re)adjustment could be the use of lead-time buffer and capacity buffer to address disturbances due to rush orders and internal performance variation. This, however, requires a careful analysis of the needed size of (re)adjustments for a recurring disturbance and the actual constraints due to the resource flexibility and buffer size.

## 4.3 CONCLUDING REMARKS

This chapter (and the proposed framework) is primarily built based on the knowledge in three different streams of research: i) manufacturing/production responsiveness; ii) operations capabilities; and iii) WLC.

Based on the initial literature review, this research identified a gap in the responsiveness literature where there was a lack of understanding regarding how response capabilities can be developed and utilized to address recurring disturbances arising along the order fulfilment process for mass customization in SME context (see chapter 1, sections 1.5). Although, previously in responsiveness literature, different mechanisms to achieve responsiveness have been discussed, there was lack of an approach to formalize those individual and sometimes scattered mechanisms into a structured framework that can be easily applied in the specific context of SMEs to develop coherent response capabilities.

On the other hand, in operations capabilities literature, a routine-based approach has been proposed and emphasized for studying and developing operations capabilities (see chapter 3, section 3.1). The routine-based approach offers an opportunity to develop operations capabilities by identifying and formalizing their underlying routines. Therefore, to develop the framework of DRCs, this research employed a routine-based approach and identified three routines, mostly from responsiveness literature, that are needed to generate dynamic and adaptive responses in the face of recurring disturbances: i) sensing and recognition routine; ii) decision-making routine; and iii) flexibility and buffer based readjusting routine.

After identification of these routines, a further literature review was performed to identify different mechanisms that can be used to operationalize these routines. The literature review led to the identification of another gap in the responsiveness literature where there is a lack of understanding regarding how decision-making processes can be structured to enable adaptive/dynamic responses in the face of recurring disturbances arising along the order fulfilment process starting from the order entry stage. In order to understand how the decision-making processes are structured and how the control logic can be embedded in the order fulfilment process to enable quick and effective decisions, a further literature review was performed regarding production planning and control methods (see chapter 2, section 2.2.1), suitable for the context in which this research is being conducted (i.e. SMEs operating ATO fulfilment strategy for mass customization). This led to the WLC literature, where WLC has been extensively investigated as a PPC method particularly for SMEs operating order-driven strategies. The recent developments in the WLC literature showed that a proper decision-making process can be structured by implementing different I/OC mechanisms at different stages in the order flow (considered as the planning stages within the order fulfilment process including the order enquiry/entry stage), which finally fits to the need to implement decision-making routines to address recurring disturbances. Thus, based on the findings of literature review, WLC is integrated with the routine-based approach and a framework of DRCs has been proposed that implements WLC-based adaptive decision-making routines at different stages in the order flow (i.e. order fulfilment process).

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# 5 CASE STUDIES

## 5.1 SCOPE OF THE CASE STUDIES AND EVALUATION CRITERIA

As discussed in chapter 3 (section 3.2), in this thesis, the case studies are used to verify the relevance and the feasibility of the proposed routine-based framework of DRCs for mass customization SMEs. The framework includes, as formalized in chapter 4, the routines required to develop DRCs of the manufacturing systems, namely the routines for sensing the current operating conditions and disturbances, WLC-based decision-making, and readjusting planned operating routines. Considering this structure, two main hypotheses are being tested with the case studies:

i)      the routine-based framework is relevant for mass customization SMEs to build DRCs;

ii)     the routine-based framework is feasible for mass customization SMEs to build DRCs (i.e. feasible by implementing framework specified routines in their specific context).

Regarding relevance, this thesis postulates that the routine-based framework is deemed relevant for mass customization SMEs to build DRCs only if they face recurring disturbances at different stages in the order fulfilment process, and if the disturbances emerge from multiple sources. If mass customization SMEs do not face any recurring disturbances, then it is not relevant for them to build DRCs and thus the routine-based framework has little usefulness for them. The main evaluation criterion regarding relevance is that case companies should at-least have two (or more) types of recurring disturbances that affect their planned operating routines, and subsequently, their production performance.

Regarding feasibility, the routine-based framework is deemed feasible for mass customization SMEs to build DRCs only if it is practically possible to implement routines, specified in the framework of DRCs, in their context. If due to any reason (e.g. limited resources, technological limitations etc.), it is not possible for case companies to implement any of the framework specified routines then the routine-based framework is considered as not feasible and thus its usefulness for mass customization SMEs to build DRCs will be limited. The evaluation criterion to verify the feasibility of the proposed routine-based framework is then related to each type of routine specified within it. The main criterion regarding sensing routine is that case companies should be able to track their current operating conditions either

manually (with paper sheets) or by using Auto-ID technologies. Regarding WLC-based decision-making routine, the main evaluation criterion is that it should be practically possible for case companies to implement I/OC mechanisms as specified in the WLC method. Regarding readjusting routine, the main evaluation criterion is that companies should have different types of flexibilities and buffers existent in their manufacturing systems that could be used to implement the needed readjustments.

## 5.2 CASE STUDY ANALYSIS IN COMPANY A

### 5.2.1 Overview of 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 (i.e. catalogue mode of mass customization, see chapter 2 section 2.1) and fulfills the needs of over 500 dealers nationally and 125 countries worldwide with the products entirely made in Italy. Figure 14 provides the view of a basic slicer.

Figure 13 Basic slicer produced by company A

Different models are divided into Product Families (PFs) where several models within a PF share a common basic module; indeed, the PFs are exploiting component-swapping modularity (see chapter 1, section 1.2). In order to offer high variety and customization, the company operates through a 'fulfilment from one of several fixed decoupling points' model, being an ATO fulfilment strategy prevalent.

The components are produced based on forecast and the stock is managed using a fixed reorder point. Usually one month of component stock is held to meet the assembly needs. An automated warehouse provides the components that are required to complete one or more work orders based on production schedule defined through the information system (the bill of materials for each product model are defined in the information system): the crane draws pallets from the automated warehouse that contain the required materials and places them in a buffer area where one or more pickers/workers can operate to prepare the assembly kits (i.e. components are picked by operators and put in the carts which are then brought to the assembly cells). Picking operations are supported by the information system that shows on a computer screen the codes and quantities to be withdrawn from the pallets according to the production schedule defined by the management.

The final assembly is organized using a batch production process in a number of assembly cells (see chapter 2, figure 10, amongst the high variety manufacturing environments; this type of configuration is suitable for *relatively* low variety and high volume) where one or more cells are dedicated to a particular PF. The assembly of all slicer models consists of five main phases that are: (1) preassembly operations on the motor; (2) preassembly operations on the blade; (3) assembly of the motor and related components on the base; (4) assembly of the blade on the base and its fitting with the motor; (5) calibration of the blade.

The company plans production on a weekly basis where the workload for the week is assigned to different assembly cells. Each cell has its own dedicated worker(s) and under normal circumstances they perform assembly operations only on the PFs assigned to their respective cells.

### 5.2.2 Findings from case company A

The company A faces two types of recurring disturbances mainly from customer-side and from internal manufacturing operations that affect its planned operating routines. The customer-side disturbances arise due to volume and mix demand variability (due to the wide spread of global customers with varying needs) while the internal disturbances arise due to performance variations and worker absenteeism (as a SME, with limited pool of resources, even one worker being absent has a significant impact on delivery schedules).

- Volume demand variability brings challenges for delivery lead-time performance. The company manages assembly on a weekly basis where the aggregate capacity and subsequently the aggregate workload limit are planned to achieve one week planned lead-

time (i.e. planned operating routine). However, due to high volume demand variability the existing plans regarding aggregate workload are frequently disturbed which then result in potentials for poor customer service in terms of delivery performance and large backlog (i.e. due to capacity constraints during 'peak demand' periods).

- Similarly, mix demand variability creates challenges for capacity management and production schedules on the shop floor. Each PF has a dedicated assembly cell with a planned weekly production capacity (i.e. planned operating routine). However, the demand of different PFs vary from week to week which adversely affects the capacity utilization (when the weekly workload of a PF is lower than the planned/dedicated capacity for the week) and results in potentials for late order deliveries (i.e. when the weekly workload of a PF is higher than the planned/dedicated capacity for the week).

- Last but not least, internal performance variation and worker absenteeism adversely affect the production schedules on the shop floor. As discussed previously, the company manages the assembly on weekly basis where the workload for each assembly cell is assigned/planned for the week (i.e. planned operating routine) but due to the internal performance variation and the worker absenteeism, the company faces challenges regarding schedule adherence, resulting in potentials for high WIP on the shop floor and late order deliveries.

In order to address the recurring disturbances and to achieve high responsiveness, the company A has implemented different adaptive decision-making routines and mechanisms along the order fulfilment process which are discussed below and are summarised in Table 4.

- At first stage of the order fulfilment process, i.e. ***order enquiry/entry stage***, to address recurring disturbances due to volume demand variability, the company A has implemented an adaptive-decision making routine and different mechanisms are used to operationalize it. The company uses a (roughly) planned aggregate workload limit. The limit is calculated according to planned aggregate capacity and lead-time (i.e. one week planned lead-time period). The planned aggregate workload limit then enables to recognize the disturbances due to volume demand variability and helps to keep the total workload in the production system under control (i.e. the workload for which the production capacities and lead-time are already planned i.e. planned operating routine). To track the WIP and production progress on the shop floor the company uses Barcode technology supported information system. Due to tracking, the company has visibility into existing WIP and thus with

incoming demand during the week the company can check if the total calculated workload is within the limits or not. If the load is within the limits the orders are accepted according to planned lead-time and are sent to the pre-shop pool where they wait for release. When the load is full, an adaptive decision is then taken (i.e. event based adaptive decision-making routine) to accept/reject the orders. To make the decision, the company may negotiate with the customers either to increase the lead-time buffer or, more rarely, to reduce the order quantity (by rejecting part of the order) so that the total workload remains within the limits. To keep the overall output of the production system stable, the company prefers to use the lead-time buffer for orders exceeding the limit. Thus, for incoming orders the lead-time buffer is used to accommodate the extra demand and the capacity for the extra load is made available as per normal operating routine during the next planning cycle (i.e. next week).

- At *order release stage* of the order fulfilment process, to address recurring disturbances due to mix demand variability, an adaptive decision-making routine is operated on weekly basis (i.e. weekly adaptive decision-making routine). At the end of the week, the Barcode technology supported information system enables to track and evaluate the total WIP of each PF on the shop floor along with the available cell capacities for each PF for the next week (i.e. planned operating routine as under normal circumstances each PF has a dedicated capacity for the week). Then, the total workload of each PF that needs to be produced during next week (according to due date) is calculated. Based on the workloads of each PF, an adaptive decision is then taken where the capacities for PFs are (re)adjusted 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). Indeed, the worker and shop flexibilities enable such (re)adjustments in capacities of different PFs to address mix demand variability.

- At *order dispatch/execution stage* of the order fulfilment process, to address recurring disturbances due to performance variation and worker absenteeism, an adaptive decision-making routine is operated on daily basis (i.e. daily adaptive decision-making routine). At the end-of-the-day, the Barcode technology supported information system enables to track and evaluate the daily production output of each assembly cell to check if the production is progressing according to the actual plan or not. If the plan is disturbed (i.e. some cells are

lagging behind schedule), for the next day, the cell capacities are (re)adjusted by moving workers among different assembly cells to speed-up the pre-assembly operations in the cell which is lagging behind the schedule, thus moving forward the WIP to the final assembly (within the cells). In this case, the worker flexibility to perform assembly tasks on different product models in different assembly cells enables such readjustments in cell capacities.

Table 4 Findings from case company A

| Order flow stages | Type and source of disturbances | Sensing Routine | WLC-based decision making routine | | Readjusting routine (using buffers and flexibilities) |
|---|---|---|---|---|---|
| | | | Input control | Output control | |
| Order enquiry/ entry stage | (Type) customer disturbance (Source) volume demand variability | Barcode technology supported information system enables to track the total WIP and the production progress on the shop floor which then enables to check with incoming orders if the total workload is within the limit 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 order quantity and lead time when the total workload exceeds the limit | *Lead time adjustment*: Lead-time buffer settings to accommodate the extra demand | Time buffer enables readjustments in the planned lead time and aggregate workload (when the load for the current planning period is full, the orders are accepted with long lead time to be produced during the next planning period) |
| Order release stage | (Type) customer disturbance (Source) mix demand variability among different PFs | Barcode technology supported information system enables weekly tracking and evaluation of: i) the total WIP of each PF on the shop floor, and ii) the total workload of each PF present in the pool that need to be produced during the current week | *Workload adjustment*: order selection and release based on due date and the available cell capacities during the week (the weekly workload of each PF is calculated based on the required time to process the demanded product models for the current week, and compared with the time / capacities available during the week). | *Capacity adjustment*: due to the dynamic allocation of capacities of the different assembly cells to different PFs | Shop and worker flexibilities enable readjustments in the planned capacities of different PFs for the week. 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 | (Type) internal disturbance (Sources) performance variations and worker absenteeism | Barcode technology supported information system enables daily tracking and evaluation of the output of each assembly cell (at the end of the day) | *Workload adjustment*: order selection and dispatch based on early due date | *Capacity adjustment*: due to dynamic allocation of workers among different assembly cells | Worker flexibility enables readjustments in planned cell capacities by dynamically re-allocating workers to assembly cells lagging behind schedule |

The findings from case company A show that, indeed, high product variety brings particular challenges for mass customization SMEs as it gives birth to different types of recurring disturbances that affect the planned operating routines at different stages in the order fulfilment

process. In fact, company A faces recurring disturbances mainly due to demand variability (affecting the delivery lead-time performance and capacity utilization) and internal performance variation (affecting the delivery schedules and WIP on the shop floor).

To address these recurring disturbances, the company A has developed DRCs at different stages in the order fulfilment process.

- The company A has implemented different adaptive decision-making routines along the order fulfillment process. More specifically, the company A has implemented event based, weekly, and daily adaptive decision-making routines at order entry, release, and dispatch/execution stages respectively. Such routines adopt different mechanisms (i.e. workload, capacity and lead-time adjustment) for input and output control.

- The company uses Barcode technology supported information system to track the WIP and the production progress on the shop floor. The tracked information helps to *recognize and evaluate* any deviation in the actual plans (i.e. planned operating routines) at different stages in the order fulfilment process. When a deviation is recognized to have a significant impact on the existing planned operating routines, different *decisions* to control the lead-time, workload, or capacity (i.e. I/OC mechanisms) are then made at different stages in the order fulfilment process.

- In terms of used flexibilities and buffers, the *readjustments* in lead-time, workload, or capacity are accomplished either by using time buffer, or based on the shop and worker flexibilities that are existent in the manufacturing system of the company A.

These evidences from company A support the routine-based framework of DRCs. The findings confirm that the routine-based framework is relevant for company A to develop DRCs to address recurring disturbances due to both demand variability and internal performance variations. The findings also confirm that the routine-based framework is feasible for company A to develop DRCs as company A is already moving towards this direction and has already implemented different adaptive decision-making routines and mechanisms at different stages in the order fulfilment process to address recurring disturbances due to both demand variability and internal performance variations.

## 5.3 CASE STUDY ANALYSIS IN COMPANY B

### 5.3.1 Overview of company B

Company B has a wide product range and currently offers more than 3500 different product models on the catalogue (i.e. catalogue mode of mass customization, see chapter 2 section 2.1). Due to the specific market, the catalogue is continuously growing to cope with the varying customer needs. The products are related to movement and handling needs for industry and home applications, i.e. wheels, rollers, brackets, and locking devices. The products are generally classified according to their functionality/material (e.g. to be used inside on a smooth floor or outside on a rough terrain etc.) and load capacity the trolley has to support (e.g. super-light, light, heavy, super-heavy, welded etc.). Figure 15 provides different product types produced by company B.



Figure 14 Different types of products produced by company B

To offer high variety and customization, the company mainly operates through a 'fulfilment from one of several fixed decoupling points' model. Over the variety, ATO fulfilment strategy prevails, while only few product models with stable demand are produced using a MTS strategy and some special orders using MTO and Purchase-to-Order (PTO) strategies (some product models use special components that are purchased from suppliers according to a pre-defined lead time).

The manufacturing/fabrication of the components is managed by a Kanban system and roughly five days stock of components is held to meet the final assembly and delivery needs. The bill of materials for each product model are defined in the information system (i.e. MES) which provides support for component picking operations, as will be cleared out in the following paragraphs.

The final assembly is organized using a jobbing production process with several fixed

position assembly stations, in the remainder shortly referred to also as workstations (see chapter 2, figure 10, amongst the high variety manufacturing environments; this type of configuration is suitable for *relatively* high variety and low volume). In fact, the company processes on average 200 orders per day, whereas, each order varies in terms of product mix: on average a single order has more than ten product models, with several pieces of each model. This mix variability creates many challenges inside the factory, as different types of material flows need to be coordinated at the shop floor to fulfill the single customer order, 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.

Concentrating on the shop floor, the company has implemented a RFID enabled MES for customer 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 (i.e. fixed-position assembly), according to a short-term production plan. In particular, a Gantt chart on a computer screen shows the sequence of orders scheduled at each workstation. Based on the sequence, the MES communicates with pickers, through radio-frequency terminals, to pick the components according to each order requirements. The status of physical stocks is then updated automatically according to the material handlings. Besides, the Gantt chart provides the production supervisor and the assembly operators with a visual aid to control the scheduled orders at the workstations. The order advancement status is then monitored and updated by tracking, thus having an integral visibility on the operations performed both by the production and the logistics functions.

Overall, the challenge in company B is due to the short delivery lead-time: a significant share of customer orders is known in advance just a couple of days before the required delivery date. Therefore, the production is scheduled in daily time buckets and, as better cleared out later, is modified frequently along the day to be responsive.

### 5.3.2  Findings from case company B

The company B also faces different types of recurring disturbances in the order fulfilment process mainly arising from customer-side and supply-side. The customer-side disturbances arise due to demand variability and rush orders; while the supply-side disturbances arise due to unreliable component supply at the workstations (i.e. late delivery of components from internal and external suppliers).

- The volume demand variability brings challenges for delivery lead-time performance. The company has organized its production around daily time buckets, being five days the planned lead-time period as maximum time allowance where the aggregate capacity and component inventories are planned accordingly to achieve it (i.e. planned operating routine). However, an unexpected increase in volume demand disturbs the existing plans regarding delivery lead-time mainly due to capacity and component inventory constraints. Also, when the demand for the product models that use special components (acquired from external suppliers) unexpectedly increases, it becomes difficult to fulfil the orders according to pre-defined lead time (due to supplier capacity constraints) which then results in late order deliveries.

- In addition to volume demand variability, the company B faces a high day-to-day demand variation which creates many challenges for daily capacity management on the shop floor. Indeed, each working day has, obviously, a fixed available (aggregate) capacity (i.e. planned daily capacity) that can be utilized to fulfil customer orders. However, the aggregate demand varies from day to day. It adversely affects the capacity utilization (when the daily aggregate workload is lower than the planned daily capacity) and results in long delivery lead times (when the daily aggregate workload is higher than the planned daily capacity).

- Rush orders are the most frequent disturbance that company B faces. The company schedules production on daily basis where plan for the day is created (i.e. planned operating routine): during the day many different rush orders requiring different quantities arrive; moreover, many (normal) orders become rush orders when waiting for release in the pre-shop pool or when already released. Overall, these rush orders disturb the existing schedules and require frequent rescheduling by changing the order priority sequence. It requires a management which is close to a real time condition, to schedule / reschedule based on a real time of the order priority sequence.

- Unreliable component supply at the workstations (due to late component delivery from internal and, in case of PTO fulfilment strategy, external suppliers) also create many difficulties at the shop floor for production schedules. The daily production plan is created assuming that components will be available on time for production (i.e. planned operating routine) but at the execution stage many times it happens that components for some scheduled orders are missing and it is not feasible to follow the schedule. Even a small

delay in component delivery can affect the daily production schedules requiring some readjustments to proceed further with the production plan.

In order to address these recurring disturbances and to achieve high responsiveness, the company B has implemented different adaptive decision-making routines and mechanisms at different stages in the order fulfilment process. The adaptive decision-making routines and the different mechanisms to operationalize them along the order fulfilment process are discussed below and are summarised in Table 5.

- At ***order enquiry/entry stage*** of the order fulfilment process, to address recurring disturbances due to volume demand variability, the company B has implemented an event-based adaptive-decision making routine and different mechanisms are used to operationalize it. The company uses different types of alerts (thanks to the MES and the tracking of WIP in the manufacturing system) in order to recognize the disturbances in volume demand and to make readjustments accordingly. Based on the capacity, component inventory, and some specific operational constraints (i.e. the bottleneck operation in the manufacturing system for component construction), maximum workload limits are defined in the information system. When the demand exceeds the maximum limits, the system generates an alert. More specifically, the information system generates four types of alerts: 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 quantity of a single order exceeds the predefined limit; iv) when the workload of products that use special components exceeds the predefined limit. If there is an alert, the commercial office and the planning department then evaluate the workload and make lead-time adjustments to accommodate the demand. If no alert is generated, the orders are sent directly to the pre-shop pool in the system.

- Similarly, to address recurring disturbances due to rush orders an adaptive decision-making routine is implemented again at ***order enquiry/entry stage*** and different mechanisms are used to operationalize it. The company uses five days planned lead-time period to deliver orders. Indeed, a five days lead-time period creates a time buffer to manage rush orders as many orders require only few hours of work for completion. When a rush order arrives (i.e. event based routine), based on the customer preference (some customers are given priority) and predefined maximum order quantity limit for a rush order, the rush orders are color-coded and the MES is used to release them directly to the workstations without involving the planning department; the rush orders are put at the start of the order queue in front of

the workstations with less load. The available lead-time buffer (due to five days planned lead-time period for normal orders) enables readjustments in existing schedules to produce rush orders with priority and thus with short lead times, while postpone some orders that can be postponed.

- At *order release stage* of the order fulfilment process, to address recurring disturbances due to day-to-day demand variability (mainly related to capacity and schedule constraints), the company has implemented a daily adaptive decision-making routine and different mechanisms are used to operationalize it. As discussed previously, the company uses five days planned lead-time period to deliver orders. Indeed, a five days lead-time period 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. (e.g., today's (excess) capacity is made available to tomorrow's (extra) workload). 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 date, spreads the workload equally across each day to different workstations. 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 the Gantt chart. Overall, the shop and worker flexibility, in different fixed positions, combined with available lead-time buffer enable to accomplish such readjustments in capacity and schedules.

- At *dispatch stage* of the order fulfilment process, to address recurring disturbances due to rush orders (mainly related to schedule constraints), the company has implemented an event-based adaptive decision-making routine and different mechanisms are used to operationalize it. The pre-shop pool contains aggregate workload of five days and many orders become rush orders when waiting in the pre-shop pool, or when already released. To manage these other rush orders, the commercial department calls the production supervisor to change the status of these orders. The MES allows immediately this change (controlled by production supervisor) and the orders are put at the start of the queue in front of the workstations. The MES uses two types of logic for readjustments: i) dynamically assigns rush order to a workstation where there is already a rush order being processed; ii) if there is no existing rush order being processed, the new rush order is assigned to a workstation with less load. In both cases, thanks to the shop and worker flexibility and the available lead-time buffer that enables readjustments in schedules, the rush orders are produced with priority and with short lead time.

- At *execution stage* of the order fulfilment process, to address recurring disturbances due to unreliable component supply (mainly related to schedule constraints), the company has implemented a real-time adaptive decision-making routine, and different mechanisms are used to operationalize it. Thanks to the MES, the orders are released from the pre-shop pool in a sequence based on their due dates. The MES has the information if some components are missing as the inventory record is updated automatically. The MES then sends the information to pickers and to the assembly stations about components and assembly requirements. The product models for which the components are missing is shown on the computer screen at the workstation. The pickers then pick the components according to the order sequence (only for the product models for which the components are available in the stock, in order to reduce complexity at the workstations the system doesn't allow to work on product models with missing components) in trolleys and bring them next to the workstations. One trolley can have components for one or more orders and at a time 2 to 3 trolleys can be placed in front of each workstation. This creates 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 execution stage, for example whenever some components are not arriving according to the scheduled order sequence, workers make real-time adaptive decisions for on field (re)adjustments in order sequence and assembly tasks as the product model for which the components are missing is shown on the computer screen at the workstation. Different rules are used to make real-time adaptive decisions (e.g. order priority rule, order near completion rule, order with (previously) missing components rule etc.). As soon as the components arrive, the system sends information to pickers through radio frequency terminals; the pickers then pick the newly arrived components in trolleys and bring them next to the workstations. In this last case, the worker flexibility and available lead-time buffer enable readjustments in assembly tasks sequence for different product models and different orders without significantly affecting the delivery schedules.

*Table 5 Findings from case company B*

| Order flow stages | Type and source of disturbances | Sensing routine | WLC-based decision making routine | | Readjusting routines (using buffers and flexibilities) |
|---|---|---|---|---|---|
| | | | **Input control** | **Output control** | |
| Order enquiry/ entry | (Type) customer disturbance (Source) volume demand variability | The information system generates four types of alerts: i) when the aggregate workload for one week time frame exceeds the pre-defined limit; ii) when the workload of a certain product exceeds the pre-defined limit; iii) when the quantity of a single order exceeds the predefined limit; iv) when the workload of products that use special 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 order quantity and lead time when the total workload exceeds the predefined limits | *Lead time adjustment*: 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 long lead time to be produced during the next planning period) |
| | (Type) customer disturbance (Source) rush orders | The commercial office assigns a colour code to rush order; as a 'shortcut', the information system assigns the rush orders directly to the workstations, that see the newly released orders | *Workload adjustment*: adopting maximum order quantity limit for rush order + making order acceptance decision for rush orders only for a subset of preferred customers | *Lead time adjustment*: available lead-time buffer enables to change the sequence of already released 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 | (Type) customer disturbance (Source) day-to-day aggregate volume demand variability | The pre-shop pool is continuously updated as the new orders are accepted and entered in the system. It allows to track all the orders for next five days, and to evaluate the existing and new workload, and then balance the workload for each workstation for each day | *Workload adjustment*: order selection and release based on due date and available daily capacity | *Capacity adjustment*: due to dynamic allocation of capacity to the workload across five days | Shop and worker flexibility, combined with time buffer, enables readjustments in capacity and daily schedules to balance the daily workload of each workstation |
| Order dispatch/ execution stage | (Type) customer disturbance (Source) rush orders | 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 adjustment* is enabled based on two logics (with the objective to decrease assembly lead time for rush orders): first logic (MES dynamically assigns rush order with priority to a workstation where there is already a rush order being processed) and second logic (if there is no existing rush order being processed, the new | Shop and worker flexibility, combined with available time buffer, enable readjustments in daily schedules to produce rush orders with short lead times |

| | | | | | |
|---|---|---|---|---|---|
| | | | | rush order is assigned with priority to a workstation with less load) | |
| | (Type) Supply-side disturbance (Source) unreliable component supply | 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. 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*: due to available lead-time buffer workers can adaptively change the sequence of orders/tasks at assembly station (to increase production lead time when the components for certain product models are late) | Worker flexibility, combined with available time buffer, enable readjustments in planned order/task sequence to produce product models (with missing components) with long production lead times |

The findings from case company B also show that, indeed, high product variety brings particular challenges for mass customization SMEs due to different types of recurring disturbances which affect the planned operating routines at different stages in the order fulfilment process. In fact, the company B faces recurring disturbances mainly due to demand variability (affecting the delivery lead-time plan, component inventory plan, daily capacity plan, and daily production schedules on the shop floor), rush orders (affecting the daily schedules), and unreliable component supply (affecting the capacity utilization and daily schedules).

To address these recurring disturbances, the company B has developed DRCs at different stages in the order fulfilment process.

- The company B has implemented different adaptive decision-making routines along the order fulfilment process. More specifically, the company B has implemented several event-based, daily, and real-time adaptive decision-making routines at order enquiry/entry, release, and dispatch/execution stages respectively. Such routines adopt different mechanisms (i.e. workload, capacity and lead-time adjustment) for input and output control.

- The company B uses RFID enabled MES to track the component inventories, WIP, logistics operations and material flows, production operations and production progress, and the order statuses. The tracked information helps to *recognize and evaluate* any deviation in the actual plans (i.e. planned operating routines) at different stages in the order fulfilment

process. When a deviation is recognized to have a significant impact on the existing planned operating routines, different *decisions* to control the lead-time, workload, or capacity (i.e. I/OC mechanisms) are then made at different stages in the order fulfilment process.

- In terms of used flexibilities and buffers ,similar to company A, the readjustments in lead-time, workload, or capacity are actually accomplished either by using time buffer, or based on the shop and worker flexibilities that are existent in the manufacturing system of the company B.

These evidences from the case company B support the routine-based framework of DRCs. The findings confirm that the routine-based framework is relevant also for company B to develop DRCs: indeed, company B has an even more challenging context in terms of types of disturbances along the order fulfilment process. The findings also confirm that the routine-based framework is feasible for company B to develop DRCs as company B is already moving towards this direction and has already implemented different adaptive decision-making routines and mechanisms at different stages in the order fulfilment process to address recurring disturbances due to volume demand variability, rush orders, and unreliable component supply.

## 5.4 CONCLUDING REMARKS

Findings from case companies provide support for the development of the routine-based DRCs both in terms of their relevance and feasibility for mass customization SMEs. Both case companies not only face multiple types of recurring disturbances due to their high product variety, they have also developed relevant DRCs to address them by implementing different adaptive decision-making routines and mechanisms along their order fulfilment processes. In fact, case company A provides support for DRCs to address recurring disturbances arising from customer-side and internal operations; thanks to second case study with company B which extends the support for DRCs to address recurring disturbances arising not only from customer-side but also from supply-side, thus enhancing the robustness of the routine-based DRCs framework.

It is worth remarking that, to implement mass customization and to manage high variety, both case companies have also taken some decisions regarding the wider production context before introducing the routines and mechanisms in the order fulfilment process. They adopted catalogue mode of operation for mass customization with ATO as a dominant order fulfilment strategy. They also defined the configuration type for their manufacturing system –

batch production process with assembly cells for case company A, and jobbing production process with fixed position layout for case company B – which appeared aligned to their specific volume-variety characteristics. They have also acted on the product architecture, when this was the needed case. For example, in order to follow the market requirements for high variety and to achieve the desired flexibility, case company A has implemented an overall review of the products design. Standardizing the components used for different products/families, increasing component commonality, implementing product platform etc. were the typical decisions taken before being able to improve their responsiveness along the order fulfilment process. In particular, in the previous years each product of the catalogue had its own configuration and components, then the range of products has been revisited and redesigned without reducing its width (indeed, even enlarging it).

After such decisions regarding the wider context of the production environment – i.e. mode of operation, order fulfilment strategy, configuration type, and product design (when needed) – the companies focused to improve responsiveness of the order fulfilment process.

Both companies have implemented WLC-based adaptive decision-making routines to address recurring disturbances and to achieve responsiveness. It is remarkable to see that the routines are supported with different Auto-ID technologies such as Barcode enabled information system (in company A) and RFID enabled MES (in company B). This shows the importance of having visibility on what is happening on the shop floor. In particular, it shows that, regardless of limited resources, SMEs can also benefit from Auto-ID technologies as the cost of implementing these systems have shrunk in the last years and have become affordable for most companies (Probst et al. 2015). Furthermore, the findings show that mass customization SMEs, thanks to the use of Auto-ID technologies, can exploit the benefits of implementing WLC method, exactly through the visibility on shop floor status (i.e. WIP, production progress etc.). In this last regard, it is worth remarking that, even if literature provides several benefits of implementing WLC (mostly based on theoretical simulation studies), its application in industry has been limited mainly due to low visibility of the production environments that hinder to achieve the full potential of implementation (Thürer, Silva, and Stevenson 2011). Nowadays, with Auto-ID technologies, and, besides, with the push from Industry 4.0 towards the implementation of MES environments (Zhong, Dai, et al. 2013), the visibility in the production systems naturally increases. Therefore, it can be deduced that, for the future of production management in SMEs, it becomes more feasible and more effective to implement different I/OC mechanisms of the WLC.

Due to the Auto-ID technology and WLC based production management methods and capabilities (i.e. DRCs), both companies are not only able to manage complexity in production, they have also achieved different types of external flexibility. The external flexibility types include volume flexibility, mix flexibility, and delivery flexibility. Volume and delivery flexibility are achieved by utilizing lead-time buffer at order entry stage, while mix flexibility is achieved by utilizing time buffer and resource flexibility (i.e. shop and workers flexibility). Overall, in both case companies, the adaptive use of time buffer and resource flexibility enables to readjust the planned operating routines to accommodate unexpected changes in volume demand, mix demand, and delivery lead time (also including rush orders).

Regarding the performance impact of implementing routine-based DRCs, managers in both case companies claim significant improvements in their performance in terms of reduction in delivery cycle time (i.e. overall short lead-time), increased on-time delivery, and reduced WIP and backlog. Although these claims seem valid, the data to support such claims was not available with the researcher for the time being as it required either complete historical data (i.e. before and after implementing routine-based DRCs) or a longitudinal study to assess the impact of routine-based DRCs on production performance over a long period of time. Therefore, to verify the effectiveness of the routine-based DRCs, the research scope was further extended as a collaborative project with case company A implementing a simulation study to further extend the empirical evidence. The scope of the collaborative project and the simulation study are discussed in next chapter. It will be evident how flexibility is achievable exactly through WLC.

# 6 COLLABORATIVE PROJECT AND SIMULATION STUDY

## 6.1 OBJECTIVES OF THE COLLABORATIVE PROJECT AND SIMULATION STUDY

After conducting the case study analysis in company A, the research scope was further expanded into a collaborative project. The purpose of the extended collaboration was threefold. The first purpose was to implement a simulation study to evaluate the impact of routine-based DRCs on production performance in the presence of recurring disturbances. Closely related to this, the second purpose was to verify if the routine-based framework of DRCs can be used as a guiding tool to improve the existing adaptive decision-making routines in a company, thus, subsequently, improving its production performance. Finally, it was worth to compare the proposed approach (i.e. WLC-based adaptive decision-making routines) with traditional PPC methods, with the aim to put in evidence the specific features brought by WLC for mass customization SMEs to achieve responsiveness.

To evaluate the impact of routine-based DRCs on production performance, it was decided to address the recurring disturbances that are more frequent and that have major effect on the production performance in company A. During case study analysis (see chapter 5, section 5.2) two types of recurring disturbances were identified that affect the planned operating routines in company A: i) customer-side disturbances; and ii) internal disturbances. It was decided with company A to implement a simulation study to evaluate the performance impact of implementing routine-based DRCs, specifically, to address recurring disturbances arising from customer-side, i.e. volume and mix demand variability. Indeed, focusing on major criticalities – those due to the customer-side – appeared adequate as links between disturbances, responses and production performance are not always well and uniformly understood by personnel working in different departments (i.e. sales, planning, production etc.) and there is a need to assist them in refining, sharing, and structuring their understanding of the responses taken and the resulting impact on the system wide performance (Matson and McFarlane 1999).

To verify if the routine-based framework of DRCs can be used as a guiding tool to improve the existing adaptive decision-making routines in a company, alternative simulation experiments were designed with different operationalization of adaptive decision-making routines. The framework guided such operationalization, leading to identification of the routines and respective I/OC mechanisms due to the WLC method. The results of the

alternative experiments were then compared to analyze their impact on the production performance.

To make evident the specific features brought by WLC as a PPC "tool" for mass customization SMEs to achieve responsiveness, the simulation results were compared with those of a PBC (Period Batch Control) method, chosen as representative of traditional PPC methods, particularly suitable for manufacturing systems with cellular configuration[1] (Benders and Riezebos 2002). It is worth observing that the PBC method has been proposed in the literature as a simple production planning and control system (Kaku and Krajewski 1995), hence it should be relevant for a SME. Eventually, it is remarkable that, traditionally, the procurement and component fabrication stages are also included in the PBC method, besides the assembly stage (Steele 1998). As this research is focused on ATO fulfilment strategy for mass customization in SMEs, the PBC method is adopted only in this scope. It is, then, a simplified PBC method, due to the limitation in the scope of assembly stage. Apart the limited scope of use for this study, the PBC method is adopted in its traditional approach: it adopts a production cycle recurring at a periodic fixed interval, with orders scheduled each cycle; therefore, the orders are released simultaneously at a single time, the beginning of each period (Steele 1998). The cycle, in company A, is the same as the one adopted by the WLC routines, i.e. i.e. weekly production cycle, which maintains similar practices as in the real setting.

## 6.2 DESIGN OF THE SIMULATION STUDY

For empirical purposes, the simulation studies are designed either to model specific real situations/environments or simply the data from a real situation is used as a basis for setting the levels of key parameters in the simulation model (Shafer and Smunt 2004).

In this research, the simulation is used to represent real production environment of case company A. As discussed in chapter 5 (section 5.2.1), company A manages its production using an ATO fulfillment strategy where the final assembly is organized using a batch production process with cellular layout, i.e. assembly cells. Thus, based on the actual functioning of the company A, a simulation model is created inside the 'Plant Simulation' software (Bangsow 2016) with following basic characteristics:

- the simulation model considers a cellular assembly shop that consists of seven assembly cells where each cell is dedicated to a particular Product Family (PF);

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[1] Company A organizes assembly using batch production process with cellular layout (i.e. assembly cells)

- the assembly is performed manually within each cell, having its own dedicated worker(s) trained to perform assembly operations on all the product models belonging to their cell (i.e. to the particular PF assigned to the cell);

- due to design differences among PFs, their assembly times vary; thus, the cell workloads are calculated based on the average assembly times of their dedicated PFs;

- the production is managed on weekly basis (i.e. weekly planning horizon) and each PF has a planned weekly capacity dedicated to it;

- the logistics is highly reliable in meeting the supply needs of the cellular assembly shop; therefore, it is assumed that there is no shortage of components and all the components needed for assembly are readily available;

- the assembly is performed manually on simple assembly benches; therefore, the setup time is considered as negligible.

Table 6 provides the input data for the simulation.

Table 6 Input data for simulation experiments

|  | PF1 | PF2 | PF3 | PF4 | PF5 | PF6 | PF7 |
|---|---|---|---|---|---|---|---|
| Average weekly demand (items) | 72 | 60 | 14 | 19 | 42 | 51 | 18 |
| Planned dedicated capacity (hours/week) | 80 | 120 | 40 | 40 | 40 | 80 | 40 |
| Average assembly time (hours/item) | 1.11 | 2.00 | 2.85 | 2.10 | 0.95 | 1.56 | 2.22 |
| Coefficient of variation of assembly time | 0.12 | 0.08 | 0.12 | 0.13 | 0.10 | 0.14 | 0.15 |

Development of the DRCs requires implementation of adaptive decision-making routines. To implement adaptive decision-making routines inside the simulation model, only those stages in the order fulfilment process are considered which are relevant to address recurring disturbances due to both volume and mix demand variability as the scope of the simulation study. Volume demand variability affects the planned aggregate workload and the delivery lead-time performance while mix demand variability affects the capacity utilization and delivery schedules on the shop floor. For the purpose of this chapter, the challenges due to volume and mix demand variability faced by company A are reproduced here, as given below.

- "*Volume demand variability brings challenges for delivery lead-time performance. The company manages assembly on a weekly basis where the aggregate capacity and subsequently the aggregate workload limit are planned to achieve one week planned lead-time (i.e. planned operating routine). However, due to high volume demand variability the existing plans regarding aggregate workload are frequently disturbed which then result in potentials for poor customer service in terms of delivery performance and large backlog*

*(i.e. due to capacity constraints during 'peak demand' periods).*

- *Similarly, mix demand variability creates challenges for capacity management and production schedules on the shop floor. Each PF has a dedicated assembly cell with a planned weekly production capacity (i.e. planned operating routine). However, the demand of different PFs vary from week to week which adversely affects the capacity utilization (when the weekly workload of a PF is lower than the planned/dedicated capacity for the week) and results in potentials for late deliveries (i.e. when the weekly workload of a PF is higher than the planned/dedicated capacity for the week)"*

Therefore, to address recurring disturbances regarding planned aggregate workload and delivery lead-time performance (caused by volume demand variability), an adaptive decision-making routine is implemented at *order enquiry/entry stage*. Similarly, to address recurring disturbances regarding capacity utilization and delivery schedules (caused by mix demand variability), an adaptive decision-making routine is implemented at *order release stage*.

In addition, as the purpose of the simulation study is also to verify if the routine-based framework can be used as a guiding tool to improve the existing adaptive decision-making routines in the company, it was decided to evaluate also the impact of different (alternative) I/OC mechanisms on production performance in the presence of recurring disturbances. More precisely, starting from the discussion of WLC method (section 2.2.1.2), the collaborative research enabled to justify the choices for I/OC, to implement *WLC-based decision making routines* (see chapter 4, figure 13), with the case company A to address recurring disturbances due to volume and mix demand variability. Different facts, backed by general motivations of literature, can be summarized to support the choices.

- ***At order enquiry/entry stage***, different options for I/OC can be considered to address recurring disturbances due to volume demand variability, i.e. when the planned aggregate workload limit is exceeded, with incoming demand: i) workload adjustment based input control; ii) lead-time adjustment based output control; and iii) capacity adjustment based output control.

  *Capacity adjustment* based output control is not considered at this stage as company A has a fixed aggregate capacity that is planned to achieve one week planned lead-time: being a SME with limited resources, providing a capacity buffer (i.e. excess capacity) to accommodate volume demand variability is not a preferred option for company A.

L*ead-time adjustment* based output control enables demand to be levelled over time (Thürer et al. 2013) thus stabilizing the workload on the shop floor, while limiting the risk of revenue losses (i.e. due to lost orders). This is preferable for company A. The only advice should be that the lead-time buffer is kept within an acceptable limit: the company indicated such time buffer between one and two weeks, therefore chosen as levels of the experimental factor. For each lead-time buffer option, the total workload need to be kept under control such that it can be produced within allowed time period.

To keep the total workload under control, *Workload adjustment* based input control is then operationalized as it reduces shop floor congestion and improves delivery performance by rejecting some orders (Land and Gaalman 1996; Kingsman and Hendry 2002).

Overall, based on these choices, three alternatives for I/OC can be considered to operationalize adaptive decision-making routine at order enquiry/entry stage to address recurring disturbances due to volume demand variability: i) planned lead-time[2] based output control + order rejection based input control; ii) one week lead-time buffer[3] based output control + order rejection based input control; iii) two weeks lead-time buffer based output control + order rejection based input control.

- *At order release stage*, two main options for I/OC can be considered to address mix demand variability (i.e. when the workload of a PF that need to be released for the current week exceeds the planned/dedicated capacity for the week): i) *workload adjustment* based input control; and ii) *capacity adjustment* based output control. The *lead-time adjustment* based output control at this stage is not possible unless further negotiated with the customer; as all the orders have already been assigned a due date at order enquiry/entry stage (according to allowed lead-time buffer option), the study assumes that further negotiation is not adopted.

With *capacity adjustment* based output control option the excess load of a PF with peak demand can be produced by providing the extra-capacity (Thürer, Stevenson, and Land 2016; Land et al. 2015). Among different options to operationalize capacity adjustment: overtime is not considered as overtime has additional cost; dynamic allocation of workers among assembly cells is not considered (as a first priority, the company aims to avoid the dynamic allocation of workers among cells) as in a cellular shop configuration each cell

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[2] Planned lead-time is the amount of time for which the aggregate capacity is planned to achieve the desired delivery lead-time performance.

[3] Lead-time buffer is the amount of extra time (on top of the planned lead-time) to accommodate the extra demand. As said in the main text, this is assumed to be 1 or 2 weeks, according to the values indicated by the company.

has dedicated resources (i.e. workers) to perform production activities with the purpose to preserve the concept of team of resources and its product and process responsibility associated to a cell and its dedicated PF. Therefore, to address recurring disturbances due to mix demand variability, it is decided to operationalize *capacity adjustment* by dynamically allocating cell capacities among different PFs. The last option is directly due to the flexibility, potentially exploitable, existent within the cellular assembly shop: in fact, besides being dedicated to its particular PF, each assembly cell is designed to also host other PFs. This capacity flexibility enables to allocate excess cell capacities from PFs with low demand to PFs with peak demand (in the remainder, this option is shortly named as "flexible capacity adjustment"). To maintain quality in assembly and to avoid complexity in assembly cells, the company indicated that one cell can host maximum 1 additional PF at a time. Furthermore, with flexible capacity adjustment, the worker efficiency is reduced when they perform assembly operations on other PFs. Therefore, 80% efficiency is decided with the company when the workers perform assembly operations on product models other than their own PF. Even if flexible capacity adjustment is operationalized the total WIP on the shop floor should be kept under control such that it can be produced during the week.

To keep the WIP on the shop floor under control, *workload adjustment* based input control is then operationalized where the workload (i.e. orders) which cannot be produced using current week's available capacities are held in the pre-shop pool to be released during next planning cycle.

Based on these choices, two alternatives for I/OC can be considered to operationalize adaptive decision-making routine at order release stage to address recurring disturbances due to mix demand variability: i) planned dedicated capacity based output control + workload adjustment based input control; ii) flexible capacity adjustment based output control + workload adjustment based input control.

- At **the dispatching/execution stage**, the company considered only relevant to adopt simple dispatching rules to avoid complexity of the workers' tasks therein. As, according to literature, in the presence of rules at order enquiry/entry and release stages, simple dispatching rules are sufficient to meet the due dates (Thürer, Stevenson, and Silva 2011), thus, FIFO (first-in-first-out) rule was decided for the dispatching stage. This general rule could be applicable also for the case company as disturbances requiring a change in schedule are not very frequent. The orders are scheduled at the start of the week according to due date and there is no particular need to change the schedule during the week as

component supply in case company is highly reliable and rush orders are a seldom event (i.e. not a recurring disturbance).

To evaluate the robustness of the WLC-based adaptive decision-making routines and respective choices of I/OC mechanisms for their impact on production performance, different levels of demand variability is used: with different levels of demand variability the *intensity* of recurring disturbances changes, the impact on performance is expected to be changing as well.

Overall, based on the choices decided with the company, the experimental factors varying through the simulation experiments are:

- Demand variability with three levels (low, medium, high);
- I/OC at order enquiry/entry stage, with three levels (planned lead-time + order rejection , one week lead-time buffer + order rejection, two weeks lead-time buffer + order rejection);
- I/OC at order release stage with two levels (planned dedicated capacity + workload adjustment, flexible capacity adjustment + workload adjustment).

Table 7 summarizes the experimental factors and their levels that have been evaluated during simulation. In total 18 different experiments are designed in order to evaluate the impact of DRCs (operationalized through WLC-based adaptive decision-making routines and their respective I/OC mechanisms) on the production performance in the presence of recurring disturbances due to demand variability.

Table 7 Experimental factors according to the design of the simulation study

| Experimental factors | Levels | Values |
|---|---|---|
| Demand variability | 3 | low, medium, high |
| I/OC at order enquiry/entry stage | 3 | (planned lead-time + order rejection), (one week lead-time buffer + order rejection), (two weeks lead-time buffer + order rejection) |
| I/OC at release stage | 2 | (planned dedicated capacity + workload adjustment), (flexible capacity adjustment + workload adjustment) |

## 6.3 OPERATIONALIZATION OF THE ADAPTIVE DECISION-MAKING ROUTINES AS EXPERIMENTAL FACTORS

This section details the operationalization of the adaptive decision-making routines by illustrating how each experimental factor is implemented in the simulation model.

### Experimental factor "demand variability".

The demand variability is introduced in the simulation model based on different values of coefficient of variation (CV) of demand for each PF. By using average weekly demand for each PF (see table 6), three different sets of weekly demand are generated for each PF. The three levels of demand variability used for experiments are: Low demand variability; Medium demand variability; High demand variability. Table 8 shows the CV values used to generate different levels of demand variability for each PF.

Table 8 Different levels of demand variability used for simulation experiments

|  | PF1 | PF2 | PF3 | PF4 | PF5 | PF6 | PF7 |
|---|---|---|---|---|---|---|---|
| CV (low demand variability) | 0.07 | 0.21 | 0.10 | 0.14 | 0.17 | 0.24 | 0.11 |
| CV (medium demand variability) | 0.14 | 0.42 | 0.20 | 0.28 | 0.34 | 0.48 | 0.22 |
| CV (high demand variability) | 0.21 | 0.63 | 0.30 | 0.42 | 0.51 | 0.72 | 0.33 |

### Experimental factor "I/OC at order enquiry/entry stage".

The I/OC at order enquiry/entry stage is 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):

$$Workload_p = Capacity_p \times LeadTime_p \quad (1)$$

Where:

$Workload_p$ is the planned aggregate workload that can be accepted by the system [hours];

$Capacity_p$ is the planned aggregate shop capacity [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. 440 hours (see table 6). When the aggregate workload required by the demand 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 disturbances due to volume demand variability, thus enabling to change the

planned operating routines (i.e. planned lead-time and planned aggregate workload) at order enquiry/entry stage.

*Experimental factor "I/OC at order release stage".*

In the simulation model, the orders are released from the pre-shop pool to the shop floor on a weekly basis. The I/OC at order release stage is implemented based on planned dedicated capacity of assembly cells for the week (see table 6). 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. With capacity flexibility, when the workload of a PF for the current week is less than the planned weekly capacity of its dedicated cell, then that cell can host other PFs with excess workload (i.e. workload more than the planned capacity of their dedicated cells) until it reaches its capacity. Thus, the cell with excess workload becomes a 'mother-cell' and the cell with excess capacity becomes a 'host-cell'. The excess workload of PFs with 'peak demand' is then released based on the readjusted capacities (i.e. due to flexible capacity adjustment). After allocating the current week's load to the mother and the host cells' available capacities, 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 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 due to mix demand variability, thus enabling to change the planned operating routines (i.e. planned weekly capacities and workload for different PFs) at order release stage.

The experimental factors, when operationalized in the simulation model, enable to implement adaptive decision-making routines. Figure 16 provides the flow chart of the adaptive decision-making routines as implemented in the simulation model to address recurring disturbances due to volume and mix demand variability.
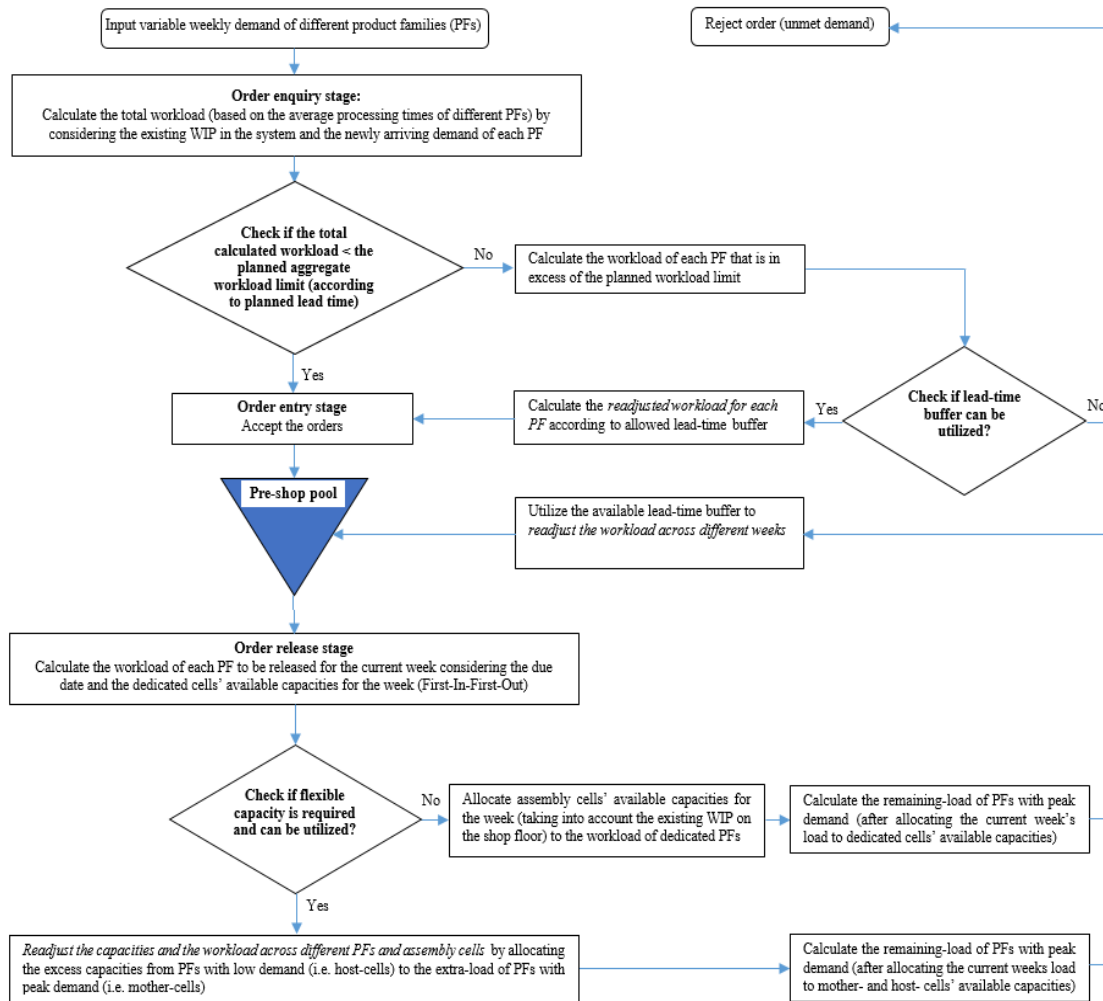
Figure 15 Flow chart of the adaptive decision-making routines implemented inside the simulation model to address recurring disturbances due to volume and mix demand variability

## 6.4 PERFORMANCE MEASURES AND EXPERIMENTAL SETTINGS

To evaluate the impact of the experimental factors on performance, five measures are used: i) demand acceptance rate; ii) order fulfilment rate; iii) capacity utilization; iv) assembly lead time; and v) throughput.

- Demand acceptance rate is calculated for each period by comparing the actual number of units (i.e. orders) accepted with the actual demand during that period.

- Order fulfilment rate is calculated for each period by comparing the actual number of units (i.e. orders) produced within their allowed time period with the total number of units accepted for that period.

- Capacity utilization is similarly calculated for each period by comparing the actual working time with the total available working time during that period.

- 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.

- The throughput, the total number of units produced by the system, is also measured for each period.

All the five 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.

## 6.5 SIMULATION RESULTS AND ANALYSIS: COMPARISON OF DIFFERENT WLC-BASED ADAPTIVE DECISION-MAKING ROUTINES

Simulation results indicate that there are multiple ways to address recurring disturbances due to demand variability. Table 9, 10, and 11 summarise the simulation results for high, medium, and low level of demand variability respectively. The results therein show the impact of implementing different DRCs (operationalized through WLC-based adaptive decision-making routines and their respective I/OC mechanisms at order enquiry/entry and release stages) on the performance measures. The tables can be read using the below index for different DRCs.

DRC1: (planned lead-time 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

DRC2: (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

DRC3: (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

DRC4: (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

DRC5: (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

DRC6: (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

Table 9 Simulation results with high demand variability [95% Confidence Interval]

| DRCs | Demand acceptance rate (%) | Order fulfilment rate (%) | Assembly lead time (days) | Capacity utilization (%) |
|------|------|------|------|------|
| DRC1 | [78.71 , 81.79] | [79.0 , 80.15] | [6.66 , 6.67] | [79.57 , 79.63] |
| DRC2 | [89.04 , 91.50] | [92.60 , 92.75] | [5.26 ,5.26] | [90.69 , 90.72] |
| DRC3 | [86.50 , 88.37] | [90.92 , 91.05] | [11.64 , 11.66] | [86.33 , 86.36] |
| DRC4 | [92.32 , 93.95] | [98.48 , 98.60] | [8.74 , 8.77] | [94.21 , 94.23] |
| DRC5 | [92.28 , 93.75] | [99.23 , 99.36] | [15.33, 15.35] | [92.20 , 92.26] |
| DRC6 | [95.11 , 96.37] | [99.76 , 99.81] | [13.72 , 13.76] | [96.46 , 96.52] |

Table 10 Simulation results with medium demand variability [95% Confidence Interval]

| DRCs | Demand acceptance rate (%) | Order fulfilment rate (%) | Assembly lead time (days) | Capacity utilization (%) |
|------|------|------|------|------|
| DRC1 | [83.05 , 85.59] | [83.06 , 83.25] | [6.46 , 6.46] | [82.84 , 82.89] |
| DRC2 | [92.29 , 94.11] | [94.66 , 94.67] | [5.15 ,5.15] | [93.15 , 93.19] |
| DRC3 | [90.75 , 92.20] | [93.79, 93.85] | [11.75 , 11.77] | [89.83 , 89.85] |
| DRC4 | [95.21 , 96.36] | [98.89 ,98.93] | [9.18 , 9.19] | [95.66 , 95.68] |
| DRC5 | [96.18 , 97.20] | [99.49 , 99.53] | [15.02 , 15.04] | [95.02 , 95.06] |
| DRC6 | [97.81 , 98.62] | [99.90 ,99.92] | [13.48 , 13.50] | [98.07 , 98.08] |

Table 11 Simulation results with low demand variability [95% Confidence Interval]

| DRCs | Demand acceptance rate (%) | Order fulfilment rate (%) | Assembly lead time (days) | Capacity utilization (%) |
|------|------|------|------|------|
| DRC1 | [83.90 , 85.38] | [83.55 , 83.58] | [6.44 , 6.44] | [84.22 , 84.29] |
| DRC2 | [95.58 , 96.55] | [95.86 , 95.88] | [5.09 ,5.09] | [96.28 , 96.31] |
| DRC3 | [95.22 , 95.96] | [95.46 , 95.50] | [11.77 , 11.79] | [94.60 , 94.62] |
| DRC4 | [97.49 , 98.07] | [98.86 , 98.87] | [10.35 , 10.36] | [97.49 , 97.50] |
| DRC5 | [98.72 , 99.11] | [99.61, 99.65] | [14.71 , 14.75] | [98.01, 98.02] |
| DRC6 | [99.43 , 99.71] | [99.92, 99.94] | [13.36 , 13.40] | [98.98 , 98.99] |

The simulation results show that, regardless of the level of demand variability, implementing DRCs lead to similar patterns of performance improvements except that with DRC3 and DRC4 a relatively short assembly lead time is achieved in the presence of high demand variability ( i.e. [11.64 , 11.66] days and [8.74 , 8.77] days respectively) than with medium demand variability (i.e. [11.75 , 11.77] days and [9.18 , 9.19] days respectively) and low demand variability ( i.e. [11.77 , 11.79] days and [10.35 , 10.36] days respectively). It is due to high order rejection rate and low capacity utilization with DRC3 and DRC4 when demand

variability is high. It is important to mention that with DRC4 more capacity is utilized with reduced efficiency (i.e. 80% efficiency) when demand variability is high compared to medium and low demand variability (due to increased potential for flexible capacity adjustment in the presence of high demand variability).

As it can be seen in table 9, the company has two main alternatives to enhance its performance in the wake of recurring disturbances due to high demand variability.

- The company can improve its performance in terms of assembly lead time (i.e. [8.74 , 8.77] days) with [98.48 , 98.60] % order fulfilment rate by operationalizing order rejection with one week lead-time buffer at order enquiry/entry stage and workload adjustment with flexible capacity adjustment at order release stage (i.e. DRC4). This, however, requires a strict control at order enquiry/entry stage (i.e. with only [92.32, 93.95] % demand acceptance rate).

- The company can improve its performance in terms of *order fulfilment rate* (i.e. [99.76 , 99.81]%) and *capacity utilization* (i.e. [96.46 , 96.52]% ) by operationalizing order rejection with two weeks lead-time buffer at order enquiry/entry stage, and workload adjustment with flexible capacity adjustment at order release stage (i.e. DRC6). This, however, results in relatively long *assembly lead time* (i.e. [13.72, 13.76] days) mainly due to high demand acceptance rate (i.e. [95.11, 96.37] %).

Note that when order rejection with planned lead-time is operationalized at order enquiry/entry stage along with workload adjustment with planned dedicated capacity at order release stage (i.e. DRC1, see table 9), it results not only in low *demand acceptance rate* (i.e. [78.71 , 81.79] %) but also low *order fulfilment rate* (i.e. [79.0 , 80.15] %). Similarly, even when flexible capacity adjustment is operationalized (i.e. DRC2, see table 9), only [92.60, 92.75] % of the accepted orders (i.e. with [89.04, 91.50] % acceptance rate) can be produced within their allowed time period (i.e. one week time period). In contrast, when order rejection with one week lead-time buffer is operationalized at order enquiry/entry stage along with workload adjustment with planned dedicated capacity at order release stage (i.e. DRC3, see table 9) the improvements can be observed not only in *demand acceptance rate* (i.e. [86.50 , 88.37]%) but also in *order fulfilment rate* (i.e. [90.92 , 91.05] %). It improves further as the lead-time buffer is increased (i.e. DRC5, see table 9). Similar improvements can be observed in capacity utilization with the increase in lead-time buffer at order enquiry/entry stage. This implies that

time buffer at order enquiry/entry stage enables to address recurring disturbances not only due to volume demand variability faced at order enquiry/entry stage but also due to mix demand variability faced at order release stage and improves the capacity utilization and delivery performance (i.e. order fulfilment rate).

Similar patterns can be observed with low and medium demand variability, except that with low demand variability level DRC2 can also be considered along with DRC4 and DRC6 as it leads to short assembly lead time  (i.e. [5.09 ,5.09] days) with relatively affordable order fulfilment rate (i.e. [95.86 , 95.88] %) and demand acceptance rate (i.e. [95.58 , 96.55] %).

It is worth observing that when order rejection with two weeks lead-time buffer at order enquiry/entry stage is utilized in conjunction with flexible capacity adjustment at order release stage (i.e. DRC6), regardless of the level of demand variability, the company can manage to deliver orders within two weeks' time period (i.e. with assembly lead times [13.72 , 13.76] days, [13.48 , 13.50] days, and [13.36 , 13.40] days for high, medium, and low demand variability respectively) even when some orders are accepted with 3 weeks lead-time period.

Overall, the simulation results show that implementing adaptive decision-making routines to utilize order rejection with time buffer at order enquiry/entry stage and time buffer with capacity flexibility at order release stage lead to improved performance in terms of *order fulfilment rate* and *capacity utilization*. Thus, depending on the *delivery lead-time* requirements, the company can choose to implement order rejection with one or two weeks lead-time buffer at order enquiry/entry stage and workload and flexible capacity adjustment at order release stage to address recurring disturbances due to customer demand variability. Moreover, as the current demand patterns may change in the future, the company should re-evaluate the I/OC mechanisms to better fit its responsiveness to the requirements of demand variability.

A further analysis is performed to test the significance of  I/OC at order enquiry/entry stage, I/OC at release stage, and demand variability for weekly throughput. In this regard, an ANOVA test is performed with a significance level of 0.05. Table 12 shows the ANOVA results.

Table 12 ANOVA results

| Source | DF | Adj SS | Adj MS | F-value | P-Value |
|---|---|---|---|---|---|
| I/OC at order enquiry/entry stage | 2 | 1320964 | 660482 | 4255.66 | 0.000 |
| I/OC at release stage | 1 | 257076 | 257076 | 1656.41 | 0.000 |
| Demand Variability | 2 | 99522 | 49761 | 320.62 | 0.000 |
| I/OC at order enquiry/entry stage* I/OC at release stage | 2 | 236672 | 118336 | 762.47 | 0.000 |
| I/OC at order enquiry/entry stage*DemandVariability | 4 | 16129 | 4032 | 25.98 | 0.000 |
| I/OC at release stage*DemandVariability | 2 | 2104 | 1052 | 6.78 | 0.001 |
| I/OC at order enquiry/entry stage* I/OC at release stage*DemandVariability | 4 | 7389 | 1847 | 11.90 | 0.000 |
| Error | 6282 | 974970 | 155 | | |
| Total | | 2914827 | | | |
| 6299 | | | | | |

It is apparent from Table 12 that I/OC at order enquiry/entry stage, I/OC at release stage, and demand variability are significantly related to the throughput of the assembly system and there is a significant effect of their interaction on the production performance.

Overall, the main insights gleaned from the simulation results are summarized as follows: *order rejection and lead-time buffer based I/OC at order enquiry/entry stage and workload and flexible capacity adjustment based I/OC at order release stage enable to achieve a standard delivery lead-time performance with high order fulfilment rate and high capacity utilization in the presence of recurring disturbances due to volume and mix demand variability.* This confirms what could be generally expected both based on general theory – i.e. Little's law and derivatives – as well as specific results from WLC theory (Kingsman and Hendry 2002; Thürer et al. 2013). While previous research on WLC has focused to find the best-fit combination of rules at different control stages (Thürer, Stevenson, and Silva 2011), the simulation results show the effectiveness of dynamic control at different stages. In particular, the simulation model considers the due date and shop floor information (i.e. the existing WIP of different PFs in assembly cells) at order release stage and every week the workload from the pre-shop pool is released accordingly to fulfil the available shop capacity for next week (i.e. the outflow of work from the shop floor determines the inflow of work to the shop floor). Similarly, the simulation model considers lead-time buffer and the pre-shop pool information (i.e. the existing WIP in the pre-shop pool) at order enquiry/entry stage to accept/reject an order (i.e. the outflow of work from the pre-shop pool determines the inflow of work to the pre-shop pool). This integrated and dynamic control (through adaptive decision-making) at different stages enables to address recurring disturbances due to volume and mix demand variability and to keep the lead time under control. To make these features of WLC evident, in next section the results of WLC-based adaptive decision-making routines are compared with those of PBC method.

## 6.6 Simulation Results and Analysis: Comparison of WLC-based Adaptive Decision-Making Routines with the Period Batch Control method

To compare the results achieved by implementing WLC-based adaptive decision-making routines with those of PBC method, a simulation model is developed which implements the PBC logic (i.e. production cycle recurring at a periodic fixed interval with orders scheduled each cycle). Figure 16 provides the flow chart for PBC method as implemented in the simulation model to manage production with a weekly production cycle. To evaluate the PBC method, the same data and procedure are used as for WLC method, the only difference is that no adaptive decision is taken at order enquiry/entry and release stages. Instead, the orders are accepted by default and the workload of each PF is calculated and assigned to their dedicated assembly cells at the start of each week.
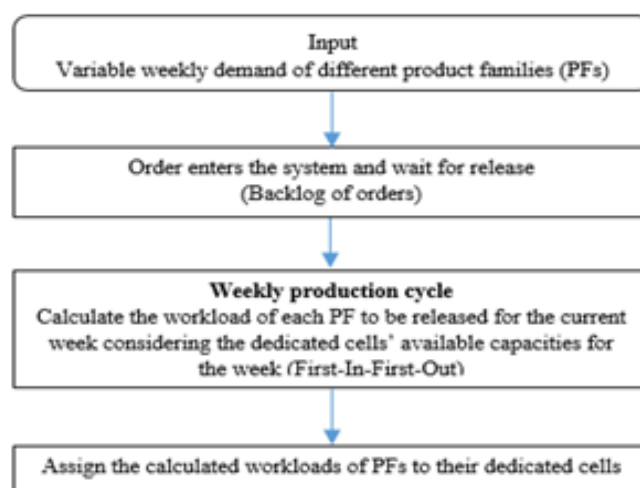


Figure 16 Flow chart for PBC method as implemented in the simulation model

Table 13 compares the results achieved by implementing PBC method with those achieved by implementing WLC-based adaptive decision-making routines (see table 9, simulation results with high demand variability).

Table 13 Comparison of WLC based DRCs with PBC method [95% Confidence Interval]

|  | Capacity utilization (%) | Assembly lead time (days) |
|---|---|---|
| DRC1 | [79.57 , 79.63] | [6.66 , 6.67] |
| DRC2 | [90.69 , 90.72] | [5.26 ,5.26] |
| DRC3 | [86.33 , 86.36] | [11.64 , 11.66] |
| DRC4 | [94.21 , 94.23] | [8.74 , 8.77] |
| DRC5 | [92.20 , 92.26] | [15.33, 15.35] |
| DRC6 | [96.46 , 96.52] | [13.72 , 13.76] |
| PBC method | [98.18 , 98.26] | [30.35 , 31.86] |

The demand acceptance and order fulfilment rates are not calculated for PBC method as all the orders are accepted by default which then create a backlog. With PBC method a 10 weeks of backlog is generated at the end of the simulation period (i.e. 500 weeks).

The comparison of results shows the importance of WLC method and that of adaptive decision-making routines (operationalized through I/OC mechanisms of WLC) to achieve responsiveness. The I/OC at different stages keep the workload and lead time under control in the presence of recurring disturbances due to demand variability. As it can be seen in the chart in figure 17, a standard delivery lead-time performance can be achieved by implementing WLC-based adaptive decision-making routines that utilize *order rejection and lead-time buffer based I/OC at order enquiry/entry stage* and *workload and flexible capacity adjustment based I/OC at order release stage* in the wake of disturbances due to demand variability. On the other hand, with PBC method the backlog starts accumulating over time resulting in long assembly lead times. Overall, the results show that the WLC method is promising for mass customization SMEs to achieve responsiveness.
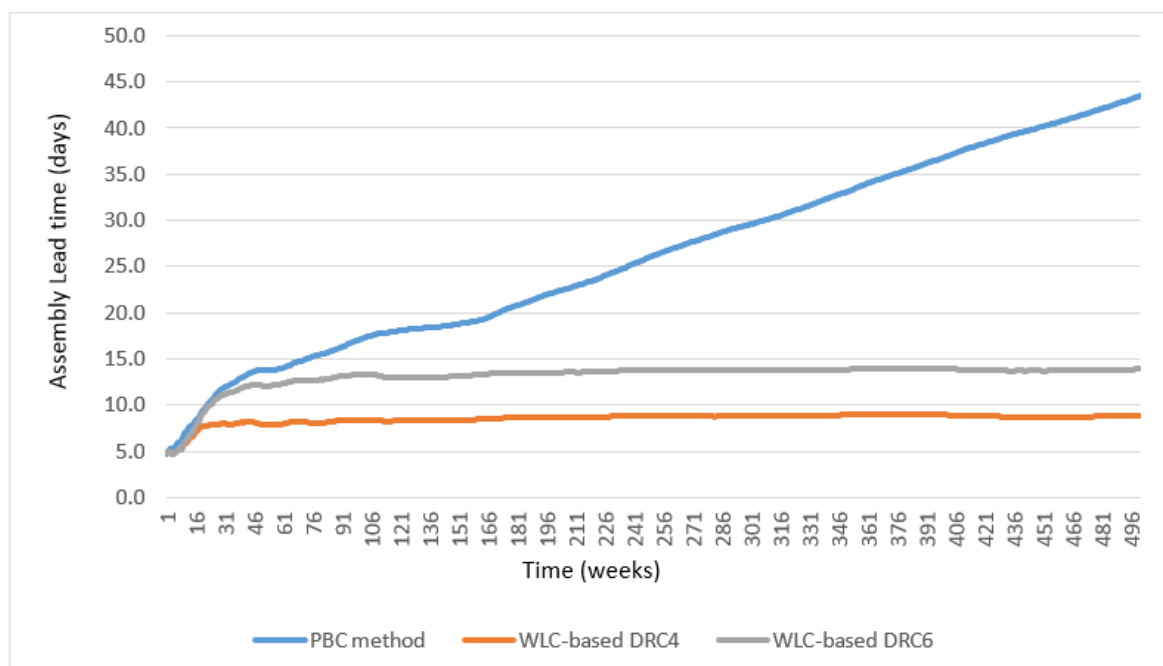


Figure 17 Assembly lead time under different control approaches

## 6.7 CONCLUDING REMARKS

The results of the simulation study provide support for the development of the routine-based DRCs. The simulation results show that responsiveness in the face of recurring disturbances due to demand variability can be achieved by implementing adaptive decision-making routines

at order enquiry/entry and release stages. Furthermore, the results show that performance in terms of order fulfilment rate, assembly lead time, and capacity utilization is enhanced by implementing specific adaptive decision-making routines and their respective I/OC mechanisms. Based on the evidences of this simulation study, it can be concluded that the *framework specified routines, implemented to address recurring disturbances arising along the order fulfilment process, lead to higher responsiveness, and overall improved production performance*.

Furthermore, the collaborative design of the simulation study with case company A shows that companies have multiple ways to operationalize framework specified routines. Thanks to the routine-based DRCs framework, several alternatives were discussed and analysed with company A for their suitability to address recurring disturbances due to volume and mix demand variability. Although many of them are not considered for this simulation study (due to the company specific constraints and the context in which company A operates), they can be evaluated and analysed in independent studies for their impact on production performance. For the purpose of this study, it was decided with company A to analyse the impact of implementing order rejection and lead-time buffer based I/OC at order enquiry/entry stage to address recurring disturbances due to volume demand variability and workload and flexible capacity adjustment based I/OC at order release stage to address recurring disturbances due to mix demand variability; thus the simulation experiments were designed. The results of the simulation experiments show that company A can effectively address disturbances regarding delivery lead-time performance, capacity utilization, and delivery schedules by implementing different adaptive decision-making routines and the respective I/OC mechanisms. In fact, company A has two alternatives to address recurring disturbances due to volume and mix demand variability: i) company can improve its performance in terms of assembly lead time by operationalizing order rejection with one week lead-time buffer at order enquiry/entry stage and workload and flexible capacity adjustment at order release stage; ii) company can improve its performance in terms of order fulfilment rate and capacity utilization by implementing order rejection with two weeks lead-time buffer at order enquiry/entry stage and workload and flexible capacity adjustment at order release stage.

Thanks to the collaborative project and the routine-based framework guided simulation study, the company can choose between different routines to improve its operations and, subsequently, the production performance according to its long term goals. Based on the experience of this collaborative project with company A it can be concluded that *routine-based*

*framework of DRCs enables guiding the improvement of existing production operations and, subsequently, of production performance in mass customization SMEs.*

Lastly, the comparative study between 'WLC based adaptive decision-making routines' approach and the PBC method shows that WLC enables to achieve high delivery lead-time performance as it enables an integrated and  dynamic control at different stages in the order fulfilment process resulting to achieve a standard performance over time. Based on the results of the comparative simulation study, it can be concluded that *WLC is a relevant and effective "PPC tool" for mass customization SMEs to achieve responsiveness in the order fulfilment process*.

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# 7 DISCUSSION AND IMPLICATIONS

## 7.1 SYNTHESIS OF RESEARCH FINDINGS

The thesis started with the aim to understand and explain how responsiveness in the order fulfilment process can be achieved for successful implementation of mass customization in SMEs. In order to address this main question, this section synthesizes the thesis findings to answer the research questions introduced in chapter one.

> **RQ1:** *how an appropriate order fulfilment process for mass customization is designed in SME context?*

This question is answered based on the literature review on mass customization from an operations perspective while considering the SMEs requirements. The findings from literature review suggest that there are different modes of operation (MacCarthy, Brabazon, and Bramham 2003), order fulfilment models (Brabazon and MacCarthy 2006), and order fulfilment strategies (Britton and Torvinen 2013) that can be used to operationalize mass customization. As this research is focused on SMEs where repeat orders due to close customer interaction and limited technological resources are the key distinguishing factors (Suzic et al. 2012; Brunoe and Nielsen 2016), the scope of the research is related to catalogue mode of mass customization. Catalogue mode of mass customization considers a pre-engineered catalogue of product variants that customers can choose from. The customer-chosen products are manufactured by the order fulfilment activities that are engineered ahead of an order being taken (MacCarthy, Brabazon, and Bramham 2003). To operationalize catalogue mode of mass customization in SMEs two order fulfilment models are considered as relevant and suitable: i) fulfilment from a single fixed decoupling point; and ii) fulfilment from one of several fixed decoupling points. The order fulfilment models can be implemented using a number of order fulfilment strategies with ATO as the dominant fulfilment strategy due to its high potential for customization with reduced delivery times (ElMaraghy et al. 2013). As appeared during framework testing phase SMEs are in fact operating different order fulfilment strategies with ATO as the main strategy. For example, in company B, DTO/MTS strategy is used for standard products that are assembled using a dedicated automated machine with Kanban planning approach while some special orders are produced using MTO and PTO fulfilment strategies. This research, however, focused on the design of the order fulfilment process under ATO fulfilment strategy for mass customization in SMEs.

Based on the scope of the research, this thesis extends the work of Brabazon and MacCarthy (2006) on the design of the order fulfilment process to SME context. In doing so, the thesis builds on the assumption that the production planning method provides the *logic* to control the order fulfilment activities (i.e. material processing/transportation activities) while production processing technologies dictate how the order fulfilment activities are *structured*; therefore, they should be configured according to the needs of high variety in the specific context of mass customization SMEs. In this regard, by analyzing different surveys on PPC methods, this research considers WLC as a relevant PPC method for SMEs (considering high demand variability and limited resources as the key factors that distinguish SMEs from large enterprises) as it enables to plan and control order fulfilment activities starting from the order enquiry/entry stage. Similarly, the literature on production processing technologies indicates that the choices regarding production process type, layout type, and equipment type influence how the order fulfilment activities are structured (Britton and Torvinen 2013; Slack, Alistair, and Johnston 2013). As this study focuses on ATO fulfilment strategy for mass customization in SMEs where the assembly activities are usually performed manually by highly skilled workers (Spena et al. 2016), the research focuses only on the choices regarding production process type and layout type for their relevance in SME context. In this regard, based on the analysis of literature, six shop configuration types (considering production process type and layout type) are considered as relevant to structure the order fulfilment activities within SME context: i) jobbing process with fixed position layout; ii) jobbing process with functional layout; iii) jobbing process with cellular layout; iv) batch process with fixed position layout; v) batch process with functional layout; and vi) batch process with cellular layout. Based on the relative volume-variety characteristics within SME context, these configuration types can be implemented to structure the order fulfilment activities.

The choice of WLC as a PPC method combined with the proper configuration type then leads to design an appropriate order fulfilment process for mass customization in SMEs.

*RQ2: how dynamic response capabilities can be developed and utilized to cope with different types of recurring disturbances arising along the order fulfilment process for mass customization in SMEs?*

This research question is answered based on the literature review and case studies. This research defines DRCs as the ability of a manufacturing system to (re)adjust its planned operating routines (i.e. planned capacity, lead time, and workload) in the wake of customer,

supplier, and internal disturbances to achieve its operational goals. In order to understand how DRCs can be developed, the literature is reviewed in three streams of research: i) operations capabilities; ii) responsiveness; and iii) WLC. Based on the reviewed literature, the research employs a routine-based approach to operations capabilities (Peng, Schroeder, and Shah 2008) and proposes to build DRCs as higher order operational capabilities of the manufacturing system by implementing WLC-based adaptive decision-making routines at different stages in the order fulfilment process. The WLC theory considers three main stages in the order fulfilment process (i.e. order enquiry/entry, release, dispatch/execution); thus, the DRCs are conceived to be developed by implementing and integrating three routines at these stages: i) sensing the current operating conditions and disturbances; ii) WLC-based decision-making; and iii) readjusting the planned operating routines. The routines are then formalized in the form of a framework by identifying their underlying micro-foundational activities. The research particularly focuses on the WLC-based decision-making routines. To implement WLC-based decision-making routines, different I/OC mechanisms are identified from the WLC literature. In particular, three mechanisms can be considered to control the input and output at different stages in the order fulfilment process: i) workload adjustment; ii) lead time adjustment; and iii) capacity adjustment (Kingsman 2000; Kingsman and Hendry 2002). The workload adjustment is used for input control while the lead time and capacity adjustments are used for output control. For I/OC mechanisms to be effective, they should be supported with proper sensing mechanisms to recognize and evaluate the disturbances (Matson and McFarlane 1999) as well as different types of buffers (Wallace J. Hopp and Spearman 2004) and flexibilities (Ruiz-Torres and Mahmoodi 2007) to enable readjustments in the planned operating routines.

The proposed routine-based framework can be used as a guiding tool to develop and utilize different DRCs to cope with multiple types of recurring disturbances arising along the order fulfilment process. The routine-based framework of DRCs is tested for its relevance and feasibility using two case studies from the SME sector. Findings from case studies show that indeed mass customization SMEs face different types of recurring disturbances from multiple sources that affect their planned operating routines and subsequently the operational performance. The findings also show that, to achieve responsiveness in the wake of recurring disturbances, mass customization SMEs are already developing different DRCs by implementing WLC-based adaptive decision-making routines at different stages in their order fulfilment processes. In particular, DRC to address recurring disturbances due to volume demand variability is developed at order enquiry/entry stage by implementing a WLC-based

adaptive decision-making routine that utilizes lead-time buffer for output control and order rejection for input control. DRC to address recurring disturbances due to mix demand variability is developed at order release stage by implementing a WLC-based adaptive decision-making routine that utilizes capacity flexibility for output control and time buffer for input control. DRCs to address recurring disturbances due to rush orders are developed at order enquiry/entry and dispatch/execution stages by implementing WLC-based adaptive decision-making routines that utilize time buffer for output control and order rejection for input control (at order enquiry/entry stage only). DRC to address recurring disturbances due to internal performance variation is developed at order dispatch/execution stage by implementing a WLC-based adaptive decision-making routine that utilizes capacity flexibility for output control and early due date for input control. Finally, the DRC to address recurring disturbances due to unreliable component supply is developed at order dispatch/execution stage by implementing a WLC-based adaptive decision-making routine that utilizes time buffer for output control and early due date and material availability for input control.

Based on the findings from literature review and case studies it is concluded that routine-based framework is relevant and feasible for mass customization SMEs to develop different DRCs by implementing WLC-based adaptive decision-making routines that utilize buffers and flexibilities to cope with different types of recurring disturbances arising along the order fulfilment process.

*RQ3: what is the impact of dynamic response capabilities on the production performance of mass customization SMEs?*

This question is answered based on a simulation study performed in collaboration with one of the case companies. Different DRCs that utilize WLC-based adaptive-decision making routines are implemented to evaluate their impact on production performance in the presence of recurring disturbances due to volume and mix demand variability. Simulation results indicate that there are multiple ways to address recurring disturbances due to demand variability. In particular, the DRCs that utilize order rejection and lead-time buffer based I/OC at order enquiry/entry stage and workload and flexible capacity adjustment based I/OC at order release stage generate better results in terms of assembly lead time, order fulfilment rate, and capacity utilization. Furthermore, a comparison between the proposed WLC-based adaptive decision-making routines approach and the traditional PPC method, namely Period Batch Control,

shows that indeed developing and utilizing DRCs to address recurring disturbances can lead to higher performance in terms of delivery lead-time, thus higher responsiveness.

Based on the findings of the collaborative simulation project it is concluded that developing and utilizing routine-based DRCs lead to improved production performance in the presence of recurring disturbances arising along the order fulfilment process.

Next sections provide some of the findings' most significant implications for theory and practice.

## 7.2 IMPLICATIONS FOR THEORY

First, while most of the previous research on mass customization is focused on large enterprises (Salvador, De Holan, and Piller 2009; Blecker and Abdelkafi 2006b; Selladurai 2004), this thesis contributes to literature on mass customization in SMEs. In doing so, the thesis also answers to a recent call to develop methods for complexity management which can be easily applied in the specific context of SMEs (Brunoe and Nielsen 2016). The present findings suggest that WLC is indeed a relevant and effective method to design an appropriate order fulfilment process for mass customization in SMEs. In addition, to achieve responsiveness in the order fulfilment process, the findings suggest to implement WLC-based adaptive decision-making routines at different stages in the order fulfilment process. Consequently, the future research on mass customization in SMEs should recognize and further investigate the role of WLC method and those of WLC-based adaptive decision-making routines for designing an appropriate and responsive order fulfilment process in different types of production environments in terms of order fulfilment strategies and shop configuration types.

Second, while previous research on manufacturing/production responsiveness has long recognized the need to develop specific response capabilities to address disturbances arising along the order fulfilment process (Kritchanchai and MacCarthy 1999), this study provides a more detailed understanding of how such capabilities could be actually developed and utilized. The findings suggest to develop DRCs as higher order operational capabilities of the manufacturing system by implementing adaptive decision-making routines at different stages in the order fulfilment process. Thus, the thesis employs the routine-based approach (a variant of resource-based theory) to develop DRCs as higher order operational capabilities by identifying their underlying routines and micro-foundational activities. In doing so, this research also extends the work of Peng, Schroeder, and Shah (2008) and verifies the

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applicability of the routine-based approach for operations capabilities by sketching out a routine-based framework of DRCs particularly relevant for SMEs. Overall, through integrating routines, the thesis verifies the notion of operations capabilities as 'bundle of routines'. Consequently, to add richness in operations management research, the thesis calls for further research on DRCs by applying routine-based framework in different types of production environments, in terms of different settings of disturbances, order fulfilment strategies, buffering strategies and resource flexibilities.

Third, while previous research on manufacturing/production responsiveness has acknowledged the importance of decision making structures and control logic to effectively react to disturbances (Kritchanchai and MacCarthy 1999; Michalos et al. 2016), the present findings provide a more detailed understanding of how such decision making structures and control logic can be developed along the order fulfilment process starting from the order enquiry/entry stage. The thesis argues that *adaptive decision-making routines, implemented at different stages in the order fulfilment process, lead to higher responsiveness in the wake of recurring disturbances*. To operationalize adaptive decision-making routines, the thesis implements WLC-based input and output control at different stages in the order fulfilment process. Indeed, the I/OC at different stages in the order fulfilment process provide a decision-making structure that adopts proper control logic and rules to use the flexibility and buffers in the wake of recurring disturbances. The present findings are in line with the work of (Michalos et al. 2016) who found that control logic based decision-making enhances the utilization of manufacturing resources and improves the performance. However, the present findings suggest to use an integrated control logic for decision-making at different stages in the order fulfilment process by implementing three I/OC mechanisms: workload adjustment, capacity adjustment, and lead time adjustment. Workload adjustment is used for input control while capacity and lead time adjustments are used for output control. Consequently, the thesis calls for further research on the application of WLC-based I/OC mechanisms to structure decision-making processes in different types of production environments along with their implications for production performance.

Fourth, while previous research on WLC recognizes the importance of integrating the I/OC mechanisms (Thürer, Stevenson, and Land 2016; Thürer et al. 2013; Thürer, Stevenson, and Silva 2011), the present findings provide a more detailed understanding of how such integration can be achieved at different stages in the order fulfilment process. The findings suggest that for WLC-based I/OC mechanisms to be effective, at each stage, they should be supported with

proper sensing mechanisms as well as different types of buffers and flexibilities. Sensing mechanisms can be implemented with the help of Auto-ID technologies such as Barcode and RFID to track the operating routines and to recognize and evaluate the disturbances arising along the order fulfilment process which then enables adaptive use of the available buffers and flexibilities to readjust the capacity, workload, and/or lead-time at different stages in the order fulfilment process. The simultaneous readjustments in workload, capacity, and/or lead-time through a joint use of buffers and resource flexibility at different stages in the order fulfilment process enables to control the input and output in an integrated way. In this regard, it is worth remarking that the integrated view provided by the routine-based framework of DRCs enables a holistic analysis of the input and output control logic and rules; this could be useful to focus on specific stages in the order fulfilment process for eventual improvements according to the needs of disturbances. Consequently, the thesis calls for further research on the implementation of integrated I/OC mechanisms supported with Auto-ID technology based information systems (e.g. MES) and different buffering strategies along with their implications for production performance and responsiveness.

Finally, while most of the past research on WLC investigates its usefulness for MTO environments featuring job shop configuration to produce high product variety with *variable routing* (Fredendall, Ojha, and Patterson 2010; Thürer, Stevenson, and Silva 2011; Stevenson, Hendry, and Kingsman 2005; Land and Gaalman 1998)*,* the thesis extends and verifies the applicability of WLC theory to ATO fulfilment strategy for mass customization with different configuration types (e.g. batch production process with cellular layout in company A; jobbing production process with fixed position layout in company B) to address recurring disturbances arising from customers, suppliers and internal operations. The present findings suggest that WLC method is a feasible and effective PPC solution for SMEs implementing ATO fulfilment strategy for mass customization. WLC theory is a promising knowledge domain and this thesis calls for further empirical research on the application of WLC method in mass customization production environments implementing different order fulfilment strategies and configuration types.

## 7.3   IMPLICATIONS FOR PRACTICE

In terms of managerial implications, the thesis contributes mainly in four ways.

First, the thesis contributes to the *design of the order fulfilment process* for mass customization in SMEs. The study considers several order fulfilment models and strategies that can be

operationalized to implement catalogue mode of mass customization in SMEs. In particular, as appeared during literature review and case studies analysis "*fulfilment from a single fixed decoupling point*' and "*fulfilment from one of several fixed decoupling points*" seem promising order fulfilment models for SMEs to implement mass customization. The models can be implemented using a number of order fulfilment strategies with ATO as the main fulfilment strategy. In addition, the thesis identifies two key elements for the design of the order fulfilment process for mass customization in SMEs. First, WLC is considered as a relevant and effective method for SMEs to plan and control order fulfilment activities starting from the order enquiry/entry stage. Second, the thesis considers six shop configuration types that are relevant to structure order fulfilment activities based on the volume-variety characteristics within SME context. Overall, to implement mass customization in SMEs, the relevant (as considered and discussed in this thesis) order fulfilment models, strategies, PPC method, and configuration types can be used as checklists and as the starting point of discussion in order to evaluate the order fulfilment process design choices at hand.

Second, the thesis contributes to the *responsiveness of the order fulfilment process* for mass customization in SMEs. The proposed routine-based DRCs framework (see chapter 4, figure 13) combined with the identified I/OC mechanisms (see chapter 2, table 2) can be utilized to support managerial decisions in addressing recurring disturbances arising along the order fulfilment process. Depending on the type of the recurring disturbances (i.e. customer, supplier, internal) arising along the order fulfilment process, different I/OC mechanisms can be evaluated to achieve responsiveness. For example, to address recurring disturbances due to volume demand variability SME managers can evaluate different choices for I/OC at order enquiry/entry stage: input control by rejecting the orders or negotiating with customers to reduce order quantity; output control by readjusting the capacity to accommodate extra demand (with planned lead time); readjusting the lead-time buffer to accommodate the extra demand (with increased lead time), or a combination of them. The choices should be carefully evaluated for their impact on the short term production goals and the long term business objectives. Overall, to address recurring disturbances arising along the order fulfilment process, the proposed framework and the identified I/OC mechanisms can be used as both checklists and the starting point of discussion in order to evaluate the response choices at hand.

Third, the thesis contributes to *operationalization of adaptive decision-making routines and I/OC mechanisms* to address recurring disturbances arising along the order fulfilment process. Based on the findings from the case studies and the simulation study, this research explicates

different adaptive decision-making routines and I/OC mechanisms to address multiple types of recurring disturbances along the order fulfilment process. It is particularly interesting to see that in both SMEs the adaptive decision-making routines and I/OC mechanisms are supported with Auto-ID technology supported information systems as well as worker and shop flexibilities existent in their manufacturing systems which enable capacity flexibility. Thanks to the capacity flexibility and the increased visibility in the production system due to Auto-ID technologies, both companies have successfully operationalized different adaptive decision-making routines and I/OC mechanisms to address multiple types of recurring disturbances. More specifically, different adaptive decision-making routines and I/OC mechanisms are operationalized to address recurring disturbances due to volume demand variability, mix demand variability, rush orders, internal performance variation, and unreliable component supply.

- To address recurring disturbances due to *volume demand variability*, both case companies have implemented an adaptive decision-making routine at order enquiry/entry stage. In both companies, with incoming orders when the aggregate demand exceeds the pre-defined planned aggregate workload limit (the limits are defined based on planned aggregate capacity for the planned lead-time), the output is controlled based on lead-time buffer while the input workload is controlled based on order rejection. The use of lead-time buffer at order enquiry/entry stage enables to accommodate the excess demand while order rejection at enquiry/entry stage enables to achieve high delivery lead-time performance. *Thus, it can be concluded that the joint use of order rejection and time buffer at order enquiry/entry stage enables mass customization SMEs to achieve high delivery lead-time performance with volume flexibility.*

- To address recurring disturbances due to *mix demand variability*, the company A has implemented an adaptive decision making routine at order release stage. In company A, when the workload of a PF exceeds the pre-defined limit (the limits are defined for each PF based on their planned dedicated capacity for the release period), the output is controlled based on capacity flexibility (i.e. due to worker and shop flexibility) while the input workload is controlled by holding the orders in the pre-shop pool. The simulation results show that the lead-time buffer decided at order entry stage enables to keep the orders waiting in the pre-shop pool for next release period and improves the order fulfilment rate. *Thus, it can be concluded that the joint use of time buffer at order entry stage and capacity*

*flexibility at order release stage can enable mass customization SMEs to address recurring disturbances due to mix demand variability and to achieve mix flexibility.*

- To address recurring disturbances due to *rush orders*, the company B has implemented adaptive decision-making routines at order enquiry/entry and dispatch/execution stages. At order enquiry/entry stage, the input workload for rush orders is controlled based on order rejection (considering maximum planned order quantity for rush orders) while output is controlled based on available time buffer (available time buffer enables to produce rush orders with priority, i.e. with short lead time) by changing the sequence of existing orders waiting in the pre-shop pool or already released to the shop floor. Similarly, at order dispatch/execution stage the available time buffer enables to change the sequence of released orders and to produce rush orders with priority. *Thus, it can be concluded that the use of time buffer at order entry and release stages can enable mass customization SMEs to address recurring disturbances due to rush orders and to achieve delivery flexibility.*

- To address recurring disturbances due to *internal performance variation* (i.e. resulting in schedule instability and late customer order deliveries), the company A has implemented an adaptive decision-making routine at order dispatch/execution stage. In company A, when the actual daily output of an assembly cell is less than the planned daily output, the input workload is controlled based on the early due date (i.e. time buffer can enable to delay the dispatch of orders to assembly cells lagging behind schedule) while the output is controlled based on capacity flexibility (i.e. due to worker flexibility). *Thus, it can be concluded that the joint use of time buffer at order release stage and capacity flexibility at order dispatch/execution stage can enable mass customization SMEs to address recurring disturbances due to internal performance variation and to achieve high customer delivery service.*

- To address recurring disturbances due to *unreliable component supply* (i.e. resulting in schedule instability and late customer order deliveries), the company B has implemented an adaptive decision-making routine at order dispatch/execution stage. When the components/material required for assembly do not arrive on planned time, the input workload is controlled based on early due date and material availability (i.e. released orders for which the components are available are selected by changing the execution sequence in real time) while the output is controlled based on available time buffer (available time buffer enables to increase the production lead time for orders with missing components). *Thus, it can be concluded that the use of time buffer at order dispatch/execution stage can*

*enable mass customization SMEs to address recurring disturbances due to unreliable component supply and to achieve high customer delivery service.*

In addition, the findings from case studies also show that adaptive decision-making routines can be operated according to different frequencies. Based on the frequency to operate, this research found four types of adaptive decision-making routines implemented by case companies: i) real-time adaptive decision-making; ii) event-based adaptive decision-making; iii) daily (or twice a day) adaptive decision-making; and iv) weekly adaptive decision-making. The choice regarding frequency to operate mainly depends on the type and frequency of recurring disturbances.

Furthermore, the cross comparison of case studies indicates different contingencies within SMEs. In particular, the application of auto-ID technology supported information systems is different in case companies. Case company A uses information system only for planning purposes and to support the component picking operations while in case company B the information system provides real-time support (due to real-time tracking of material and operations on the shop floor) both for planning and execution of assembly activities. This difference in the application of auto-ID technology supported information systems is mainly due to difference in product variety level and the delivery lead time pressure that both companies face. *With increasing product variety level and short delivery lead-time requirements, the tracking of materials and operations on the shop floor becomes increasingly important to achieve responsiveness in the order fulfilment process for mass customization in SMEs.*

Finally, the thesis contributes to practice based on the findings from the collaborative simulation project performed with one of the case companies where routine-based framework of DRCs is applied in real settings to address recurring disturbances due to volume and mix demand variability. The findings suggest that companies have multiple ways to operationalize adaptive decision-making routines and I/OC mechanisms to address a particular recurring disturbance. The choice, however, relates to the competitive priorities that a company wants to pursue. For example, the findings suggest that to address demand variability operationalizing order rejection with planned lead-time leads to improved assembly lead time but poor order fulfilment rate and poor capacity utilization. On the other hand, operationalizing order rejection in conjunction with lead-time buffer at order enquiry/entry stage leads to improved order fulfillment rate and capacity utilization but with relatively long assembly lead time. The choices regarding I/OC should be carefully analyzed for their impact on the performance

dimensions that a company wants to pursue in the long terms. *Thus, it is important that the operationalization of the adaptive decision-making routines and I/OC mechanisms, to address day-to-day recurring disturbances, consider the long term view and the strategy of the company.*

The proposed routine-based DRCs framework enables to identify and analyze alternative I/OC mechanisms for their impact on production performance. It is expected that the proposed routine-based framework will provide SME managers a great support in identifying, analyzing, and developing different DRCs to address recurring disturbances and to achieve their operational as well as strategic goals.

# 8 Conclusion and Future Research Directions

The thesis aimed to understand and explain how responsiveness in the order fulfilment process can be achieved for successful implementation of mass customization in SMEs. The question is answered by identifying and explaining two key actions that are needed for successful implementation of mass customization in SMEs: i) designing an appropriate order fulfilment process; ii) developing Dynamic Response Capabilities to address recurring disturbances arising along the order fulfilment process.

Regarding the first action, the research focuses on the design of the order fulfilment process under ATO fulfilment strategy with catalogue mode of mass customization in SMEs. With this scope, the research considers WLC as a relevant PPC method for mass customization SMEs to plan and control order fulfilment activities starting from the order enquiry/entry stage. Similarly, six shop configuration types are considered as relevant for mass customization SMEs to structure the order fulfilment activities: i) jobbing process with fixed position layout; ii) jobbing process with functional layout; iii) jobbing process with cellular layout; iv) batch process with fixed position layout; v) batch process with functional layout; and vi) batch process with cellular layout. The configuration types can be implemented based on the volume-variety characteristics within SME context. The choice of WLC as a PPC method combined with the proper configuration type then leads to design an appropriate order fulfilment process for mass customization in SMEs.

Regarding the second action, the thesis proposes to develop DRCs as higher order operational capabilities of the manufacturing system by implementing adaptive decision-making routines at different stages in the order fulfilment process. This research defines DRCs as the ability of a manufacturing system to (re)adjust its planned operating routines (i.e. planned capacity, lead-time, and workload) in the wake of recurring disturbances (i.e. customer, supplier, and internal disturbances) to achieve its operational goals. The research argues that in SME context DRCs can be developed by implementing WLC-based adaptive decision-making routines at different stages in the order fulfilment process. The I/OC mechanisms of WLC utilize different types of buffer and flexibilities to readjust the planned operating routines in the wake of recurring disturbances from customers, suppliers, and internal manufacturing operations. For I/OC mechanisms to be effective, they should be supported with proper sensing routines and mechanisms to have visibility into the current operating conditions in order to recognize the disturbances as they arise along the order fulfilment process and to adapt the

planned operating routines by using available buffer and flexibilities. Thus, to develop DRCs of the manufacturing system a routine-based framework is proposed which implements WLC-based adaptive decision-making routines to readjust the workload, capacity and lead time at different stages in the order fulfilment process.

The empirical evidence from two case studies show the relevance and the feasibility to develop DRCs that utilize different WLC-based adaptive decision-making routines to address recurring disturbances. The findings show that SMEs are already moving towards this direction and are developing DRCs by implementing WLC-based adaptive decision-making routines at different stages in their order fulfilment processes. To test the effectiveness of the proposed routine-based framework of DRCs, a collaborative research is performed with one of the case companies. Based on the routine-based framework, different DRCs to address recurring disturbances due to volume and mix demand variability are developed and tested through simulation. The simulation results show that implementing DRCs lead to improved production performance. In particular, the simulation results show that the DRCs that utilize order rejection and lead-time buffer for I/OC at order enquiry/entry stage and time buffer and capacity flexibility for I/OC at order release stage generate better results in terms of order fulfilment rate and capacity utilization. Furthermore, a comparison between the proposed WLC-based adaptive decision-making routines approach and the traditional PPC method, namely Period Batch Control, shows that indeed developing and utilizing DRCs lead to higher performance in terms of assembly lead time. Thus, it can be concluded that, mass customization SMEs can achieve responsiveness in their order fulfilment process by building DRCs that utilize WLC-based adaptive decision-making routines at different stages in the order fulfilment process.

Based on the findings of this research and their implications for theory and practice, different future research directions are identified.

- First, there is need to further investigate the theory and practice of mass customization in the specific context of SMEs and how it is different than large enterprises. In particular, it will be worth investigating how SME specific factors influence the implementation of mass customization and consequently the order fulfilment process design choices. More specifically, the future research on mass customization in SMEs should recognize and further investigate the role of SME specific factors such as low sales volume, limited technological and organizational resources, close customer interaction, and high demand variability in shaping the order fulfilment process for mass customization in SMEs.

- Second, the future research should particularly investigate the role of WLC method in designing an appropriate and responsive order fulfilment process for mass customization in SMEs operating in different types of production environments in terms of order fulfilment strategies and shop configuration types. In this regard, it will be worth investigating how the I/OC mechanisms of WLC can be used in an integrated way to structure the decision-making processes in different types of production environments in terms of order fulfilment strategies and shop configuration types along with their implications for production performance.

- Third, the future research should investigate DRCs by applying the routine-based framework in different types of production environments, in terms of different settings of disturbances, order fulfilment strategies, buffering strategies, and resource flexibilities. In addition, the future research should consider operationalization of I/OC mechanisms supported with different Auto-ID technologies to address recurring disturbances along with their implications for production performance.

- Last but not least, the future research should investigate the impact of different DRCs on the production performance in the presence of customer-side, internal, and supply-side disturbances all together. Such investigation would require simultaneous readjustments at different stages in the order fulfilment process by using different types of buffer and flexibilities. This will further improve the understanding regarding interaction between I/OC mechanisms at different stages in the order fulfilment process and their impact on the overall production performance while considering all types of disturbances.

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