Narrowing the gap between workload control theory and practice: exploring the opportunities of smart manufacturing

A case study at Fokker Aerostructures

MSc Thesis

MSc Double Degree in Operations Management

University of Groningen, Faculty of Economics and Business

Newcastle University, Business School

Name: Arjen van der Valk
Email: C.a.van.der.Valk@student.rug.nl
Student Number: 1892835 University of Groningen
140613852 Newcastle University
Supervisor Dr. J.A.C. (Jos) Bokhorst
Co-assessor Prof. C. (Chris) Hicks
Preface

With this thesis, I complete the dual degree master programme in Supply Chain and Operations Management for the University of Groningen and Newcastle University.

First of all, I would like to express my enormous gratitude to my first supervisor, Jos Bokhorst, for his helpful and sympathetic way of supervision and for the constructive feedback he gave me in the many discussions I had with him. He has given me the opportunity to gain practical experience while conducting my research and writing my thesis. Then I wish to thank my second supervisor, Chris Hicks, for his guidance and the detailed feedback I received from him.

Furthermore, I would like to express my gratitude towards Martijn Jaasma of Fokker Aerostructures, who gave me intensive guidance and attention during my time in the company. Without his perseverance and determination, my ideas would not have developed so effectively and had so much impact for the company in that short period. I hope that the ideas we developed together will be put into operation in the near future. I enjoyed our many formal as well as informal conversations.

Then I would like to thank Thijmen Reinders for his input and his large contribution to my research.

A special thanks for Peter Burke, who greatly assisted me with my English and helped to sharpen the formulation of my thesis.

I would like to thank Sander Luders for his time and patience in teaching me Visual Basic programming language and his support in constructing the simulation model used for analysis.

Finally I want to thank my parents, girlfriend and friends, who have supported me during this project.

Arjen van der Valk

15th December 2015
Abstract

Recent developments in information technology offer manufacturing organisations promising opportunities to improve control of their work processes. Smart devices and machines enable real-time monitoring of the shop-floor status and autonomous decision-making. For companies manufacturing a high variety and low volume of products, Workload Control (WLC) is widely seen as the most appropriate production control concept. However, few successful practical applications have been described in the literature because of a mismatch between theory and practice. The main objective of this study is to narrow this gap and to explore whether smart concepts can reconcile WLC theory and practice. Until now, the literature has not paid any attention to the potential of smart features to narrow the gap and thereby improve the applicability of WLC. We use an aerospace parts manufacturer as a case study to explore these opportunities. By studying this company’s shop floor control procedures through observations, conducting interviews and the design of a simulation model, this paper aims to reconcile WLC theory and practice: firstly, by indicating how practice in real life jobs shops can be aligned so as to match more closely the assumptions about reality in the WLC literature; and secondly, through developing WLC theory by proposing a production control system able to identify future process fluctuations. The academic as well as managerial contribution of this research is a presentation of three opportunities that innovative technologies are able deliver to the well-studied WLC concept. The results of this case study can be seen as a starting point for further research.

Keywords: Smart Manufacturing, Workload Control (WLC), Job shop.
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1 Introduction

A fairly large body of operations management literature has been devoted to the study of Production Planning and Control (PPC). In order to meet the growing demand for high quality and customisable products, more and more companies are shifting to work on a Make-To-Order (MTO) basis. Companies of this type, known as job shops, commonly produce highly customised orders for individual customers. Workload Control (WLC) is seen as the most appropriate production control concept for companies that produce a wide variety of products with variable routings and processing times (Stevenson et al. 2005). “The principle of the WLC concept is to control the length of the queues of orders waiting to be processed by releasing a restricted amount of orders to the shop floor” (Land & Gaalman 1996a p.536). By determining specific workload norms on the shop floor, stable throughput times can be established and hence a reliable and short due date setting becomes possible (Bechte 1988). The concept is acknowledged by researchers and practitioners because of its robustness and its potential simplicity in theory (Cransberg 2015). Various simulation studies have proved the effectiveness of WLC in MTO environments (Land & Gaalman 1998; Oosterman et al. 2000).

Although WLC has great potential in theory, its real value in practice is questionable. Stevenson et al. (2005) noted that very few successful applications have been described in the literature because of a mismatch between theory and practice. While WLC has been developed as a simple system, field researchers and practitioners have reported several complexities that impede successful application of WLC in real-life job shops (Stevenson et al. 2011). Firstly, long or assembly type routings, sequence-dependent set-ups and process batches are examples of complexities described in the literature (see e.g. Oosterman et al. 2000; Hendry et al. 2008). These examples are intended to enable more efficient processing of orders, but the required allowance of workload or the sequence in which orders are then required to be processed may violate the key principles of WLC. Secondly, real-life job shops impede successful application by hindering appropriate decision-making. Often, this is caused by a lack of accurate information, which leads to less well-informed decision-making.

It is frequently argued that the success of WLC is highly dependent on the availability of accurate shop-floor information (Melnyk & Ragatz 1989; Henrich et al. 2004). Recent technological
developments – referred to as smart concepts – have improved the ability to provide this information. More and more objects have become “smart” in everyday life. Nearly everyone has a smartphone, we have smart TVs and even smart thermostats, which are able to detect when we are driving home from work and automatically turn on our heating. Similarly, manufacturing organisations are trying to incorporate smart features in their systems to improve control of their production processes. It may be that applying Smart Manufacturing will be able to facilitate more effective application of WLC in practice.

With Smart Manufacturing, it is possible to predict equipment failures, track and trace individual products through the production process and to create a real-time overview of the shop floor. Several studies describe the emergence of Smart Manufacturing as a real-time, context-sensitive manufacturing environment that is able to buffer against turbulence using information and communication structures (Lucke et al. 2008; Zuehlke 2010). Incorporating smart features in manufacturing may satisfy the demand for feedback by increasing the visibility and transparency of operations on the shop floor. Sensors, chips and radiofrequency technologies can provide real-time information about location, temperature and routing progress at all stages of the production process.

Previous studies have analysed Smart Manufacturing and WLC as independent concepts but no previous has addressed how WLC’s shortcomings can be overcome by adding smart features to the concept. It is therefore relevant to explore if smart concepts can reconcile WLC theory and practice to increase its applicability and to address the identified job shop complexities in the literature.

This case study considers a real-life industrial case of a plant producing composite parts for aerostructures that can be characterised as a job shop. This company entails the production of a high variety of components, each at a low volume, a so-called Low Volume – High Variety (LVHV) environment. This research is of academic importance since it proposes a refinement to WLC theory to reflect practice more accurately. It is also important from a managerial viewpoint, since this paper presents opportunities to increase the practical applicability of WLC. Within the case study, a simulation model is designed to gain further insights. This study aims to answer the following research question:

How can smart concepts increase the applicability of Workload Control in practice?
The remainder of this paper is organised as follows. Section 2 provides a theoretical framework that will form the background for this research. Section 3 discusses the methodology used for answering the research questions. Section 4 introduces the company under consideration. Section 5 presents the results of an empirical case study and discusses the opportunities identified. Finally, section 6 provides the conclusion and outlines directions for further research.

2 Theoretical framework

This section presents theories that serve as background for exploring the opportunities of Smart Manufacturing concepts in job shops. Section 2.1 introduces the WLC concept and indicates why it is especially applicable to MTO environments. Section 2.2 reviews the literature concerning the difficulties that can be encountered in practice. Section 2.3 outlines the concept of Smart Manufacturing in general and discusses recent developments in data-capturing technologies. Section 2.4 investigates Smart Manufacturing more thoroughly and elaborates on the opportunities it offers for developing the WLC concept. Based on these theories, both a research model and three propositions are derived in section 2.5 that will structure the remainder of this paper.

2.1 Workload Control (WLC)

Many researchers have acknowledged that WLC is a Production Planning and Control (PPC) concept especially applicable to MTO companies (Hendry & Kingsman 1991; Land & Gaalman 1996b; Stevenson et al. 2005; Thürer et al. 2013). “WLC aims to control throughput times by incorporating a restricted release of customer orders to the shop floor, while maintaining an order pool prior to release to buffer against the many uncertainties involved with MTO companies” (Soepenberg et al. 2012, p.443). Job shops have to deal with turbulent situations and often face a great variety of product mixes, volumes and production rates and a large number of rush orders (Henrich et al. 2004). The key principle of WLC is to maintain the queues of parts waiting on the shop floor at the right levels to meet due delivery dates while capacity and capabilities of the system are taken into account (Fernandes & Carmo-silva 2011). Consequently, Work-in-Process (WIP) levels can be controlled. WLC enables organisations to control inventories, capacity and lead times by integrating sales and production into three hierarchical levels (Kingsman 2000). These
hierarchical levels consist of the entry level, the release level and the dispatching level, as illustrated in figure 2.1

First, Entry-level decisions regulate the total amount of accepted jobs. Accepted orders are placed in a so-called job pool waiting to be released to the shop floor. The period between job entry and job release provides the opportunity for process planning and checking the availability of material (Land 2004).

Second, Release level decisions regulate the amount of jobs currently in progress on the shop floor and thereby determine the total amount of WIP. In the literature, release decisions are considered to be the main control point of the WLC concept and are based on two criteria: (1) the urgency of an order; and (2) its influence on the current shop floor loading (Henrich et al. 2004). According to Land (2004), this decision serves two purposes: controlling timing and balancing workloads. The timing function determines at what moment in time an order is released so as to meet its due date, whereas the load balancing function considers the number of orders currently on the shop floor and is concerned with creating and maintaining a balanced workload there. The release decision limits the workload at each workstation, by comparing the amount of work to be released within predetermined workload norms. Figure 2.2 illustrates this control point within a production process where certain orders arrive at a workstation directly from the job pool, while others may arrive from other workstations upstream. In addition, the figure shows that the actual throughput time of a job for a given workstation consists of the waiting time plus its own processing time. Since there are
jobs coming in from other operations, it is a complicated task to estimate the total time an order will need to wait in its queue. It is important to note that release decisions should ideally be based on the current shop floor situation (e.g. actual WIP-levels, actual capacity). Achieving optimal (release) decision(s) in job shops is difficult, as variations in products and routings need to be taken into consideration.

![Figure 2.2: Control point at release in the WLC concept (from Henrich et al. 2004)](image)

Release decisions can be made periodically (e.g. daily, weekly) or continuously. Fernandes & Carmo-silva (2011) conducted a simulation study and found that making continuous order release decisions can shorten delivery times and the percentage of tardy jobs. However, Alblas (2014) argued that in order to facilitate a continuous order release system, continuous feedback is required from the shop floor.

Finally, Dispatching level decisions determine in which order jobs will be processed by giving specific jobs higher priority. Generally, this is established by applying one or more predetermined rules. The subject of dispatching rules has been widely studied and numerous options proposed in the literature (see: e.g. Blackstone et al. 1982), ranging from simple rules like the well-known First-Come-First-Served (FCFS) to more complex criteria such as Operation Due Date (ODD) (Kanet & Hayya 1982). ODD-oriented dispatching rules keep track of the progress of orders and correct any deviations from the expected progress of orders (Land et al. 2014). It is assumed in operations management literature that if order release is controlled (as is the case in the WLC concept), dispatching rules need to be simple (Land et al. 2014). In contrast, Soepenberg et al. (2012) argued that more sophisticated priority rules are required to improve delivery performance in job shops with long and complex routings. However, Land et al. (2014) also identified a conflict between
ODD-oriented rules and controlled order release. Section 2.2.2 will discuss this conflict in more detail.

ODDs are determined by calculating back from the agreed due date. Planned Station Throughput Times (PSTTs) are stored in Enterprise Resource Planning (ERP) systems and consist of a predetermined waiting time plus the specific processing time for the corresponding step. For each station, PSTTs are used and subtracted from the due date. Figure 2.3 illustrates the calculation of ODDs for a three-step routing. This figure shows that the Planned Release Date (PRD) of an order is determined by adding the individual PSTTs of the three steps and subtracting the result from the agreed due date. ODD-oriented rules apply corrections to allow for disturbances and deviations by speeding up delayed orders or slowing down orders that are ahead of schedule.

![Figure 2.3: The calculation of ODDs for a three-step routing (from Land et al. 2014)](image)

Despite the above-mentioned advantages of WLC, several job shop aspects, referred to here as complexities, impede the successful application of WLC in practice. The effect of these complexities might be reduced by incorporating smart features in production systems. Moreover, these concepts may be used to develop the theory of WLC. The next section will discuss these complexities in more detail and propose a categorisation. Section 2.4 will explore the potential synergy of Smart Manufacturing and WLC.

### 2.2 Complexities of WLC in practice

In the literature, WLC is praised for its robustness and its simplicity. Simulation studies have demonstrated its effectiveness and viability for several types of job shops (Land 2004; Thürer et al. 2012a; Thürer et al. 2012b). However, in practice, specific demands or characteristics of real-life cases can conflict with the principles of WLC and force managers to take decisions that do not conform to those principles or that hinder them from making optimal decisions.
If we consider the literature identifying job shop complexities encountered in practice, it is relevant to make a distinction between the ways in which these aspects complicate successful application. By recognising that complexities influence WLC application in different ways, we can address them more effectively and explore how smart concepts can be of assistance. In this study, we propose to distinguish between two types of complexities:

**Type 1 complexities give rise to a conflict between the time and balancing functions of WLC.**

**Type 2 complexities make it difficult to make well-informed and appropriate decisions.**

*Type 1* complexities are real-life job shop characteristics that require a trade-off to be made between timing and balancing of jobs. In section 2.1, we have seen that if orders are selected from the pre-order pool, the timing function determines the moment a job will be released. In turn, the load balancing function takes the actual workload on the shop floor into account and aims to stabilise the workload. In the remainder of this section, we will see that there may be several reasons why non-urgent orders must be released to the shop floor and that this may lead to premature completions. This additional load may hinder the release of orders that are relatively more urgent (Land 2004). Releasing early orders clearly violates the principles of WLC to achieve stable and small queues, since more workload is released onto the shop floor.

*Type 2* complexities reduce the opportunity to make well-informed decisions within WLC and therefore reduce the effectiveness of the decisions. In other words, some aspects do not necessarily have an effect on either the load or balancing function, but hinder management in making optimal decisions. Disturbances like breakdowns, rush orders or long and complex routings reduce the effectiveness of decisions made. In determining workload levels, the extent to which estimates of future workload are accurate contributes greatly to the effectiveness of the WLC concept. We assume that as the size of organisations or the complexity of its processes increases, WLC decision-making becomes more complex and less effective.

### 2.2.1 Function-conflicting complexities - type 1

An illustrative example of a complexity that requires orders to be pulled forward is parallel batch processing. This type of processing treats multiple orders simultaneously to improve efficiency and
hence reduce costs. When orders are processed in batches, many jobs are completed simultaneously, causing output to emerge not in a continuous process but rather in waves to be passed on to workstations further down the production line. As the time taken to process a batch increases, these waves will get larger as more jobs are competed simultaneously. Another example of a function-conflicting complexity is the phenomenon of sequence-dependent set-ups. In this case, jobs are processed in a specific order to minimise set-up times required between jobs. Other type 1 complexities are rush orders (Thürer et al. 2010) and assembly requirements (Thürer et al. 2012). These complexities all cause conflict between balancing and timing and so tend to undermine the purpose of the WLC concept (Cransberg et al. 2015).

When this type of complexity is ignored, the output achieved from a workstation will be limited (Cransberg et al. 2015). Type 1 complexities can be addressed by taking their characteristics into account when making decisions at the release and dispatching stages. Decisions could be made at these stages to release or dispatch jobs in a sequence that will enable workstations to handle the work in an effective order and damp fluctuations. Cransberg et al. (2015) developed a framework that determines whether to address a complexity at the release or dispatching stage.

2.2.2 WLC - Application based complexities - type 2

Type 2 complexities affect the viability of WLC in a different way. We reason that this type of complexity is mainly caused by reduced availability of current process information from the shop floor. Without this information, fluctuations and disruptions cannot be identified and no decisions can be made on how to prevent their occurrence or to reduce their influence if they do occur. Three type 2 complexities that are identified in the literature are now discussed.

**Determining indirect loads**

At the release level, jobs are selected from the job pool to be released to the shop floor. A significant part of WLC is comparing the actual workload level with the workload norms. This is done by estimating the contribution that a job will make to the actual workload levels of all workstations in its routing (Thürer et al. 2011). “Determining workload norms is one of the most important outstanding problems of WLC if this PPC solution is to be successfully adopted in
practice” (Thürer et al. 2011 p.1155). In support, Stevenson et al. (2005) stressed that determining workload norms is often hard to achieve in practice, since regular shop floor feedback and detailed information concerning current and future WIP levels is required.

It is a complex task for job shops in particular to include the amount of workload that will arrive from other stations, as different routings reduce the visibility regarding the progress of orders through the various processes. The workload that will arrive at a station from other operations is called that station’s indirect load while load that is currently located at a workstation is referred to as that station’s direct load. When the actual workload at a workstation falls below the norm for that workstation, orders are selected from the order pool and released to the shop floor.

To determine workload levels, researchers and practitioners have mainly used the following two approaches, which differ in the way they treat indirect loads:

**Load conversion approach (Figure 2.4a)** - This approach estimates the indirect load from jobs upstream of a workstation and adds this to the direct load. A “discount factor” is used, based on the probability that the job will reach that workstation in the planning period. This means that the contribution of a released job increases as the job progresses on its routing (Oosterman et al. 2000). For this approach, detailed and regular feedback from the shop floor is required to predict the discount factor, which is difficult to achieve in practice (Henrich et al. 2004b)

**Aggregate load approach (Figure 2.4b)** - Bertrand & Wortmann (1981) developed an approach that calculates the workload as an aggregate of the individual processing times. In other words, the indirect workload of a station is added to its direct load (Land & Gaalman 1996). Here, a major challenge is to determine the indirect load of a workstation and receive adequate feedback from the shop floor (Henrich et al. 2004).
Figure 2.4: Calculation of workload: the contribution of job J across time for converted load (a) and aggregate load (b) (from Breithaupt et al. 2002)

The aggregate load method does not consider a job’s position and adds the indirect load to a station’s direct load. In response, a corrected version of the aggregate load approach was introduced to take routing lengths into account (Land and Gaalman 1996; Oosterman et al. 2000). This approach predicts the expected direct load using a multiplication factor based on the position of a job in its routing. In this method, it is assumed that the mix of orders will not change from that currently released and actual station throughput times remain as planned. As a job shop’s workload is turbulent and disturbances are common, the latter assumption in particular is highly unrealistic. Section 5 will show that smart concepts can be of value in predicting future direct loads.

**Conflict between controlled release and ODD-oriented dispatching rules**

Land et al. (2014) identified a two-way conflict between load-based order release and the use of ODD-dispatching rules. Controlling the release of orders limits the workload, thereby reducing the options available for selecting jobs to be dispatched (Ragatz & Mabert 1988). On the other hand, ODD-dispatching counteracts the aim to balance loads, since when orders are not released on the PRD, ODD-oriented rules will adapt the speed of throughput so that the products will meet their originally planned due dates. When this happens, the initial calculations of workload levels no longer provide a reliable indication of expected future loads (Land 2004). Land et al. (2014 p.1064) stated that: “the best estimate of the future direct load is achieved when orders do not proceed slower or faster than planned.” In response to this conflict, Land et al. (2014) proposed to increase
or decrease all PSTTs by the same percentage in order to ensure that the ODD for the last operation is equal to the original order due date. This avoids the speeding up or slowing down of orders.

**Long routings and process disruptions**

Research has shown that the length of a routing has great influence on the performance of WLC (Thürer et al. 2010). Longer routings reduce the effectiveness of WLC for two reasons. First, controlling the progress of a long routing is a challenge, since workload levels must be considered for many operations (Perona and Portioli 1998; Soepenberg et al. 2012). Second, when a job is released to the shop floor, it complies with all the workload norms, but by the time the parts arrive at workstations further in their routing, the workloads can have changed completely as a result of other fluctuations in the process (Soepenberg et al. 2012). This puts more pressure on the need for accurate and reliable shop floor information and complicates the decisions the managers have to take as to which orders to release. Products with long routings and large processing times suffer especially from being re-sequenced before being released, since they have to fit more workload norms (Land 2004).

In the case of long routings, the extent to which release decisions can influence workload levels diminishes. Allowing extra work to reach the shop floor has no direct influence on the stations furthest downstream, since there are earlier steps that have to be completed first. Cransberg et al. (2015) advocated this view, arguing that dispatching-level decisions should determine the order in which jobs in their final steps should be processed. As the probability increases that disruptions could interfere with progress in the case of an order with a long routing, future workload estimates become less reliable. Job shops are characterised by the frequent occurrence of disruptions. Breakdowns, worker illness and quality issues can interfere with the planned progress of a job. Currently, WLC theory is not able to deal with such disruptions or fluctuations.

*Table 2.1* presents a comprehensive overview of the above-mentioned complexities and classifies each complexity under one or more headings according to type. For an extensive review of these complexities, the reader is referred to Hendry et al. (2008).
<table>
<thead>
<tr>
<th>Complexity</th>
<th>Type 1: Function conflicting</th>
<th>Type 2: WLC Decision-making</th>
<th>References:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequence-dependent set-ups</td>
<td>×</td>
<td></td>
<td>Fernandes &amp; Carmo-Silva 2011; Thürer et al. 2012, 2014; Cransberg et al. 2015</td>
</tr>
<tr>
<td>Sequential batching</td>
<td>×</td>
<td></td>
<td>Missbauer 2002; Cransberg et al. 2015</td>
</tr>
<tr>
<td>Simultaneous batching</td>
<td>×</td>
<td></td>
<td>Hendry et al. 2008; Taylor et al. 2010; Cransberg et al. 2015</td>
</tr>
<tr>
<td>Rush orders</td>
<td>×</td>
<td>×</td>
<td>Hendry et al. 2008; Thürer et al. 2010</td>
</tr>
<tr>
<td>Complex or long type Routings</td>
<td></td>
<td>×</td>
<td>Soepenberg et al. 2012; Cransberg et al. 2015</td>
</tr>
<tr>
<td>Disturbances</td>
<td>×</td>
<td>×</td>
<td>Soepenberg et al. 2012</td>
</tr>
</tbody>
</table>

Table 2.1: Overview of job-shop complexities presented in the literature

The complexities listed in table 2.1 all contribute to the mismatch between WLC theory and practice. We will now first look at the definition of Smart Manufacturing and consequently explore how this may narrow the gap.
2.3 Smart Manufacturing

Several descriptions of Smart Manufacturing have emerged in the literature, all referring to the same technology or approach. *Industry 4.0, Real-time Factories, Ubiquitous Manufacturing* and the *Internet of Things* are all examples of terminology used to describe this approach.

The word “smart” is used with different meanings in white papers and the scientific literature. At times, a smart device is defined as a self-regulating object that consists of a sensor, an actuator, a microcomputer and a transceiver (Reza 1994). At other times, “smart” is introduced as a broad concept, indicating an autonomous intelligent device or system that uses data to make well-informed decisions. Smart objects are able to detect, process and even reason with information about their status and movements, assisted by background information systems (Huang et al. 2009). The rapid developments in technology of Wi-Fi, Bluetooth, Radio Frequency Identification (RFID) and other technologies initiated the emergence of Ubiquitous Manufacturing (UM) (see e.g. Zhang et al. 2012; Yoon et al. 2012).

A UM system is able to capture real-time data from the production process and makes the status of activities visible in real-time. This increased visibility allows for adaptive production planning and control (Huang et al. 2008; Huang et al. 2009). Yoon et al. (2012 p.2178) defined a UM factory as an “innovative factory combining ubiquitous computing technology as an enabler for solving problems on the shop floor with existing components”. In other words, a smart or UM factory enables an organisation to react to changing conditions with built-in intelligence. A UM system is able to capture real-time data from the production process and allows for real-time visibility of status of activities. This increased visibility allows for adaptive production planning and control (Huang et al. 2008; Huang et al. 2009).

By using smart features, manual data collection activities can be reduced and therefore chances of human errors are avoided (Jun et al. 2009). To illustrate the potential advances, real-time traceability and visibility of WIP materials and orders give managers the opportunity to identify and react directly when high workload levels will emerge and thereby improve shop-floor performance. Moreover, disturbances can be identified and corrective actions can be carried out to deal with them.
quickly. Through using smart features, manual data collection activities can be reduced and therefore chances of human errors are avoided (Jun et al. 2009).

Recently, several studies have reported on the integration of technology in manufacturing to propose a real-time, context-sensitive manufacturing environment to buffer against turbulence using information and communication structures (see e.g. Lucke et al. 2008; Zuehlke 2010). Correspondingly, Zuehlke (2010) argued that a smart factory has the characteristics of a “factory of things”, which is derived from the “internet of things” where even the smallest piece of equipment has a certain degree of built-in intelligence. In this vision, ordinary objects are interconnected via Wi-Fi, Bluetooth or other technologies. These objects are able to connect and communicate with each other to enable autonomous and intelligent decision-making.

Radziwon et al. (2014) suggested a definition based on a meta-analysis of literature on Smart Manufacturing: “A Smart factory is a manufacturing solution that provides flexible and adaptive production processes that will solve problems arising on a production facility with dynamic and rapidly changing boundary conditions in a world of increasing complexity”.

In other words, a smart factory can adapt to changes in dynamic circumstances and is able to learn and think by itself regardless of the increasing complexity.

2.3.1 Shop-floor feedback and data capturing

Without complete information about the status of production processes, companies face issues of ineffective production planning, scheduling and control and low product quality (Chongwatpol & Sharda 2013). This view is supported by Henrich et al (2004b) who argued that, for job shops, PPC is complex and often based on unreliable and incomplete data. Melnyk & Ragatz (1989) noted that the timeliness, accuracy and completeness of shop floor information are crucial for the functioning of the order release mechanism.

To meet this need for accurate and reliable shop-floor data, manufacturing organisations can employ several methods. Many organisations use barcode readers to register start and end times of process steps. However, recent developments have made several other options available, such as a wide variety of sensors or RFID technologies. When objects are identified, they can be assigned a unique
ID number, which can be stored in a database and used for different purposes. Huang et al. (2008) proposed an RFID-based approach to improve the provision of real-time shop-floor information.

Simply capturing shop-floor data is not sufficient. In the first place, this will lead to very large databases containing many items of data. In an attempt to convert such “big data” into meaningful business information, more and more organisations are adopting a Manufacturing Execution System (MES).

### 2.3.2 Manufacturing Execution Systems (MES)

These days, many MTO companies make use of an ERP system to support establishing better integration and flow of information between business functions (Ehie & Madsen 2005). However, Zhong et al. (2013) stated that, by itself, an ERP system is not sufficient for two reasons: it concentrates only on the managerial level of decision-making and is weak in supporting frontline workers and supervisors and, to generate flawless decisions, it needs real-time and accurate shop floor data. To address these issues, more and more companies are adopting an MES system. An MES is an integrated computerised system that communicates between the ERP system and shop-floor control systems (MESA International, 1997).

*Figure 2.5* shows the virtual position of an MES in an organisation. The figure shows that an MES forms the bridge between the organisational long-term planning (ERP-level) and shop floor control (control-level). Furthermore, the figure shows that the device-level provides signals via sensors, actors and machines to the top-level. In the literature, these “device-level” objects are often referred to as smart concepts. These Smart Objects (SOs) provide data to the MES. Where an ERP system provides aggregated information, an MES captures shop-floor data and converts that data into meaningful information. Therefore, an MES can be regarded as a practical implementation of Smart Manufacturing.
An MES is in charge of managing shop-floor operations such as the detailed scheduling of activities, launching of orders and providing information to supervisors and workers about equipment status and order progress (Blanc et al. 2008). Zhong et al. (2013) proposed a Radio Frequency Identification (RFID)-enabled Real-Time Manufacturing Execution System (RT-MES) to track and trace manufacturing objects and collect real-time production data. Here, the dynamics of shop-floor WIP items were visualised in real time and could be managed accordingly. As a result, planning and scheduling decisions became more ‘hands on’.

Looking at the above-mentioned definitions, we can conclude that Smart Manufacturing is a very broad concept and many technologies are available that can deliver intelligent solutions. To narrow the scope of this concept and to give a clear direction to this research, the remainder of this paper defines Smart Manufacturing as follows:
Smart Manufacturing comprises capturing shop-floor data in real time and using it to derive meaningful information that will help management to make informed decisions regarding shop-floor control.

2.4 Smart Manufacturing and Workload Control

The previous sections have already indicated the importance for effective WLC of reliable feedback from the shop floor. The main motivation for this exploration of how to increase WLC applicability is the fact that recent developments in technology are now able to provide up-to-date and reliable shop-floor information. Without this process feedback, unfounded decisions have to be made, resulting in sub-optimal decisions. In 2004, Henrich et al. undertook research with the aim of reducing this feedback requirement by adapting the concept to deal with limited information (see Henrich et al. 2004). Now, eleven years later, smart concepts allow for real-time data capturing and can therefore offer the required up-to-date information. This availability of information not only provides an opportunity to bring practice closer to theory by meeting the assumptions in the WLC literature, it also creates new opportunities to refine and develop WLC theory. Consequently, narrowing the gap between theory and practice may increase the ability to deal with the complexities identified in the literature. This section outlines three propositions that may contribute to enhancement of the applicability of WLC in real-life job shops. These propositions and their corresponding illustrations form the basis for the model in section 2.5 that represents a high-level overview of this research.

2.4.1 Bringing practice closer to WLC theory

Nearly all papers and publications in the literature regarding WLC research assume complete availability of shop-floor information. Recent developments in RFID, sensor and MES technologies have made it possible to achieve a real-time supply of information from the shop floor. Smart features enable managers and planners to monitor WIP and keep track of specific products throughout the process (Chongwatpol & Sharda 2013). Moreover, Smart Manufacturing principles can identify breakdowns and monitor the condition of equipment. Accurate and reliable information could bring WLC practice closer to theory, as smart concepts are able to provide the information
assumed to be available in WLC literature and simulation research. This leads to the following proposition (see figure 2.6):

**P1.** Smart Manufacturing principles are able to increase the extent to which practice fits the assumptions made about reality in WLC theory

![Figure 2.6: Schematic overview of proposition 1, which proposes that the use of smart principles can bring practice closer to WLC theory](image)

2.4.2 Improvement of WLC theory

We have seen that smart principles are able to provide up-to-date and accurate shop-floor information. Having real-time shop floor information available provides opportunities for developing or refining the theory to bring it closer to practice. To identify which aspects WLC theory can benefit from real-time information, we firstly discuss each decision level as described in WLC theory.

The *entry* level consists of two input control methods: the acceptance of jobs and the assignment of due dates. Accepting more or fewer orders from customers directly affects the amount of work to be released to the shop floor. Entry-level decisions “do not require knowledge of the actual shop floor status to regulate the amount of workload, since the quantity of work on the shop floor is being controlled at the release level” (Land 2004 p. 33). It follows that smart principles can be of little assistance for entry-level decisions.

*Release* level decisions directly control the amount of workload on the shop floor. Release decisions could benefit from detailed shop-floor information when trading off the balancing and timing functions. In addition, the theory section 2.2.2 elaborated on the various methods attempted to
determine indirect workloads. Detailed information about current workloads as well as future order progress could be used to make effective decisions about releasing orders to the shop floor.

If actual order progress information is available, dispatch decisions can be adjusted to anticipate or react to process fluctuations. For instance, when there is a large amount of WIP at a workstation that is found to require maintenance, alternative decisions could be made to redistribute workload to other workstations that currently have a smaller workload. Anticipated progress of future orders can be useful as well to predict future progress deviations. With more frequent feedback from the shop floor, corrective decisions can be made even more quickly.

Finally, output control decisions can influence throughput times by adjusting or relocating production capacity. Information about actual and estimated future workload levels may increase the effectiveness of such decisions. Clearly, several opportunities to develop or refine WLC theory based on smart principles can be identified, as given in the second proposition (see figure 2.7):

P2 Smart Manufacturing principles are able to refine WLC theory to match practice more closely

Figure 2.7: Schematic overview of proposition 2, which proposes that the use of smart principles can refine WLC theory to match practice more closely

2.4.3 Addressing job shop complexities

“There is nothing more practical than a good theory” (Lewin 1952, p. 169). Narrowing the gap between WLC theory and practice by using smart principles may increase the ability to deal with the complexities found in the literature and thereby increase the chance of successful implementation. Type 1 complexities, which give rise to a conflict between the time and balancing functions, could be addressed by using smart principles to anticipate for future process fluctuations. Releasing or dispatching orders while taking into account this information could reduce the adverse effects of

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type 1 complexities. On the other hand, smart principles also could assist addressing type 2 complexities by delivering information on which decisions could be based, or by using new information to correct decisions made earlier. This results in the following proposition (see figure 2.8):

**P3** Narrowing the gap between WLC theory and practice increases the ability to deal with the complexities found in the literature

![Figure 2.8: Schematic overview of proposition 3, which proposes that narrowing the gap between WLC theory and practice, can increase the ability to deal with complexities](image)

### 2.5 Research model and definition of key concepts

The introduction presented the following research question:

**RQ: How can smart concepts increase the applicability of Workload Control in practice?**

A high-level overview of the exploration to answer this research question is illustrated by a model that presents the concepts, the relationship between them and the propositions as defined in the previous section. Moreover, it shows that an advance in either theory or practice can narrow the gap between the two, which means that an improvement in either of these can improve the applicability of WLC in practice. The remainder of this paper is structured according to this overview as illustrated in figure 2.9.
Figure 2.9: High-level overview of research

For clarity, table 2.2 defines some of the concepts in figure 2.9 above as they are applied in this study.

<table>
<thead>
<tr>
<th>Concept:</th>
<th>Definition:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Job shop complexities</td>
<td><em>Job-shop specific characteristics that complicate successful WLC application</em></td>
</tr>
<tr>
<td>Smart concepts</td>
<td><em>Intelligent features that enable provision of real-time shop-floor information</em></td>
</tr>
<tr>
<td>WLC applicability</td>
<td><em>Ability to apply the principles of WLC in order to make reliable decisions</em></td>
</tr>
</tbody>
</table>

Table 2.2: Definitions of key concepts
3 Methodology

3.1 Research design

As the aim of the main research question is to find ways in which the applicability of WLC can be improved, this research is explorative in nature. An exploratory study aims to investigate “what is happening; to seek new insights; to ask questions and to assess phenomena in a new light” (Robson 2002 p. 59). In this case, empirical research was carried out by means of a single case study. Voss et al. (2002) discussed several challenges in conducting a case study: it is time consuming, it needs skilled interviewers and care is needed in drawing generalizable conclusions. Furthermore, a case study can indicate directions for further research and, in addition, allows for synchronising empirical data and observations with concepts and theories. A detailed description of the company under consideration in this study is presented in the next chapter.

Alongside a thorough investigation of the case company, a quantitative model using information about the processes and dispatching rules as applied in the company was constructed in Microsoft Excel – Visual Basic programming language – to test ideas. Through simulation, potential problems and issues could be further identified. This model provided valuable insights and served as a basis for further discussions. Several group meetings were organised to introduce the proposed calculation model and to discuss its potential shortcomings and its practical applicability. The presentation of this model has led to new ideas in the case company, which are currently being put into operation.

3.2 Data collection

Primary data

Data were collected by a single researcher working full time within the case company over a period of 9 months. Data collection methods included interviews, observations and documentary analysis conducted to facilitate correlation of results. During the first phase, interviews based on open questions were held with individuals from several levels of the organisation to collect initial
qualitative data and to identify problem areas. To ensure validity, information was collected from individuals working at different levels in the organisation. These individuals included operators on the shop floor, production planners, logistic managers and operation managers. The first one-hour interviews were held with the aims of getting a sense of problem areas and becoming acquainted with the company’s processes and culture. A different protocol was followed for each interview, adapted to the specific role of the interviewee.

Later, more focused structured interviews took place to grasp the production process more fully and to obtain ideas to develop a model for addressing the issues encountered. In addition to these interviews, group meetings and observations on the shop floor provided extra insights and understanding about habits, production processes and methods. Data for designing the model was extracted from the ERP system and from the interviews. The group meetings provided fruitful discussions and, at the same time, achieved input and support from the stakeholders. Any observations and insights were noted on a clipboard for later use. As the researcher was present at the case company on a full-time basis, there were opportunities to visit the shop floor when necessary.

Secondary data

The company in this study has a vast amount of secondary data available. First, its own intranet contained background information about the company’s culture, customers and practices. The company provided project reports on earlier pilot studies and experiments with introducing smart features into their production process. These pilot reports were analysed to identify opportunities and challenges. Furthermore, related improvement project reports concerning shop floor control were studied and used for background knowledge and preparing interviews.

3.3 Design of measurements

Within the case study conducted, a deterministic simulation model was designed to acquire insights and to further investigate the opportunities for applying smart principles within the company concerned. This model served as a basis for discussions and for getting input from the interviews. Figure 3.1 below, shows a screenshot showing the set-up of the model, where, for the sake of
simplicity, three stations are modelled with their corresponding queues. For an overview of the entire model, the reader is referred to appendix A. Appendix B shows the outcomes of the simulation model with time intervals of 10. This model enabled investigation of events by increasing or decreasing the time, or by running a full simulation. Dispatching rules and capacity constraints can be configured. It is important to note that for simplicity, the three stations are positioned in a line and therefore no work arrives from other workstations. Section 5 will further discuss the functioning and findings of this model.

Figure 3.1: Screenshot of the data set in the simulation model, showing three stations with corresponding queues

### 3.4 Data analysis

The interviews were, if the interviewees agreed, recorded in order to facilitate comparison between them and listening to them afterwards. The key points mentioned in the interviews were documented and returned to the interviewees at a later time for verification. This ensured that the adopted statements could not be misunderstood and that interviewees agreed with the conclusions and information as adopted in this research. The outcomes of the simulation model were used to analyse the functioning of the practices discussed in the interviews and to assess the viability of the simulation model. Attempts were made to improve the deterministic model by incorporating variations in processing times; however, time constraints prevented these from being fully worked through. The conclusions of the interviews and the insights from the simulation model were incorporated into writing a functional design of an improvement plan. This plan was presented and discussed during several meetings with the stakeholders.
3.5 Ethical responsibility

Research ethics relates to questions about how the research topic is formulated and clarified, research is designed and access to information is gained. Furthermore, it ensures that data are collected, processed, stored and analysed in an ethical way. Finally, it ensures that research findings are written in a moral and responsible way (Saunders et al. 2009). Likewise, Easterby-Smith et al. (2008) introduced ten key principles of research ethics.

This research was conducted in accordance with such principles. Before the interviews, participants were asked for consent and informed about the aim of the interview as well as the research. Prior to the interviews, interviewees were informed that their participation was voluntary and that they had the right to withdraw from the process at any time. The data and information that individuals provided were treated anonymously and stored in a single desktop computer in such a way as to prevent the identification of individuals. Where applicable, participants were asked for permission to record the interview. Finally, as the case company relies on confidentiality, unnecessary details were left out.

4 Case description

4.1 Diagnosis of the current situation

The company used for the case study manufactures parts for civil and military aerostructures from composite materials and is a typical job shop. The company is organised according to a functional layout and manufactures products with a high variety of sizes and shapes. The company is considering whether to adopt Smart Manufacturing and has already conducted a pilot study to explore the requirements for an MES and identify the desired results. The company faces high WIP levels and unreliable or unknown information on how orders are progressing. Because of these problems, the management wishes to improve the delivery performance to the customer as well as between internal workstations and intends to achieve this by improving their estimation of due dates and performance in achieving them. Since the company concerned is delivering products to the aerospace industry, quality is paramount at all times and products are often scrapped for quality
non-conformance reasons. Once products are taken out of the process, a thorough inspection is required to enable a decision as to whether a rush order can be released or the part must be repaired.

In this company, long-term contracts are negotiated with several international customers. The company is planning on the basis of infinite capacity, which means that all orders will be accepted without any consideration of the actual shop-floor situation. Previously, the management had considered implementing WLC in their process but has since decided to release orders every day according to a plan prepared each week. The main processing sequence is illustrated in figure 4.1.

![Figure 4.1: Main processing sequence in company used in case study](image)

### 4.1.1 Process description

The first step in the production process is to cut out multiple component layers, called *plies*. The required materials are received from suppliers on large rolls. At the cutting workstation, multiple orders are batched to optimise throughput time and to minimise material waste, called *dynamic nesting*. A specific article can require several different materials. An important remark to be made concerning these materials is that they have a certain expiry date (open time) as soon they are removed from the freezer. This means that a product that exceeds its maximum open time is no longer of acceptable quality and must be scrapped. After the plies are sorted for each order, they are delivered to the lay-up department where they are placed into moulds and covered with vacuum bags.

When completed, moulds are placed into an oven or an autoclave and heated according to a product-specific temperature curve. The high temperature and pressure cause the plies to melt together and become a solid material. As each program has its own temperature curve and pressure schemes, orders need to be batched simultaneously at the autoclave station because of time- and cost-efficiency issues. As soon as the products are placed in the autoclave and heated, the open-time ends.
After autoclaving, the vacuum bags are removed and the products are removed from the lay-up moulds (debagging). After that, the machining department drills the necessary holes in the products and processes it according to the product specifications. After machining, the products are subjected to several quality checks and if within the set specifications, delivered to the assembly department. The production process can be separated into two parts. In the first part, production takes place in batches due to the efficiency gains at the autoclave stations. The second part of the production process can be considered as single piece flow process where orders move individually. Finally, this process delivers to an internal customer that assembles the products into larger sub-assemblies.

4.1.2 Current procedures and issues

The management wants to improve the due date delivery performance to the internal customer. This internal customer assembles the produced sub-assemblies and is therefore dependent on timely delivery. For the assembly department, the only way to estimate arrival time of orders is via verbal communication between the planners on the shop floor. The assembly department will benefit from accurate due date forecasts, since they can prepare their assembly activities.

The case company is facing a large variety in lateness. Some products start many days early, while others are up to hundred days late. Figure 4.2 shows a lateness histogram from 2014, when the case company completed 10,866 orders, of which 47.52% of the products exceeded their planned due date (from Alblas 2014).

![Lateness histogram](image-url)

*Figure 4.2: Lateness histogram of 10866 completed orders*
With the aim of reducing the variation in lateness, the company decided to give jobs priority by means of their individual lateness. This means that orders that are very late will be given higher priority in dispatching than products that are ahead of schedule. A major downside of this policy is that orders that arrived too early will remain at that station until their slack is totally used up. An order will only qualify to be selected when other orders with a higher lateness are completed. Because of this, unplanned load fluctuations occur in front of a workstation. Since the company releases orders based on infinite capacity, there are currently no workload norms or capacity constraints that limit the amount of work on the shop floor.

In order to reduce the amount of work and thereby create a controlled shop floor, the operations and logistics management departments of the case company are interested in implementing the WLC concept into their production process. However, until now, this has not been accomplished for several reasons. Interviews held with different individuals in the company revealed that many aspects complicate effective WLC implementation. As one of the interviewees remarked: “since we produce delicate products, quality is paramount. If we have to scrap a product, a rush order has to be released to replace it, resulting in an unreliable shop floor”. Sequence-dependent set-ups, parallel batching processes and complex routings complicate WLC implementation. In addition, several other aspects hinder WLC implementation in the case company:

First, the case company faces large deviations in their planned and actual station throughput times. This is caused mainly by the fact that most processes involve manual work and thus are more liable to variation. The standard processing times of every routing step are stored in the company’s ERP system. As we will see in the next section, these deviations can reduce the effectiveness of ODD-oriented dispatching rules.

Second, since aerospace manufacturing is a delicate process, many non-conformances to quality issues make the production process outcomes very unpredictable. In case of a quality issue, quality engineers must investigate the product and decide whether it can continue in the process. If not, a new production order must be released to the floor to replace the scrapped one.

Finally, there is no reliable or accurate information available about order progress. Planners and operators must search the floor in order to locate a product and communicate with each other in
order to get an idea of future workloads. Moreover, many rush orders are scheduled, which disturb the initial planning. Consequently, estimating direct as well as indirect workloads is a complex task.

5 Results

The previous sections have highlighted the gap between theory and practice regarding the WLC concept. Section 2.4 already presented some initial ways to overcome the complexities found in the literature. Now, this section presents the results of the case study conducted with reference to the three propositions presented. First, section 5.1 will discuss the findings regarding the implementation smart principles in the case company, thereby trying to bring practice closer to WLC theory. A control system is proposed in section 5.2 that develops WLC theory based on these findings. This system is able to detect major process fluctuations and trigger alerts when action needs to be taken to correct them. This section also elaborates on the identified opportunities; making smart release and smart dispatch decisions and implementing smart output control. Section 5.3 discusses how job shop complexities can be addressed.

5.1 Bringing practice closer to WLC theory

In the case company, several project groups were found to be working on the subject of Smart Manufacturing. Their joint goal is to capture and improve the supply of accurate, real-time information throughout the company. Interviews revealed that in the case company more and more technologies are being adopted to capture relevant shop-floor data.

Several kinds of RFID technology are being implemented to locate raw materials and to keep track of the open time of the materials. RFID tags are placed on individual plies to track their progress from the inventory to the production process. When a roll of material leaves the inventory storage, RFID receivers identify the unique tags and transmit signals to a server, which keeps track of the open time of that material. When the permitted open time is about to expire, an alert is triggered to warn operators to process the material soon.

During the time the researcher was present at the case company, an innovative scanning system was implemented to track the progress of individual products. This system enabled the location of orders
to be tracked. This data is transferred to the ERP system and is updated every four minutes. This “nearly” real-time information is presented to the shop floor via large screens and indicates the orders currently located at each workstation. Furthermore, this information is presented to the operators to inform them about the sequence in which orders must be picked up according to the dispatching policy.

These developments in information and tracking technologies are able to satisfy the shop-floor feedback requirements for successful WLC implementation as indicated in the literature (see Henrich et al. 2004). These findings and observations are considered to be a confirmation of the first proposition.

5.2 Development of WLC theory

The scanning system used in the case company allows for the creation of a real-time overview of all the queues and their contents that are currently in the factory. This fact creates a great opportunity to refine WLC theory (see figure 5.1). Insights gained from the simulation model have led to the proposal for development of a production control system that will be introduced in this section. This production control system allows for making smart release decisions and dispatch decisions and implementing smart output control, as discussed in 5.2.1, 5.2.2 and 5.2.3 respectively.

![Figure 5.1: Schematic overview of the development of WLC theory, where a production control system provides three opportunities](image)

However, as WLC is known and admired for its robustness and its simplicity, as much as possible of the existing concept will be retained in order to maintain its ease of use. Based on the opportunities found in the case company, the simulation model created was used to explore the
opportunities and to gain insights. These insights resulted in the design of a control system that maintains the integrity of the existing WLC concept while offering an alternative method that can be followed in the event of major process fluctuations. The following sections only provide the theoretic design of the control system.

**Design of the production control system**

The proposed control system uses real-time data to predict the consequences of certain release and dispatch decisions and simulates the scenarios regarding future workload levels that can be expected based on current performance. The starting point of this system is the estimation of the arrival time of every single job at each step in its routing. The estimated time a specific part will leave its current station is determined by its own processing time plus the processing times of the orders that will be processed before that specific part. In fact, this represents the estimated time an order will be present at a workstation. This time will be indicated by an order’s Estimated Station Throughput Time (ESTT). Smart concepts are able to monitor the process and record the required information continuously in an integrated system. These data can be used not only to detect actual fluctuations as soon as they occur but also to predict potential fluctuations.

The practice of simulating future progress of orders is not an innovation of itself. The company under consideration already performs such calculations in order to estimate the completion times of the steps in its processes and currently does so in two ways. The first way, without taking shop floor information into account, uses predetermined PSTTs to predict the progress of each job: this is similar to the process used to determine ODDs but carried out in reverse. The second way does take the shop floor information into account: the planners check the actual queues manually at each station and make complex calculations, which are very time-consuming and the results are valid only for a limited period, as fluctuations make these calculations unreliable. In the proposed system the results are also valid only for a limited time, but as they are calculated automatically without relying on manual checks and updated continuously, this is less of a problem.

Data provided by smart concepts can be used to determine ODDs based on the current performance on the shop floor. From now on, we will refer to an ODD calculated from real-time information as ODD*. Whereas ODDs are constant, ODD*s will vary continuously, since they are calculated from
actual information regarding the progress of orders, which itself is liable to vary. Calculating the ODD* for a job’s current operation is relatively simple. The calculation of ODD*s is similar to that used to determine ODDs in section 2.1, but with the important difference that the calculations are based on the real-time shop floor situation rather than on the processing times in the initial plan. Based on the priority assigned to orders in accordance with the dispatching criteria for that workstation, calculating a specific job’s ODD* is achieved by adding the processing times from all the other jobs with higher priority that will be processed before that job. In contrast, calculating the time a job will enter and complete subsequent steps in its routing is far more complex. In this case, the calculation now requires processing times and priority information of orders that have not yet arrived at the subsequent workstations. Creating virtual queues can overcome this problem.

**Creating virtual queues**

Creating virtual queues to estimate future order progress and workload levels requires two sorts of information: information about jobs currently in the queue waiting to be processed (direct load) and information about jobs that will arrive in a certain period at this workstation (indirect load). For each workstation, a virtual queue can be constructed, in which information on both direct and indirect loads on the system can be assembled and updated and which can be used to track the sequence in which these jobs will be processed. This sequence is determined by the order in which both direct and indirect loads are listed in the queue is determined by the dispatching policy associated with that workstation.

An ESTT represents the estimated amount of time an order will need to complete a step in its routing. It should be noted that this is a real-time estimate of a product’s waiting time plus its specific processing time. Therefore, an ESTT is calculated by *formula 1*:

\[
(1) \quad ESTT = p + pd + pi
\]

where \( p \) represents the processing time of the order under consideration, \( pd \) the sum of processing times of the direct load at the station with a higher priority according to the dispatching policy and \( pi \) the sum of processing times of the indirect load at the station with a higher priority according to the dispatching policy.
When the ESTTs of all steps in an order’s routing are known, the corresponding ODDs* and the ODD*\text{final} can be derived, the latter representing the moment each part will leave its final operation and can be dispatched to the customer. Figure 5.2 shows how ODDs* can be calculated with ESTTs. The ODD* for a specific workstation is derived by adding the ESTTs from the preceding workstations starting with the one where the job is currently being processed.

![Diagram showing calculation of ODDs*](image)

**Figure 5.2: Calculation of improved ODDs based on real-time information**

*Formula 2* shows the calculation of an ODD* for the \( k \)th operation of an order \( j \) with \( K_j \) operations in its routing:

\[
ODD^* = now + \sum_{i=k+1}^{K_j} ESTT_{ij} \quad for \quad k = 1 \ldots K_j
\]

As ESTTs are based on the actual shop floor situation where – especially in job shops – fluctuations are common, ODDs* will fluctuate as time passes. Actual station throughput durations and delivery times will match the ESTT and an ODD* respectively when: a) process times are as planned and b) when each station adheres to the fixed dispatching policy. Especially for machine-intensive operations, these estimations will in general be reliable, as planned processing throughput times rarely deviate much from those achieved in practice. Although similar to other calculation methods, in that it also relies on standard processing times, the proposed method is still valuable since it provides a real-time indication of the likely future progress of orders. An additional advantage is that no human actions are required. The calculation of ODDs* can assist the application of WLC by correcting significant fluctuations, as the next sections will demonstrate.

*Figure 5.3* shows the construction of virtual queues for station 2 and 3, based on the initial set-up situation in the simulation model. The virtual queues for workstation 2 and 3 are sorted according to all jobs’ individual lateness at this specific workstation, as the company in our case study follows
this policy to determine priority of dispatching. A negative value represents an order that is early according to its planned ODD. An algorithm determines the sequence in which orders in the virtual queues will be processed. This sequence is the basis for the calculation of ODD*s, which represent the estimated units of time that will pass until that order will leave the station. This means that if we assume that station 3 is the final routing step, the ODD* for that station will also be the order’s ODD*final. When a complete simulation is run, these values match the forecasts.

![Figure 5.3: Creation of virtual queues based on initial set-up](image)

**Parallel use of ODDs within the control system**

The control system should be able to provide ODDs* in real-time, so we can compare scheduled ODDs with ODDs*. This comparison enables identification of significant deviations between these values and hence the need to take corrective action. When a job’s ODD* is earlier than its ODD, that job is expected to arrive ahead of schedule. In turn, when the ODD* is later than the ODD, that job is expected to arrive later than scheduled.
These deviations can be reduced by applying alternative dispatch decisions. “Smart” dispatch decisions are able to correct an unwanted order progress fluctuation. We propose to use this system in parallel with original ODD information to identify deviations between the initial set ODDs and the calculated ODDs*. These systems should always be used in parallel, as basing production decisions on fluctuating ODDs* would result in a very volatile production environment. Since we base the estimations on information that is constantly liable to variation, ESTTs are also liable to change. Therefore, alternative decisions should be made only when deviations exceed a predetermined norm. When this system is used in parallel with WLC, it can assist the achievement of the objectives of WLC by damping the effects of severe disturbances.

Figure 5.4 shows the parallel functioning of these two systems. First, the PRD is determined by backward scheduling with PSTTs in the usual way and orders are released to the floor on that date. All ODDs will then be determined as usual. After an order is released to the shop floor, the parallel system continuously calculates all ODDs* based on the actual shop floor status.

![Figure 5.4: Difference between ODDs and ODDs*, resulting in Δt_{final}](image)

The difference between a job’s ODD and ODDs* is calculated by formula 3.

\[
\Delta t = ODD - ODD^*
\]

where Δt represents the difference between the planned due date and estimated actual completion date. Figure 16 illustrates this process by showing that the ESTT of the job’s second operation is larger than the PSTT that was used to determine its ODD. Disturbances may have caused a large workload at the second station and the ESTT of the second operation is therefore larger than its
PSTT. Although $\Delta t$ can represent a deviation at workstation level, we are also able to derive an $\text{ODD}^{*}_{\text{final}}$, referring to the moment at which an order will complete its total routing. This can be calculated as the sum of the $\text{ODD}^{*}$s for all steps in the order’s routing. In this example, the $\text{ODD}^{*}_{\text{final}}$ of this order is later than its planned due date and therefore the order is expected to arrive late. This results in a negative $\Delta t$, since the $\text{ODD}^{*}_{\text{final}}$ is larger than the $\text{ODD}_{\text{final}}$.

A negative value of $\Delta t$ indicates an order that is behind schedule and, if significant, can alert management to the need to consider whether the agreed due date can still be met or what alterations or decisions have to be made to still meet the due date. There are two options available for accelerating or decelerating orders: firstly by altering priorities in dispatching and secondly by increasing or decreasing production capacity of workstations. The following three subsections discuss the opportunities that a more sophisticated algorithm could bring in a real-life job shop.

### 5.2.1 Smart release decisions

As discussed in the theoretical background, various authors have tried to develop methods to include the indirect load when calculating workload levels. The limited availability of shop-floor information made accurate forecasting of incoming workloads impossible. Most methods used an arbitrary discount factor to distribute the amount of workload to a job’s subsequent workstations. By aggregating all jobs that have their $\text{ODD}^{*}$ in a particular period, we can derive an expected future direct load. This information can be used to create an overview of the amount of workload that is estimated to arrive during that period. Adopting this method overcomes the complexity of estimating indirect workloads as discussed in section 2.2.2, as an indication of expected workload is now continuously available. *Figure 5.5* shows an example of a chart based on the information in the simulation model indicating the expected workload for a specific workstation in steps of a day.
Figure 5.5: Representation of expected workload for station 2, based on the actual shop floor information

We can develop a new method of making release decisions, based on the additional information now available about the estimation of the future workloads at all stations in an order’s routing. These levels are an indication of the sum of a station’s direct and indirect loads. When making the release decision, future workload levels can be compared with the workload norms. For the jobs in the order pool waiting to be released, the control system is able to calculate the contribution of the workload for each workstation in an order’s routing. This is calculated in the same way as the contribution of workloads already released to the shop floor. An order is selected for release when its contribution to the workstations in its routing falls below the expected workload norms of all its routing steps (see figure 5.6). This method of releasing orders contributes to the effectiveness of the timing as well as the balancing function.

Figure 5.6: Example of an improved release decision. Estimated future workloads are compared with the workload norms
Breithaupt et al. (2002) have argued that a release decision should not consider workload levels of stations further than four process steps away from the order pool, since this guarantees the consideration of the actual loading situation at the workstations. On the other hand, events that will take place in the distant future and which will influence the release of orders can be avoided. If we assume that future workload estimates are accurate, we could argue that this scope of four routing steps can be increased, since we are considering the actual shop-floor status and subjective discount factors can therefore now be omitted.

5.2.2 Smart dispatch-level decisions

Land et al. (2014) focused on overcoming the conflict between order release and dispatching by combining load-based order release and due date oriented dispatching rules. They found that redistributing the extra or reduced slack at the actual release dates across all ODDs avoids both acceleration and deceleration of released orders in the initial routing steps. Although their findings address this conflict, unforeseen circumstances can still arise after the release decision, of which WLC currently takes no account. The findings of their research suggested no methods for addressing disturbances when orders have already been released to the shop floor. In their recommendations for future research, they indicated the need to put more emphasis on developing effective priority dispatching rules to control the progress of orders that have been released to the shop floor. Making use of ODDs* in parallel to the original concept, may address this issue. As Cransberg et al. (2015) concluded, fluctuations that arise further down an order’s routing can hardly be influenced by release decisions and therefore should be corrected at the dispatching stage.

If the value of $\Delta t$ at the operation as well as at the process level exceeds a predetermined norm, the operator of a station may decide to alter the priorities of orders to be dispatched. A negative $\Delta t$ indicates an order that would be delivered too late if no alternative dispatch decisions are made. It is particularly important to take urgent corrective action in cases where $\Delta t$ is large, since this can involve late deliveries to the customer. As the company under consideration is delivering products to the aerospace industry, on-time delivery of orders to the customer is crucial. Large penalty costs would be imposed for each day an order is delivered late. Therefore, if $\Delta_{\text{final}}$ is large and negative, indicating a large delay beyond the agreed due date, alternative dispatching decisions would need to
be made. Figure 5.7 gives an illustrative example of a common situation within the case company where making alternative dispatch decisions could be appropriate.

![Diagram showing a dispatch decision example](image)

**Figure 5.7: Smart dispatch decision where pulling item B forward could be appropriate because of large penalty costs**

This example considers a dispatching decision at station 1. In this case, item A is 30 days behind schedule according to its ODD, whereas item B currently is 10 days behind schedule. Normally, when an ODD-oriented dispatching rule is applied at station 1, order A would be selected for processing. Currently, operators in the company under consideration can receive information about the workload at other stations only by calling other operators at the other stations, which requires investigation and communication.

If the control system performs the proposed calculations based on the actual shop-floor situation, item A will complete its final operation 10 days behind schedule, whereas item B will be 20 days late. The lateness at the start of item A is mostly eliminated by the fact that its throughput times in the remainder of its routing will be lower than planned. The expected lateness at the final station of item B will remain the same. It turns out that – because of high workload levels in the routing of item B – the $\Delta t_{\text{final}}$ of B is larger than that of A.

If on time delivery of item B is critical, as is common in the aerospace industry, large penalty costs can be imposed. In this case, it could be wise to deviate from the dispatching rules currently in force. Especially when processing times are large, alternative decisions can be effective. This paper
does not argue that the calculations of $\Delta t_{\text{final}}$ should be followed in every case. Nevertheless, information on the completion time of an order can assist dispatch decisions by indicating process fluctuations. If these fluctuations are critical, alternative dispatch decisions can correct them.

*Figure 5.5* illustrated that by aggregating ODDs* excessive future workloads could be identified in advance. Basing priority of dispatching on these estimates could contribute to the balancing function of WLC. If there is an indication that a workstation will receive little load or will be idle in the near future, it could be beneficial to alter the priority of orders with long processing times and redistribute them to this station. Moreover, redistributing work to idle stations gives the opportunity to release additional orders, since overall workloads will decrease and may fall below the workload norms. In the literature, this is referred to as “*premature idleness*”.

### 5.2.3 Smart output control

A second way to correct workload fluctuations is taking advantage of opportunities to control output from specific workstations. We have already seen that ODDs* enable the calculation of estimated future loads. If these estimates are compared with the actual capacity of a workstation, possible capacity surpluses and shortages can be identified. *Figure 5.8* illustrates an example situation displaying the expected workload per day, but now with the workstation’s actual production capacity projected over it. Here, the blue bars indicate the expected load and the green and red bars indicate the expected surplus and shortages in capacity respectively. It should be noted that output control will be most effective for workstations where capacity is largely determined by machines. In case of dual resource constrained systems, referring to workstations where both machine and human resources influence the production capacity, it is a more complex task to determine to determine maximum capacity.
In this example, management could choose to allocate extra workers on days 7 and 8, or try to pull some orders forward to earlier days. The figure also shows a clear capacity surplus period during days 2-6. This surplus could also be used to give operators days off or to perform maintenance on machine-intensive workstations. Another opportunity to use this information is to replace operators to other stations that are expected to have shortages in capacity. In conclusion, adapting production capacity based on estimates of future workloads could help to damp peaks in workload.

5.3 Addressing job shop complexities

Type 1 complexities

One of the important process steps in the routing of most orders in the company under consideration involves a process where large batches are processed simultaneously in an autoclave. As this processing step is located early in most routings, release decisions can influence the work that will arrive at this workstation to a relatively high extent. On the one hand, WLC tries to balance the workload, while on the other hand the autoclave must be filled as much as possible for efficiency reasons. Interviews with planners revealed that considering anticipated progress of orders already at the release stage could contribute towards making an effective trade-off. For example, estimates provided by the proposed model as to the progress of future orders could provide early warning of problems likely to occur regarding filling batches; making alternative release decisions can
contribute to making this trade-off. This information could identify the need to relax the workload norms or to reconsider release decisions, thereby assisting the effectiveness of release decisions. This could greatly support to an appropriate filling of the autoclave stations. As Cransberg et al. (2015) have argued, for processes further downstream in a routing, dispatch decisions should assist in trading off the functions of WLC. Section 5.2.2 has discussed these opportunities.

Type 2 complexities

Type 2 complexities make it difficult to make well-informed and appropriate decisions within WLC. The proposed control system, based on continuously updated information, could provide support to those making the decisions. Once decisions have been taken, the control system can indicate significant fluctuations and indicate the need to take corrective action. The previous sections discussed the opportunities offered by smart release, dispatch and output control decisions. Following the opportunities discussed in these sections to improve WLC theory and bring practice closer to theory could help to address type 2 complexities by providing accurate information that will enable decisions to be reconsidered if necessary.

Considering information indicating fluctuations in the progress of orders could be a starting point for addressing the conflict identified by Land et al. (2014) between controlled release and ODD-oriented rules. ODD-oriented dispatching slows down early orders and speeds up late orders, thereby creating unnecessary workload on the shop floor. If major fluctuations in the progress of orders occurs, the parallel system will indicate unwanted deviations in ODDs and actions can be taken to correct the disturbances or order progress fluctuations that may have occurred after the orders were released to the shop floor. This will reduce the conflict between controlled release and ODD-oriented dispatching rules because when major fluctuations are corrected in advance, orders will follow the planned schedule and thus their ODDs more closely.

This paper argues that incorporating smart features in the production process could reduce the effects of type 2 complexities by providing up-to-date information about shop floor process fluctuations.
5.4 Validation

Validation of the proposed model was performed in two ways. Firstly, a simulation model was designed for a simple three-step routing that dispatched orders according to the rules currently followed in the company under consideration. A random data set was used to find out more about how arrival times of orders could be estimated in the company. Applying this model demonstrated that if dispatching rules are followed and there is no variation in processing times, a sophisticated model can be created in reality to estimate actual arrival times of individual orders and thus workload levels. Secondly, group meetings with different individuals from the company strengthened the development of the model by incorporating practical experience. Finally, interviews were conducted with operators and planners to find out whether a more sophisticated model could be viable and useful in practice. The analysis showed that there are currently no ways to get any indication of future workloads and therefore operators are confronted with an unidentifiable workload. Reactions to the proposed method have been positive; however it is also clear that more empirical research is required. Following the reactions, the idea of controlling output based on estimates of future workloads was especially welcomed.

6 Conclusion and directions for future research

In order to increase the practical applicability of WLC, this paper has explored the opportunities that smart concepts can deliver to narrow the gap between WLC theory and practice. Previous studies have tried to bring WLC theory and practice closer together, but no-one seems to have addressed this issue by incorporating smart features. By investigating a production company in a case study, this study aimed to reconcile WLC theory and practice: firstly, by indicating how practice in real-life jobs shops can be aligned so as to match more closely the assumptions about reality in the WLC literature; and secondly, through developing WLC theory to overcome two types of complexities and dampen process fluctuations.

An in-depth literature research on the subjects of WLC and Smart Manufacturing indicated potential opportunities for improvements that smart principles could effect to the well-studied WLC concept. Based on the complexities described in the literature that complicate successful implementation of
WLC, a categorisation of complexities is proposed. With data obtained from interviews, observations and documentary analysis, a deterministic simulation model was constructed to acquire insights and to further investigate the opportunities for applying smart principles within the company concerned. These insights have led to the formulation of three propositions, which form the basis of the research model used in this study to identify ways to increase the applicability of WLC in practice by incorporating smart principles.

Observations and interviews held in the case company revealed that smart principles are able to bring practice closer to the theory by providing the shop-floor information assumed to be available in the WLC literature. These findings and observations are considered to be a confirmation of the first proposition and thus contribute to narrowing the gap between theory and practice.

Improvements to the supply of information in the case company and the findings and insights gained from the simulation model have led to the suggestion to develop WLC theory by designing a production control system. This control system uses real-time data to predict the consequences of certain release and dispatch decisions and simulates the scenarios regarding future workload levels that can be expected based on current performance. If such a sophisticated production control system is put in operation, three clear opportunities can be identified that refine WLC theory: smart release and smart dispatch decisions and the implementation of smart output control, which together enable the second proposition to be achieved. The last opportunity in particular, was welcomed in the case company. These opportunities may be able to refine the theory, thereby narrowing the gap from the theory side.

Finally, the third proposition stated that narrowing the gap could increase the ability to deal with the identified complexities. Interviews revealed that using information from the control system could address type 1 complexities by identifying the need to relax the workload norms or to reconsider release and dispatch decisions so as to overcome the consequences caused by, for example, large batch processes. On the other hand, this information could help to address type 2 complexities by providing accurate information that will enable decisions to be reconsidered if necessary.

Future research could, for example, investigate in more detail the functioning of smart release and dispatch decisions based on up-to-date information. Simulation studies could prove the viability of the calculations presented and investigate to what extent estimates are useful when process times are
liable to variation. Besides these, a study could focus on the issue of determining at what point fluctuations become significant and when alternative decision-making is relevant. Furthermore, from a more practical point of view, researchers could think of ways to incorporate actual information into ERP or MES systems on the shop floor.

### 6.1 Discussion and limitations

A major limitation to the arguments and opportunities proposed in this study is the occurrence of process fluctuations in job shops. The proposed calculation model is accurate if dispatching policies are followed and process times are as planned. However, job shops without fluctuations, unfortunately, hardly ever exist in practice. This paper argues that using the actual progress of orders to estimate arrival times is a large step towards improving the process control of job shops. Certainly, fluctuations will inevitably exist, but forecasting them and taking correcting actions or alternative decisions in advance is a big step towards coping with them and reducing their influence.

Although many opportunities can be identified that could contribute to improved WLC applicability, it is beyond dispute that thorough research is required to build on the propositions made in this case study. This is considered to be only the beginning of the search for advancements in production planning and control of job shops and it may well be that Smart Manufacturing will make WLC redundant, an idea that the discussion section elaborates further.

The creation of a more sophisticated simulation model could achieve further advances in performance. Time constraints prevented the creation of such a model as part of this study. The required information was available; however programming such a sophisticated model was a task too complex for the time available. Although this research has focused on a single case, the proposed general principles could be applied to other job-shop-type production environments. This single case can then be seen as an example of how smart principles can be incorporated in order to take more control of the shop floor, by estimating future order progress.

A few decades ago, the WLC concept was developed as a simple autonomous system that ensured that little monitoring was required. The ideas presented in this research can be seen as a sort of simulation-based scheduling and this practice is moving away from WLC, where the system itself
determines the decisions that are made. Therefore, it could well be that in the near future Smart Manufacturing features will make WLC principles redundant, as having real-time shop-floor information available is becoming more and more of a reality.

Other researchers may wish to explore this interesting new field of research further and build on the opportunities identified in this paper.
References


Fowler, J. et al., 2010. Workload control in the semiconductor industry, Production Planning and Control (June 2015), pp.37–41.


Appendix A– Overview of simulation model
Appendix B – Simulation steps with time intervals of 10 T

The screenshots below show the functioning of the simulation steps, increasing time (T) with intervals of 10. On the right hand side, you can see the finished products.

T=0

T=10