

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Materials Handling in Production Systems:
Design and Performance of Kit Preparation

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Gothenburg, Sweden 2019

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PATRIK FAGER
ISBN 978-91-7905-143-3

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Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr 4610
ISSN 0346-718X

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Printed by Chalmers Digital Print
Gothenburg, Sweden 2019

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Abstract

This thesis focuses on processes for kit preparation, which are applied with the materials supply principle of kitting in production systems for mixed-model assembly. With kitting, assembly processes are supplied with portions of pre-sorted components, and each portion makes up a kit that holds the components needed for one assembly object at one or several assembly processes. When kitting is applied, picking activities, which are otherwise performed at assembly processes, are instead carried out in a process for kit preparation. Kit preparation involves collecting components designated for a particular assembly object into a single unit load that is delivered to assembly.

Kitting is widely seen as beneficial for quality and flexibility in assembly processes when there are a large variety of components. Performance effects in assembly processes normally associated with kitting largely depend on the performance of kit preparation. Previous research indicates that a picking system's design greatly impacts its performance. While research that has dealt with kit preparation points out several design aspects that can affect its performance, the available knowledge is far from exhaustive. The purpose of this thesis is to contribute to the knowledge of how kit preparation design aspects govern kit preparation performance.

Case research, experiments, and modelling have been used to study how flexibility, kit quality and man-hour efficiency are affected by kit preparation design aspects related to work organisation, layout, policies, packaging, equipment, picking information, automation and control. Two case research studies respectively address kit preparation flexibility and kit quality, identifying how kit preparation design aspects can be configured to support these two performance areas. Two experiments focus on how picking information systems and confirmation methods affect kit preparation man-hour efficiency. One modelling study focuses on how collaborative robots can support man-hour efficient kit preparation. Through involvement in three research projects and an extensive review of the literature, this research has been guided by the needs of industry and by previously established knowledge.

This thesis contributes to theory and to practice in the form of knowledge about relationships between kit preparation design aspects and the performance areas flexibility, kit quality and man-hour efficiency. The theoretical contribution consists of building upon and underpinning the limited knowledge about the topic that has been previously available, while also adding new knowledge. This includes, for example, glasses with integrated computer displays, RFID-scanning wristbands, and collaborative robots, and how they are linked to kit preparation performance. The practical contribution consists of concise yet holistic descriptions of relationships between kit preparation design and performance, which industry can readily adopt with some consideration to the situation's characteristics.

Keywords: materials supply systems, kitting, kit preparation, order picking

List of appended papers included in the thesis

This thesis is based on research reported in five research papers. Each research paper is included in full after the cover paper.

Paper I

Fager, P., Hanson, R., Medbo, L. and Johansson, M. I. (2019), “Supporting flexibility of kit preparation for mixed-model assembly”, *Submitted to International Journal of Logistics Systems and Management*.

Paper II

Fager, P., Hanson, R., Medbo, L. and Johansson, M. I. (2019), “Links between kit quality and kit preparation design”, *Submitted to International Journal of Production Research*.

Paper III

Fager, P., Hanson, R., Medbo, L. and Johansson, M. I., (2019), “Kit preparation for mixed model assembly – efficiency impact of the picking information system”, *Computers and Industrial Engineering*, Vol 129, March 2019, pp. 169-178, DOI: 10.1016/j.cie.2019.01.034

Paper IV

Fager, P. (2018), “Kit preparation for mixed-model assembly: efficiency impact of confirmation methods”, *Industrial Management and Data Systems*, Vol. 119, No. 3, pp. 547-560, DOI: 10.1108/IMDS-07-2018-0287

Paper V

Fager, P., Calzavara, M. and Sgarbossa, F. (2019), “Cobot-supported kit preparation for mixed-model assembly”, *Submitted to The International Journal of Advanced Manufacturing Technology*.

Acknowledgements

I would here like to express my gratitude to the people and organisations who have contributed to my research. This thesis would not have been realisable without your guidance and contributions.

I have written this thesis as part of three successive research projects, all of which have involved parties from both industry and academia. I am deeply grateful for this opportunity, as I have been able to learn first-hand from experts both from industry and academia. I would like to thank Vinnova for the financial support via the FFI-research programme.

I especially would like to thank my supervisors at Chalmers, Lars Medbo, Mats Johansson, and Robin Hanson, for guiding me throughout this process. Lars, thank you for your relentless energy and supportive leadership, always keeping my head on straight and ensuring that things move in the right direction. Mats, thank you for your steadfast guidance and your superhuman ability to identify flaws in my texts and reasoning, you have taught me a lot about writing and thinking clearly. Robin, thank you for the fruitful collaborations and for sharing your vast knowledge of the research area, you have taught me a great deal about conducting research. I have thoroughly enjoyed our conversations and learnt a lot from each one of you.

I would also like to express my gratitude towards my colleagues at Chalmers, it has been a privilege and a pleasure working with you.

Patrik Fager

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1. Introduction

This thesis deals with materials handling in production systems, in the form of materials handling activities that are performed to support assembly processes in an assembly system. Specifically, the thesis focuses on processes for ‘kit preparation’, which are applied with the materials supply principle of ‘kitting’.

The introductory chapter of this thesis begins by presenting the research area’s background, describing the characteristics of the type of industry studied and the conditions set for materials handling activities. Thereafter, kit preparation is introduced and the role of kit preparation design and performance within production systems is described. Subsequently, the purpose of the thesis is presented, leading to a derivation of three research questions that have guided the thesis. Finally, the research scope is presented, followed by an outline of the thesis content.

1.1. Background of the research area

Materials handling in production systems is closely tied to the production system’s characteristics, and it is crucial to first understand the characteristics of the type of production that this thesis involves before kit preparation is dealt with. Therefore, this subchapter presents the background to the thesis’ research area.

The subchapter explains how kit preparation performance plays an important role for many performance effects of assembly processes normally associated with materials supply by kitting. Furthermore, previous research that has dealt with design of kitting and order picking systems is highlighted, in order to show that kit preparation performance can be affected, and potentially enhanced, by choice among options of kit preparation design aspects. The subchapter lays out the foundation for the thesis’ purpose, which is stated in the next subchapter.

1.1.1. Kit preparation for mixed-model assembly

In most of today’s manufacturing industries, a company’s ability to satisfy its customers’ needs for variety, quality and pricing provides a critical competitive advantage. End-product customisation is often central, and principles of mass-customisation are typically applied to achieve the desired customisation levels with economies of scale (Da Silveira et al., 2001). Within the assembly industry, mixed-model assembly is a typical approach to mass-customisation, by which a multitude of end-products can be assembled using the same set of resources. With mixed-model assembly, the assembly work going into the finished product is divided amongst assembly processes, and the end-products are typically built from interchangeable platforms and components. For example, this can be used in the automobile industry, where car models can have billions of variants (Pil and Holweg, 2004). Here, there is a need for materials supply systems that can effectively handle a multitude of component variants (Boysen et al., 2015).

The widespread use of mixed-model assembly production principles has resulted in new requirements for materials supply systems (Boysen et al., 2015). Materials supply systems involve various interrelated elements, including materials feeding, storage, transportation, materials handling, packaging and manufacturing planning and control, each of which plays an important role in supporting production (Johansson, 2006). Materials feeding determines how materials are arranged when supplied to, and presented at, assembly processes, and can be carried out according to different principles of materials supply (Hanson, 2012). Previous research has dealt with performance effects on mixed-model assembly processes from use of various principles of materials supply, for example, several variations of line stocking (e.g. Caputo et al., 2018; Hanson, 2012), part-sequencing (Sali and Sahin, 2016; Johansson and Johansson, 2006) and kitting (Limère et al., 2015; Caputo and Pelagagge, 2011). Kitting is frequently adopted with mixed-model assembly, widely seen as beneficial when there is a large variety of components (Limère et al., 2012; Caputo

and Pelagagge, 2011; Medbo, 2003). As previously stated, the focus of this thesis is on the materials supply principle of kitting.

With kitting, assembly processes are supplied with portions of pre-sorted components, and each portion makes up a kit that holds the components needed for one assembly object at one or several assembly processes (Bozer and McGinnis, 1992; Johansson, 1991). When compared with other materials supply principles, such as line stocking (Hanson, 2012), kitting is typically distinguished for improving flexibility (Caputo et al., 2015; Hanson and Brolin, 2013; Hanson, 2012; Caputo and Pelagagge, 2011) and quality (Caputo et al., 2017a; Caputo et al., 2017b; Caputo et al., 2015; Hanson, 2012; Medbo, 2003) in assembly processes.

Two typical reasons for introducing kitting have been reported as: 1) to improve space utilisation through increasing the amount of product variants that can be assembled by only presenting the components needed for one assembly object at a time (Limère et al., 2012; Hanson, 2012); and 2) to improve assembly efficiency by reducing time spent in walking and searching for parts (Caputo et al., 2015; Hanson and Brolin, 2013; Limère et al., 2012). A third reported reason is that the use of kitting can facilitate assemblers' cognitive processes, and shorten learning times associated with assembly tasks, by presenting components in a way that assembly procedures become obvious, thereby supporting that components are assembled correctly (Medbo, 2003; Brynzér and Johansson, 1995).

Kitting involves a variety of activities. When it is applied, picking activities otherwise performed in assembly processes are instead carried out in a process of *kit preparation*. Kit preparation involves collecting components designated for a particular assembly object into a single unit load – a *kit* – that is then delivered to assembly (Johansson, 1991). In addition to kit preparation, kitting involves transportation activities to replenish kit preparation workspaces with materials, and, often, delivering kits to assembly processes (Hanson, 2012). Moreover, kitting involves return flows of containers, and kitting activities must be accounted for within the manufacturing planning and control system (Bozer and McGinnis, 1992). While all these activities are critical with respect to kitting, the focus of this thesis is on the kit preparation.

Processes for kit preparation can be configured in many ways (Brynzér and Johansson, 1995), and the suitable kit preparation design to use depends on characteristics in the context, and the performance requirements of a specific application (Hanson, 2012; Brynzér and Johansson, 1995; Brynzér, 1995). Generally, kit preparation is organised as compact workspaces at which components are collected from storage and sorted into kits (Hanson et al., 2017). These activities can be performed manually, semi-automatically, or fully automatically (Brynzér and Johansson, 1995). With manual kit preparation, pickers collect components from storage and sort these into kit containers, guided by information about which components are required for specific kits. Kit preparation can be performed at different locations in the materials supply system, and by different categories of personnel (Hanson, 2012). For example, it can be performed by assemblers as part of assembly work, or it can be performed by logistics personnel who work exclusively with kit preparation in a warehouse (Brynzér and Johansson, 1995), and depending on what configuration is used, performance will differ (Hanson et al., 2011). There are many other aspects to how kit preparation can be configured, and, to some extent, all of these factors govern kit preparation performance, and must be chosen with respect to context characteristics for specific applications. As shown in Chapter 2, literature that describes how kit preparation design aspects govern kit preparation performance is scarce, and there is no consensus in industry as to which aspects are important or which options should be used.

1.1.2. Performance effects of kit preparation

As previously mentioned, several performance effects in assembly processes from use of kitting with mixed-model assembly have been identified in the literature. This section presents an overview

of performance effects that have been consistently reported in the literature and in industrial applications of kitting, aiming to show that many reported performance effects in assembly processes from use of kitting are intertwined with performance of kit preparation.

Kitting is often reported to save space and to reduce work-in-process at assembly workstations, since materials are stored at kit preparation workspaces, which usually are separated from the assembly processes (Bozer and McGinnis, 1992). In fact, kitting may even enable assembly in situations with many end-product variants, where space at assembly processes is particularly scarce (Hanson, 2012). However, kitting has also been reported to increase space requirements at other places in the production system, due to the space required for kit preparation workspaces, and, if kits are prepared ahead of production, the kits themselves can require additional storage space (Caputo et al., 2018; Hua and Jonsson, 2010). Furthermore, if there are temporary material shortages during kit preparation, partially complete kits require storage space until new materials have been replenished (Bozer and McGinnis, 1992). Hence, space requirements directly associated with kit preparation are largely responsible for the space requirements associated with kitting.

Kitting has been ascribed effects with respect to inventory levels (Hanson, 2012), as well as improving the control and visibility of inventory (Hanson et al., 2011) and work-in-process (Bozer and McGinnis, 1992) within production systems. The use of kit preparation necessitates that sufficient amounts of inventory be available at kit preparation workspaces, which often contributes to inventory storage points in the material flow (Hanson et al., 2011). Kitting also has an effect on transportation within the production facility, as materials need to be transported to kit preparation workspaces, and kits need transportation from kit preparation workspaces to assembly processes (Hanson et al., 2011).

From an ergonomic standpoint, kitting is often seen as beneficial at assembly processes, since assemblers can easily access components readily available from kit containers (Medbo, 2003). However, some researchers have raised concerns with respect to ergonomics of kit preparation, as it involves materials handling work, which can consist of repetitive tasks, heavy lifts, and straining body postures (Christmansson et al., 2002). Previous research has shown, for example, that the manner in which materials are presented to pickers can affect ergonomics associated with kit preparation (Calzavara et al., 2017), and it is important that such aspects of kit preparation are accounted for when kitting is used.

Kitting has been credited with improving flexibility in assembly processes. For one, kitting can facilitate product changeovers, thereby supporting production of small batch sizes, since all change related to components can be concentrated to kit preparation workspaces instead of assembly workstations (Caputo and Pelagagge, 2011; Bozer and McGinnis, 1992). For another, kitting promotes flexibility with respect to production mix by enabling presentation of more component variants, as only the components needed for each assembly object are presented at assembly processes at a time (Wänström and Medbo, 2009; Bozer and McGinnis, 1992). Moreover, kitting has been recognised to improve learning of assembling procedures, promoting flexibility associated with product introductions and changeovers (Medbo, 2003). However, it has also been reported to reduce flexibility in the production schedule when kit preparation workspaces are located far from assembly, as kits must then be prepared in advance of production (Hanson, 2012). Furthermore, to achieve quick changeovers and flexibility with the use of kitting, kit preparation must also be flexible and able to change, when for example new products are introduced in production systems, when production mixes vary, or when production schedules change.

Kitting has been reported to improve control and visibility for high-cost and perishable components and subassemblies (Bozer and McGinnis, 1992) and to support assembly quality and productivity by presenting components readily available and prepositioned in kit containers (Hanson, 2012; Medbo, 2003). Furthermore, it can enable robotic assembly, as it allows for exact control of the quantity, position, and orientation of components in kit containers (Bozer and McGinnis, 1992;

Sellers and Nof, 1989). However, this requires that kits are prepared with satisfactory kit quality, and that they are devoid of errors (Caputo et al., 2017a; Caputo et al., 2017b; Hanson, 2012). In practice, kit errors have severe consequences for assembly processes and can prolong lead times, interrupt the production flow, necessitate expensive rework and costs, or even result in the delivery of defective end-product to customers (Boysen et al., 2015). Many situations during kit preparation can lead to kit errors. This includes temporary shortages of components, forcing kits to be completed with parts missing, or defective components with damages or manufacturing errors included in kits (Caputo et al., 2017a; Caputo et al., 2017b; Brynzér and Johansson, 1995; Bozer and McGinnis, 1992). Hence, with respect to quality, an intertwined relationship exists between kitting and kit preparation.

Kitting may improve assembling efficiency by removing the need to search for and fetch components (Hanson, 2012). However, using kitting, instead of material supply principles by which components are delivered to assembly in containers holding a single component number, such as with line stocking (Caputo and Pelagagge, 2011; Hanson and Finnsgård, 2014), introduces extra handling into materials flow activities, in the form of kit preparation (Hanson, 2012; Limère et al., 2012). This aspect has received great criticism in discussions of alternatives for materials supply (Caputo and Pelagagge, 2011; Limère et al., 2012; Bozer and McGinnis, 1992). Some researchers have pointed out that the additional materials handling work of kit preparation can be balanced, or at least mitigated, by the man-hour efficiency gained in assembly from less walking and searching during component collection (Limère et al., 2012). As such, efficiency with respect to kit preparation is central to improving the overall production system efficiency when a kitting approach is applied.

1.1.3. Design and performance of kit preparation

Previous research explains that a picking system's design greatly impacts performance associated with its operation and output (e.g. Battini et al., 2015; Hanson, 2012; Brynzér, 1995; Goetschalckx and Ashayeri, 1989). Researchers have indicated several design aspects that can affect kit preparation performance. Examples include aspects related to the layout of kit preparation work spaces (Hanson et al., 2011; Brynzér and Johansson, 1995), work organisation (Hanson and Brolin, 2013), policies (Hanson et al., 2015; Brynzér and Johansson, 1995), packaging (Calzavara et al., 2017; Hanson and Brolin, 2013), materials handling equipment (Boudella et al., 2018), and picking information (Hanson et al., 2017).

Although previous research is clear about the relationship between design and performance of kit preparation, there are two substantial complexities associated with understanding this relationship. First, kit preparation has close ties with its context, in terms of production system characteristics (Bozer and McGinnis, 1992). For example, if production systems produce products of high volume and low variety, a suitable kit preparation design can be very different from when products are produced according to low volume and high variety. The kit preparation's context can in this way impact the relationship between kit preparation design and performance, and must be accounted for when the relationship is dealt with (Hanson and Medbo, 2019). Second, with regard to the design of picking systems, there are often interplays among design aspects that are crucial to account for (De Koster et al., 2007; Yoon and Sharp, 1995). These interplays can create synergies and trade-offs with respect to performance, and may also be affected simultaneously by the context.

In addition, the relationship between kit preparation design and performance is accentuated by recent technological developments that give rise to new ways of supporting kit preparation. Examples include solutions based upon radio frequency identification (RFID), which are becoming increasingly reliable at lower costs and are thereby approaching viability in industrial applications (Battini et al., 2015; Andriolo et al., 2016), and solutions based on wearable computing (Hanson et al., 2017), in the form of smart glasses and head-up displays (HUDs) that make up visual interfaces

capable of displaying virtual (Guo et al., 2015) or augmented picking information (Schwerdtfeger et al., 2011). Furthermore, the recent emergence of lightweight and flexible robotics (Sadrfaridpour and Wang, 2018) and advancements in gripper technology pave the way for applications involving robotics and kit preparation (Boudella et al., 2018). In effect, new applications, such as those outlined above, make up entirely new design options and thereby raise questions about how such technologies apply to kit preparation and their effects on performance.

1.2. Research purpose

From the preceding subchapter, it is clear that kit preparation design aspects contribute to kit preparation performance. It was also made clear that satisfactory performance of kit preparation is essential for realising the benefits of kitting. It was indicated that kit preparation has close ties with its context, and that these ties may affect which design is the most suitable. The ability to appropriately select among kit preparation design options to achieve desired performance is key for production systems in dealing with numerous component variants. All this comes to the fore considering new technological developments, for example with respect to picking information systems and robotics, which present new alternatives for design. In the published literature, knowledge about how design aspects of kit preparation contribute to performance is, at best, fragmented (see Chapter 2 for a full overview). There are considerable gaps in the published literature regarding the relationships between the kit preparation design aspects and performance. Such knowledge is needed by industry when kitting is the applied materials supply principle. Hereby, the purpose of this thesis is stated as follows:

To contribute to the knowledge of how kit preparation design aspects govern kit preparation performance.

1.3. Scope

This thesis deals with materials handling processes for kit preparation in mixed-model assembly systems. A materials handling process is, in this thesis, seen to involve the equipment, policies and principles applied for supporting assembly processes. The assembly process itself is not included as a part of the materials handling process, but seen as the entity served by the materials handling process. The interfaces towards materials supply to kit preparation, and towards assembly processes, are, however, included within the scope.

With respect to kit preparation design, the term *design* as used in the thesis refers to the configuration of the equipment, policies, and the principles which make up a process for kit preparation. Thereby, design does not refer to the procedure by which options of equipment, policies, and principles are decided, but specifically involves the options themselves and how they relate to performance. Furthermore, decisions of which components to supply by kitting is not part of the scope of this research.

With respect to kit preparation performance, the thesis deals with flexibility, kit quality, and man-hour efficiency as associated with kit preparation.

Kit preparation context is accounted for to the extent it affects relationships between kit preparation design aspects and performance, so that the relationships cannot otherwise be understood. Context is viewed as any aspect that impacts kit preparation performance, but is outside of a kit preparation designer's influence. The characteristics of end-products and components are typical examples of aspects in the context that are considered in the thesis.

1.4. Research questions

This subchapter presents three research questions addressed by the thesis. These questions align the research with the purpose presented in Subchapter 1.2, and allow for the research area to be addressed in a broad, yet precise, fashion.

As explained in Subchapter 1.1, kit preparation plays an important role in many of the performance effects that have been associated with the use of kitting and mixed-model assembly. The three research questions presented here each target a performance area of kit preparation that is important with respect to this role, and that at the same time is important for production performance.

Together, the three research questions make room for focused research studies that can address important issues with industrial applications for kit preparation and can build on established knowledge from literature on the topic of kit preparation design and performance. Answers to these questions make up significant contributions to the research purpose in terms of developing knowledge about how kit preparation design aspects govern kit preparation performance.

The three research questions are presented in individual sections, and each research question is preceded by a summarising overview of central arguments from the literature that motivate the questions. An exhaustive, comprehensive review of the published literature about the topics is withheld in this subchapter, and is instead presented in together with the theoretical framework in Chapter 2.

1.4.1. Research Question 1

In literature, kitting is often attributed as having benefits of flexibility compared with other materials supply principles (e.g. Hanson et al., 2012; Caputo and Pelagagge, 2011). When kitting is used, more component variants can be presented at the same time at assembly processes (Limère et al., 2015; Hanson, 2012), and changes of the product's structure, or in the assembly schedule, can be concentrated to kit preparation workspaces (Caputo and Pelagagge, 2011). However, the flexibility associated with using kitting-based materials supply relies on the ability of kit preparation to adapt in accordance to the requirements of the assembly processes. A lack of flexibility in kit preparation risks costly and slow changeovers when new products are introduced in production systems, inability to deal with fluctuations of volume or mix, and higher costs when production schedules change (Slack, 2005). Some studies have pointed out that design aspects of kit preparation can impact its flexibility. These include, for example, the kit container's design (Hanson and Brolin, 2013; Brynzér and Johansson, 1995), the location of kit preparation workspaces within material flows (Hanson et al., 2011), and the type and configuration of picking information systems (Hanson et al., 2017; Brynzér and Johansson, 1995). However, apart from scattered observations such as these, literature that explains how kit preparation flexibility can be supported is virtually nonexistent. Studies dealing with warehouse order picking have viewed flexibility as necessary for dealing with volume fluctuations and structural changes of item assortments (Marchet et al., 2015) but often focus on developing flexible frameworks for re-planning of order picking operations (e.g. Lu et al., 2016; Manzini et al., 2005) and rarely address relationships between design aspects and flexibility. The need for more knowledge of the factors that govern kit preparation flexibility has been expressed for some time in previous research that has dealt with choice among materials supply options (see e.g. Hua and Johnson, 2010), but literature that can explain these relationships remains absent. The lack of knowledge about relationships between kit preparation design aspects and kit preparation flexibility limits achievement of kit preparation flexibility, and by extension, achievement of kitting and production flexibility. Therefore, the thesis' first research question targets the relationship between kit preparation design aspects and flexibility, and is stated as:

Research Question 1: *How is kit preparation flexibility governed by kit preparation design aspects?*

1.4.2. Research Question 2

Quality is often viewed as a central performance area of picking systems (e.g. Grosse et al., 2015; Brynzér and Johansson, 1995; Goetschalckx and Ashayeri, 1989). With kit preparation, high kit quality contributes to efficient and smooth assembly processes without quality-related interruptions and costs. Within the literature, researchers have modelled costs of manual errors in kit preparation

and developed taxonomies over the various types of kit errors that can arise (Caputo et al., 2017a; Caputo et al., 2017b). Moreover, within the literature dealing with warehouse order picking, design aspects and their effect on quality have been addressed to some extent, for example with respect to how pickers' knowledge and experience of order picking processes can impact quality (Glock et al., 2017; Grosse et al., 2015). However, research concerned with how to achieve satisfactory kit quality has been scarcer, and apart from some publications (e.g. Brynzér and Johansson, 1995), there is no literature available to guide how satisfactory kit quality can be achieved. Previous research has shown that aspects of design in kit preparation, for example, how picking information is conveyed (Hanson et al., 2017) and how kit containers are designed (Hanson and Brodin, 2013), can affect kit quality, but this literature is at best scant. As previously indicated, one reason for using kitting in industry is to promote quality in assembly processes through more effective presentation of components (Medbo, 2003), but for this to be realisable, the kits must also be of high quality. A main criticism of kitting-based materials supply is kit errors in kits, which are usually difficult to quickly correct at assembly processes, as the right components must be retrieved from kit preparation workspaces (e.g. Caputo et al., 2017a; Caputo et al., 2017b; Hanson et al., 2011). In this way, the legitimacy of kitting-based materials supply hinges on the kit quality outcome of kit preparation. Thereby, more knowledge of how kit preparation design aspects govern kit quality is needed in industry and substantial gaps in established knowledge need to be addressed. Research Question 2 of the thesis, therefore, targets kit quality with respect to kit preparation, and is stated as follows:

Research Question 2: *How is kit quality governed by kit preparation design aspects?*

1.4.3. Research Question 3

In literature dealing with selection of material supply principles, an often-cited disadvantage is that kitting adds materials handling activities in the form of kit preparation (Limère et al., 2012; Caputo and Pelagagge, 2011; Bozer and McGinnis, 1992). Some authors explain that this added handling is partly mitigated by the savings from having components presented in kits for assembly processes, which leads to less searching and walking for assemblers (Limère et al., 2012; Medbo, 2003). In this light, man-hour efficiency of kit preparation is essential for ensuring a low running cost and for also making kitting attainable from a financial standpoint. Some researchers have identified aspects of kit preparation design and context to be important for man-hour efficient kit preparation (Hanson and Medbo, 2019; Brynzér and Johansson, 1995). Here, the picking information system, which guides the picker and allows completed activities to be confirmed, is often highlighted as critical (Hanson and Medbo, 2019; Brynzér and Johansson, 1995) as is the approach of order batching, referring to how many and which orders are completed in picking tours (Hanson et al., 2017; Hanson et al., 2015). However, apart from a few focused studies, kit preparation design aspects and man-hour efficiency have rarely been addressed in any detail (Hanson and Medbo, 2019). Furthermore, new applications that can support man-hour efficient kit preparation are emerging, for example picking information systems that present information on head-up displays as mixed- and augmented-reality (Hanson et al., 2017; Guo et al., 2015), RFID-reading gloves and wristbands for automatic confirmations (Andriolo et al., 2016; Battini et al., 2015), and lightweight and flexible robotics that can collaboratively support pickers in kit preparation activities (Boudella et al., 2018). In effect, new applications, such as those outlined above, motivate new research that can shed light on the potential to support man-hour efficient kit preparation. Hence, a clear opening for valuable contributions with respect to man-hour efficiency exists, both in theory and in practice. Therefore, the third research question of the thesis targets kit preparation man-hour efficiency, and is stated as follows:

Research Question 3: *How is kit preparation man-hour efficiency governed by kit preparation design aspects?*

1.5. Thesis outline

Chapter 1 (Introduction) introduces the research area and presents the background. The chapter also presents the research purpose, along with the scope of research. Additionally, the chapter presents the three research questions addressed by the thesis, and an overview of the thesis' contents.

Chapter 2 (Frame of reference) presents a review of relevant literature for the thesis purpose and research questions. Furthermore, important takeaways from the literature with respect to the thesis are pointed out.

Chapter 3 (Research method) presents a description of the research method applied in the thesis. The chapter includes descriptions of the research process, the research strategy, the research methods used in the five papers, and presents a discussion of validity and reliability.

Chapter 4 (Results) presents the thesis' results from the five research papers appended to the thesis, in the form of answers to the thesis' three research questions.

Chapter 5 (Discussion) presents a discussion of the thesis' results and highlights implications for future research. The chapter includes discussions about generalisability of the thesis' results, and how the thesis' findings apply to theory and practice.

Chapter 6 (Conclusions) presents the thesis' conclusions.

2. Frame of reference

This chapter presents the thesis' frame of reference and serves as the theoretical basis for the research. This is achieved by a review of literature that is relevant to the thesis' purpose, as stated in Subchapter 1.2, to contribute to the knowledge of how kit preparation design aspects govern performance. This chapter explains the contributions from previous research that make up starting points for finding answers to the research questions addressed by this thesis. Furthermore, the chapter provides structure for later expressing the thesis' results and contributions.

The chapter is organised in three subchapters. Subchapter 2.1 presents a discussion of literature dealing with design and performance related to kit preparation, Subchapter 2.2 presents a discussion of kit preparation context, and Subchapter 2.3 presents a comprehensive overview of available literature with respect to the three research questions (Subchapter 1.4).

2.1. Design and performance of kit preparation

With respect to the thesis' purpose, it is important to understand how relationships among kit preparation design aspects and performance are constituted and what aspects are important. Therefore, this subchapter presents a review of literature that has dealt with design and performance related to kit preparation. Furthermore, useful categorisations for the research are derived based on the review.

The subchapter is organised into two sections. Section 2.1.1 presents a review of literature dealing with the design of picking systems, and Section 2.1.2 presents a review of literature dealing with relationships among design aspects and performance of kit preparation.

As indicated in the thesis' scope (Subchapter 1.3), the reviews presented here do not consider the steps involved with making a decision with respect to design, but rather address the relevant aspects considered when decisions are made and how such factors are viewed. Additionally, the review should be viewed as non-exhaustive. The frameworks in the review were selected because they deal with topics that are relevant to kit preparation, whereby they are seen as suitable for illustrating which categories are important for the thesis' purpose.

2.1.1. Design of picking systems and selection among materials supply principles

Researchers typically describe a picking system's design as complex, consisting of several interdependent subsystems that all are dependent on their surroundings (De Koster et al., 2007; Yoon and Sharp, 1996). Therefore, a structured approach for how to deal with the above complexity seems most useful. This section presents a literature review dealing with the design of order picking and kitting systems. It also deals with the selection among materials supply principles that involve kitting. Finally, implications from the reviewed literature are pointed out, and a summary is presented in **Table 2.1**, highlighting the aspects of design, context and performance that have been brought forth by previous research.

Frameworks for design and planning of kitting systems

While publications that present structured frameworks of kit preparation design are generally lacking in the literature (Caputo et al., 2015), the first part of this section discusses two frameworks that have dealt with planning and design of kitting systems. These two frameworks include Brynzér (1995), who identified six design areas of kitting systems and outlined a procedure for how the design areas should be addressed, and Caputo et al. (2015), who presented a framework for planning of kitting operations. These two frameworks are briefly reviewed in the following, and key takeaways with respect to the thesis purpose are highlighted.

Brynzér (1995) studied methods for evaluating kitting system performance and derived six design factors of kitting systems, partly based on Goetschalckx and Ashayeri (1989). These design factors were highlighted as central for picking efficiency in kitting systems and included layout, storage

policy, batching policy, picking policy, equipment and picking information. Brynzér (1995) further identified various aspects related to these factors about which kitting systems designers must make decisions. The author pointed out the importance of location of the kit preparation workspace in relation to assembly processes, the width and length of aisles, and the location of shared equipment at and around the workspaces. Brynzér also highlighted the value of the picking information media, meaning the hardware by which picking information is conveyed, and the picking information structure. In addition to equipment, two other main considerations were the design of storage equipment and the picking package, referring to the packaging within which picked components are placed. Storage policy referred to the applied logic for organising individual component numbers among storage locations, and batching policy referred to the orders included in individual picking tours. Picking policy signifies the sequence in which storage locations are visited during individual picking tours, and whether picking packages pass through zones and, hence, are completed by several pickers.

Caputo et al. (2015) developed a framework for estimating costs and planning operations in kitting systems. The framework was based on a comprehensive review of the literature, from which several important factors associated with costs of kitting systems were identified. The costs included investments related to vehicles, containers, and storage racks; direct operating costs related to the workforce, vehicle maintenance and energy consumption; and indirect operating costs related to space requirements, work-in-process, safety stock holding costs, administration and control. They also considered costs for kit preparation error corrections and security. With respect to work-in-process inventory, they explained that they only considered inventory in the form of kits at assembly processes, since the amount of inventory tied up in kit preparation workspaces does not affect the amount of inventory in the material flow when kitting is compared with other materials supply principles. However, they do account for safety stocks kept at the kit preparation workspaces and explain that kit preparation workspaces act as centralisation points for safety stocks, in contrast with keeping the safety stocks at assembly processes. With respect to costs for kit preparation error corrections and security, Caputo et al. (2015) differentiated between four error types: missing parts or wrong number of parts in kits, wrong parts inserted in the kit, defective parts inserted in the kit and insertion of the right part but in the wrong place in kits. They developed event trees with probabilities for such occurrences, which can be used to estimate the quality-related costs. The framework considers two types of quality-related costs: costs of having the right component resupplied and costs for making corrections to end-products at quality control departments. There is also an obsolescence cost for components that have become outdated during production.

These authors present important takeaways with respect to the thesis' purpose. Brynzér's framework (1995) is important because it considers relationships between kit preparation design aspects and picking efficiency, and also because it outlines a comprehensive overview of kitting system design factors. Caputo et al. (2015) focus less on design options of kit preparation; rather, they present a comprehensive overview for how to estimate resource requirements and costs of using kitting. Both Brynzér (1995) and Caputo et al. (2015) present valuable input and develop frameworks wherein the type of knowledge aimed for in this thesis, i.e. knowledge of relationships between kit preparation design aspects and performance, is important. As also seen from these two frameworks, relationships between kit preparation design aspects and performance is dealt with sparingly, where Brynzér (1995) mainly focus on how design aspects impact picking efficiency, and Caputo et al. (2015) are mainly concerned with the costs of a fixed design.

Frameworks for design of order picking systems

There are a multitude of frameworks available in the literature that address design of warehouse order picking systems (Manzini et al., 2007). In this section, three frameworks, which each present a comprehensive approach to warehouse order picking system design, are discussed. These include the works from Goetschalckx and Ashayeri (1989), Yoon and Sharp (1996), and Manzini et al.

(2007), which are all comprehensive in their approach and provide recommendations for the aspects that are important. Finally, takeaways from the frameworks with respect to this thesis are highlighted.

Goetschalckx and Ashayeri (1989) presented a framework called the 'systematic planning and designing procedure for order picking systems' (SYD-OPS). This is aimed at order picking processes in warehousing and distribution settings, but presents several relevant considerations for this thesis' focus. The procedure considers external and internal strategies of order picking systems that have to be planned or controlled in order to achieve some objective. Typical objectives, according to Goetschalckx and Ashayeri (1989), are to maximise the service level in terms of delivery time, integrity and accuracy; to minimise the overall cost to achieve a desired service level; to maximise picking rates; and to minimise the overall picking time. External strategies are policies concerned with the company's strategy, and must be accounted for when planning and controlling internal strategies. External strategies consist of four aspects: marketing channels, customer demand patterns, supplier's replenishment patterns and inventory levels. Internal strategies mirror that which is referred to as design aspects in this thesis, and are policies concerned with organisation and management. These must be chosen and controlled with respect to external strategies, and consist of five aspects: command cycle, warehouse dimensionality, mechanisation level, information availability, and policy level.

Yoon and Sharp (1996) presented a comprehensive model for design that considered order picking systems from a total system standpoint. Additions to the framework were made by Dallari et al. (2009) who simplified characterising of order picking systems in the initial design phase, based on the expected volumes and order variety. Yoon and Sharp's model (1996) described order picking systems as consisting of eight functional departments: a receiving area, a pallet reserve area, a case pick area, an item pick area, two sorting areas, a unitizing area and a shipping area. This thesis is most concerned with the item pick area and the sorting areas, as these correspond to the functional role of kit preparation in production systems. Compatibility among the eight functional departments must be controlled for when various decisions are made regarding a set of design issues. The design issues involve constraints of environmental and economic nature, material properties, transaction data, operating strategies, system alternatives and system requirements. Yoon and Sharp (1996) explained that central to the objective of order picking systems is the concept of physical transformations, referring to how materials are repackaged in different configurations. They further stressed the importance of information transformations, representing how transaction data is transformed into useful information within the order picking system. According to Yoon and Sharp, (1996), these objectives can be represented by performance in terms of storage capacity or system response time.

Manzini et al. (2007) developed a procedure for design and control of warehouse order picking systems, by which dynamic simulation is applied to make design decisions. They explained optimisation of order picking systems to be NP-hard problems as 'a huge portfolio of parameters are capable of influencing its performance' (ibid. p. 814). Their approach is, therefore, to make use of a variety of decision-making techniques in their dynamic simulation-based approach. Their framework differentiates between two categories of decisions, namely strategic management decisions, referring to long-term decisions relevant for the whole company, and control decisions, referring to short-term operational decisions in the order picking system. Focusing on control decisions related to picker-to-part systems, they outlined four central parameters for performance, namely the item features, the physical configuration of the storage area and the unit load size, the storage equipment, and the order picking system's operating rules. The system's operating rules involve storage location assignment, batching strategies, and routing strategies. By applying the framework, an estimate of the total picking cycle time is attained.

Two key takeaways from the reviewed frameworks concern: first, the distinctions made between aspects for which there are design considerations, and other aspects which cannot be affected within the scope of design of order picking systems but must be accounted for. This is represented by the distinction of internal and external strategies as used by Goetschalckx and Ashayeri (1989), the distinction of design issues and constraints as used by Yoon and Sharp (1996), and the distinction of control and strategic management decisions as used by Manzini et al. (2007). This distinction between aspects for which there are design considerations, and aspects that cannot be affected within the scope of design, is most relevant to this thesis, as many production system characteristics cannot be controlled when deciding amongst design options of kit preparation, but must instead be accounted for (Brynzér, 1995; Bozer and McGinnis, 1992). Aspects of this kind are viewed as part of the context in this research.

The second takeaway concerns the stress put on the interplay among various aspects brought up in these frameworks, for example amongst internal factors in Goetschalckx and Ashayeri's framework (1989), amongst design issues in Yoon and Sharp's framework (1996), and amongst control decisions in Manzini et al. (2007). These factors mirror design aspects of kit preparation in this thesis, and it is important that interplay amongst design aspects is accounted for within the scope of this thesis.

Frameworks for deciding between assembly materials supply principles

Several frameworks are available in literature that can help make decisions regarding which materials supply principle to apply in production systems. In the following, three such frameworks, which have considered kitting as an option, are discussed in terms of what they consider important with respect to kitting-based material supply. The frameworks are from Bozer and McGinnis (1992), Limère et al. (2012; 2015), Caputo and Pelagagge (2011) and Caputo et al. (2018). At the end, takeaways from the frameworks with respect to the thesis' purpose are highlighted.

Bozer and McGinnis (1992) developed a descriptive model to decide between kitting and line stocking. The model compared the two supply methods based on the costs associated with storing and retrieval of containers, container flow within the plant, work-in-process and floor space requirements. They emphasised that their model is a simplification of real applications, as a kitting implementation with assembly is closely coupled with many other subsystems that also support the production operations. Furthermore, they indicated that the interactions between the kitting systems and the other subsystems vary considerably according to the situation. Bozer and McGinnis (1992) brought up several advantages and disadvantages associated with kitting-based materials supply. The advantages include space savings at assembly processes, easier product changeovers, more flexible transportation throughout materials supply systems and facilitating robot handling in assembly processes by increasing control over how components are presented in the assembly processes. Some of the disadvantages include the costs and resource requirements for kit preparation, overall increase of storage space requirements, added planning requirements and more difficulties replacing wrong and defective components. They also noted that 'designing the kit assembly operation itself could be as complicated as designing the assembly area' (Bozer and McGinnis, 1992, p. 7).

Limère et al. (2012) developed a method for comparing the costs between a kitting approach and a line stocking approach with respect to component characteristics and production mix. The framework was later enhanced by Limère et al. (2015) to also consider variable walking distances for assemblers during the assembly process. The framework considers material supply costs in the form of picking work performed at assembly processes, internal transports, kit assembly and replenishments to kit assembly workspaces. With numerical applications, they found that components of component families with many variants reaped more benefits from a kitting approach, as these only take up one slot in the kit, but require multiple storage locations at the assembly process with a line stocking approach. Furthermore, they found that when kits were

batched, there was not much discrepancy between the work required in kit assembly and picking from bulk at the assembly line. Moreover, smaller parts showed to be more viable with kitting, as these are easier to fit in a kit, as are parts normally stored in pallets, since these free up more space at assembly when kitted instead of being line stocked.

Caputo and Pelagagge (2011) and Caputo et al. (2018) developed models to support the choice of materials supply method in assembly systems. The models estimated the costs of alternative methods of materials supply and involved three methods: kitting, just-in-time, and line stocking. The model in Caputo and Pelagagge (2011) also included hybrid configurations, where more than one of the materials supply methods could be applied to supply the same assembly process. The costs associated with the three methods are modelled as the sum of man-hour cost, equipment cost, work-in-process cost and the floor-space cost for storing materials alongside the assembly process. Caputo and Pelagagge (2011, p. 99) emphasised that ‘a non increasing degree of inventory level control and workforce or organizational effort should be associated to classes of components having decreasing relevance’. The performance of interest includes work-in-process inventory, holding costs, number of daily handling moves, personnel expense, capital investment and floor occupation. They also highlighted that qualitative performance aspects, such as organisational complexity, may be important and that these should be scored to allow ranking amongst alternative materials supply methods.

A main takeaway from the above reviewed frameworks is the multitude of aspects that need to be accounted for when these decisions are made. Another conclusion is that the frameworks typically do not differentiate between design aspects of kit preparation, but rather consider this design as static with a certain fixed resource requirement and output rate. Furthermore, performance aside from man-hour expenditure and error rates associated with kit preparation are rarely considered.

Implications for the thesis’ purpose from the reviewed frameworks

The frameworks that have been reviewed in this section, dealing with design and operations planning of kitting and order picking systems, and choosing what materials supply principle to apply, present several implications for the thesis’ purpose. These are outlined in the following and their relevance to the thesis scope is highlighted. An overview of the frameworks that were reviewed in the section, in terms of aspects of design, context, and performance is shown in **Table 2.1**.

An important similarity between the frameworks is that decisions related to the design of picking systems are usually made with respect to certain outcomes. Between the reviewed frameworks, the outcomes in focus varied, where Caputo et al. (2015), Limère et al. (2012), and Caputo and Pelagagge (2011) focused on costs in the context of selecting materials supply principles. Goetschalckx and Ashayeri (1989), Yoon and Sharp (1996) and Manzini et al. (2007) focused on total system outcomes in the form of throughput, picking cycle times, and storage capacities in the context of order picking in warehouses, and Brynzér (1995) focused on picking accuracy and efficiency in the context of kitting system performance. The frameworks bring up different aspects of design that may affect these outcomes, but generally do not explain how choices among design aspects actually affect the outcomes (e.g. Goetschalckx and Ashayeri, 1989; Yoon and Sharp, 1996). Further, the picking system is optimised or evaluated with respect to only a single outcome, for example costs in the case of Caputo et al. (2015), Limère et al. (2012), and Caputo and Pelagagge (2011), or total picking cycle time in the case of Manzini et al. (2007). With respect to focus areas of this thesis, only man-hour efficiency is dealt with to any extent; quality is acknowledged by a few publications (e.g. Caputo et al., 2015; Brynzér, 1995); while flexibility is not addressed at all.

Table 2.1. *Overview of the frameworks discussed in Section 2.1.1, highlighting how context, performance, and design are viewed in the literature.*

<i>Publication</i>	<i>Context</i>	<i>Performance</i>	<i>Design</i>
Caputo et al. (2015)	Component characteristics Number of component variants, component size, weight, demand rates	Costs Investment (vehicles, containers, storage racks), direct operating costs (workforce, vehicle maintenance, energy consumption), indirect operating costs (space requirements, work-in-process, safety-stock, administration, control), quality (error correction and safety), obsolescence costs	None identified
Brynzér (1995)	Assembled product	Performance objectives Picking efficiency, picking accuracy	Design factors Layout, picking information, equipment selection, storage policy, batching policy, picking policy
Goetschalckx and Ashayeri (1989)	External strategies Marketing channels, customer demand pattern, supplier replenishment pattern, inventory levels	Objectives Service level, order delivery, order integrity, order accuracy, total cost, picking rate, picking time	Internal strategies Command cycle, warehouse dimensionality, information availability, layout design, storage policy, batching policy, picking policy, zoning policy
Yoon and Sharp (1996)	Constraints related to: Environment (layout, safety), economic factors (budget and life span of design project), Material properties (item size, weight, flammability etc.), transaction data	System objectives Storage requirements, system response time, physical transformations, information transformations	Strategies and alternatives Operating strategies (retrieval method, storage rules), and system alternatives (hardware alternatives, operators' work organisation)
Manzini et al. (2007)	Strategic management decisions (long term) Fulfilment policy, plans for best use of resources	Performance parameters Picking cycle time, throughput	Control decisions (short term) Item features, configuration of storage area and unit load size, storage equipment, operating rules (storage assignment, batching, routing)
Bozer and McGinnis (1992)	Factors related to other subsystems present in assembly systems Bill-of-materials, process plan, production volumes and batch sizes, facility layout, materials handling system, shop floor control system	Costs Storing and retrieval of containers, container flow within plant, work-in-process, floor space requirements	Design configurations Kit container design, kit structure
Limère et al. (2012) and Limère et al. (2015)	Component characteristics Component's commonality among end products, production mix	Total in-plant logistics costs Picking at assembly processes, internal transports, kit assembly, replenishments to kit assembly area	None identified
Caputo and Pelagagge (2011) and Caputo et al. (2018)	Component characteristics Commonality of components between end-products, dimensional features of components, component weight	Performance Work-in-process, holding cost, daily handling moves, personnel expense, capital investment, floor occupation	Resource requirements Workforce, equipment

Another important similarity between the frameworks brought up in the section is that they all involve factors that are not subject to design, but rather that must be considered when design choices are made. This includes external strategies brought up by Goetschalckx and Ashayeri (1989), strategic factors brought up by Yoon and Sharp (1996), strategic management decisions brought up by Manzini et al. (2007) and component characteristics brought up by Caputo and Pelagagge (2011) and Limère et al. (2012). It is clear that decisions amongst design aspects must be made with respect to such factors. This thesis views such factors as part of the context, and as emphasised by, for example, Bozer and McGinnis (1992), the relationships between kitting systems and their context may be closely tied with the application, and different factors in the context may be important depending on the application. The relationships between kit preparation and its context will be dealt with further in the next subchapter (2.2).

In conclusion, this section has shown that frameworks for design of kitting and order picking systems, and for deciding between materials supply principles, tend to distinguish between three categories of aspects: design, context, and performance. The distinctions made by the respective frameworks, and examples of factors that the frameworks consider to be part of the three categories, have been summarised in **Table 2.1**. The section also shows that the frameworks brought up in the section for the most part do not describe relationships between design aspects and performance, but rather stops at highlighting those aspects that are deemed important for consideration. Furthermore, the frameworks seem to focus on singular performance areas, such as costs or time expenditures. With respect to this thesis' purpose, there is an evident lack of explanation as to how design aspects govern performance, especially with respect the performance areas targeted by the research questions, in terms of flexibility, kit quality, and man-hour efficiency.

2.1.2. Design aspects of picking systems

This section presents a discussion of previous research that has dealt with design aspects of picking systems. As there are a considerable number of design aspects that can be relevant under the thesis' purpose, a categorisation would be useful to overview the relevant aspects. Based upon previous research related to the design of kitting and order picking systems (e.g. Brynzér, 1995; Brynzér and Johansson, 1995; Goetschalckx and Ashayeri, 1989), as has been identified during the research behind this thesis, design aspects which have been dealt with in previous research are here organised into eight design areas: 1) *layout*, 2) *work organisation*, 3) *policies*, 4) *equipment*, 5) *packaging*, 6) *picking information*, 7) *automation* and 8) *control*.

This decomposition of kit preparation design areas is motivated by the resemblance to taxonomies proposed by, for example, Goetschalckx and Ashayeri (1989) for design of order picking systems, and with Brynzér (1995) and Brynzér and Johansson (1995) for design of kitting systems. Previous research has addressed various aspects among these eight design areas, and the meanings assigned to the design areas in the thesis, and examples of which design aspects they typically concern in the literature, are summarised next.

- 1) *Work organisation* involves design aspects related to how kit preparation work and processes are organised. Examples include the picker's job role, which refers to if the operator who performs kit preparation also performs assembly tasks, and whether these assembly tasks are performed in the same work cycle (see e.g. Brynzér and Johansson, 1995). Furthermore, work organisation includes how reorganisations are conducted, for example, if the assembly department is responsible for reorganisations at kit preparation workspaces (see Hanson et al., 2011).
- 2) *Layout* refers to design aspects related to where in the materials flow kit preparation workspaces are located in terms of the design aspect *location* (see e.g. Hanson et al., 2011), *picking density* (Hanson and Medbo, 2019), and how the *layout at the kit preparation workspace* is configured (see e.g. Boudella et al., 2018).

- 3) *Policies* reflect the rules by which items are organised in the kit preparation storage, in terms of *storage policy* (see e.g. Brynzér and Johansson, 1996) and what orders are handled during picking tours, in terms of *batching policy* (see e.g. Hanson et al., 2017; Hanson et al., 2015).
- 4) *Packaging* refers to the type of *storage packaging* applied in the storage at kit preparation areas (see e.g. Calzavara et al., 2017), and *kit containers*, representing how kitted components are kept together (see e.g. Hanson and Brolin, 2013).
- 5) *Equipment* involves design aspects related to *storage racks* (see e.g. Wänström and Medbo, 2009), *lifting supports* (see e.g. Hanson and Medbo, 2019), and *kit carriers* (Brynzér and Johansson, 1995).
- 6) *Picking information* refers to design aspects related to the means of information conveyance (see e.g. Hanson et al., 2017), confirmation methods (see e.g. Battini et al., 2015), and how picking information is designed (see e.g. Brynzér and Johansson, 1995).
- 7) *Automation* refers to applications that automate kit preparation activities, in terms of control or power (Goetschalckx and Ashayeri, 1989). Examples of automation solutions can be automatic guided vehicles for transportation of kit carriers (see e.g. Hanson et al., 2018) or automated picking by means of robot arms (see e.g. Boudella et al., 2018).
- 8) *Control* refers to design aspects related to how kit preparation is planned in terms of capacity and inventory (Caputo et al., 2015) and controlled in terms of, for example, procedures for how to correct kit errors that reach assembly processes.

The available literature about design aspects of picking systems is generally scattered, and difficult to coherently organise. Therefore, the previous research highlighted in this section is discussed one study at a time, whereby the study is described in terms of its aim and which design areas and associated aspects were considered. The section brings up literature that deals directly with kit preparation, but it also includes literature from the related areas of warehouse order picking and assembly workstation design. This is because these areas often involve similar picking activities as those carried out in kit preparation, and thereby make up relevant complements to the frame of reference. At the section's end, **Table 2.2** presents an overview of the design areas addressed in previous studies that have dealt with design of picking systems.

Design aspects of kit preparation in previous studies

Brynzér and Johansson (1995) carried out comprehensive case research in the automotive industry dealing with design and performance of kitting and order picking systems. They addressed a range of design areas and identified several aspects to be important for flexibility, quality, and man-hour efficiency of kit preparation. According to their findings, with respect to flexibility, the kit container's design can reduce flexibility when fitted slots are applied, as the slots need to be redesigned if the components change. They also found that volume flexibility can benefit from having assemblers perform both kit preparation and assembly tasks, as it provides possibilities to rebalance activities. Brynzér and Johansson (1995) also pointed out the batching time horizon – that is, how long kits are tied up in the batching process – to be important for delivery flexibility. With respect to kit quality, Brynzér and Johansson (1995) proposed several approaches to prevent errors in kit preparation. Examples include colour-coding pick lists to match coloured segments of storage to facilitate accuracy, and reducing disturbances during work cycles to decrease the risk for mistakes. A main conclusion from their studies was the importance of how the picking information system is designed to obtain a satisfactory kit quality. In a later study, Brynzér and Johansson (1996) developed a method for storage assignment based on the pickers' perspective. The benefit of this method claimed to improve man-hour efficiency and reduce errors in picking work cycles.

Hanson et al. (2015) studied the impact of batching policy on kit preparation man-hour efficiency by means of experiments in industrial settings and considered two batch sizes, four and six kits,

respectively. Their findings showed that large batch sizes can display superior efficiency over preparing a single kit per picking tour, and that the larger batch size of six kits was more man-hour efficient than the batch size of four kits. When discussing the results, Hanson et al. (2015) noted that batch preparation of kits may be problematic from a quality point of view, as distribution of components among multiple kit containers introduces the risk of placement errors.

Hanson et al. (2017) addressed picking information and man-hour efficiency in a laboratory experiment of kit preparation. They compared man-hour efficiency and the amount of kit errors associated with two types of information conveyance, a paper pick list and a head-up display (HUD) that rendered information as mixed-reality. The experiment considered the two systems when applied with single-kit or four-kit-batch preparation. Their findings suggest that picking information conveyed by means of mixed-reality better supports efficiency. In their discussion, Hanson et al. (2017) noted that the ability to present all picking information digitally, as is possible with mixed-reality, may benefit flexibility, as it removes the need to have physical components, such as signs with text information, available at the workspace. This idea may extend to other types of picking information systems, as some systems (e.g. pick-by-light systems) require a more physical component, such as light indicators and displays, to be present at the kit preparation workspace than, for example, pick-by-voice systems.

Hanson et al. (2011) dealt with layout and conducted a multiple-case study in the automotive industry about the impact on in-plant materials supply performance from the location of kit preparation. With respect to flexibility, Hanson et al. (2011) found that floor space for expanding the preparation area is more likely to be available further away from the assembly area, which promotes flexibility as it facilitates accommodation of new components and additional inventory. They also found that continuous improvement activities and reorganisation of the kit preparation area are affected by the work organisation. Here, having the picker involved with both kit preparation and assembly tasks, and having the reorganisation taking place within the same organisational unit, for example, within the assembly department, promotes organisational integration in terms of what organisational units are involved, and facilitates reorganisation, which can benefit flexibility.

Hanson and Brolin (2013) addressed packaging and work organisation associated with kit preparation when studying the relative effects associated with kitting and continuous supply in a multiple case study. With respect to flexibility, they identified how the design of the kit container can reduce flexibility when fitted slots are applied to the various components in the kit, as the slots need to be redesigned if the components change. Echoing the findings of Brynzér and Johansson (1995), they also found that volume flexibility can benefit from having assemblers perform both kit preparation and assembly tasks, as there is a possibility to rebalance activities between kit preparation and assembly processes. However, as explained by Hanson and Brolin (2013), the rebalancing possibilities may be restricted if the kit container has fitted slots, as components then cannot freely be moved between the kit preparation and assembly.

Boudella et al. (2018) addressed automation in the form of robotics and developed a mathematical model for assigning components between two kit preparation work cells operated by an operator and a robot, respectively. The two work cells represented two different zones, wherein the robot first picked components and put them on a conveyor that transported them to kit containers on a rotating table. The operator then retrieved kits from the table and added the remaining components during a separate picking tour. The setup was compared across a range of design aspects, including batch size, storage policy, and component characteristics. Their findings showed that storage policy had little effect on the setup's total cycle time, but that batch size and component characteristics could greatly affect the cycle time. The setup was compared with a fully manual setup, and showed to have about equal cycle times but greatly reduced man-hour consumption, as the robot performed a substantial part of the work content.

Hanson and Medbo (2019) addressed a wide range of context and design aspects and their relationships with kit preparation man-hour efficiency in a comprehensive case research study consisting of 15 cases of industrial kit preparation. Amongst their findings, picking information system, batch size and configuration of component racks were identified as highly important. Furthermore, several factors in the kit preparation context were found important for man-hour efficiency, including the amount of component variants at kit preparation workspaces, component size, picking density, and the number of components per kit.

Design aspects in warehouse order picking and assembly workstation design

Literature dealing with warehouse order picking usually focuses on a few design aspects. As highlighted in the previous sections, the design problem with warehouse order picking usually concerns decisions about the routing policy, the batching policy, the storage policy and the layout, and the key objective is usually to minimise the time spent travelling (De Koster et al., 2007). Previous research on kit preparation has indicated that workspaces for kit preparation can usually be compactly organised owing to the product structure (Brynzér and Johansson, 1995). With a compact workspace, the travelling distance plays less of a role for performance, while the effects of other design aspects can be more important. In the literature on warehouse order picking, aspects other than those that affect the travel time typically receive little attention (Grosse et al., 2015), but some research has been directed at aspects that are relevant to kit preparation as well, such as the picking information system (e.g. Battini et al., 2015; Andriolo et al., 2016) and the picker's personality (De Vries et al., 2016) and experience Grosse et al. (2015). From that perspective, there are important differences between kit preparation and warehouse order picking, but the current literature applies to both topics.

Battini et al. (2015) studied picking information by modelling and comparing five picking information systems on the basis of economic and technical factors when these were applied in warehouse order picking. The study compared handheld barcode scanning, handheld RFID scanning, pick-by-voice, pick-by-light and a novel pick-by-light system. The novel pick-by-light system applied confirmations by means of RFID scans from an RFID-reading glove, and all systems included a confirmation when components were extracted from storage. This system, and its development, was described in full detail in another publication by Andriolo et al. (2016). In their study, Battini et al. (2015) considered the quality impact of applying picking information systems and described how various error types can occur when the picker interacts with the picking information system. The errors were modelled into two main categories: detectable and propagating errors. Detectable errors could be detected during the picking work cycle when the confirmation was wrong. Propagating errors could only be detected by the recipient of the items when the confirmation was correct, but the items or quantity were wrong.

De Vries et al. (2016) addressed work organisation and picking information by studying the link between picker personality and three types of picking information systems: pick-by-light, pick-by-voice, and RFID terminals. The study applied a comprehensive experiment with 101 participants in a simulated warehouse environment. They found that the personality trait of openness, in terms of being imaginative, cultured, curious, original and broad-minded (De Vries et al., 2016) and conscientiousness, in terms of being careful, thorough, responsible, organised and persevering (De Vries et al., 2016) can impact productivity associated with the picking information systems. Furthermore, they found that extraversion, in terms of being sociable, assertive, talkative and active (De Vries et al., 2016) and neuroticism, in terms of being anxious, depressed, angry, worried, insecure and emotional (De Vries et al., 2016), had a strong negative impact on quality.

Guo et al. (2015) compared the efficiency and picking accuracy of order picking using four means of information – paper list, light indicators, a trolley-mounted display, and a head-up display – in an experiment focusing on efficiency, accuracy and ergonomic factors of order picking. Although

they did not include confirmations in their study, Guo et al. (2015) suggest that this be studied in further research, especially from an efficiency standpoint.

In a literature review of human factors in warehouse order picking, Grosse et al. (2015) highlighted four design aspects with respect to quality: storage assignment, batching policy, layout and work organisation. Based on a comprehensive case research study of order picking in warehouses, Glock et al. (2017) identified how deviations from the prescribed work standard, so-called maverick picking, can affect quality. They found that quality comes at risk with maverick picking, but also that pickers can find more effective ways to carry out the work in poorly designed systems.

When studying materials picking at manual assembly stations, which is a context with many similarities to kit preparation, Wänström and Medbo (2009) found that wheel-equipped storage racks can improve new products, mix and volume flexibility at assembly stations, in contrast to when racks are bolted to the floor. They also determined that storage packaging type and size was important for new product, mix and volume flexibility, as these affect the amount of space required for presenting a variety of components. Here, it was easier to adjust the size of plastic boxes, as opposed to EUR-pallets, to better suit the necessary amount of inventory at assembly processes. The boxes also took up less space than the EUR-pallets, thereby allowing more component variants to be presented at once.

Compilation of the reviewed literature

From the above, it can be seen that literature has dealt with a multitude of design aspects related to kit preparation and order picking systems. Furthermore, some design aspects have been studied several times, such as the kit container's design (Hanson and Brolin, 2013; Brynzér and Johansson, 1995) and the design of picking information systems (e.g. Hanson et al., 2017; Guo et al., 2015; Battini et al., 2015). The design aspects, here categorised more broadly as design areas, which are highlighted in the current section, have structured the research presented in this thesis. The design areas are also applied later to structure the results (Chapter 4) and discussion (Chapter 5).

An overview of how previous studies have dealt with design areas is presented in **Table 2.2**. In **Table 2.2**, an uppercase 'X' indicates which design areas were the main focus in the studies, and a lowercase 'x' indicates that although the area was considered, it was not the main focus of the study.

Table 2.2. *Design areas of picking systems previously addressed in the literature.*

<i>Author(s)</i>	<i>Work organisation</i>	<i>Layout</i>	<i>Policies</i>	<i>Packaging</i>	<i>Equipment</i>	<i>Picking information</i>	<i>Automation</i>	<i>Control</i>
Brynzér and Johansson (1995, 1996)	x	x	x	x	x	x		x
Hanson et al. (2015)			X			x		
Hanson et al. (2017)			x			X		
Hanson et al. (2011)		X						
Hanson and Brolin (2013)	X			X			x	
Hanson and Medbo (2019)	x	x	x	x	x	x		x
Boudella et al. (2018)		x	x		X		X	x
Grosse et al. (2015)	X	X	X					
Battini et al. (2015)		x	X			X		
Andriolo et al. (2016)						X		
De Vries et al. (2016)	X	x				X		
Guo et al. (2015)			x			X		
Glock et al. (2017)	X							
Wänström and Medbo (2009)	x	x		X	X			

2.2. Context of kit preparation in production settings

Previous research typically describes relationships between picking systems and their contexts as complex, and to consist of a multitude of interdependencies (Yoon and Sharp, 1996). With respect to the thesis' scope, context consists of factors beyond a designer's control that have relevance for relationships between kit preparation design aspects and performance. This subchapter describes the perspective applied in the thesis with respect to kit preparation context, providing an overview of factors that the literature typically highlights as important. To structure the discussion, the subchapter is divided into four sections.

Section 2.2.1 is concerned with the materials supply system, Section 2.2.2 concerns implications for the thesis' from end-product and component characteristics, Section 2.2.3 concerns implications from plant layout, and Section 2.2.4 concerns implications for the thesis' from pickers' knowledge and experience.

2.2.1. The materials supply system

As stated in Chapter 1, previous research typically describes materials supply systems as consisting of interrelated subcomponents, of which materials handling processes, such as kit preparation, make up one subcomponent (Finnsgård, 2013; Hanson, 2012; Johansson, 2006). Other subcomponents of materials supply systems, such as, transportation or manufacturing planning and control, are important to account for when they affect relationships between kit preparation design aspects and performance, thereby making up context with respect to the thesis' scope.

The scope of the thesis concerns kit preparation and its interface with assembly processes, both of which are closely related materials supply systems. The role of materials supply systems in production settings is to maintain a reliable supply of components for the assembly processes within production systems, and is important in the design of kitting systems (Hanson, 2012; Bozer and McGinnis, 1992).

Various meanings can be ascribed to the term 'materials supply system', and it is therefore appropriate to here explicate the meaning applied in this thesis. Within literature dealing with design of materials supply in production settings, the term 'materials supply system' has been described to consist of the subcomponents materials supply principles, materials handling processes, transportation, packaging, manufacturing planning and control, and storage (Finnsgård, 2013; Hanson, 2012; Johansson, 2006). This meaning of the term 'materials supply system' is adopted in the thesis. The relevance of the materials supply system's subcomponents for the thesis scope is presented next.

Materials supply principles

A materials supply principle represents the way in which components are arranged as they are supplied to, and presented at, assembly processes (Hanson, 2012). There are various materials supply principles available, and kitting makes up one of the available approaches. Kitting can be applied for supply of some components to assembly processes (Johansson, 1991), but can also be applied as a sole principle of materials supply (Hanson, 2012; Caputo and Pelagagge, 2011; Johansson, 1991). There are substantial amounts of research available for how to assign components to various principles of materials supply, and the choice of principle to apply depends on various factors, such as the component characteristics (Hanson, 2012; Limère et al., 2012; Caputo and Pelagagge, 2011).

As previously stated, kit preparation is closely tied with the kitting materials supply principle, and the characteristics of a kitting implementation can have implications for its associated kit preparation. For one, the kits supplied to assembly processes by kitting can be of stationary kind – meaning that that each kit holds components which are consumed at a single assembly work station (Hanson and Brolin, 2013; Caputo and Pelagagge, 2011) – or they can be of travelling kind –

meaning that the kits travel along with the assembly object and are consumed across multiple assembly work stations (ibid.). The kind of kits that are produced, whether they are of stationary or of travelling kind, thereby can affect the types and amounts of components that are available at kit preparation workspaces or how the kit container is designed in order to grant assemblers access to components in the right order in during the assembling sequence.

Previous research has also suggested there is an interrelationship between kitting and other materials supply principles when applied together that also presents implications for kit preparation. One example is in the design of the kit container and carrier, which can take up varying space depending on how they are designed (Caputo and Pelagagge, 2011). If space is already occupied at the assembly process, this could limit the possible designs of the kit carrier and container. Considerations such as these are important with respect to materials supply principles and the thesis' scope.

Materials handling processes

Kit preparation is one type of materials handling process, but there are many others, and these may impact the relationship between kit preparation design and performance.

Generally, a materials handling processes involve activities by which the materials are transformed in some way to alter the dimensions of disorder (Öjmertz, 1998). According to Öjmertz (1998), the dimensions of disorder can be altered by picking, positioning, orienting, sorting and gathering. Kit preparation involves all these activities, but the extent to which the activities are present in a kit preparation application depends on the requirements of the assembly process. For example, in some contexts, there is no explicit requirement on positioning of components in the kit as there could be only a few components included, and it is obvious how the components should be assembled. This has implications for how the kit container should be designed or what the requirements are for a robot arm that carries out kit preparation activities. In other contexts, for example when robotics is applied to support assembly, the components in the kit may have to be in a specific orientation for robot picking to function properly (Boudella et al., 2018).

When kit preparation is present in materials supply systems, possibilities for choices in kit preparation design and options may be affected by other types of materials handling processes. For example, a typical approach in industry is to locate kit preparation workspaces at supermarkets. These are typically decentralised somewhere in the plant (Battini et al., 2013), and there may be workspaces for other types of materials handling processes present, such as workspaces for repacking, sequencing, and loading and unloading of containers at transport vehicles. These workspaces can affect kit preparation design in various ways. For example, allocating inventory amongst various materials handling processes at the supermarket can affect what inventory must be kept at kit preparation workspaces (Caputo and Pelagagge, 2011), and the amount of floor space available for changing the layout of kit preparation workspaces can be restricted if there are many other materials handling processes nearby (Hanson et al., 2011). The impact from other types of materials handling processes, including other processes for kit preparation, are thus important, and must be considered within the thesis' scope.

Transportation

Transportation activities are required to move materials within materials supply systems, and these can have close ties with kit preparation design and performance. Two types of transportation activities are viewed as important with respect to kit preparation.

First, transportation is necessary to replenish kit preparation workspaces, usually from a warehouse upstream in material flows of where kit preparation is carried out. This transportation ensures availability of the components that are needed to prepare kits (Limère et al., 2012). Delays or inconsistencies in the materials replenishment can create acute problems at kit preparation

workspaces, and such problems need to be anticipated in kit preparation. Furthermore, there are return flows of empty packaging from kit preparation workspaces upstream in material flows that also involve transportation, which must be reliable and efficient.

Second, transportation occurs downstream of kit preparation in materials flows when kits are transported to assembly processes, and this may also affect the relationship between kit preparation design and performance. One example is when a transport serves multiple assembly processes, as is often the case when transportation is made between warehouses and assembly processes (Limère et al., 2012), where there may be less flexibility in determining when to complete the kits, as the kits must be available when the transport vehicle arrives. Moreover, return flows of empty kit containers from assembly processes back to kit preparation workspaces must also be considered, so that kit containers are available when needed. In these ways, influences from transportation activities up- and downstream of kit preparation must be considered within the current scope.

Packaging

An integral aspect of materials supply systems that is of keen relevance for kit preparation design and performance is the packaging in which components are contained (Hanson, 2012; Caputo and Pelagagge, 2011). In this thesis, the term ‘packaging’ is seen in light of Chan et al.’s (2006) studies of manufacturing packaging logistics, where packaging is ‘a means of ensuring safe and efficient delivery to the ultimate consumer in sound condition followed by an efficient recovery at minimum cost’ (ibid., p. 1088). As far as packaging relates to kit preparation in this thesis, it is only packaging for storing components at kit preparation workspaces that are of concern. Other forms of packaging related to kit preparation, such as the packaging used for kit containers, are instead viewed as a design aspect and, therefore, not addressed in the current section.

Several studies have shown impact on the kit preparation’s performance based on the packaging applied to store components at kit preparation workspaces. This can affect ergonomics in terms of the posture taken by pickers (Calzavara et al., 2017) as well as the man-hour efficiency (Hanson et al., 2017) by affecting the size of kit preparation workspaces and thereby the distance that has to be travelled between picking locations. In some situations, it may be possible to adapt the packaging applied in storage to what is best suited for kit preparation, whereby storage packaging also can be viewed as a design aspect within the thesis’ scope.

In some situations, storage packaging may be determined in the context of materials supply systems, such as in protecting sensitive components or in the convenience of easier handling at various places in materials supply systems (Chan et al., 2006). The type of packaging may also be decided based on overall costs throughout supply chains. For example, it might be financially beneficial to use higher load factors and thereby reduce transportation costs (Baraldi and Kaminski, 2010) or to use the type of packaging that most benefits suppliers. In those cases, kit preparation design and performance must be considered with respect to the already decided packaging. As such, the role of packaging for kit preparation design and performance can be viewed as situationally dependent, but, regardless of the situation, it is a crucial consideration when dealing with kit preparation design and performance.

Manufacturing planning and control

To timely produce kits that hold necessary components, available information about the sequence of assembly objects to be produced must be considered. This is an important aspect of manufacturing planning and control that is of concern in this thesis. Manufacturing planning and control have been described as encompassing all aspects of manufacturing, including scheduling of machines and materials and ensuring that there is sufficient capacity available (Jonsson and Mattsson, 2009). Many activities that are normally seen as part of manufacturing planning and control fall outside the thesis scope, but previous research has shown that some such activities can have implications for kit preparation design and performance.

The information used in kit preparation to guide picking activities is the same information that is available to the rest of the materials supply system. This information stems from market demand for end-products, and is translated within the scope of manufacturing planning and control into production schedules, which together with product structures are operationalised into picking information (Brynzér and Johansson, 1995; Bozer and McGinnis, 1992). In this way, picking information makes up the demand characteristics for components in kit preparation, reflecting the production volumes, mixes, and delivery timing required by the assembly processes. There are manifold implications for kit preparation design and performance from this aspect of manufacturing planning and control. For example, this can affect inventory levels needed at kit preparation workspaces (Hanson, 2012), capacity requirements of kit preparation (Caputo et al., 2015) or where different components are best stored to reduce walking distances (Boysen et al., 2015; Glock and Grosse, 2012). Furthermore, changes related to production schedules and product structures necessitate kit preparation flexibility.

Another part of manufacturing planning and control that factors into this thesis is the principle by which kit preparation is synchronised with production processes. Here, it can be desirable in some situations to pace kit preparation with the production rate of the production system, in accordance with a pull-based approach, for example, in production systems adhering to lean production (Baudin, 2004) or just-in-time principles (Sali and Sahin, 2016). In other situations, it can be more desirable to conduct kit preparation according to a plan with a push-based approach.

As highlighted earlier, the importance of kit preparation performance in terms of flexibility, kit quality, and man-hour efficiency can be understood from the viewpoint of assembly requirements. However, there may be constraints imposed on kit preparation that are not directly associated with kit preparation performance but affect the applicable options in design. One example is the order time horizon, which refers to the amount of time available from when the picking information is provided until the kits must be available in assembly. This sets restrictions for when kits can be prepared (Brynzér and Johansson, 1995). A very short order time horizon could limit the batch size that can be applied.

Storage

A variety of storage systems are used for components. For instance, they can be part of a warehouse, buffers, supermarkets or a goods receiving area. For kit preparation to be in the materials supply system requires an additional storage point along the material flow (Caputo and Pelagagge, 2011). Sometimes centralised storage is possible, whereby inventories at several kit preparation workspaces can be combined to lower the overall inventory (Battini et al., 2009). Depending on the storage in materials supply systems, there may be opportunities with respect to kit preparation design and performance.

2.2.2. End-product and component characteristics

Characteristics of end-products and components, which are used in kit preparation, are important in kitting systems (Hanson, 2012; Limère et al., 2012; Caputo and Pelagagge, 2011). This section first presents a discussion of end-product characteristics, in terms of product structure and assembling sequence, and thereafter a discussion of how component characteristics, in terms of size, weight, shape, and sensitivity to damage, can affect the relationship between kit preparation design and performance.

Product structure and assembling sequence

The end-product structure can be seen to make up derived requirements for kit preparation, and usually allows it to be organised as ‘end-of-aisle’ order picking, meaning that all components going into kit preparation are concentrated at designated workspaces (Bozer and McGinnis, 1992). In this way, workspaces for kit preparation are typically described as compact, and the picking is carried

out at a high frequency, in comparison to warehouse order picking (Hanson et al., 2017). This also shifts the relative priorities among design areas of picking systems, as travelling time becomes less prominent compared with warehouse order picking (Boysen et al., 2015).

The product structure is also related to the assembling sequence, which means the order by which components presented in kits should be assembled at assembly processes. Typically the preferred order in which kitted components are assembled is the reverse order in which they must be kitted. There may even be physical restrictions related to the order in which components must be assembled. For example, it may not be possible in some situations to assemble a component onto the end-product after another component has already been assembled. Previous research has highlighted that using a structured kit container is a viable approach for ensuring that components are presented in the correct order in kits (Hanson and Brolin, 2013). Furthermore, Hanson and Brolin (2013) also reported on a kit preparation application wherein assemblers performed kit preparation and assembly tasks within the same work cycle, whereby several assemblers continually rotated in a loop between the two tasks. In such a case, kit preparation becomes integrated with the assembling task.

Component characteristics

Characteristics of components can affect the relationship between kit preparation design and performance. Previous research has addressed various characteristics related to components that may be necessary to consider with respect to kit preparation design and performance, including size (Hanson and Medbo, 2019; Caputo et al., 2018), weight (Caputo et al., 2018; Limère et al. 2015), and sensitivity (Limère et al., 2015; Caputo et al., 2015) of components.

Component size refers to dimensions, in terms of length, height, and width, of components and can set constraints for the type of packaging that can be applied in the storage and for the kit container (Hanson and Medbo, 2019). Heavy components may be problematic from an ergonomic standpoint, not only when these components are retrieved from storage locations, but also with respect to the kit carrier becoming heavy when kits are filled with components. Component sensitivity may necessitate components to be stored in protective packaging, such as plastic wrapping, both in the storage package and in the kit container to protect the component from scratches or other damages during transport and handling within the materials supply system. In kit preparation, protective packaging may have to be discarded during picking tours, in which case this activity must be properly accounted for.

2.2.3. The plant's layout characteristics

Several authors have highlighted the plant's layout characteristics as a most relevant concern for the design of materials handling systems and processes (e.g. Finnsgård, 2013; Hanson, 2012; Hanson et al., 2011; Battini et al., 2009; Johansson, 2006).

The amount of floor space available can impact the possibility of expanding kit preparation workspaces, or even for conducting kit preparation at all at some locations, which is important from a flexibility perspective. Some researchers suggest that the amount of floor space to be available for future expansion can be affected by the location of kit preparation workspace, as locating the workspace at certain areas within the plant may grant better access to floor space (Hanson et al., 2011).

The amount of floor space available will also set limits for layout and movement pattern design, as all storage shelves need to be accessible for materials supply to and from kit preparation workspaces (Hanson et al., 2011). Furthermore, the paths of transportation vehicles can impact how the layout of the kit preparation work space can be designed (Hanson et al., 2011).

2.2.4. Pickers' experience and knowledge

Experience and knowledge of the people who carry out kit preparation activities is an important aspect often brought up in literature dealing with warehouse order picking (see e.g. De Vries et al. (2016) or Grosse et al. (2015)). This is also important with respect to kit preparation, as it is often performed by manual labour (Hanson and Medbo, 2019). Previous studies of warehouse order picking have shown that pickers' knowledge and experience can greatly affect performance (De Vries et al., 2016; Grosse et al., 2015).

Previous research has identified the picker's experience level (Grosse and Glock, 2013) and knowledge of the product structure (Hanson and Brolin, 2013; Brynzér and Johansson, 1995) as influencing performance in picking operations. Reports suggest that these traits can either improve performance, when the picker 'fills in the blanks', or it can reduce performance, when the picker circumvents the system and thus diminishes the quality assurance provided by the picking information system (Glock et al., 2017).

Some researchers suggest that kit quality of kit preparation can improve when assemblers perform kit preparation, owing to the knowledge about the assembling sequence and the end-products, which makes the picker better at identifying correct components (Brynzér and Johansson, 1995) and more apt to assess the component's quality if there are damages or other quality-related deficiencies. Furthermore, some studies have suggested that the use of kits to present components to assemblers can support the assembler in learning the assembly procedure (Medbo, 2003). Previous studies of warehouse order picking have suggested that workers typically have little experience, due to high personnel turnover rates, and learning curves can, therefore, be steep (Grosse et al., 2013). The personality traits of pickers make up another aspect that has been identified as affecting performance in picking systems (De Vries et al., 2016).

The available literature suggests an interdependency between the picker's experience and knowledge and the practice of kit preparation. With respect to the thesis, which deals with design aspects and performance of kit preparation, the influence of the picker's experience and knowledge on the relationships between the design and performance must be accounted for. While some design aspects, for example, related to work organisation, are close to the contextual factors discussed here, experience and knowledge of pickers is treated as a part of the context, since these traits cannot be fully controlled, and often, must be accounted for with respect to the thesis' scope.

2.2.5. Summarising overview of kit preparation context in previous literature

To conclude this subchapter about kit preparation context, **Table 2.3** presents an overview of the context aspects various authors have acknowledged in studies concerned with kit preparation and order picking.

Table 2.3. *Summarising overview of how previous research has dealt with context in kit preparation and order picking.*

<i>Author</i>	<i>Materials handling system</i>	<i>End-products and components</i>	<i>Plant's layout</i>	<i>Picker's experience and knowledge</i>
Hanson et al. (2011)	X		X	
Hanson and Medbo (2019)	X	X	X	X
Hanson and Brolin (2013)	X	X	X	X
Battini et al. (2009)	X		X	
Brynzér and Johansson (1995)	X	X		X
Medbo (2003)	X	X		X
Grosse and Glock (2013)	X			X
Grosse et al. (2015)	X			X
Caputo et al. (2018)	X	X		
De Vries et al. (2016)	X		X	X
Caputo et al. (2015)	X	X		
Limère et al. (2015)	X	X		
Bozer and McGinnis (1992)	X	X		
Boysen et al. (2015)	X			
Boudella et al. (2018)	X	X		

2.3. Kit preparation performance

Kit preparation performance plays a central role with respect to the thesis' purpose (Subchapter 1.2). As presented in Chapter 1, there are many performance areas associated with kit preparation that are important with respect to kitting and assembly, such as ergonomics, inventory levels, and transportation. The research questions, which were formulated in Subchapter 1.4 to address the thesis purpose, target relationships between kit preparation design aspects and three performance areas of kit preparation in terms of flexibility (Research Question 1), kit quality (Research Question 2), and man-hour efficiency (Research Question 3). When the research questions were formulated in Subchapter 1.4, the central arguments in the literature were presented as motivations for the research questions. This subchapter provides the full motivation for the research questions by reviewing the published literature with respect to the performance areas that the research questions address.

The subchapter is organised in three sections. Section 2.3.1 deals with kit preparation flexibility performance; Section 2.3.2 deals with kit quality performance; and Section 2.3.3 deals with man-hour efficiency performance.

Each section is structured similarly. First, the performance area's relevance for kit preparation is discussed with respect to available literature, after which important terms are defined. Thereafter, an overview of the available publications that have dealt with the performance area is presented. Within each section, the publications are organised according to the research method applied. Furthermore, since kit preparation flexibility, kit quality, and man-hour efficiency are discussed in separate sections, some publications that have dealt with more than one type of performance are discussed in more than one section.

At the end of each section, the reviewed publications are summarised in a table (see **Table 2.4** regarding flexibility performance, **Table 2.5** regarding kit quality performance, and **Table 2.6** regarding man-hour efficiency performance), and the relevance of the research questions are highlighted.

2.3.1. Kit preparation flexibility

Kitting has been acknowledged as providing flexibility benefits when applied with mixed-model assembly, especially when there is a multitude of component variants (Caputo and Pelagagge, 2011; Bozer and McGinnis, 1992). Some authors explain that the flexibility benefits associated with a kitting approach come from the smaller space occupied by the kits at the assembly process, in contrast to presenting components in packages with uniform contents (Hanson and Brolin, 2013; Caputo and Pelagagge, 2011; Wänström and Medbo, 2009). Other authors have pointed out that change in production systems related to components, such as in product structure and the assembly schedule, can more easily be accommodated with a kitting approach, as many changes can be concentrated to the kit preparation workspace (Caputo and Pelagagge, 2011). However, some reports have highlighted aspects of kit preparation design that can inhibit the flexibility normally associated with a kitting approach. First, when applying kit containers with fitted slots for keeping components in predictable positions within the kits, new product introductions can be problematic since kit containers need to be redesigned to make room for new component types (Hanson and Brolin, 2013; Brynzér and Johansson, 1995). Second, flexibility can be affected by where kit preparation workspaces are located (Hanson et al., 2011). Locating the kit preparation workspace close to the assembly process may restrict redesigns and expansions of the workspace since floor space generally is very limited close to the assembly process, whereas it is often more plentiful further away, such as in the warehouse (Hanson et al., 2011). These examples highlight how flexibility constraints associated with kit preparation design aspects inhibit flexibility of kitting as an approach of materials supply, which, thereby, also restricts flexibility in assembly processes. Knowledge of how kit preparation flexibility can be achieved is thereby desirable, but as is shown later in this section, there is no consensus in published literature about which factors govern flexibility of kit preparation.

The term 'kit preparation flexibility' as applied in this thesis

The thesis views the term 'kit preparation flexibility' to be composed of flexibility types, which consist of new product, modification, mix, volume, and delivery flexibility types. This view of flexibility is rooted in literature dealing with production flexibility, and was deemed suitable owing to the close relationship between flexibility of kit preparation and production systems. Relevant literature that underpins this view is highlighted next.

From a general standpoint, production flexibility can be said to represent the ability of individual manufacturing resources (Slack, 2005), including the material handling units (Sánchez and Pérez, 2005; Sethi and Sethi, 1990), to respond with little penalty in time, effort, cost or performance, to environmental uncertainty and variability of outputs (Upton, 1995; Correa and Slack, 1994). Flexibility is often categorised according to the reasons that the flexibility is beneficial (Slack, 2005; Parker and Wirth, 1999). Some authors have suggested that the flexibility types to consider should be decided with respect to the uncertainty or variability that needs to be managed (Beach et al., 2000; Gerwin, 1993). For kit preparation, uncertainty and variability stem from changes in production systems. Typical changes in production systems that would require kit preparation flexibility include new product introductions (Slack, 2005; Koste and Malhotra, 1999), engineering changes of existing products and components (Koste and Malhotra, 1999; Gerwin, 1993), alterations of the product mix (Slack, 2005; Koste and Malhotra, 1999), changes in production volume or production rate (Slack, 2005; Bartezzaghi and Turco, 1989) and changes in the delivery schedule (Slack, 2005; Beamon, 1999). These changes require, respectively, the flexibility types new product, modification, mix, volume, and delivery flexibility. Each of these changes in production systems and the corresponding flexibility types are relevant for kit preparation in fulfilling its role in production systems, as indicated by previous studies on flexibility in materials handling and supply chain management (e.g. Wänström and Medbo, 2009; Hanson et al., 2011; Johansson et al., 2012).

Furthermore, flexibility is often distinguished as dimensions that reflect different measures of the flexibility types. Flexibility dimensions have been described as the ‘characteristic coordinates which help describe the nature of the flexibility types’ (Parker and Wirth, 1999, p. 430). This thesis recognises the distinction between the two flexibility dimensions of range and response (Slack, 2005) with respect to kit preparation. These dimensions are acknowledged because they have been prominent in the literature, although often referred to using different terminology, such as capability and capacity flexibility (Manzini et al., 2004). Furthermore, these dimensions have their roots in production systems and their associated operations (see e.g. Koste et al., 2004; Upton, 1995) to which kit preparation is closely related.

Previous studies that have dealt with kit preparation flexibility

Research that has dealt with flexibility related to kitting systems usually considers flexibility from the viewpoint of how assembly processes are affected by the use of kitting (e.g. Hanson, 2012; Hanson and Brolin, 2013). Rarely has flexibility been dealt with as directly related to the process of kit preparation. However, some of the studies have included relationships between kit preparation design aspects and flexibility. The following sections address these relevant publications.

The literature discussed in this section has ascribed flexibility effects to kit preparation design aspects and their associated options. The highlighted publications are only discussed in terms of how they have addressed flexibility as relevant for kit preparation, while other flexibility effects mentioned in the articles are not considered. Furthermore, only publications that have focused on kitting or kit preparation and flexibility are reviewed in this section.

A few studies have addressed flexibility related to kit preparation by means of case research. In their comprehensive case research on picking systems, Brynzér and Johansson (1995) highlighted that the kit container’s design can have implications for flexibility. The reasoning was that when kit containers are designed with fitted slots for components, they need to be redesigned when new components are incorporated into kits, following, for example, new product introductions. They also highlighted that the batching time horizon can affect flexibility in handling order changes. Hanson and Brolin (2013) studied the relative effects of using principles of kitting and continuous supply for materials supply to assembly processes in a multiple case study, and considered flexibility as one of the effects. They identified how the kit container’s design can reduce flexibility when components change and cannot use the existing fitted slots. Furthermore, they identified that having assemblers perform kit preparation and assembly tasks within the same work cycle can benefit volume flexibility, as it is easy to rebalance the activities for dealing with volume fluctuations. In a multiple case study dealing with the impact on in-plant materials supply performance from the location of kit preparation, Hanson et al. (2011) considered flexibility and found that floor space for expanding the preparation area is more likely to be available further away from assembly. They indicated that the ability to expand the preparation area is important for new product, modification, mix, and volume flexibility, as the availability of floor space facilitates accommodation of new components and additional inventory.

Some studies in discussing implications for flexibility were primarily concerned with other performance areas. Hanson et al. (2017) compared man-hour efficiency of kit preparation supported by a paper pick list with a HUD-system (head-up display) in a kit preparation experiment in laboratory settings. When discussing the results, they noted that presenting all picking information digitally, as was possible with the HUD-system, may benefit flexibility as it removes the need to have physical components, such as signs with text information, present at kit preparation workspaces. When discussing their model for kitting operations planning, Caputo et al. (2015) noted that future additions to their model could be to include reconfigurability and flexibility to analyse how kitting systems dynamically adapt to requirements in production systems. When studying the choice between line stocking and kitting in assembly processes, Limère et al. (2012) reasons that kitting is associated with a lower flexibility in handling defects or when there are

changes in the assembly schedule, because the workspace is normally some distance from the assembly processes.

Previous studies dealing with flexibility in warehouse order picking and assembly

Some publications on topics of warehouse order picking and assembly workstation design have brought forth aspects that influence flexibility. This section presents a brief discussion about flexibility in order picking and assembly operations, and highlights literature that has dealt with design aspects associated with these processes which have close ties to kit preparation. Although studies that deal with flexibility in warehouse order picking indeed are scarce (Staudt et al., 2015), the overview presented in the section should be viewed as non-exhaustive. Instead of an exhaustive account, the section aims to only highlight aspects that are related to flexibility and are of relevance with respect to the design areas of kit preparation dealt with in this thesis (see Subchapter 2.1).

Manzini et al. (2007) developed a framework for design of order picking systems applying a class-based picker to product approach. They explained that order picking systems that involve less than unit load picking present several constraints and limitations that can come into conflict with flexibility, in terms of dealing with seasonal demands, product introductions, and changes related to packaging. In a literature review on the topic of design and control of warehouse order picking systems, De Koster et al. (2007) discuss flexibility impacts associated with order retrieval times and storage policies. They highlight that short order retrieval times can benefit flexibility, as late changes in customer orders can more easily be accommodated. They highlight that policies that specify where individual products should be stored, such as dedicated or class-based policies, are associated with lower flexibility since the products must be reshuffled along with changes of product demand. This relationship between storage policies and flexibility has also been recognised by other researchers that have dealt with design and control of warehouse order picking (e.g. Roodbergen, 2012; Chan and Chan, 2011; Yu, 2008). Chan and Chan (2011) discuss flexibility related to storage and routing policies when studying implementation of class-based storage as a means to improve productivity in manual and multi-level order picking in a distribution warehouse. With respect to routing policies, they explain that policies that allow for transversal and return routings have flexibility benefits that contribute to higher overall performance in order picking operations. The flexibility effects related to storage and routing policy were also reported by Yu (2008) and Roodbergen (2012) when modelling order picking systems with objectives of enhancing performance.

In a literature review of human factors in order picking planning models, Grosse et al. (2015) explain that many firms still prefer manual order picking over automated order picking, as humans are more flexible than machines in dealing with unexpected changes that require logical reasoning. This relationship between flexibility and automation has also been addressed by other researchers dealing with warehouse order picking design. Baker and Halim (2007) studied the reasons for, and the nature of, warehouse automation implementations by means of interviews and surveys addressed to warehouse managers. They explained that automation is often viewed as a means of attaining flexibility to deal with peak volume fluctuations on short notice, especially when there are issues with staff availability. They concluded that solutions for automation tend to generate concerns in companies about disrupting ongoing operations in the short-term, and about delimiting flexibility in the long-term. They stress that scenario-planning and careful analysis of business requirements is key for assuring flexibility of automated solutions, and that flexibility must be built into the solution in order to ensure abilities of dealing with changes in market requirements. In discussing typical issues, systems and models for order picking systems, Park (2012) highlighted several advantages associated with automation, including greatly reduced labour costs and increased accuracy of inventory and picking operations, but also indicated that a drawback with automation is reduced flexibility in being able to reconfigure the system when adapting to new

business requirements. For automation to be viable, Park explains, it has to be well designed and implemented, and ideally accompanied with work simplification and standardisation.

Some studies dealing with assembly processes present relevant input for a discussion of kit preparation flexibility. When studying materials picking at manual assembly stations, Wänström and Medbo (2009) found that wheel-equipped storage racks can improve new product, mix and volume flexibility at assembly stations, in contrast to when racks are bolted to the floor. They also found the storage packaging type and size to be important for flexibility types as it affects the amount of space required for presenting a variety of components. Manzini et al. (2004) developed a framework for design of flexible cellular assembly systems in a conceptual study. They considered two kinds of flexibility, capability and capacity flexibility. Capability flexibility refers to the ability to deal with market changes in form of product variations, and capacity flexibility means the ability to deal with changes in product quantities. They emphasised the importance of relationships amongst various processes in the assembly systems and the importance of work organisation around the tasks associated with creating flexible assembly systems. They also stated that ‘production flexibility is the sum of flexibility possessed by individual equipment, products, process and operations’ (ibid., p. 3505).

Relevance of Research Question 1 considering the reviewed literature

Some of the reviewed studies have considered flexibility directly related to kit preparation design aspects (e.g., Hanson and Brodin, 2013; Hanson et al., 2011; Brynzér and Johansson, 1995), but most of the available studies seldom focus on flexibility, but rather discuss implications for flexibility when focusing on other performance areas (e.g., Hanson et al., 2017; Brynzér and Johansson, 1995). Furthermore, as the term ‘kit preparation flexibility’ is applied in the thesis, flexibility production systems are typically viewed as a multidimensional construct and the flexibility of interest depend on the uncertainty or variability that is desirable to handle. The available literature does point out and briefly describes how various design aspects of kit preparation can affect kit preparation flexibility, but this knowledge is, at best, fragmented.

The reviewed studies that have touched upon kit preparation flexibility add up to a rudimentary understanding of what kit preparation flexibility is, and how it is affected by aspects of kit preparation design. For the most part, the relevant literature consists of studies that have addressed flexibility with respect to materials supply and kitting; meanwhile, flexibility with respect to kit preparation has merely been recognised as important. Furthermore, there are important relationships between design and flexibility in the related areas of warehouse order picking and assembly, which have yet to be studied in the context of kit preparation. Examples include storage policies, automation, materials handling equipment and packaging, which have been pointed out as important for flexibility in these related areas, but no knowledge exists about how these aspects affect flexibility in kit preparation. Hence, research that addresses Research Question 1, which asks how kit preparation design aspects govern kit preparation flexibility, is scarce in the literature.

A summary of the research studies, which have been reviewed in this section, is presented in **Table 2.4**, highlighting the research approach, perspective on flexibility, design aspects, and context that have been considered.

Table 2.4. *Overview of published literature that in some way has dealt with flexibility and kit preparation design aspects.*

<i>Study</i>	<i>Research approach</i>	<i>Flexibility perspective</i>	<i>Design aspects</i>	<i>Context</i>
Brynzér and Johansson (1995)	Case research (multiple)	None identified	Kit container, batching policy	Batching time horizon
Hanson and Brolin (2013)	Case research (multiple)	Ability to handle large numbers of part variants, variations in production volumes, new product introductions, and the ability to quickly perform product changeovers	Kit container Work organisation	Plant layout Materials supply system Pickers' knowledge and experience
Hanson et al. (2011)	Case research (multiple)	Flexibility of handling changes related to production volumes, new product introductions, product modifications, and product mix	Location	Plant layout
Wänström and Medbo (2009)	Case research (embedded)	Volume, mix, new product, and modification flexibility	Storage packaging type, storage rack design	Plant layout
Hanson et al. (2017)	Experiments (laboratory)	Reconfigurability of kit preparation areas	Picking information system	None identified
Baker and Halim (2007)	Survey	Ability to deal with changing market requirements, including production volumes and SKU ranges over short and long terms	Automation	None identified
Limère et al. (2012)	Modelling (mathematical)	Flexibility in dealing defects and sequence changes	Location	None identified
Caputo et al. (2015)	Modelling (mathematical)	System flexibility and reconfigurability	None identified	None identified
Yu (2008)	Modelling (mathematical)	None identified	Storage policy	None identified
Manzini et al. (2007)	Modelling (analytical)	Ability to deal with changing operating conditions, in terms of seasonal demand, introduction of new product, and changes in packaging	None identified	None identified
Manzini et al. (2004)	Modelling (analytical)	Capability flexibility and capacity flexibility	None identified	Market developments, technological developments
Grosse et al. (2015)	Conceptual study)	(literature Flexibility in reacting to unexpected changes	Automation	None identified

2.3.2. Kit quality

As stated in the introduction, some reports maintain that using kitting can improve quality in assembly processes by making it easier for the assembler to find the right components (Caputo et al., 2015; Medbo, 2003). However, other reports suggest that kitting can compromise quality of assembly processes, as kit errors can arise in kit preparation (Caputo et al., 2017a; Caputo et al., 2017b; Hanson and Brolin, 2013). To apply kitting effectively in industry, reducing the number of kit errors and quality-related costs of kit preparation is crucial. However, there is little consensus in industry about how kit preparation quality can be supported. Furthermore, empirical analysis of kit preparation errors is a challenging task as the errors occur infrequently, and it can be difficult to obtain reliable statistics. This is likely the reason that so few studies have addressed kit quality in the past (Caputo et al., 2017a; Caputo et al., 2017b). As shown later in this section, the literature offers virtually no guidance as to how kit quality should be supported.

The term 'kit quality' as applied in the thesis

Most authors who have dealt with quality related to kit preparation seem to agree that kit preparation quality reflects the amount of errors (or quality problems as termed by some authors, e.g. Caputo et al., 2017a) resulting from kit preparation. One term that has been applied to describe kit preparation quality is 'picking accuracy' (Hanson et al., 2017; Brynzér and Johansson, 1995), referring to the proportion of correctly picked components, correctly executed order lines, or correctly prepared kits, relative to total amounts. Error rates is a term similar to picking accuracy and also reflects the amount of errors in kits (e.g. Caputo et al., 2017a; Caputo et al., 2017b; Caputo et al., 2015;). Error rates can refer to the proportion of erroneous components, incorrectly executed order lines, or erroneous kits relative to total amounts. The term 'error rate' is also commonly applied in literature dealing with quality in warehouse order picking (e.g. Grosse et al., 2015; Battini et al., 2015), although picking accuracy has also been used in some instances (e.g. Park, 2012). Picking accuracy and error rates can refer to the same data, in which case they are each other's inverses, but the terms may also refer to different data. To avoid confusion, the term 'kit quality' is applied in the thesis, taken to represent numbers of kit errors that can be found in completed kits. Hence, this view includes errors in the product structure, as the kits then contain wrong components, with respect to the needed components at assembly processes. Speaking about higher kit quality naturally implies a higher quality associated with kit preparation.

Some studies of systems for kit preparation and order picking have used a wider scope with respect to quality, more than just the number of errors; they consider the costs incurred in correcting the errors. Two examples in this respect are Caputo et al. (2017a) and Caputo et al. (2017b), wherein quality was modelled with respect to probabilities for various types of kit errors to occur and the subsequent costs of correcting kit errors. Other examples whereby quality is viewed in a wider sense than picking accuracy alone include Hanson et al. (2011), Battini et al. (2015), and Glock et al. (2017). Some studies have shown that kit preparation design aspects may impact corrections of kit errors, for example, from the choice of location within the materials flow for the kit preparation workspace (Hanson et al., 2011). Therefore, the thesis takes the term 'quality' as associated with kit preparation to include both numbers of kit errors, represented by kit quality, and their associated corrections.

Previous research that has dealt with kit quality

Quality as associated with kit preparation has been addressed by various research methods, including case research (e.g. Brynzér and Johansson, 1995), experiments (e.g. Hanson et al., 2017), and modelling (e.g. Caputo et al., 2017a). Apart from a few notable exceptions (e.g. Caputo et al. 2017a, Caputo et al., 2017b), the available literature that has thoroughly dealt with kit quality is scarce, but several studies have discussed implications for kit preparation kit quality in results from studies with other focuses. In the following, publications that have dealt with kit quality associated with kit preparation are discussed. The publications have been organised by the research method used.

One line of research by which kit preparation quality has been addressed is case research, with industrial applications for kit preparation as empirical basis. Brynzér and Johansson (1995) carried out comprehensive case research in the automotive industry and proposed several approaches to prevent errors in kit preparation. For example, they highlighted that the pick list's design can facilitate picking accuracy, and that reducing disturbances during the work cycle can reduce the risk for mistakes that lead to kit errors. A main conclusion from their studies was the importance of the design of picking information systems in achieving satisfactory kit quality. When studying the impact of the location of kit preparation on in-plant materials supply performance, Hanson et al. (2011) did not identify any direct links to how the location affected the number of kit errors. However, they found that the location in the materials flow where kit preparation is carried out is important for the response time of supplying components to correct kit errors. In a case study of the

relative effects of materials supply by means of kitting, Hanson and Brodin (2013) highlighted the kit container's design as an important aspect for kit quality and emphasised that the picker's knowledge of the assembly process could be beneficial.

Another approach in previous research to address quality in kit preparation has been to conduct experiments in industrial and laboratory settings. In an industrially relevant experiment of kit preparation, Hanson et al. (2017) compared the number of kit preparation errors when applying a paper pick list or a HUD with mixed-reality for conveying picking information. They found that the HUD system resulted in markedly fewer errors, owing to a more effective conveyance of picking information. Hanson et al. (2015) conducted two experiments in studying the efficiency impact of batch size in kit preparation and determined that while batching appears beneficial for efficiency, it may be more difficult to ensure kit quality when a batching approach is applied.

Quality in kit preparation has also been addressed with mathematical modelling. Caputo et al. (2017a) and Caputo et al. (2017b) developed comprehensive models for estimating the costs of manual errors in kit preparation. They defined five error types: missing components, wrong components, damaged components, wrong number of components and wrong component position, and developed event trees for estimating quality-related costs based on the severity of the error types in regard to the assembly process. While these models allow the quality-related costs of kit preparation to be estimated when selecting among supply principles, they do not deal with what kit preparation design to apply for supporting kit quality. An earlier version of the models presented in Caputo et al. (2017a) and (2017b) was also available in Caputo et al. (2015), wherein a model for kitting operations planning was developed. The key difference between these two sets of models is the level of detail. The model was grounded in the much richer area of manual errors in assembly processes in Caputo et al. (2017a) and (2017b), although the main components of the frameworks are the same.

Previous research that has dealt with quality in warehouse order picking

Quality has been described as an important performance area of warehouse order picking operations (Park, 2012), and researchers have addressed the topic using a variety of approaches. The following section discusses relevant publications that have addressed design aspects and their relationship with quality in order picking operations. Of interest here are publications that have brought forward quality-related effects of design aspects that are also relevant in the context of kit preparation. Examples in this regard are effects related to picking information and work organisation, while other aspects that are of less concern in kit preparation, such as routing policy, are not discussed here. The publications have been organised by the research approach used to address the topic.

Conceptual studies have addressed quality in warehouse order picking. In a literature review of previous research that has considered human factors in warehouse order picking design, Grosse et al. (2015) highlighted four design aspects with importance for quality: storage assignment, batching policy, layout and work organisation. They propose a set of directions for further research dealing with how the design of picking information affects quality. An example would be how a poorly structured pick list compares quality-wise to a well-structured pick list.

Based on a comprehensive case research study of order picking in warehouses, Glock et al. (2017) identified how deviations from the prescribed work standard – so-called maverick picking – can have an effect on picking quality. They found that quality comes at risk with maverick picking, but also that pickers can find more effective ways to carry out the work in poorly designed systems.

Experiments that included quality-related measurements have been performed in warehouse order picking. Guo et al. (2015) conducted an experiment comparing the number of quality problems associated with various types of picking information systems in order picking for distribution. They found that systems in which a HUD or a cart-mounted display was used resulted in markedly fewer errors than did pick-by-light or a paper pick list. However, they focused on how information was

conveyed by means of the four systems, and as they state, they did not consider confirmations but highlighted that confirmations may influence the observed outcomes. De Vries et al. (2016) studied the impact of pickers' personalities on performance of warehouse order picking, including quality by means of a large-scale experiment. The experiment involved over a hundred participants and they were able to identify significant relationships between the picker's personality, the applied picking information system and the order picking quality.

Mathematical modelling has been applied to address quality in warehouse order picking. When comparing the economic impact of different types of paperless technologies in warehouse order picking, Battini et al. (2015) showed how various error types can occur when pickers interact with picking information systems. The errors were modelled in two main categories: detectable and propagating errors. Detectable errors were noticed during the picking work cycle, such as when the confirmation was wrong. Propagating errors could only be detected by the recipient of the items when the confirmation was correct, but the items or quantity were wrong. Brynzér and Johansson (1996) developed a method for storage assignment with respect to the picker's perspective. The benefit of this method was improved efficiency and reduced errors in the picking work cycle.

Summary of the reviewed literature and relevance of Research Question 2

An overview of the reviewed literature is shown in **Table 2.5**. It can be seen that previous research has explained the types of human errors that can arise in kitting systems and how their costs can be estimated if probabilities of the errors' occurrences are known (e.g. Caputo et al., 2017a). Moreover, previous research has defined the types of errors that can occur in order picking when a picking information system is applied as well as the economic impact (e.g. Battini et al., 2015). However, research regarding how design aspects of kit preparation govern the kit quality associated with kit preparation has remained scarce, and apart from a few contributions (e.g. Brynzer and Johansson, 1995), there is an evident lack of knowledge about the relationships between the design aspects of kit preparation and their effect on kit quality.

Empirical studies that address kit quality of kit preparation have been reported as scarce (Caputo et al., 2017a; Caputo et al., 2017b), and as other researchers point out (Hanson et al., 2017), research methods that rely on statistical analysis of empirical data are challenging to apply, as kit preparation errors occur infrequently. Still, practitioners need more knowledge about how to prevent kit errors and reduce the costs of correcting such errors. Some researchers have proposed directions by which such knowledge may be sought; for example, Grosse et al. (2015) requested more research on how the design of the picking information can impact quality. In light of the available literature, there is a clear need for knowledge about how the design aspects of kit preparation govern kit quality. Thereby, contributions that address Research Question 2 of this thesis are important.

Table 2.5. *Overview of studies that have dealt with quality related to kit preparation and order picking processes.*

<i>Study</i>	<i>Approach</i>	<i>Quality perspective</i>	<i>Design aspects</i>	<i>Context</i>
Brynzér and Johansson (1995)	Case research	Picking accuracy	Storage location Picking information Kit container	Parts commonality Component characteristics Production process characteristics Amount of component numbers for one object
Hanson et al. (2011)	Case research	Picking accuracy based on the number of faulty parts	Location	Floor space availability within the plant
Hanson and Brolin (2013)	Case research	Quality deficiencies in form of kit preparation errors (missing, incorrect, and defective parts)	Kit container Picker's job role Configuration of kit preparation area	Transports to assembly
Glock et al. (2017)	Case research	Pick error rates among error types wrong part, wrong quantity, and missing parts	Picking information system (information technology)	Industry type Company size Warehouse size Order picking process type (e.g. pick-by-order)
Hanson et al. (2015)	Experiments (industry)	Kits with correct contents	Batching policy	None identified
Hanson et al. (2017)	Experiments (laboratory)	Picking accuracy measured through the number of errors observed in kits in relation to the total number of components picked	Means of information conveyance; Batching policy	Picking density
Guo et al. (2015)	Experiments (laboratory)	Pick errors in form of substitution errors, missing-part errors, and additional-part errors	Picking information system Batching policy	Picking density Task variety
Caputo et al. (2017a), Caputo et al. (2017b)	Modelling (mathematical)	Logistic errors (part missing from kit, wrong part in kit, part unfit for use/damaged, incorrect parts number (in case of multiple parts), parts in wrong sequence/position)	None identified	None identified
Caputo et al. (2015)	Modelling (mathematical)	Errors in kitting-supported assembly (missing parts or wrong number of parts, wrong part, defective part, right part at the wrong place in kit)	None identified	Component characteristics
Battini et al. (2015)	Modelling (mathematical)	Errors during picking tours in form of detectable errors (right item picked and wrong item confirmed; wrong item picked and wrong item confirmed) and propagating (wrong item picked but right item confirmed; wrong quantity picked)	Picking information system	Picking density
Brynzér and Johansson (1996)	Modelling (analytical)	Picking errors	Storage policy	Component characteristics (frequency, size, weight)
Grosse et al. (2015)	Conceptual (literature study)	Quality (pick errors)	Layout Batching/routing policy Storage assignment Work organisation	None identified

2.3.3. Kit preparation man-hour efficiency

Kit preparation is normally performed by manual labour (Hanson and Medbo, 2019) and the literature typically highlights the man-hours required as the main drawback of applying kitting-based materials supply (e.g. Limère et al., 2012; Caputo and Pelagagge, 2011; Bozer and McGinnis, 1992). When kitting is used, the materials handling activities associated with kit preparation involve

collecting components and sorting these into kits, so that the assembler can carry out assembly with little searching and fetching of components by collecting all the needed components from kits. In this way, picking activities are moved from assembly processes to kit preparation (Baudin, 2004), and the assembling time is shortened owing to the reduced time spent on searching and walking in assembly processes (Limère et al., 2012). Hence, there is a clear trade-off associated with the use of kitting between the efficiency gained in assembly processes and the man-hours required for kit preparation. On these grounds, kit preparation man-hour efficiency is important to ensure a low running cost, and to realise the benefits normally associated with a kitting approach (Hanson and Medbo, 2019).

The term 'kit preparation man-hour efficiency' as applied in the thesis

Various perspectives have been used in previous studies as reference to time expenditure in kit preparation. In studies that have involved kitting and kit preparation when dealing with choice among materials supply principles, it is often total time expenditures associated with kit preparation activities that are considered. Here, Hanson and Brolin (2013) used the term 'man-hour consumption', signifying the absolute number of man-hours associated with kitting and line stocking. Caputo et al. (2015) instead used the term 'work hours' when dealing with kitting operations planning, and Limère et al. (2012) estimated the total time and costs of kit preparation when comparing kitting with line stocking. Similarly, Limère et al. (2015) estimated total time and costs of kit preparation when components were assigned between kitting and line stocking in supply to assembly processes.

Studies dealing with design options for kit preparation have also used total time expenditures as a comparative basis (e.g. Brynzér and Johansson, 1995), but averages of kit preparation time relative to some activity have also been used by some authors (e.g. Hanson et al., 2017; Hanson and Medbo, 2019). With total time expenditures, Brynzér and Johansson (1995) made use of the term 'picking efficiency', referring to the proportion of time spent on picking activity relative to the total time spent during picking tours, when studying how design options of kitting and order picking systems impacted performance. Another view taken by some authors is to express man-hour efficiency as the average time spent per picked component. This approach was used by Hanson et al. (2017) in an experiment comparing options for conveying picking information with respect to time-efficiency, by measuring time-efficiency as average time spent per kitted component. Hanson and Medbo (2019) used the term 'man-hour efficiency' for same measurement, when analysing what aspects of kit preparation design and context that are most impactful on kit preparation man-hour efficiency. A similar approach to that of Hanson and Medbo (2019) was used by Guo et al. (2015) when conducting experiments in warehouse order picking settings. They then compared the average task time when using different types of picking information systems to carry out a set amount of work.

The above highlights two different viewpoints with respect to time expenditure in kit preparation. One perspective is to view time expenditures in absolute terms, often with the purpose of estimating costs of kit preparation activities. This view is used, for example, when dealing with costs of alternative materials supply principles, as in Limère et al. (2012), Limère et al. (2015), and Hanson and Brolin (2013). It has also been applied when dealing with options for kit preparation design, for example, by Brynzér and Johansson (1995) when they studied how much time is spent on various kit preparation tasks in proportion to the total cycle time. The other view considers time expenditures in relative terms, as the average time spent to complete a set amount of work, for example the average time spent to kit a component. This view is maintained by Hanson et al. (2017), Hanson and Medbo (2019), and Guo et al. (2015), and is used as a basis for comparison of options regarding man-hour efficiency.

It seems more useful to consider man-hour efficiency as relative to a set amount of work rather than in absolute terms when dealing with options for kit preparation design. This is because what would

be of interest when comparing options is the extent to which the man-hour efficiency is affected by use of the different options, and not the time spent on various activities. Therefore, the perspective of man-hour efficiency applied in this thesis is to view kit preparation man-hour efficiency in line with Hanson and Medbo's (2019) definition, i.e. the average time spent during kit preparation work cycles per kitted component. This thesis concerns kit preparation design aspects and their associated options, and this perspective can readily show the effects various options have on man-hour efficiency, without delving into details about how much time is spent on various activities.

Previous studies that have dealt with man-hour efficiency in kit preparation

In the following, studies that have addressed man-hour efficiency and kit preparation design aspects are discussed. The term 'man-hour efficiency' is used as a general reference to time expenditure in kit preparation and in place of other terms that may have been used in the publications. However, significantly different interpretations than the perspective applied in the thesis are explained.

Previous research that has dealt with man-hour efficiency related to kit preparation and order picking has used a variety of research methods. One group of publications has addressed man-hour efficiency by means of case research. Brynzér and Johansson (1995) used time studies and grouped the expenditure during kit preparation into different activities to highlight differences between alternate designs of kit preparation applications. They highlighted a number of design aspects as important to this topic, including the design of the kit container, the work organisation, the storage policy, and the picking information system. Brynzér et al. (1994) developed a method evaluating man-hour efficiency in order picking systems called 'zero-based analysis'. The method was applied by recording the time spent in an industrial application for kit preparation and compared this with various activities with ideal and waste-free versions of the application, which were theoretically constructed. Hanson and Medbo (2019) performed comprehensive case research using 15 different cases of industrial kit preparation to identify what factors in the design and context that most affected kit preparation man-hour efficiency. Amongst their findings, influential design aspects were found to be the picking information system, the batch size, and the configuration of the component racks. Furthermore, they identified several factors in the kit preparation's context as important for man-hour efficiency. Amongst the more influential ones were the amount of components at the kit preparation area, the component size, the picking density, and the number of components per kit. They concluded that the impact on kit preparation man-hour efficiency from aspects of kit preparation design and context is decisive and complex. They recommended that time expended in preparation of kits should be viewed as variable in light of kit preparation design and context, and that viewing the time as constant, as typical in studies based on mathematical modelling, should be done cautiously.

Experiments in industrial and laboratory settings is another approach that has been applied to study man-hour efficiency. Hanson et al. (2015) compared the impact of various batch sizes on man-hour efficiency of kit preparation. In the study, they video-recorded the kit preparation when various batch sizes were applied, and then extracted the time it took to complete a fixed amount of work with the various batch sizes and compared these statistically. Hanson et al. (2017) applied a similar approach when they compared man-hour efficiency associated with picking information being conveyed by a paper pick list and a HUD-system, which rendered the picking information as augmented reality. That study also applied video-recording and post-experiment statistical analysis to compare the time-efficiency associated with the two applications.

There are some examples in the literature whereby the man-hour efficiency of kit preparation has been addressed with mathematical modelling. For the most part, the mathematical modelling approaches have been applied in comparative frameworks to decide between various materials supply principles on basis of supply cost (see Caputo et al., 2018; Caputo et al., 2017a; Caputo et al., 2017b; Caputo et al., 2015; Limère et al., 2015; Limère et al., 2012; Caputo and Pelagagge, 2011; Bozer and McGinnis, 1992). A recent study by Boudella et al. (2018) studied kit preparation

man-hour efficiency with respect to two work cells, one cell controlled by an operator and the other controlled by a robot, that worked in series to produce kits for an assembly process. Their model helped minimise the cycle time by assigning components between the two work cells, and was compared with a fully manual setup. Their findings showed that proper assignment of components amongst the work cells could achieve the same cycle time as the manual setup, but with substantially improved man-hour efficiency owing to the robot cell. However, aside from Boudella et al. (2018), mathematical modelling has rarely been applied to compare alternative designs of applications for kit preparation (Kilic and Durmusoglu, 2015).

Previous studies dealing man-hour efficiency in warehouse order picking

In warehouse order picking, there is substantial literature that uses mathematical modelling aimed at improving man-hour efficiency. Oftentimes in these publications, efficiency is used as an optimisation objective, and the optimal settings of various aspects in the order picking system are sought in order to minimise travel time during picking tours (De Koster et al., 2007). As indicated by Hanson and Medbo (2019), there are some aspects that are important for man-hour efficiency in warehouse order picking that are of less relevance for kit preparation, and much of the literature that addresses man-hour efficiency in warehouse order picking is outside the scope of this thesis. There are, however, some studies that are relevant to this thesis, and these are discussed next.

Some research studies of warehouse order picking have addressed man-hour efficiency of order picking by means of experiments. Guo et al. (2015) carried out an experiment comparing the man-hour efficiency associated with various types of picking information systems when applied in order picking for distribution. They found that systems by which the picking information is conveyed by a HUD or a cart-mounted display were statistically more efficient than when information was conveyed via a pick-by-light system and a paper pick list. De Vries et al. (2016) studied the impact of pickers' personality on performance, including productivity, by means of a large-scale experiment. The experiment involved over a hundred participants and they were able to identify significant relationships between the picker's personality, the applied picking information system, and the order picking productivity.

A study based on mathematical modelling was carried out by Battini et al. (2015). The model which they developed compared the economic impact of different types of paperless technologies in warehouse order picking, and detailed operating schemes for the paperless technologies were developed to model the man-hour consumption. The operating schemes displayed the activities performed by the picker when using the technologies. The activities included getting information, searching, picking and confirming. In a numerical application of the model, they showed that pick-by-voice systems are economically viable for less frequent picking, while pick-by-light systems with an RFID-reading glove for carrying out confirmations was more economically beneficial for higher picking rates.

Summary of the reviewed literature and relevance of Research Question 3

An overview of the reviewed literature is shown in **Table 2.6**. From the above, it is evident that man-hour efficiency is central with respect to the design of picking systems. Furthermore, man-hour efficiency is typically applied as a criterion by which different approaches, such as materials supply principles or various batch sizes, are compared and prioritised. It has also been applied for assessing the potential for new applications to support kit preparation, as in Hanson et al. (2017). Knowledge about the aspects that govern the man-hour efficiency of kit preparation has been dealt with to some extent, by Brynzér and Johansson (1995) and by Hanson and Medbo (2019). For the most part, the factors of greatest importance have been highlighted, but, as pointed out by Hanson and Medbo (2019), they have rarely been quantified.

In light of the available research, there is a clear need for precise studies that can estimate the impact from design aspects of kit preparation regarding man-hour efficiency. This need is accentuated by the rapid developments in information technology, which, gives rise to new applications for picking information systems that make use of mixed- and augmented reality, as these developments needs to be understood in regard to their potential to support kit preparation. The same need can be seen with robotics, where new lightweight and flexible applications make robot-supported kit preparation conceivable (Boudella et al., 2018). The man-hour efficiency associated with such developments will effectively determine the viability of the applications that these developments enable for use in industrial applications. With the above in mind, Research Question 3 of the thesis is of outmost relevance at this current time of technological progress.

Table 2.6. *Overview of studies that have dealt with man-hour efficiency in kit preparation and warehouse order picking.*

<i>Study</i>	<i>Approach</i>	<i>Man-hour efficiency perspective</i>	<i>Design aspects</i>	<i>Context</i>
Brynzér and Johansson (1995)	Case research	Picking accuracy	Storage location Picking information Kit container	Commonality of parts Component characteristics Production process characteristics Amount of component numbers for one object
Hanson and Medbo (2019)	Case research	Time spent on various kit preparation activities	Batch size Kit carrier (various aspects) Layout (several aspects) Location Tasks in picking cycle Storage racks	Amount of component numbers Component characteristics (several aspects e.g. size, weight, commonality) Demand for component positioning Operator height Production volumes Number of components per kit Picks per hour Type of product Use of lifting aid Standard or variant kits
Hanson et al. (2011)	Case research	Picking accuracy based on the number of faulty parts	Location	Floor space availability within the plant
Hanson et al. (2015)	Experiments (industry)	Kits with correct contents	Batching policy	None identified
Hanson et al. (2017)	Experiments (laboratory)	Time spent per picked and sorted component	Means of information conveyance; Batching policy	Picking density
Guo et al. (2015)	Experiments (laboratory)	Pick errors in form of substitution errors, missing-part errors, and additional-part errors	Picking information system Batching policy	Picking density Task variety
De Vries et al. (2016)	Experiments (laboratory)	Productivity in terms of completed order per time period	Picking information system	None identified
Boudella et al. (2018)	Modelling (mathematical)	Cycle time of kit preparation	Automation level Batch size Storage policy	Component characteristics Production rate
Battini et al. (2015)	Modelling (mathematical)	Time spent per completed order line	Picking information system	Picking density
Brynzér et al. (1994)	Conceptual	Time expended for necessary work and losses in order picking	None identified	None identified

3. Research method

This chapter presents the research methods that have been used in this thesis. This thesis is based on five research papers, which, in turn, are each based on an individual research study. The chapter is organised into four subchapters.

Subchapter 3.1 presents a description of the research process, describing how the research got started and how the research behind the five appended papers was formulated and organised.

Subchapter 3.2 describes the research strategy, which has guided the research process throughout the course of the thesis.

Subchapter 3.3 goes into detail about the research methods that have been used, describing why the methods were selected to address the research problems, and how the methods were applied.

Subchapter 3.4 presents an assessment with respect to validity and reliability of the applied research methods.

Since each of the research papers is based on an individual research study, the term ‘paper’ is used as a reference to both the research paper and the research study conducted in association with each research paper.

3.1. Research process

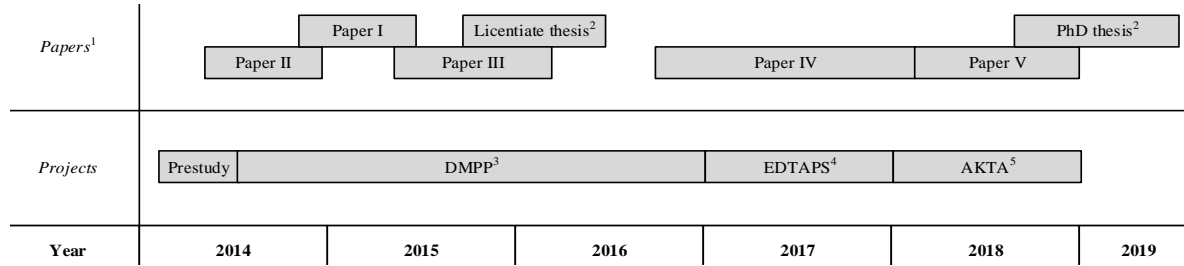
This thesis is the outcome of five years of research. This subchapter presents an overview of the activities carried out within the research process during these five years. A time line of the research process is shown in **Figure 3.1**, showing when the research activities took place.

The research has been carried out in association with three research projects within the VINNOVA FFI-programme of sustainable production, all organised as collaborations between academia and industry. The first project, ‘Design of Materials Preparation Processes’, began in June 2014 and ended in December 2016. The second project, ‘Emerging Digital Technologies and their Applicability as Picking as Support in Materials Handling’, began in December 2016 and ended in December 2017. The third project, ‘Automation of Kitting, Transportation and Assembly’, began in December 2015 and ended December 2018. The author was not part of the third project from the start, but joined at the beginning of 2018.

The first research project was a collaboration between Chalmers University of Technology (Chalmers) as the academic partner, and Volvo Group, Scania, Volvo Car Corporation, and FKG as the industrial partners. FKG is an association that represents the automotive supplier industry in Sweden. From FKG, DB Schenker, VBG and Bulten participated. The second research project was carried out with the same constellation of academic and industrial partners as the first. The third project was composed of Chalmers as the academic partner and various automotive OEMs, suppliers to the OEMs, and developers of automation systems as industrial partners.

The three research projects shared a similar focus, i.e. the design of high-performing materials handling processes in production settings. The design of kit preparation was not the sole objective of the projects, but has always been within each of the projects’ scope. The research underpinning Papers I, II and III of this thesis was carried out under the scope of the first research project. The research underpinning Paper IV was carried out under the scope of the second research project, and research underpinning Paper V was carried out under the third research project.

The remainder of the subchapter is organised into six sections. Section 3.1.1 presents how the research presented in the thesis was initiated. Sections 3.1.2 to 3.1.6 provide a presentation of the research processes of the five appended papers.



¹ The time line represents the time spent on writing the first version of the papers. This includes planning, data collection and writing of the paper. All papers were rewritten after the first version, but this is not accounted for in the figure.

² This represents the time spent on writing the cover paper.

³ The abbreviation DMPP stands for: Design of Materials Preparation Processes

⁴ The abbreviation EDTAPS stands for: Emerging Digital Technologies and their Applicability as Picking Support in materials handling

⁵ The abbreviation AKTA stands for: Automation of Kitting, Transport and Assembly

Figure 3.1. The time line of the research process

3.1.1. Initiation of the thesis' research

Leading up to the start of the PhD programme in February 2014, the author took part in creating the grant application for the first research project that funded the first half of the author's research studies (VINNOVA, dnr: 2013-05626), by doing parts of the writing and supporting administrative tasks.

The first research project had the aim to develop guidelines for design of materials preparation processes. The term 'materials preparation' was introduced by the project as reference to processes whereby picking operations are carried out in production settings to arrange materials in accordance with customer requirements, for example requirements of assembly processes. The term 'materials preparation' envelops kit preparation, but also other forms of picking processes such as part-sequencing (Sali et al., 2015) and repacking (Hanson, 2012). There was a consensus among the academic and industrial parties that were part of the research project that while there was some knowledge available for making decisions among alternatives for materials supply, such as between kitting and continuous supply (e.g. Hanson, 2012) and how to design interfaces between assembly and material supply activities (e.g. Finnsgård, 2013), knowledge was scarce about how materials preparation processes, such as kit preparation, should be designed to achieve desirable performance. This lack of knowledge was apparent both in-house at the industrial parties of the research project, as well as in the literature.

During the first two weeks of the PhD studies, the author participated in kit preparation activities at one of the industrial partner's production sites. This was a way for the author to experience first-hand how kit preparation was carried out, by walking along with and supporting workers involved with the activity. This experience allowed for discussions with the workers as well as industrial engineers who had designed the kit preparation. In retrospect, this experience facilitated the start of the research process by providing the author with a personal understanding that would have been impossible to achieve with only theoretical studies.

Leading up to the start of the first research project, and continuing for the first few months, a pre-study was carried out at the project companies' facilities. This pre-study aimed to establish an understanding of the current state of the companies' kit preparation and materials handling operations, as a means for specifying the focal areas of the research project. The pre-study included direct and participatory observation of kit preparation at the project companies' production sites. Drafts of data collection templates, which were derived from the literature, were used for capturing data about the processes to use for developing rudimentary process descriptions. These descriptions

were later used to guide case selection in the case research conducted in Papers I and II. Over the first six months of the first research project, several workshops were organised together with the project companies. Here, expectations from all parties involved were matched with the literature, in order to select viable directions of both industrial and theoretical relevance for the research to be carried out within the project.

It was discovered at an early stage that knowledge of how to design kit preparation varied substantially among the different industrial parties. For example, some of the project companies were working on reducing kit preparation error levels downward from 22 errors per million parts picked in a highly standardised environment, while others were having trouble in properly implementing picking information systems other than paper pick lists. There was also a notable difference between the degree of detail of the guidelines used to design kit preparation at the companies, ranging from globally standardised and detailed guidelines, to almost ad-hoc solutions conducted on a case-by-case basis that did not follow any specific guidelines beyond the previous in-house experiences.

It was clear from the dialogue with the project companies and from the pre-study, that the main performance areas of concern in kit preparation were flexibility, kit quality, man-hour efficiency, and ergonomics. The four performance areas of flexibility, quality, man-hour efficiency, and ergonomics were focused on by the research project as a whole, while the author chose to focus on flexibility, kit quality and man-hour efficiency as associated with kit preparation in this thesis.

3.1.2. Paper I

A central issue of the project companies was that floor space was limiting the use of kit preparation and sequencing operations, where current workspace designs took up too much floor space in relation to the amount of component variants each process managed. In other words, the processes lacked the necessary flexibility to handle all component variants necessary for materials supply principles. Hence, the aim expressed by the companies was to understand how their kit preparation and sequencing processes should be designed to be more flexible with respect to production volumes and mix, and thereby manage more component variants using the same amount of floor space. It was also observed during the pre-study that picking information systems at some of the project companies were not up-to-date with their current bill of materials, leading experienced picking operators to neglect the instructions provided by the systems and, instead, pick from experience. Obviously, the risk for errors was high when the order content changed, which was indicated by the high error levels observed from the available picking error records. It was at this point proposed that the updating of picking information be avoided due to a lack of flexibility in the kit preparation. The lack of flexibility showed in terms of it being difficult or time consuming, to update the systems in accordance with changes in the bill of materials or the assembly process and keep the picking information up-to-date with the requirements from the production system.

These two starting points—the ability to handle more component variants using the same amount of floor space and the ability to keep the kit preparation up-to-date with production system requirements—indicated that a flexibility-focused study could contribute to company practices. From reviewing literature on flexibility and kit preparation, it was understood that previous research rarely focused on flexibility for any type of picking operations. This has, for example, been indicated by Staudt et al. (2015), who only identified three publications dealing with flexibility in warehouse order picking when they reviewed literature concerned with performance measurements for order picking systems. With respect to kit preparation design aspects, only a few studies mentioned these with respect to flexibility (e.g. Hanson and Brolin, 2013), and mostly as part of a larger reasoning on the effects of kitting-based materials supply (e.g. Limère et al., 2012; Caputo and Pelagagge, 2011). Overall, the literature was unclear on what flexibility meant for kit preparation, and more so with regards to how to attain flexibility.

The intention of Paper I was to derive a framework for how flexibility could be assessed for kit preparation, and to learn how design aspects influenced this flexibility. Owing to the scarce literature about kit preparation flexibility, a case research approach was chosen, as this is a method that is often beneficial when it is desirable to build theory from empirical data (Eisenhardt, 1989). With this approach, a framework for kit preparation flexibility could be derived from related topics where more research had been conducted, for example within manufacturing-related literature, and then applied to cases of kit preparation in industrial settings in order to gather and formalise knowledge of how kit preparation design aspects related to flexibility.

From studying literature, primarily on manufacturing and materials supply flexibility, a framework for how to assess flexibility was derived, focusing on cost, time and organisational disruption associated with changing processes for kit preparation when adapted to new production system requirements (see Section 2.3.1 for details). This framework had a wider scope than the two original starting points as the literature review revealed that flexibility is a multi-dimensional construct (Sethi and Sethi, 1990). The application of the framework to industrial cases was the foundation for the conference paper presented at the EurOMA conference in June 2015. After receiving positive and constructive feedback at the conference, and from discussions with the project companies, it was understood how the framework could be refined, given the data that had been collected, where particularly the mechanism of flexibility could be explained in greater detail. This was the primary aim during the revision of Paper I into the version appended in this thesis.

3.1.3. Paper II

It was emphasised in Chapters 1 and 2 that attaining a satisfactory kit quality in kit preparation is important for kitting to be a viable approach. As highlighted in Chapter 2, previous research on quality in picking systems is mostly concerned with the cost of kit errors, as accounted for in models for comparison of line supply principles (see Caputo et al., 2017a and 2017b; Caputo et al., 2015). However, as discussed by Grosse et al. (2015), the relation between picking errors and the design of order picking systems is not well understood in literature, apart from some observations, such as in Brynzér and Johansson (1995) who recognize it as part of a broader scope when dealing with other performance areas. At the time that Paper II started, there was generally little guidance available in literature on how to achieve a satisfactory kit quality in kit preparation. Furthermore, in discussions with the industrial parties associated with the research project, it was understood that there was a lot of confusion with respect to how the kit preparation design could support kit quality. From the available literature, it was clear that several aspects of the design were important for kit quality. Therefore, the focus of Paper II was to identify approaches related to the kit preparation design that supports kit quality.

Already in the planning stage of Paper II, kit quality associated with kit preparation was understood as a challenge to study empirically from a research standpoint due to the nature of kit errors. In industrial applications, kit errors typically occur infrequently, why observing kit errors in real time and then finding ways of preventing them, would be a difficult and inefficient research approach. However, most industrial parties lacked knowledge of how to support quality in their processes for kit preparation due to the very same reason, i.e. kit errors are rare. The approach used had been to devise, more or less, ad-hoc solutions to reoccurring kit errors. At this point, it was understood that an important contribution could be made if a viable strategy could be imagined.

First, a pre-study was conducted that considered how kit preparation was carried out at the production sites to gain a better understanding of how quality was currently dealt with. The pre-study included between 15 and 20 processes for kit preparation, and for each process, discussions about kit quality associated with the case process were held with the managers and pickers. Secondary data, in the form of records of kit errors, was collected and analysed when available. For most of the processes that maintained records, the procedures for record keeping were often unclear,

which made the reliability of the records questionable. Therefore, at this stage of the study, strategies relying on statistics, such as experiments or modelling-based approaches, were ruled out.

A noteworthy point from the pre-study involved how much the knowledge of kit quality varied, not only among companies, but also among departments and individual processes within the same company. Overall, there was considerable confusion regarding how to attain satisfactory kit quality, but due to some of the processes uncovered during the pre-study, this issue was dealt with in greater depth and some in-house guidelines became available.

For a few of the processes for kit preparation covered during the pre-study, the managers explained how they had altered their processes for kit preparation to remove reoccurring kit errors. They claimed that these worked, for the most part, or were adjusted until they worked. The managers explained that it was typically necessary to find a solution that prevented errors from reoccurring, as these caused irritation among the assemblers and the pickers when replacement components had to be supplied and that there was risk of making errors during the assembly process or stopping the process entirely. From a researcher's standpoint, these design alterations which had successfully removed reoccurring kit errors, can be viewed as the outcomes of many tests and adjustments.

Instead of relying on a statistical approach, which required records with statistical data of kit errors, the strategy was to gather the knowledge and experience of the people responsible for the design of kit preparation on how kit errors could best be prevented. A multiple case study method was applied to this end, which will be explained in detail in Section 3.3.1.

As a first step, detailed descriptions of how various settings and situations in kit preparation led to kit errors were developed based on the case data. These were the basis for the conference paper presented at the Swedish Production Symposium in August 2014. As a second step, the mapped relationships between kit preparation design aspects and kit errors from the conference paper were discussed with experts from the industrial parties associated with the research project, and studied further for three of the cases at which kit quality had been thoroughly addressed. This second stage analysis led to a set of approaches for how to support kit quality, which is presented in Paper II as appended in the thesis.

3.1.4. Paper III

The third focus in the research was directed towards man-hour efficiency as associated with various types of picking information systems when used to support kit preparation activities. The focus was established from the pre-study and workshops during the early stages of the research project, when there was confusion among the companies regarding the picking information to use. The confusion revolved around the type of picking information system to use with respect to varying characteristics of components, plant layouts, and materials supply structures. Furthermore, at the time, new technology was emerging, such as head-up displays (e.g. Guo et al., 2014; Schwerdtfeger et al., 2011) and RFID scanning devices (Battini et al. 2015). Knowledge was scarce in the literature with respect to using this technology in kit preparation. Furthermore, requests for comparisons between alternative picking system designs were also apparent in the literature, for example, Hua and Johnson (2010) and Grosse et al. (2015).

Available comparisons in the literature (e.g. Guo et al., 2014; Battini et al., 2015; Hanson et al., 2015) acknowledged the need for performing confirmations when components were picked and sorted to support quality, but these had not considered the impact of performing confirmations on man-hour efficiency. Hence, there was the potential for both a practical and a theoretical contribution from comparing different picking information systems with respect to their impact on man-hour efficiency. The project companies, for the most part, used confirmations to ensure quality in their kit preparation, and it was, therefore, natural to account for these when the study was designed.

In discussions with the project companies, the impact of order batching on man-hour efficiency in kit preparation was often the focus. However, there was no literature available to explain how performing confirmations actually impacted man-hour efficiency. Therefore, it was natural to consider the relationships between various types of picking information systems and man-hour efficiency when confirmations were required. In addition, the two approaches of single-kit and batch preparation with respect to batching policy were also considered.

Comparisons of picking information systems by Battini et al. (2015) showed that the distance travelled in picking activities can affect the man-hour efficiency, as some activities can be performed while travelling. Therefore, the study was designed to also account for the impact of varying picking density, which was operationalised as differently sized packaging and varying numbers of shelf levels in different sections of a picking tour.

It was realised during the planning of Paper III that a different approach than for Paper I and Paper II, focusing on quality and flexibility respectively, was required to accurately understand how picking information systems relate to man-hour efficiency. Particularly, a controlled environment was deemed necessary to accurately compare alternate designs. Therefore, an experimental study design was chosen.

The planning of the study lasted for approximately three months, which in addition to specifying the study purpose and formulating the hypotheses also included making arrangements with participants involved in the research project. Preparations were also made with external parties, that is those who developed the picking information systems. The planning also involved construction of the laboratory kit preparation workspace, including installation and adjustment of the equipment. Once everything was in place, the actual data collection was completed during three full days of trials.

3.1.5. Paper IV

Paper III made it clear that the type of picking information system that is applied in kit preparation plays an important role in man-hour efficiency. However, when analysing the results, it was also clear that each type of picking information system consisted of two distinct parts. One part was the means of information conveyance, which provided the picker with information about which components to pick from the shelves and in which kits to place components. The other part was the confirmation method, by which the picker could report the location from which a component had been picked and in which kit it had been placed, and then get feedback on whether the activity had been performed correctly.

Moreover, it was noticed how the different types of picking information systems benefitted markedly different from being applied with batch preparation. Particularly, the pick-by-list system showed a remarkable improvement in man-hour efficiency when applied with batch preparation, while the other system types improved less, in terms of pick-by-voice, or even got less efficient, as in the case of pick-by-light and pick-by-HUD. A prominent difference between the pick-by-list system type and the other three system types was how the confirmation method worked, in the sense that with pick-by-list a confirmation was performed for the whole order line at once, while with the other systems the a confirmation was performed for each storage location and each kit container. However, as it was outside the scope of Paper III to determine whether the confirmation method had an impact on its own, as only typical system types in industrial applications were compared, the core idea behind Paper IV was conceived.

Upon reviewing the literature, there was little guidance available about how various confirmation methods affected the man-hour efficiency of kit preparation. Actually, for the most part confirmation methods were not even considered in studies dealing with picking information systems, but rather the focus was on the means of information conveyance. Some studies on warehouse order picking considered confirmations when components were picked from the shelf,

but no studies considered confirmations when components were put into kits. This was remarkable, since most of the industrial applications of kit preparation at the project companies applied confirmations when components were placed in kits with batch preparation to ensure that components were sorted correctly. The gap for Paper IV was clear, and another experiment was deemed appropriate for identifying the impact that the type of confirmation method had on the man-hour efficiency of kit preparation.

The planning of the experiment lasted for approximately six months. In addition to specifying the research purpose and formulating hypotheses, the planning also included arrangements with parties external to the project who developed and installed the selected picking information systems and confirmation methods in the laboratory setup. The planning also involved modifying the laboratory setup used in the experiment associated with Paper III to fit the purpose of Paper IV, which included adjustment and testing of the equipment. Once everything was in place, the data collection was completed over ten full days of trials.

3.1.6. Paper V

The first two research projects focused on manual applications for kit preparation. However, throughout the dissemination of results, questions about automation of kit preparation continually arose. In the literature concerned with materials handling, robotics has been part of the discourse for decades. However, with the recent emergence of more lightweight and flexible robotic applications, questions related to automated kit preparation have increased. At the conclusion of Papers III and IV, which focused on technological support in picking information systems and confirmation methods, the idea of studying robotics in kit preparation emerged.

Upon reviewing the literature, many publications dealing with robotic automation were identified. However, for the most part, the available literature dealt with situations where most of the materials supply and the assembly activities were also automated, typically in the electronics industry. Generally, the components had fixed and predictable orientations and positions, which is rare in most industrial applications of kit preparation, for example, in the automotive industry. As is often pointed out with respect to robotic picking, unpredictable shapes, positions and orientation of components are problematic from an automation standpoint. However, there is a fast-growing body of literature that presents solutions of vision-based technology and end effectors that can deal with such unpredictable component characteristics (see e.g. Kootbally et al., 2018; Pérez et al., 2016; Martinez et al., 2015).

A study by Boudella et al. (2018) showed the use of robotics in picking components. However, the solution required a sophisticated sorting system for its operation, and the operator and the robot completed kits in series using separate work cells. However, with improved safety regulations and sensors on robots, collaborative applications between the operator and a robot were conceivable.

At this time, the setup for carrying out the experiments in Papers III and IV was relocated to a production laboratory, and plans were made to introduce a robotic arm to conduct kit preparation. However, apart from Boudella et al. (2018), the literature was scarce with models that explained the potential ways of applying the robot. Hence, a mathematical modelling design for Paper V was conceived, which used the previously generated experiment data, together with the installation of the robotic arm in the laboratory setup. The idea was to consider how a robot could support an operator in kit preparation by performing some of the activities, thereby promoting man-hour efficiency.

3.1.7. The author's responsibilities with respect to the appended papers

To conclude this subchapter about the research process that has underpinned this research, the five appended papers are summarised in **Table 3.1** in terms of the author's responsibilities.

Table 3.1. *The author's responsibilities with respect to the five appended papers.*

<i>Paper</i>	<i>First author</i>	<i>Co-author 1</i>	<i>Co-author 2</i>	<i>Co-author 3</i>	<i>Responsibility of the first author</i>
I	Fager, P.	Hanson, R.	Medbo, L.	Johansson, M. I.	The first author had principal responsibility for planning the study, collecting and analysing data and writing the paper.
II	Fager, P.	Hanson, R.	Medbo, L.	Johansson, M. I.	The first author had principal responsibility for planning the study, collecting and analysing data and writing the paper.
III	Fager, P.	Hanson, R.	Medbo, L.	Johansson, M. I.	The authors jointly planned the study. The first author and Co-author 1 jointly carried out the data collection. The first author had principal responsibility for analysing data and writing the paper.
IV	Fager, P.	-	-	-	The first (and sole) author was responsible for all tasks involved with planning the study, collecting and analysing data and writing the paper.
V	Fager, P.	Calzavara, M.	Sgarbossa, F.	-	The first author had principal responsibility for planning the study, modelling and analysis and writing the paper.

3.2. Research strategy

A structured approach has been applied throughout this research. This subchapter describes the structured approach that has been applied in the thesis, and explains in which ways the approach has been particularly useful.

The thesis' research questions, as well as each paper's scope and aim, were derived from a combined assessment of practice and the literature. The state of practice has been assessed via research projects, wherein several industrial parties have been involved. The needs of the industrial parties have been continually assessed throughout the research projects, and issues raised by the industrial parties have been matched with the available literature to determine the need for additional research. New trends in the literature regarding RFID-reading wristbands included in the experiments in Papers III and IV and with respect to collaborative robots in Paper V, were also discussed with the industrial parties, and when it became clear that there was practical relevance to studying how these technologies could support kit preparation, it led the research to focus on such new design options. The research projects enabled study visits to organisations external to the project, where relevant applications to the research projects' scope were seen.

Both theory and practice played a role for developing the theoretical framework presented in Chapter 2 of the cover paper. This is most evident in the categorisations of design aspects into design areas in Subchapter 2.2, and context aspects into context areas in Subchapter 2.3. With the design areas, the starting point was the categorisations presented in the literature, which formed the basis for categorising the available literature early on, and the categorisation evolved alongside the research projects and papers associated with this thesis. Theory and practice played a similar role also with respect the theoretical framework of kit preparation context. As shown in Chapter 2, various factors in production systems and supply chains can affect performance associated with picking systems. While the focus of this thesis is on relationships between design aspects and performance of kit preparation, the literature clearly shows that such relationships cannot be accurately understood without considering the context. Therefore, from the outset of the research process, context has been accounted for wherever relationships between kit preparation design aspects and performance cannot otherwise be properly understood. In this way, the research projects associated with this thesis, together with literature, have influenced the thesis' account of kit preparation context.

A variety of methods has been applied in the research, including case research, laboratory experiments and mathematical modelling. The applicable methods were selected based on the research problems. Papers I and II both applied multiple case study methods. This was because knowledge concerning the areas of flexibility and kit quality was scarce at the time, and case research is recognised for being particularly useful when the phenomenon is poorly understood

(Voss et al., 2002). Papers III and IV were based on experimental studies performed in laboratory settings and addressed more narrow questions than Papers I and II. From studying the literature, it was realised with respect to Papers III and IV that while there was some knowledge available that explained how picking information systems support kit preparation, the available knowledge did not quantify any of the relationships. To conduct experimental studies enabled a control of the settings, and this was considered an appropriate choice of methods. With Paper V, which uses a mathematical modelling approach, there was no previous research available that could explain how collaborative robots can be applied to kit preparation. The mathematical modelling approach allowed the phenomenon to be studied before any installations had been made.

Figure 3.2 shows how the thesis' purpose fits together with the research questions, the cover paper, and the research papers, highlighting the methods used.

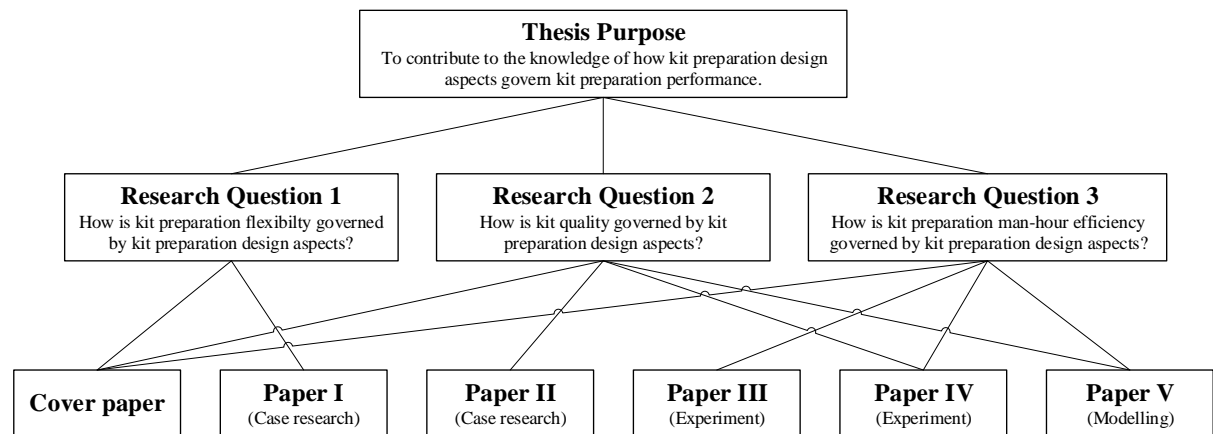


Figure 3.2. Overview of the thesis structure, showing how the thesis' purpose, research questions, and research papers fit together.

Literature has been used continually throughout the research as a means of creating a theoretical starting point for the papers. However, as shown in Chapter 2, the available literature around the topics of the research questions was scarce when the research began. The approach taken has, therefore, been to consult the literature in related research areas, such as warehouse order picking and assembly operations, in order to complement the scarce literature that deals with kit preparation. This complementary knowledge that has been borrowed from related fields has been used as propositions, which have been studied in the context of kit preparation in association with the research papers.

3.3. Methods applied in the five research papers

The research presented in the thesis involves three different methods: Papers I and II were based on case research, Papers III and IV were based on experiments, and Paper V was based on mathematical modelling. All three of these methods are common within research of supply and operations management, but make up three different approaches of research. This subchapter details how the methods were applied in each of the papers. In the next subchapter (Subchapter 3.4) the validity and reliability of the research associated with the papers is discussed. In **Table 3.2**, an overview of the methods and data types that each of the papers involve is provided.

Table 3.2. *The research methods and data types in the five appended papers.*

<i>Paper</i>	<i>Method</i>	<i>Data</i>
I	Multiple case study	Interviews, direct observations, secondary documentation
II	Multiple case study	Interviews, direct observations, secondary documentation
III	Experiments	Time study, records of kit errors
IV	Experiments	Time study, records of kit errors
V	Mathematical modelling	Secondary data from experiments, testing in laboratory environment

3.3.1. Methods applied in Paper I

Paper I has the purpose to support the design of flexible processes for kit preparation. Thereby, it contributes to answering Research Question 1.

In the paper, a theoretical framework consisting of design aspects identified as central to kit preparation flexibility was derived from a literature study on kitting, order picking and manufacturing, and then applied in a multiple case study (for details, see appended Paper I).

Case selection

Five cases were chosen on the basis of the theoretical framework using theoretical replication logic (e.g. Voss et al., 2002), and each case exhibited a unique characteristic among those selected. For example, one case had a stationary rack design with few components per kit and a high number of kits per kit carrier. In addition, it had a high number of product variants in the kit preparation workspace and used a pick-by-voice system with finger scanning. Another case had a fewer number of kits per kit carrier, although it still had many in comparison to the other cases. It also had a higher number of components per kit, and used a pick-by-light and place-by-light system for picking information. Both cases had roughly the same number of component variants in their kit preparation workspaces. A third case, in contrast to the two previously described, had relatively few parts per kit and kits per picking package, but used a pick-by-light system for picking information. The reader is referred to the appended Paper I for more details concerning case selection.

Data collection

The data collected from the cases in Paper I includes interviews with managers, team leaders and pickers associated with the five case processes, secondary documentation in the form of layout drawings, component lists, and kit orders, as well as notes, photos and video recordings collected in association with direct observation. A summary of the data collected for Paper I is provided in **Table 3.3**.

Table 3.3. *Summary of the data collected for Paper I.*

<i>Source</i>	<i>Data</i>	<i>Description</i>
Interviews	Audio recordings, transcripts	- One to two-hour semi-structured with kit preparation managers (one to three managers for each case). All interviews were performed on site. - Informal interviews with pickers, logistics team leaders and technicians (performed during guided tours).
Secondary documentation	Layout drawings, component lists, kit orders	- Retrieved via computer transfer on site or received afterwards via e-mail.
Direct observation	Notes, photos, video recordings	- Performed during guided tours of the cases (at least one manager was tour guide). - Notes via templates derived from the theoretical framework. - Video recordings of cases during operation.

An extensive literature review was conducted at the outset of Paper I. This led to a theoretical framework from which a research protocol and data collection templates for direct observation and interviews were derived. The focus when developing the data collection templates was to account for hard aspects, in terms of sizes and count, as well as soft aspects, in terms of how the work was

conducted and perceived. In a way, the data collection templates can be said to have included both exploratory and confirmatory parts, which yielded rich and precise data.

The sites associated with the cases were visited at the outset of each case study. Direct observation was performed in association with the visits for all cases. Interviews were performed with site visits for two of the cases, while the interviews in the three other cases were performed during a second visit. Data in the form of archival records was collected either in association with the site visits or received afterwards via e-mail.

An observation template was used to ensure that the descriptive data concerning the design aspects was captured. As emphasised by Yin (2009), direct observation of the phenomenon or aspects related to the phenomenon can prove invaluable during the later stages of study, which, indeed, was the case here. Notes were taken and questions about the operation of the cases were answered by managers and team leaders who guided the visits. When permission was obtained, the cases were video recorded. Additionally, many photographs were taken during the visits for future reference regarding the layout and specific settings of the design aspects.

Since a multitude of changes associated with kit preparation flexibility were considered in the study, it was impossible to observe them all. Hence, the information gathered from direct observation concerned the operation of the cases, and not the changes themselves, while the changes were discussed in detail during the interviews. It should also be noted that at this stage of the study, the specific cases to be included in the paper had not yet been selected, but the same types of information were gathered for all observed case candidates.

The interviewees were identified with support from the key informants. Each interview was preceded by a visit to the site, and most of the descriptive aspects of the protocol could be completed at these initial visits. Any unresolved aspects of the description were resolved during the interviews. During the interviews, the author and at least one other researcher were present. For all interviews, the author led the interview and the other researchers kept track of the conversation and emphasised key points to be developed further.

The interviews were conducted in sessions ranging between one and two hours and followed an interview template derived from the conceptual framework. All interviews were arranged after the initial site visit and after the cases had been selected. As pointed out by Yin (2009), interviews should be conducted with the purpose of the inquiry in mind. During the initial visits and discussions with the process managers and team leaders, an idea of how the framework applied to the cases emerged. Therefore, an approach that focused more on the parts of the framework that were less certain, rather than the understanding attained during the initial visits, was employed for the interviews.

An interview template was sent to all interviewees beforehand with a request to review the questions before the interview. This enabled a focused approach during the interviews, ensuring that the questions on the template would be discussed. The template was organised with open questions leading to more specific questions. The questions were formulated on a 'how' basis, which enabled the interviewees to explain without being led towards a certain answer, thus strengthening the internal validity (Yin, 2009).

Secondary documentation in the form of layout drawings, component lists and kit orders were collected either in association with the site visits, or afterwards via e-mail. The archival records played a supplementary role with respect to interviews and direct observation. The layout drawings helped understand the extent to which the case process had to change with respect to flexibility. The component lists and kit orders helped to understand which component numbers were most affected by changes in the production system, such as changes in mix or volume.

After each visit and interview, the collected data was compiled to determine if the theoretical framework was covered. Any missing parts were supplemented on short notice by telephone or e-mail.

Analysis

The analysis for Paper I was conducted in three stages. The first stage began after the data had been collected from the five cases. First, the collected data was matched with the theoretical framework to see if the data addressed all parts. The missing parts, mostly concerning details regarding the cases, were supplemented via e-mail or telephone conversations with the interviewees.

The second stage involved a more detailed analysis of how the data matched with the theoretical framework, and consisted of two parts. The first part involved a within case analysis, whereby each case was analysed individually in terms of the five flexibility types. This showed how the cases were affected by kit preparation design, in accordance with the theoretical framework (see Paper I for details). In the second part, the findings were compared across the five cases, allowing differences with respect to how different settings of design aspects impacted flexibility.

In the third stage, the findings were discussed with the project companies, including those where the case studies were conducted. This yielded refinement of the results, both empirically with regard to details of the individual cases, and theoretically, with respect to kit preparation flexibility. The findings were also presented at the scientific conference EurOMA 2015, and additional viewpoints, mostly theoretical, were received there. The paper was revised based on the feedback from industry and academia described above, yielding the version of Paper I appended in this thesis.

3.3.2. Methods applied in Paper II

Paper II has the purpose to create an understanding of the links between kit preparation design aspects and kit preparation error types, that can be useful to support kit quality. The paper contributes to answering Research Question 2.

In Paper II, a theoretical framework consisting of kit preparation design aspects is derived from the literature and applied in a multiple case study. The case research comprises three cases of kit preparation in automotive materials supply.

Case selection

Case selection was carried out in two stages. The first stage involved studying case candidates at the production sites of the industrial parties associated with the research project. This involved mapping of typical design settings and developing basic descriptions of how kit preparation was conducted and how kit quality was viewed.

From the case candidates identified in the first stage, three cases were selected based on theoretical replication logic among design aspects identified from the literature. The cases were selected so that they differed in their design in accordance with the theoretical framework. Therefore, different experiences with respect to kit quality could be expected, i.e. a theoretical replication (Yin, 2009). To exemplify the applied logic for case selection, the logic is described below as it was applied in Paper II with respect to the design aspects picking information and location.

The first case applied a pick-by-voice system together with barcode-scanning confirmations; the second case applied pick-and-place-by-light, and the third case applied a pick-by-light system. Furthermore, all three cases had previously used pick-by-paper before switching to these systems. The differences in picking information allowed for comparing the effects on kit error prevention from principally different system types (pick-by-voice in one case and pick-by-light in the other two cases), as well as showing how these system types compared with pick-by-paper. Furthermore, the use of pick-by-light and order batching in one case, and pick-by-light and single-kit preparation

in in another case, allowed for studying interplays between picking information and batching policy in kit error prevention.

The kit preparation workspace in the first case was located in a warehouse, while the kit preparation workspaces associated with the other two cases were located in association with assembly. Here, based on previous research by Hanson et al. (2011), differences in kit error correction were expected.

Data collection

Data collected from the cases involved in Paper II included interviews with kit preparation managers, logistics team leaders and pickers; direct observation that resulted in notes, photos and video recordings; and secondary documentation in the form of layout drawings, component lists, kit orders and kit error records. An overview of the data collected in association with Paper II is provided in **Table 3.4**.

Table 3.4. *Summary of the data collected for Paper II.*

Source	Data	Description
Interviews	Audio recordings, transcripts	<ul style="list-style-type: none"> - One to two-hour semi-structured with kit preparation managers (one to three managers for each case). All interviews were performed on site. - Informal interviews with pickers, logistics team leaders, and technicians (performed during guided tours).
Secondary documentation	Layout drawings, component lists, kit orders, kit error records	<ul style="list-style-type: none"> - Retrieved via computer transfer on site or received afterwards via e-mail.
Direct observation	Notes, photos, video recordings	<ul style="list-style-type: none"> - Performed during guided tours of the cases (at least one manager was tour guide). - Notes by help of templates derived from the theoretical framework. - Photos and video recordings of cases during operation.

A theoretical framework was derived from a literature review at the outset of the research associated with Paper II. This framework was applied as a research protocol, and allowed for data collection templates for direct observation and interviews to be developed. The focus when developing the data collection templates was to include aspects that had been pointed out in literature as important for kit quality, for example aspects related to component characteristics, picking information systems, and the design of kit carriers and containers.

The sites associated with the cases were visited for direct observation at the outset of each case study. The observations, organised as guided tours led by the managers and team leaders associated with the cases, were aided by an observation template that guided descriptive data concerning the design aspects to identify.

Notes were taken in association with direct observation, and any questions about the cases were answered by the managers and team leaders. When permission was obtained, kit preparation was video recorded. Additionally, many photographs were taken during the visit for future reference, showing details with respect to layout and distances.

As kit errors are rare and occur infrequently, it is impossible to plan observations. Hence, the direct observation focused on how kit preparation was normally conducted, rather than observing kit errors specifically. It should also be noted that at the time direct observation was carried out, the specific cases to be included in the paper had not yet been selected, but the same types of information were gathered for all processes observed.

Interviewees were identified with support from key informants connected to the research project. Each interview was preceded by a visit to the facility where the processes were observed and most of the descriptive aspects of the protocol could be completed. Any unresolved points with respects to the descriptions were resolved during the interviews.

At each interview the author and at least one other researcher were present. For all interviews, the author led the interview and the other researchers kept track of the conversation and emphasised key points to be developed further. After each visit and interview, the collected data was roughly compiled to see if the framework was covered. Any detected missing parts were supplemented on short notice via telephone.

The interviews were conducted in sessions ranging between one and two hours and followed an interview template derived from the theoretical framework. All interviews were arranged after the initial site visit after the cases had been selected. As pointed out by Yin (2009), interviews should be conducted with the purpose of the inquiry in mind. Here, an idea had formed during the initial site visits of how to apply the theoretical framework to the cases. Therefore, the approach used for the interviews in each of the cases was to focus on vague parts of the theoretical framework, rather than complementing the understanding attained during the initial visits.

An interview template derived from the theoretical framework was used as a guide during the interviews. The interview template was sent to all interviewees beforehand with a request to review the questions before the interview. This enabled a focused approach during the interviews, ensuring that the questions on the template would be discussed. The template was organised using open questions that led to more specific questions. The questions were formulated on a 'how' basis, which enabled the interviewees to explain without being led towards a certain answer, thus strengthening the internal validity (Yin, 2009).

Analysis

The analysis for Paper II was conducted in three stages. The first stage began after the data had been collected from the three cases. First, the collected data was matched with the theoretical framework to see if the data addressed all parts. The missing parts, mostly concerning details regarding the cases, were supplemented via e-mail or telephone conversations with the interviewees.

The second stage involved a more detailed analysis of how the data matched with the framework, and consisted of two parts. The first part involved within case analysis, where each case was analysed individually in terms of links between design aspects, kit error prevention, and kit error correction, in accordance with the theoretical framework (see Paper II for details). In the second part, the findings were compared across the three cases, allowing differences with respect to kit error prevention and correction between the cases to be identified.

In the third stage of the analysis, the findings were discussed with the project companies, including the companies where the case studies were conducted. This yielded refinement of the results, both empirically with respect to details of the individual cases, and theoretically with respect to kit quality. The findings were also presented at the scientific conference, the Swedish Production Symposium 2014, where additional viewpoints, mostly theoretical, were received. The paper was revised based on the feedback from industry and academia described above, yielding the version of Paper II appended in this thesis.

3.3.3. Methods applied in Paper III

Paper III has the purpose to establish the extent to which the type of picking information system impacts the time-efficiency of kit preparation when confirmations are required. It considers the two cases of single-kit and batch preparation as well as the density of the picking area. The paper contributes to answering Research Question 3.

Paper III is based on a laboratory experiment, where a workspace for kit preparation was built in a laboratory setting to compare man-hour efficiency of kit preparation as associated with different types of picking information systems regarding different batching policies and picking densities.

Experimental design

When setting up the experiment, the procedure proposed by Coleman and Montgomery (1993) for planning and design of experiments was followed. The experiment was designed with the strategy of arranging the set-up as close as possible to real life industrial and high-performing kit preparation, such as identified in the pre-study described in Section 3.1.1. In addition to the literature, a parallel study that was ongoing at the time and presented in Hanson and Medbo (2019), provided guidance on which aspects of kit preparation design and context to account for in the experiment. In that study, research of 15 cases was used to determine the influence of kit preparation design aspects on man-hour efficiency. Furthermore, the experience from previous studies within the research group, for example, Hanson et al. (2015), was another input. The resulting experimental design was cross-referenced with literature and discussed on multiple occasions with the company representatives in terms of its representativeness for industrial kit preparation.

Data collection

The data collection for Paper III was conducted in a laboratory environment. Given the topic of Research Question 3, the focused measurement was the time required to complete one picking tour, which was converted during the analysis to the average time to pick a component. All experiment runs were video recorded from two angles. Video analysis software was used to extract the times from the experiment runs. Video recording and subsequent analysis have shown several advantages over stopwatches in previous research (Engström and Medbo, 1997), for example by enabling close examination of outliers. The video recordings also enabled the number of kit errors to be evaluated. The reader is referred to the appended Paper III for more details about the data collection.

Analysis

The data analysis for Paper III was straightforward, owing to the quantitative data in the form of time measurements of the experiment runs. The time measurements were organised per picking information system type and batching policy, resulting in sets of data with 50 time measurements for each picking information system and batching policy. The data sets were then analysed and compared using one-way analysis of variance (ANOVA) and post-hoc tests, with the software Statistical Package for the Social Sciences (SPSS).

3.3.4. Methods applied in Paper IV

Paper IV has the purpose to determine the extent to which the type of confirmation method relates to time-efficient kit preparation when order batching is applied. Hence, the paper contributes to answering Research Question 3. Furthermore, the importance of confirmation methods for kit quality, and the fact that the paper recorded and discussed kit errors in the experiment, contributes to answering Research Question 2.

Paper IV is based on a laboratory experiment. A workspace for kit preparation was built in a laboratory setting in order to compare man-hour efficiency of kit preparation as associated with different types of confirmation methods when used as pick-from and place-to confirmation with batch preparation of kits.

Experimental design

The strategy when planning the experiment was similar to that in Paper III, and the setup aimed to replicate real life industrial kit preparation at high performance. The experiment planning was made in accordance with the procedure outlined by Coleman and Montgomery (1993). The resulting design was cross-referenced with literature and discussed on multiple occasions with the project company representatives in terms of its representativeness for industrial kit preparation.

Three factors were identified as central with respect to the paper's purpose from a literature review. One factor was order batching policy, as place-to confirmations are only applicable when there is

more than one kit prepared for each work cycle. Thereby, batch preparation was chosen as a fixed setting for the experiment. Another factor was picking density, which in Paper III was shown to be important for how different types of picking information systems perform in kit preparation. The picking density was set to be fixed at a high setting, as travelling times were of little interest with respect to the purpose. This allowed for the differences between various types of confirmation methods to be more distinct.

Data collection

The data collection for Paper IV was conducted in a laboratory environment. Given the topic of Research Question 3, the focused measure was the average time per kitted component, which was estimated as the time it took to complete one picking tour. To extract the time from the trials, the confirmations performed in the setup were logged in a server computer, which generated time logs of the experimental runs. The experiment was also video recorded from two angles to complement the time logs by enabling close examination of outliers. To evaluate kit quality, all kits were weighed on an industrial scale after each picking tour. Knowing the different weights of the components, the kit quality could be controlled afterwards by checking if the weight of the components that should be included in the kits showed up on the scale. The reader is referred to the appended Paper IV for more details on data collection.

Analysis

The data analysis for Paper IV was straightforward after extracting the times for each individual picking tour and organising it per operator and system. Data sets with 28 times were compiled for each of the 16 confirmation method combinations. These data sets were then analysed and compared using one-way analysis of variance (ANOVA) with post-hoc tests from the software Statistical Package for the Social Sciences (SPSS).

3.3.5. Methods applied in Paper V

Paper V has the purpose to identify the potential of a cobot to support time-efficient batch preparation of kits. The paper considers how kit preparation cycle time and time allocation among activities of an operator change when a robot is used for sorting components into a batch of kits. Hence, the paper contributes to answering Research Question 3.

Paper V is based on a mathematical modelling approach, with which a model is developed for comparing the cycle times between manual kit preparation and collaborative robot supported kit preparation.

Model development

The model involves two different processes, one which is fully manual and another where an operator collaborates with a robot.

For the manual process, the operator activities were modelled based on a literature study. Additionally, operating schemes developed for various types of picking information systems in Paper III and Paper IV were used to define the tasks of the operator.

With the robot-supported process, the model of the operator's activities was used for the pick and travelling tasks. However, the sort task, which consists of placing components in the collaborative zone, was estimated based on a combination of literature study and small-scale tests and measurements in a laboratory. Here, previous studies by Boudella et al. (2018) played an important role for modelling the robot's activities, as did video recordings retrieved from the web, discussions with a collaborative robot developer and user manuals for relevant models of collaborative robot-arms.

Model validation

The model of the manual process and the operator's activities in the robot supported process, were checked against the experimental data collected for experiments in Papers III and IV. With face validity, which is important when building mathematical models of real life processes (Banks, 1998), the output generated by the model matched well with the experiment data. The model of the collaborative robot supported process was checked against other studies that had considered robot-supported picking activities, e.g. Boudella et al. (2018) and Coelho et al. (2018), and the model output seemed plausible in this light. The case example reported in Paper V was created based on data from the experiments in Papers III and IV, along with example values from the above mentioned publications from the literature.

3.4. Validity and reliability

To assess the validity and reliability of the research presented in the thesis, the framework from Yin (2009) is used. Yin's framework (ibid.) consists of four criteria: construct validity, internal validity, external validity, and reliability. Accordingly, this subchapter is structured into four sections, each dealing with one of the four criteria. In each section, the criteria's meaning is first explained, whereafter the criteria is discussed with respect to Papers I through V.

3.4.1. Construct validity

Construct validity as applied in this thesis can be expressed as the extent to which correct operational measures are established for the concepts being studied (Voss et al., 2002, p. 211). This has different implications for the different research methods applied in the papers.

Construct validity is strengthened by use of multiple sources of evidence, so that the evidence can converge on the line of inquiry (Yin, 2009). This convergence maintains a 'chain of evidence', meaning that the data is traceable over time, and the sequence in which the data is collected must be recorded, to ensure that no evidence is lost or neglected (ibid.). Construct validity is also supported by having key informants review drafts of case study reports (ibid.) and by making observations that can help confirm predictions of relationships among variables (Voss et al., 2002). In the following, construct validity is discussed with respect to the research methods applied in the five appended papers of the thesis.

In Papers I through V, a literature study was carried out at the outset of the research, from which theoretical frameworks were developed. These frameworks acted as a guide during the research, providing predictions for relationships between variables of interest, and thereby supporting construct validity.

In Papers I and II, which are both based on case research, the same procedure was applied for establishing a chain of evidence. Here, case descriptions were developed based on direct observation, notes, photos and video recordings collected during the site visits. All interviews were voice-recorded and transcribed within a week after each interview. Secondary documentation from the company was sent by e-mail or received in conjunction with the site visits, and was archived together with the other case data in a database for each case study. Key informants were asked to review drafts of the case study reports that were sent to them via e-mail, and comments were received via e-mail or telephone and used to refine the findings. Moreover, on several occasions before Papers I and II were finalised, the conclusions from both papers were discussed with representatives from industrial parties associated with the research project, including the companies at which the case studies were performed and the key informants for each case.

Papers III and IV used experiments in laboratory settings. Three approaches were used to ensure that the laboratory settings represented industrial kit preparation, and thereby that correct operational measures were applied with respect to the concepts. First, the research group's previous experiences with research related to kit preparation facilitated the decision-making on the settings

to use for the experiments. Second, as explained in Section 3.3.3, at the time when the experiment setup applied in Paper III was constructed, a multiple case study dealing with the factors affecting man-hour efficiency of kit preparation was ongoing, from which rich data from several kitting systems was available to validate the experiment settings. Third, a continuous dialogue about how to set up the experiments was maintained with the industrial parties associated with the research projects. Upon the author's request, the companies provided equipment and layout drawings, and could provide answers on short notice to questions regarding the settings used in industry. The project company representatives also reviewed and approved, the setup during a project workshop organised in the laboratory.

A possible threat to construct validity associated with the experiments in Papers III and IV would be if there was substantial variability between different variants of the same picking information system type (Paper III) or confirmation method type (Paper IV). This is because only a single variant was tested for each type of picking information system in Paper III, and only a single variant was tested for each type of confirmation method in Paper IV. However, this threat was dealt with owing to the researchers' knowledge about typical variants used in industry, which in part was gained from the case research in Papers I and II. It is also due to the detailed scrutiny by the industrial parties when the experiment setups were built. Therefore, the construct validity is still judged as high for the experiments in both Papers III and IV.

Paper V applied mathematical modelling, involving a manual setup and a robot-supported setup for kit preparation. Construct validity for the manual setup was ensured by basing the model on concepts dealt with earlier in the research, as presented in Papers I through IV. For the robot-supported setup, there was an ongoing implementation of a collaborative robot in a laboratory environment to which the researchers had access, and this provided valuable input on how to model the setup.

3.4.2. Internal validity

Internal validity in this thesis is expressed as the extent to which casual relationships can be established, whereby certain conditions are shown to lead to other conditions, as distinguished from spurious relationships (Voss et al., 2002, p. 211).

Yin (2003, p. 36) explains that case research involves an inference every time an event cannot directly be observed, and that these must in some way be ensured to be correct in order for the findings to have internal validity. Both Paper I and Paper II do rely on inferences made on events that could not be directly observed with respect to changes made to kit preparation workspace in Paper I, and with respect to kit errors in Paper II.

In Paper II, the root cause analyses of kit errors discussed during the interviews made up inferences to the actual situations when the kit errors had occurred. With respect to internal validity, the findings from the interviews were matched with the theoretical framework derived from the literature, the direct observation of the processes, and kit error records, which provided multiple perspectives on the root cause analyses discussed during the interviews. Hence, kit quality was studied by means of all of these sources of data, and the findings with respect to the individual cases were the result of analysing findings from the interviews, secondary documentation, pattern matching with the theoretical framework and cross-case comparisons. This approach helped to distinguish findings from spurious relationships, and thereby strengthen internal validity.

In Paper I, the activities associated with making changes in the kit preparation workspaces associated with the cases, which were discussed in interviews, constituted inferences to events that could not be directly observed. With respect to internal validity, a similar approach was used as described above for Paper II. Here, pattern matching with the theoretical framework, cross-case comparisons, secondary documentation, and discussing the mechanisms behind the changes in

detail during the interviews, provided multiple perspectives that together helped distinguish findings from spurious relationships. This approach strengthened the internal validity.

In Papers III and IV, the experiments were conducted in a laboratory environment, and the experimental settings were fully controlled. This allowed the settings to be adjusted in accordance with the research aim, and a high internal validity could be achieved. Likewise in Paper V, which applied mathematical modelling, the method relied on internal validity between theoretical constructs, and that is why the internal validity can be judged as high.

3.4.3. External validity

External validity concerns the findings' generalisability beyond the immediate study (Yin, 2009).

External validity can be problematic in case research, as each case exists in its own unique context and events are observed for a single time period. One approach for improving external validity of case research is to use replication logic in multiple case studies (Yin, 2009). Replication logic was used in the research for Papers I and II, which was possible owing to the use of multiple case study research designs. In both Papers I and II, design aspects of kit preparation were embedded in each case, allowing replication logic to be used for the respective design aspects when cases were selected. The replication logic used, together with the pattern matching and the theoretical framework applied in the analyses, strengthened the external validity associated with Papers I and II.

In Papers III and IV where experiments were applied, the use of laboratory settings for the experiments, as opposed to an industrial setting, is a threat to the external validity since a laboratory environment does not necessarily replicate a real application in industry. However, as discussed with respect to construct validity in Section 3.4.1, several measures were taken to ensure that the setups resembled industrial kit preparation. In the research associated with both papers, previous literature was thoroughly studied before the experimental setups were built, ensuring alignment with previous research. Rich data about industrial applications of kit preparation was available from the ongoing multiple case studies against which the laboratory setups could be evaluated. This was done in parallel with thorough scrutiny by the project companies, thus strengthening the external validity of the study.

Paper V applied a mathematical modelling approach. The model for kit preparation was based on a thorough review of previous research, which helped guide what variables to consider in order to make the model applicable to typical kit preparation setups found in literature. Furthermore, rich data about industrial applications of kit preparation was available from the previous case research and experimental studies reported in Papers I through IV, providing detailed input for how to model various settings. These aspects strengthened external validity.

3.4.4. Reliability

Reliability of research concerns whether the same findings and conclusions could be arrived at if the research was replicated by another researcher (Yin, 2009).

With case research and reliability, it is important that there is replicability when analysing the same case several times and arriving at the same conclusions, rather than conducting another case study and arriving at the same conclusions (Yin, 2009). To ensure reliability, a case research protocol should be used, and a case research database should be maintained (Yin, 2009). As described in Section 3.4.1 concerning the construct validity, a case research data base was maintained during the research associated with Papers I and II. The data collection procedures, and the data itself, was thoroughly documented, in terms of audio recordings and transcriptions of the interviews, summative notes of each site visit, video recordings and photos collected in association with direct observation, as well as time and activity logs of the research activities. Case research protocols, based on literature studies, were also applied, which allowed data collection templates to be

developed and pointing out central criteria during the data collection process. If the same protocols were applied to the same case studies again, similar findings would likely be arrived at. This strengthened reliability of the findings in Papers I and II.

With Papers III and IV, the possibility of controlling the settings of the experiments allowed for a detailed understanding of the conditions during which the data was collected. This understanding, combined with notes taken during the experiment runs of unexpected events, such as if a run had to be restarted due to a low battery in one of the devices, strengthened reliability. The numerical example presented in Paper V illustrates that replicability is high, as the same results are obtained with the same input data, and the same mathematical formulas should be arrived at by other researchers, should the same assumptions on which the model is based be repeated.

4. Results

This chapter presents the thesis' answers to the three research questions that were formulated in Subchapter 1.4. The answers are based on the five appended papers. This chapter is organised into three subchapters, and each presents an answer to one of the research questions.

Research Question 1: How is kit preparation flexibility governed by kit preparation design aspects? (Subchapter 4.1)

Research Question 2: How is kit quality governed by kit preparation design aspects? (Subchapter 4.2)

Research Question 3: How is kit preparation man-hour efficiency governed by kit preparation design aspects? (Subchapter 4.3)

4.1. How kit preparation flexibility is governed by design aspects

This subchapter presents the thesis' answer to Research Question 1, focusing on how kit preparation design aspects govern kit preparation flexibility. This response is based on the results reported in Paper I.

In terms of the design areas outlined in Chapter 2 (see Section 2.1.2 for the full list of the eight design areas), the results concerned with kit preparation flexibility cover the impact from 1) work organisation, 2) layout, 3) policies, 4) packaging, 5) equipment, and 6) picking information.

This subchapter is divided into six sections. Each presents the results related to flexibility and one of the design areas outlined above, explaining how design aspects associated with that design area affect kit preparation flexibility. Only the design areas for which the thesis has generated results are addressed in the subchapter.

4.1.1. Work organisation and flexibility

With work organisation and flexibility, the thesis' results concern the picker's job role and organisation of change in processes of kit preparation.

With respect to the pickers' job role, it was found that volume flexibility increases when pickers perform kit preparation and assembly within the same work cycle. This was represented by one of the cases in Paper I, which when compared with the other four cases, showed benefits of volume flexibility. This was because by using this approach, kit preparation and assembly were performed in loops that involved several operators, and it was simple to rebalance activities among kit preparation and assembly to adapt to volume fluctuations. In the four cases where operators only performed kit preparation, other approaches had to be applied in order to deal with volume fluctuations. For example, two of the cases implemented spare capacity when the applications were designed, and the other two cases relied on an opportunity presented by the context, where the additional required capacity was allocated to an evening shift.

The case research presented in Paper I showed how flexibility associated with making physical and information-related changes benefits from being performed with higher organisational integration. This has a moderating effect on all flexibility types, where higher organisational integration benefits all of new product, modification, mix, volume, and delivery flexibility.

4.1.2. Layout and flexibility

The results related to flexibility and layout concern the location of the kit preparation workspace within the materials flow. In Paper I, it was clear from comparing the cases on basis of two principally different locations that flexibility outcomes are affected by the location.

Amongst the three cases in Paper I that were located in a warehouse, there were no issues with expanding or reorganising the kit preparation workspaces, as additional floor space was plentiful.

In the two cases located close to the assembly processes, however, there was no space available for expanding the workspaces, and the possibilities of reorganising the space were restricted. The two cases located close to the assembly were forced to rely on alternative and less flexible approaches for handling change in production systems, for example by adding storage locations at the assembly processes, or by pre-sequencing low-runner component variants at an earlier stage in the materials flow. These differences indicate that locating kit preparation workspaces closer to assembly processes can reduce new product, modification, mix, and volume flexibility.

A reverse relationship was identified in delivery flexibility. Here, the cases located close to the assembly processes could handle late changes in the production schedule with less effort, while those located in warehouses required a larger effort. Here, context in terms of lead time requirements at assembly plays a role in how important delivery flexibility is, as it affects how much time is available for kit preparation.

4.1.3. Policies and flexibility

The multiple case study of Paper I indicated that both the storage and batching policies can affect flexibility.

The findings of Paper I show that a more rigorous storage classification leads to more frequent, and more extensive, reshuffling, and thereby lower levels of mix flexibility. However, two of the studied cases in Paper I applied a class-based policy along the picking aisle as a means of maintaining man-hour efficiency by keeping the more frequently picked components closer to the stationary kit carrier. Here, the importance of using classification depends on the number of component variants, which is an aspect of context, as it affects the proportion of component variants with low consumption rates at the workspace. The two cases that applied class-based policies within each shelf section, had a moving kit carrier and, therefore, had no need for classification along the aisle.

The multiple case study in Paper I identified that larger batch sizes tie up kits for longer time periods, thereby exposing the kits to changes in the delivery schedule. In this way, large batch sizes seem associated with lower levels of delivery flexibility.

4.1.4. Packaging and flexibility

The results of Paper I with respect to packaging and flexibility, concern the kit container design and the type of storage packaging applied in kit preparation.

Applying fitted slots for components in kit containers was associated with a lower new product and modification flexibility compared to kit containers with standardised compartments or no structure. One case in Paper I applied fitted slots in the kit containers, while three cases used standardised compartments, and one case applied kit containers without an inner packaging structure. When using new components with new products or with modifications in accordance with engineering change orders, fitted slots must often be redesigned, which can involve extensive work. This is not required when any component fits into any compartment or place in the kit container, indicating higher flexibility.

In storage packaging, all five cases in Paper I applied EUR-pallets for some of the components at the kit preparation workspaces. All cases reported that additional work was required to carry out changes that concerned the pallets, in contrast to when changes concerned plastic boxes. This relates to new product, modification, and mix flexibility, since adding new storage locations for pallets or moderating the number of components in the kit preparation workspaces is more costly and time consuming, and thereby less flexible than when using boxes. Packaging that can be applied is, however, affected by the component size, which is an aspect of the context.

4.1.5. Equipment and flexibility

Two of the cases in Paper I applied wheel-based storage racks for boxes, tiltable wheel-based fixtures for pallets, and hook-attached bolt-free shelves. These facilitated reorganisation in comparison with the other three cases, as there was no need for tools and heavy lifting equipment. This was beneficial for both volume and mix flexibility, as shelves could be moved and rearranged with little effort, without necessarily emptying them.

Paper I also identified that the presence of lifting supports complicates reorganisation, as these devices typically involve robust structures that are difficult to move. The presence of lifting supports, thereby, reduces new product, volume and mix flexibility. However, context, in terms of the weight of components, affects the need to use lifting devices.

4.1.6. Picking information and flexibility

The results from Paper I indicate the means for conveying information to pickers and the methods for carrying out confirmations to affect flexibility.

Picking information systems used in Paper I involved three cases that applied pick-by-light, one case that applied pick-by-voice, and one case that applied paper pick lists. It was clear from comparing the cases that pick-by-light systems, which involve physical components in the form of cables, light indicators, and buttons, are associated with more work when reorganising kit preparation workspaces than other types of picking information systems.

In comparison, pick-by-voice systems require only check digits to be presented at storage locations at kit preparation workspaces, and less effort was associated with this type of system when reorganisation was necessary.

Paper pick lists were associated with similar levels of flexibility as pick-by-voice, as they also involved signs with text information that needed updating when reshuffling the storage, or when introducing new component numbers in the storage. The paper pick list was, however, eventually ranked with higher flexibility, as all pick-by-light and pick-by-voice applications kept signs with component numbers at the storage locations, so that a backup paper pick list could be used if the system malfunctioned.

4.1.7. Overview of the results for Research Question 1

To sum up the results to Research Question 1, an overview of the results is presented in **Table 4.1**. The table highlights the design areas for which the thesis presents results (column one), describes the impact the design aspects have on man-hour efficiency (column two), summarises any identified influence from the context (column three), and highlights interplay among design aspects with respect to flexibility (column four). Interplays were not presented in Section 4.1.1 to 4.1.6 in order keep the presentation of each design area separate, but they are presented here to give a complete account of the results.

Table 4.1. Overview of results with respect to Research Question 1, showing the design areas for which the thesis presents results, a description of the identified impact from design aspects on flexibility, identified influence from context, and identified interplays with other design aspects.

Design area	Flexibility impact	Context influence	Identified interplays
Work organisation	Job role of pickers governs volume flexibility by affecting work balancing (Paper I).	Manufacturing planning and control affects the available options (e.g. an extra evening shift) in the production system for absorbing volume fluctuations.	Location affects the feasible job roles (Paper I).
	Organisation around change governs new product, modification, mix, and volume flexibility by affecting organisational integration (Paper I).		Has a moderating effect on the flexibility types of new product, modification, mix, volume, and delivery (Paper I).
Layout	Location governs new product, modification, mix, and volume flexibility by affecting available floor space for reorganisations (Paper I).	Plant layout affects floor space availability (Paper I)	
		Component variety affects storage space requirements (Paper I).	
	Location affects delivery flexibility by affecting transportation methods and distances (Paper I).	Production rate affects the time available for kit preparation (Paper I).	
Policies	Storage policy governs mix flexibility by affecting the amount of reorganisations necessary (Paper I).	Component variety affects the proportion of component variants with low consumption rates (Paper I).	Kit carriers , when stationary, require classification to maintain efficiency (Paper I).
	Batching policy governs delivery flexibility by affecting how long kits are tied up in kit preparation (Paper I).		
Packaging	Kit container design governs new product and modification flexibility by affecting how often kit containers must be redesigned (Paper I).		
	Storage packaging governs new product, modification, mix, and volume flexibility by affecting the ease of changing unit loads and storage locations (Paper I).	Component size affects the type of storage packaging that can be used (Paper I).	
Equipment	Storage racks govern mix flexibility by affecting the ease of reorganisations (Paper I).		Storage packaging affects which storage racks can be applied (Paper I).
	Lifting supports govern new product, modification, mix, and volume flexibility by affecting the ease of expansions and reorganisations (Paper I).	Component weight affects the need to use lifting supports (Paper I).	
Picking information	System type governs new product, modification, mix, volume flexibility, and delivery flexibility by affecting the effort associated with expansions and reorganisations and access to supportive functionality (Paper I).		

4.2. How kit quality is governed by design aspects

This subchapter presents the thesis' answer to Research Question 2, which targets how kit preparation design aspects govern kit quality.

The answer to Research Question 2 is formulated based upon the results reported in Papers II, IV and V.

Paper II has the purpose to create an understanding of the links between kit preparation design aspects and kit preparation error types, that can be useful to support kit quality. In terms of the design areas outlined in Chapter 2, the results from Paper II concern the design areas: 1) work organisation, 2) layout, 3) policies, 4) packaging, 5) equipment, 6) picking information and 8) control.

Paper IV has the purpose to determine the extent to which the type of confirmation method relates to time-efficient kit preparation when order batching is applied. The experiment reported in Paper IV considered the numbers of kit errors as a means to ensure that efficiency was not achieved at the expense of kit quality, and thereby produced results related to design areas 3) policies, in terms of results related to batching policy, and 6) picking information, in terms of results related to types of confirmation methods.

Paper V has the purpose to identify the potential of a cobot to support time-efficient batch preparation of kits. Paper V provides input concerning the design areas 3) policies, in terms of results related to batching policy, and 7) automation, in terms of results related to how robots impact kit quality when used in kit preparation.

This subchapter is organised into eight sections, where each section focuses on one of the eight design areas outlined in Chapter 2 (see Section 2.1.2). Within each section, it is explained how the design aspects associated with that design area were found to affect kit quality. Only the design areas for which the thesis has generated results are considered.

4.2.1. Work organisation and kit quality

From the case research reported in Paper II, it was found that the picker's knowledge about assembly processes can be beneficial for kit quality. This was identified in two cases where assemblers performed kit preparation. Here, knowledge about the end products and assembly tasks was learnt from performing assembly work, which was useful for identifying correct and non-defective components in kit preparation.

4.2.2. Layout and kit quality

The results related to layout and kit quality concern the location of kit preparation workspaces within material flows.

The three cases in the multiple case study reported in Paper II represented two principally different locations of kit preparation workspaces in material flows. It was clear from the cases that it was more problematic and costly to correct kit errors when kit preparation workspaces were located farther away from assembly processes, than when located nearby.

Furthermore, there was a direct line of sight between kit preparation and assembly processes in one of the cases. This was found to facilitate corrections, as the assemblers could directly communicate with kit preparation operators when a kit error occurred.

4.2.3. Policies and kit quality

The findings from Paper II include results related to policies and kit quality. The results concern both storage and batching policies.

All of the cases studied in Paper II used storage policies whereby similar-looking components were separated in storage. This prevented pickers from confusing two similar-looking components during the picking cycle. The policy also prevented wrongly picked components from being restocked in the wrong location. The restocking activity could occur, for example, when too many components were picked, or when wrong components were picked, and the error was realised before the components were sorted into kits. However, the order in which components are assembled, which is an aspect of context, impedes the possibilities of separating components in storage.

It was clear from analysing the cases in Paper II that there was a risk of placing components in the wrong kit when kits are prepared in batches (two cases). This risk does not apply when preparing a single kit each picking tour (one case). The cases that prepared kits in batches applied place-to confirmations to support components being placed in the correct kit. The place-to confirmations provided feedback when components were placed in kits, indicating whether the correct kit

container was confirmed or not, and were considered effective by the interviewed managers and pickers for preventing errors.

The experiment in Paper IV involved batch preparation of kits, demonstrating how different types of confirmation methods supported correct placements of components. Some methods, for example RFID-reading wristbands, require that the hand visits the correct kit container for the confirmation to register. Other methods, such as button presses and voice commands, can be performed without the hand visiting the kit container.

The automation-based application studied in Paper V showed how a collaborative robot-arm can remove the risk of placement errors when kits are prepared in batches. With the application, an operator selects components from the shelves, one component number at a time, which the collaborative robot then sorts into the kit containers.

4.2.4. Packaging and kit quality

Findings from Paper II show that kit quality can benefit from the use of fitted slots in kit containers. This was because it was easier for the pickers to judge that the correct components had been picked, based on whether the picked components fitted into the slots or if a slot was empty.

The case research reported in Paper II also identified that kit containers with standardised compartments, in which all components are allotted the same amount of space, can aid the picker in keeping track of the next activity by looking at the compartments that have already been filled. This also supports detecting if a component is missing when kits require the same number of components, which depends on context in terms of end product structure.

In all three cases studied in Paper II, irregular yet frequent activities, such as discarding of packaging, created distractions that could lead to errors during kit preparation. In two of the cases, discarding points, i.e. trash bins and output lanes for empty containers, had been positioned at places that the picker normally visited, such as next to the kit carrier. This reduced the disturbances, and was recognised to reduce the risk of error.

4.2.5. Picking information and kit quality

With respect to picking information and kit quality, the findings reported in Paper II show that the picking information system can support kit quality in four different ways.

First, the case research reported in Paper II showed that picking information systems that can help verify that materials are replenished correctly, for example the pick-by-voice systems, can aid in preventing kit errors. Furthermore, functions for handling material shortages also seemed beneficial for kit quality.

Second, confirmations were applied in all the three cases in Paper II as a means of supporting kit quality, and were seen as effective. Confirmations allow pickers to receive feedback on accomplished activities, and are usually performed in order for a picker to receive the next set of instructions. The experiment reported in Paper IV observed three kit errors that occurred when confirmation methods were applied. The descriptions of how the kit errors occurred, observed through video recordings of the experiment, highlighted that it is important for confirmation to be directly associated with the activity it supports and that it provides clear feedback.

Third, Paper II identified that the order in which the pick or place locations are indicated during the work cycle can be important for kit quality. Here, having light indicators for all kits that should receive components light up at once, or having all picking locations in the shelves light up at once, can lead to a dissociation between confirmations and activities carried out to save time. In contrast, if the next instruction can only be received once a previous activity has been confirmed, it seems more beneficial for kit quality.

Fourth, the findings from Paper II indicate that kit quality can be affected by how picking information is conveyed. In the three cases studied in Paper II, paper pick lists had either been used previously or were used as a backup when the system currently in use malfunctioned. Drastic improvements of kit quality were reported in all three cases when the paper pick list was replaced.

4.2.6. Automation and kit quality

In Paper V, a model was developed of a process for kit preparation where a collaborative robot is responsible for sorting components into kits. Using a robot is an approach to remove kit errors that comes from misplacing components when kits are prepared in batches. The approach is applicable only with components that have characteristics allow for robot picking, which is an aspect of context.

4.2.7. Control and kit quality

From the case research reported in Paper II, it was clear that effective error communication with respect to identifying and correcting kit errors can relieve the assembler of having to deal with correcting kit errors in the assembly process. When a kit error is detected and routines are in place, the routine is initiated by the assembler and correct components soon arrive. If routines are not in place, assemblers and their team leaders must deal with correcting kit errors ad hoc, creating various kinds of disturbances in the production system.

4.2.8. Overview of the results for Research Question 2

To sum up the results to Research Question 2, an overview of the results presented earlier in the subchapter is presented in **Table 4.2**. The table highlights the design areas for which the thesis presents results (column one), describes the impact the design aspects have on kit quality (column two), summarises any identified influence from the context (column three), and highlights any interplays with other design aspects (column four). Interplays were not presented in Section 4.2.1 to 4.2.7 to keep the presentation of each design area separate, but they are presented here instead in order to give a complete account of the results.

Table 4.2. Overview of the results with respect to Research Question 2, showing the design areas for which the thesis presents results, a description of the identified impact from design aspects on kit quality, identified influence from context, and identified interplays with other design aspects.

Design area	Quality impact	Context influence	Identified interplays
Work organisation	Job role governs pickers' knowledge of quality requirements (Paper II).		
Layout	Location governs how kit error corrections are carried out (Paper II).		
Policies	Batching policy can help prevent misplacement of components among kit containers (Paper II and Paper IV).		
	Storage policy can help prevent confusion with similar looking components (Paper II).	Assembling procedure can restrict the possibility to separate components (Paper II).	Kit carrier , if mobile during work cycles, can restrict the possibility of separating components (Paper II).
Packaging	Kit container design (fitted slots) can support picking of correct types and numbers of components (Paper II).	End product structure affects similarity of contents between kits (Paper II).	
	Kit container design (e.g. compartments in kits) can help prevent missing component errors (Paper II).	End product structure affects similarity of content between kits (Paper II).	
	Storage packaging handling is associated with disturbances that can impact kit quality (Paper II).	Component characteristics affects what packaging can be used (Paper II).	
Picking information	Information conveyance can help reduce ambiguity during work cycles (Paper II).	Component variety affects how picking information must be conveyed (Paper II).	Batching policy affects how picking information must be conveyed (Paper IV).
	Confirmation method type affects kit quality feedback during work cycles (Paper II and Paper IV).		Batching policy affects how confirmation methods are applied (Paper IV).
	Supportive functionalities are important for effectively handling materials shortages and order changes (Paper II).		
Automation	Robot-supported sorting can help remove kit errors from misplaced components (Paper V).	Component characteristics affect the components that can be handled by a robot (Paper V).	Batching policy determines if sorting of components among kits is necessary (Paper V).
Control	Error communication affects available assembly information for kit error prevention (Paper II).		Location affects how error communication can be set up (Paper II).

4.3. How kit preparation man-hour efficiency is governed by design aspects

This subchapter presents the answer to Research Question 3, focusing on how kit preparation design aspects govern kit preparation man-hour efficiency.

The response to Research Question 3 is formulated based on the research reported in Papers III, IV, and V.

Paper III has the purpose to establish the extent to which the type of picking information system impacts the time-efficiency of kit preparation when confirmations are required, considering the two cases of single-kit and batch preparation as well as the picking density of the picking area. In terms of the design areas outlined in Chapter 2, the results from Paper III concern design areas 2) layout, 3) policies, 4) packaging, and 6) picking information.

Paper IV has the purpose to determine the extent to which the type of confirmation method relates to time-efficient kit preparation when order batching is applied. The paper provides results related to design areas 3) policies and 6) picking information.

Paper V has the purpose to identify the potential of a cobot to support time-efficient batch preparation of kits. The paper highlights, for example, how the operator's activities change when a

collaborative robot is used. The results from the paper that contribute to the answer of Research Question 3 relate to the design area 7) automation.

This subchapter is organised into five sections, where each section focuses on one of the design areas outlined in Chapter 2 (see Section 2.1.2). It explains how the design aspects associated with the design area affect man-hour efficiency. Only the design areas for which the thesis has generated results are considered.

4.3.1. Layout and man-hour efficiency

With respect to layout and man-hour efficiency, the experiment reported in Paper III considered the impact on man-hour efficiency from picking density, which is an aspect of the layout design area.

The results from the experiment in Paper III show that higher picking density, meaning shorter walking distances in between picking locations, reduces the benefits of a batch preparation approach compared to single-kit preparation. Paper III also indicates that a pick-by-voice system benefits from being applied with lower picking density, as there is more time in between picks to administer the voice dialogue.

4.3.2. Policies and man-hour efficiency

The thesis results related to policies and man-hour efficiency concern the impact from the batching policy. In the experiment reported in Paper III, the batching policy made up one of the experimental variables and two settings were studied: one kit prepared per work cycle, and four kits prepared per work cycle. The results showed that the batching policy affects kit preparation man-hour efficiency, but also that the relative efficiency between single-kit and batch preparation depends on the type of picking information system used and picking density the kit preparation workspace has.

For some of the picking information systems studied in Paper III, such as pick-by-light and pick-by-HUD, a single-kit policy was more man-hour efficient. However, batch preparation was as or more efficient with pick-by-list and pick-by-voice systems.

In Paper III, the findings are explained as follows. Normally, the advantage with batch preparation over single-kit preparation from a man-hour efficiency standpoint is that the average walking distances are reduced owing to more components being picked at once. However, in a higher density setting, the walking distances were short, and the benefits of using a batch preparation approach were small, as seen from the experiment in Paper III. At the same time, the impact on man-hour efficiency from the type of confirmation method used when placing components in kits was substantial. This was necessary with batch preparation but not with single-kit preparation, leaving the single-kit approach as the more man-hour efficient alternative for some settings.

4.3.3. Packaging and man-hour efficiency

The results from the experiment in Paper III showed a relationship between packaging and man-hour efficiency, specifically with respect to storage packaging. Here, differently sized plastic boxes were used as storage packaging at the kit preparation workspace to simulate different levels of picking density. As described with respect to layout in Section 4.3.1, batch preparation of kits was found to be more efficient when picking from larger plastic boxes, that is, with lower picking density. Here, the larger plastic boxes contributed to longer walking distances and lower picking density.

4.3.4. Picking information and man-hour efficiency

The experiment in Paper III shows how man-hour efficiency with different types of picking information systems varies according to the order batching policy used and the picking density of the kit preparation workspace.

The findings in Paper III showed that some systems, i.e. pick-by-light and pick-by-HUD in the experiment, may benefit from single-kit policy as opposed to batch preparation, owing to the smaller number of components handled at once, and from that there is no need to carry out place-to confirmations with single-kit policies. For these systems, the benefits of the single-kit policy were greater with higher picking density.

The experiment also showed that types of picking information systems with which the time is spent on performing confirmations is small, for example as with the pick-by-list system for which whole order lines were confirmed at once, can benefit man-hour efficiency when applied with batch preparation of kits.

The impact on kit preparation man-hour efficiency from the type of applied confirmation method was the focus of Paper IV. The findings show that the type of method used for carrying out confirmations with batch preparation of kits impacts man-hour efficiency. Two methods stood out with respect to man-hour efficiency, namely RFID-reading wristbands and button-presses. Both methods allowed pickers to carry out confirmations when picking from shelves with small or no additional motions or waiting times. These methods also stood out when used for carrying out place-to confirmations. Here, both methods allowed the picker to place components into two kit containers at once, something which was not possible with either barcode-scanning or voice commands, with which confirmations must be performed one at a time.

4.3.5. Automation and man-hour efficiency

Kit preparation man-hour efficiency was central to Paper V. The model developed shows how a collaborative robot can carry out kit preparation tasks and highlights several differences to carrying out the tasks manually. An important difference is that robots have difficulty handling more than one component at a time. Numerical applications of the model showed that the setup supported by a collaborative robot can result in a similar cycle time as if kit preparation is performed manually, but with more time freed up for the operator.

4.3.6. Overview of the results for Research Question 3

To sum up the results with respect to Research Question 3, an overview of the results is presented in **Table 4.3**. The table highlights the design areas for which the thesis presents results (column one), describes the impact the design aspects have on man-hour efficiency (column two), summarises any identified influence from the context (column three), and highlights any interplays with other design aspects (column four). Interplays were not presented in Section 4.3.1 to 4.3.5 in order keep the presentation of each design area separate, but they are presented here to give a complete account of the results.

Table 4.3. Overview of the results with respect to Research Question 3, showing the design areas for which the thesis presents results, a description of the identified impact of design aspects on man-hour efficiency, identified influence from context, and identified interplays with other design aspects.

<i>Design area</i>	<i>Man-hour efficiency impact</i>	<i>Context influence</i>	<i>Interplays</i>
<i>Layout</i>	Picking density governs travelling time during work cycles and time in between picking activities (Paper III).	Component characteristics affect storage space requirements and the packaging used (Papers III and IV).	Picking information system , in terms of the type used, can be associated with activities that can be performed while travelling (e.g. receiving information) (Papers III and V).
<i>Policies</i>	Batching policy governs the number of components picked at once (Paper III).		Picking density and confirmation method affect man-hour efficiency associated with batching policy (Paper III).
<i>Packaging</i>	Storage packaging , in terms of type and size used, governs walking distances (Paper III).		
<i>Picking information</i>	Information conveyance governs how and in what order picking information is presented (Paper III).		Batching policy affects how picking information is presented (Paper III).
	Confirmation method governs time associated with pick-from and place-to confirmations (Papers III and IV).		Batching policy affects how confirmation methods are applied (Papers III and IV).
<i>Automation</i>	Robot-supported sorting of components can affect man-hour efficiency associated with batch preparation of kits (Paper V).	End product structure affects similarity of content between kits (Paper V).	Number of compartments in the zone between picker and robot affects balancing between picker and robot during work cycles (Paper V).

5. Discussion

This chapter presents a discussion of the thesis results and its contributions. The chapter is organised into three subchapters.

Subchapter 5.1 presents a discussion of the answers to each of the three research questions, which were formulated in Subchapter 1.5 and answered in Chapter 4. The discussion explains the thesis' contributions to both theory and practice.

Subchapter 5.2 presents a discussion of how the thesis addresses its purpose of contributing to the knowledge of how kit preparation design aspects govern kit preparation performance (as stated in Subchapter 1.2).

Subchapter 5.3 presents a discussion of avenues for future research related to kit preparation design and performance, by discussing how the findings can be applied beyond this thesis, both with respect to theoretical applications for researchers and academia, as well as with respect to practical applications for practitioners and industry.

5.1. Discussion of the thesis' results

This subchapter presents a discussion of the thesis' results, earlier presented in Chapter 4, and their contribution to theory and practice.

In Sections 5.1.1 through 5.1.3, the results related to the three research questions are discussed separately. Each of the sections is organised following the design areas outlined in Chapter 2. For each area, the results in terms of relationships between design aspects and performance are discussed individually, first by how the result is important for supporting kit preparation design, then by how the result adds to the existing literature and, finally, the ways in which the new understanding of the relationship is useful.

Section 5.1.4 presents a comprehensive overview of relationships between kit preparation design aspects and flexibility that have been identified in this thesis and previous research (see **Table 5.1**).

5.1.1. How design aspects govern flexibility (RQ1)

This section discusses the results presented in Subchapter 4.1, which constitute the response to Research Question 1: 'How is kit preparation flexibility governed by kit preparation design aspects?'.

Discussion of work organisation and flexibility

The thesis identified two important relationships between the work organisation design area and flexibility. One was with respect to the picker's job role, and the other involved how to organize changes in kit preparation workspaces.

It was found that when operators prepare their kits and then carry out assembly tasks, volume flexibility can benefit. Using this approach, several operators are involved in the same process, and it is simple to rebalance activities among kit preparation and assembly in response to volume fluctuations, which is important in production systems. When job roles that only involve kit preparation are used, other approaches may be more viable, albeit more costly. Examples include having spare capacity in kit preparation (Paper I) or, if possible within the context, preparing some of the kits during another work shift (Paper I).

The above is in line with findings from previous research that has considered how the picker's job role, in terms of the work responsibilities other than kit preparation, can affect flexibility (Hanson and Brodin, 2013; Hanson et al., 2011; Brynzér and Johansson, 1995). The contribution of this thesis that extends beyond these earlier works is represented by the flexibility perspective used. This thesis adds details as to how the relationship is comprised, in terms of considering the penalties of cost, lead time and organisational disruption. The variety of ways volume fluctuations can be handled

with respect to kit preparation, in terms of keeping extra capacity or planning extra kit preparation on another shift, make up another contribution with respect to this relationship that has received little attention in previous research.

This thesis has also identified that the way change of processes for kit preparation is organised can impact flexibility. Paper I indicated that greater organisational integration benefits flexibility, as it reduces the need for planning and foresight, affecting all flexibility types. This is important because flexibility is typically viewed to be about the ability to change processes in response to new requirements. For companies that make use of kitting, the findings imply that it is crucial to not only consider what types of equipment and policies are applied to support flexibility, but also how responsibilities for managing and changing processes for kit preparation are organised within the company.

The relationship between flexibility and how the change of processes for kit preparation is organised has been discussed by Hanson et al. (2011, p. 128), who explained. 'Based on the cases, it seems that continuous improvement work can be facilitated both by the fact that the operators then have an understanding of both assembly and kit preparation, and by having potential changes and reorganisations taking place within the same organisational unit of the company'. The thesis results support this notion and further reveal that how the work is organised affects all the considered flexibility types focused on in the thesis.

The relationship between work organisation and flexibility, addressed by previous research, together with the knowledge uncovered in the thesis, present immediate input for consideration by practitioners dealing with planning and design of processes for kit preparation. The knowledge can also support prioritisation among performance areas in both assembly and materials supply systems.

Discussion of layout and flexibility

The results as related to Research Question 1 and the layout design area show that the location of kit preparation workspaces within material flows has a mixed impact on the flexibility types focused on in the thesis.

Locating kit preparation workspaces farther from the assembly processes, as opposed to nearby, seems to improve new product, modification, mix and volume flexibilities, since more floor space is available for carrying out expansions and reorganisations. This aligns well with Hanson et al. (2011), who found that the location of kit preparation workspaces within material flows affect flexibility by governing the amount of floor space available for expanding and reorganising kit preparation workspaces. The thesis thus found support for this notion and refined this understanding by also distinguishing among the flexibility of dealing with new products, modification, mix and volume.

From a delivery flexibility standpoint, locations closer to assembly processes seem beneficial, as shorter transportation distances allow pickers to deliver kits manually and thereby have more control of when deliveries take place. Thus, order changes can be handled more quickly. The mechanics of the relationship between location and delivery flexibility has been brought forth by previous research (see Hanson et al., 2011; Brynzér and Johansson, 1995), but this has been linked to the ability to respond to quality deficiencies in kits rather than flexibility. The findings echo understandings of flexibility in warehouse order picking, where the length of pickers' routes has been linked with flexibility in dealing with order changes (Roodbergen, 2012).

The above highlights a trade-off with respect to location and flexibility types. Whereas delivery flexibility benefits from locating kit preparation workspaces closer to assembly processes, new product, modification, mix and volume flexibility benefits more from more remote locations. This trade-off has not been acknowledged in previous research and is a contribution of the thesis. It shows that flexibility is multi-faceted and that trade-offs exist between flexibility types with respect

to location of kit preparation workspaces. This trade-off depends on the context, as the availability of floor space affects what locations are applicable and the required lead time affects the need for delivery flexibility. This is relevant for kitting applications that are already in-use or when new applications are introduced as a means to improve performance with respect to desirable flexibility types.

It should be noted that floor space availability depends on context in terms of the plant's layout, and it cannot be taken for granted that more floor space is available farther from the assembly process. Moreover, in some situations it may not even be possible to locate kit preparation workspaces close to assembly processes due to lack of floor space.

With the thesis findings along with prior knowledge about the relationship between location and flexibility from, for example, Hanson et al. (2011) and Brynzér and Johansson (1995), industry managers are equipped with knowledge of how to support different flexibility types in kit preparation. This represents a means of realising the flexibility benefits normally associated with kitting and can help prioritisation between performance areas when systems for production and material supply are designed, such as in situations when production volumes fluctuate frequently.

Discussion of policies and flexibility

The thesis identified relationships between the policy design area and flexibility related both to storage policy and batching policy.

It is clear from the results that storage policies based on rigorous classification negatively affect mix flexibility. Examples of this would include class-based policies for keeping high-runner components at an optimal picking height or close to kit carriers that are stationary during picking work cycles. This negative effect is because the classification must be maintained and updated when there is a change in the production mix. The results present considerations for managers with respect to kit preparation design. When flexibility of mix is a priority, storage policies that involve classification are best avoided, and a moving kit carrier may be a preferable option, as classification can be necessary to upkeep efficiency at kit preparation workspaces when kit carriers are stationary.

In literature dealing with warehouse order picking, several researchers (e.g. Roodbergen, 2012; Chan and Chan, 2011; Yu, 2008; De Koster et al., 2007) have highlighted that storage policies affect flexibility. However, this has not been evident in literature dealing with kit preparation. In this light, the thesis thus makes an addition to the available knowledge by showing that the relationship also exists with kit preparation.

This study indicates that the batching policy influences delivery flexibility. Here, larger batch sizes tie up kits as work in process for longer periods of time and expose them to schedule changes that can require the kit contents to change. Using smaller batch sizes can reduce the need to adjust kit content that has been fully or partially prepared. The results show that flexibility effects should also be considered along the quality- and efficiency-related effects that normally go into the choice of what batching policy to apply.

The above echoes findings from previous research. Brynzér and Johansson (1995) stated, 'An important task is to choose a proper time horizon for the batching. The batching horizon is affected by... (3) flexibility concerning changes in the order'. This research supports this notion and adds explanations for how the relationship is constructed with respect to delivery flexibility.

Knowledge of the relationship between policies and flexibility, consisting of previous research and the thesis' results, lead to the construction of flexible kit preparation applications. The available knowledge explains that the rules imposed on how the storage is organised, i.e. the storage policy, must not only respect quality and man-hour efficiency, but must also account for the work that will have to be exerted to maintain the policy, respecting flexibility. The available knowledge also

explains that when various options for order batching policy are weighted against each other, there is a drawback regarding delivery flexibility for larger batch sizes.

Discussion of packaging and flexibility

The thesis' results involve flexibility-related effects related to both the applied type of storage packaging and the packaging used for the kit container.

The results showed that smaller sized packaging, such as plastic boxes, generally led to higher flexibility than larger sized packaging, such as EUR-pallets, when handling change related to new products, modifications, production volumes and production mix. This is because smaller sized packaging requires less storage space and can allow for more precise adjustments of packaging size to alter the amount of inventory kept at kit preparation workspaces. This obvious yet important finding shows that when it is possible to make a choice of what storage packaging to use at kit preparation workspaces, there are flexibility benefits to using smaller packaging.

Researchers who have dealt with flexibility of assembly processes (e.g. Wänström and Medbo, 2009) and kitting (e.g. Hanson, 2012) have shown that the type of storage packaging used can affect for flexibility in handling large amounts of component variants. This thesis supports these reports and additionally shows how the type of storage packaging impacts a variety of kit preparation flexibility types.

Using kit containers with fitted slots for components can impede flexibility related to handling new products and product modifications, as these slots need to be redesigned to accommodate new components. This is not required when kits do not have an inner packaging structure or when kits are composed of compartments that allocate a set amount of space for each component. These options benefit flexibility in contrast to fitted slots.

Without an inner packaging structure in the kit container, it is difficult to control the order by which components are extracted from kits in the assembly process. This can delimit flexibility with respect to the order in which components are put into the kit, as the components used first in assembly must be presented on top in the kit and thereby must be put last in the kit during kit preparation. This would likely not be a problem with fitted slots or compartments, as often any component can be accessed first with these kit container designs.

Several publications have highlighted that the packaging used as kit containers can be of importance for flexibility (Hanson and Brolin, 2013; Brynzér and Johansson, 1995). New product and modification flexibility is reduced when containers are customised in accordance with existing components and seem to be promoted by more generic designs of kit containers, such as by using no structure at all or standardised compartments. The available knowledge is useful for managers to account for flexibility effects when the choice of packaging is made with respect to kit preparation.

The available knowledge from previous studies and this thesis, show that the packaging applied in kit preparation for storage packages and kit containers can affect flexibility associated with kit preparation. The knowledge is useful not only with respect to kit preparation, but also with respect to design of materials handling systems, wherein packaging is central to different kinds of processes, such as transportation, storage and materials handling.

Discussion of equipment and flexibility

Studying the cases in Paper I identified how applying wheel-equipped storage racks and hook-attached shelves can facilitate reorganisations of kit preparation workspaces. This is important when reorganising in the storage to accommodate production mix changes, thereby promoting production mix flexibility.

As stated in Chapter 2, materials handling equipment used in assembly (Wänström and Medbo, 2008) and warehouse order picking (Park, 2012) has been associated with flexibility in previous literature. In particular, the design of storage racks (Wänström and Medbo, 2008) and various applications for supporting materials handling activities (Park, 2012) have been pointed out. The findings in Paper I show how these relationships also present concerns.

Another aspect related to equipment and flexibility are the devices used for lifting support, such as telpher cranes, in kit preparation workspaces. In two of the cases in Paper I, these were found to affect flexibility negatively by making it more difficult to rearrange or expand the storage, due to the robust structures required for these devices. Lifting supports are necessary when components are too heavy for manual lifting without risk of injury, and while components that go into kit preparation typically are below such weight-thresholds (Caputo et al., 2018), there are situations when heavier components are present and lifting supports are required. The relationship between flexibility and lifting supports identified by the thesis can be useful to consider when planning and designing materials supply systems.

Little attention has been paid to how the use of lifting supports affect kit preparation performance. Hanson and Medbo (2019) considered the impact with respect to man-hour efficiency, but they did not report any effects. The findings here echo knowledge of the relationship between automation and flexibility, in the sense that automation is often described as delimiting flexibility over longer time periods (Baker and Halim, 2007). At the same time, the ability to kit heavier components in kit preparation improves production system flexibility, since heavier components can also be supplied by kitting to assembly processes.

Aspects such as storage racks and lifting supports should be considered from a flexibility standpoint when selecting equipment to be used in kit preparation. While flexible equipment alternatives may not generate much additional costs, the findings show that they can facilitate flexibility of reorganisations and expansions of kit preparation workspaces.

Discussion of picking information and flexibility

The case research reported in Paper I identified that the number of physical components associated with picking information systems plays a role in flexibility. Here, pick-by-light systems, which involve extensive structures composed of cables, light-indicators and buttons, are associated with more work during reorganisations and are, thereby, less flexible than systems for pick-by-voice, which only require picking locations to be labelled with check-digits and identifiers. In turn, pick-by-voice systems were found to be less flexible than paper pick lists, as these only need the component number. This is important with respect to deciding what type of picking information to apply in kit preparation, which may otherwise be easily overlooked when deliberating among choices.

Previous research has ascribed flexibility effects to various types of picking information systems when reflecting upon results where flexibility has not been the focus. One example is Hanson et al. (2017), who noted that presenting picking information digitally in kit preparation may improve flexibility, as there are fewer physical components associated with the picking information system that need to be rearranged when changes are carried out. The thesis found support for this notion and shows that it also applies to established system types which are already frequently applied in industry.

The available knowledge about flexibility and picking information systems explains that the physical components of picking information systems needs to be arranged in much the same fashion as equipment used at kit preparation workspaces. The amount of work required to keep the picking information system up-to-date with current product structures and policies can easily become substantial, and the work is mandatory to carry out for kit preparation to properly function. The

impact on flexibility when choosing the type of picking information system needs to be accounted for alongside the impact on kit quality and man-hour efficiency.

Discussion of automation and flexibility

While the relationship between automation and flexibility has not been explicitly studied in the thesis, some reflections about this relationship can be made with respect to Paper V.

Paper V studied a solution for automation-supported kit preparation, in terms of a collaborative robot that supports an operator by carrying out sorting during batch preparation of kits. In this setup, it is important that the collaborative robot is up-to-date with current requirements from the assembly processes in order to properly carry out sorting, and thus, it has to be flexible. While the automation-based application considered in Paper V was simple to reprogram in laboratory settings, previous studies recognise reprogramming of robots in response to variability as one of the major challenges in using viable robot-applications in live production settings (Kootbally et al., 2018).

As explained in Chapter 2, the notion that automation by default is inflexible usually refers to flexibility limitations when capabilities are expanded over longer time periods (Baker and Halim, 2007). In this sense, automation seems to affect new product, modification and volume flexibilities. However, with respect to mix flexibility, which in kit preparation is concerned with allocation of components among storage locations, automation possibly has little effect on flexibility over manual approaches, as reshuffling components among storage locations is not hindered in any significant way. Delivery flexibility, which concerns changes in schedules, may be easier with an automated rather than a manual system to integrate schedule changes in the picking information used, and, therefore, delivery flexibility could possibly increase.

Discussion of control and flexibility

Control refers to how kit preparation communicates with other subsystems in production systems, and how resources and capability requirements are analysed and kept up-to-date. While the thesis' empirical results do not deal with the relationship between control and flexibility, this relationship has been considered peripherally in this research.

An example of the above involves the cases in Papers I and II. Here, there were discussions with case representatives that revolved around the planning and control system, as to how production plans were operationalised into picking information for use in kit preparation.

Previous research in kit preparation has scarcely dealt with control issues related to flexibility, but some authors have acknowledged this relationship. For example, the use of kitting can improve inventory control and, hence, the ease at which inventories can be changed, since component storages are concentrated to kit preparation workspaces rather than dispersed alongside assembly processes (Caputo et al., 2015; Caputo and Pelagagge, 2011). There should be links between control and flexibility, and future research could consider how models and frameworks for control issues in kit preparation can be designed for flexibility.

Concluding discussion of kit preparation flexibility

Flexibility with respect to kit preparation has received limited attention in previous research. For the most part, it has been considered with respect to choosing amongst alternatives of materials supply principles. Several researchers have highlighted the importance of flexibility in kit preparation (Hanson, 2012; Hanson et al., 2011; Caputo and Pelagagge, 2011), and some studies have brought up kit preparation design aspects that may flexibility, for example, the location (Hanson et al., 2011), the picking information system (Hanson et al., 2017) and the batching policy (Brynzér and Johansson, 1995). However, the available literature has been fragmented, and a comprehensive understanding has not been available on the topic.

Flexibility concerns the ease by which kit preparation can adapt to changes in production systems. This was modelled amongst the five flexibility types involving new product, modification, mix, volume and delivery, which are all needed to deal with changes in production systems. The flexibility types were considered in regard to range and response, which reflect the capability range and the effects of changing within this range.

The answer to Research Question 1 improves the understanding of how kit preparation design aspects govern kit preparation flexibility, by showing how options for design aspects influence the ability to manage changes in requirements from production systems in kit preparation. It is clear from the results that it is not only important how the work is organised, but also how activities are maintained in terms of managing changes in the physical system and the IT system.

The findings reported in Paper I contribute to the literature by building on general models of flexibility from manufacturing, for example, Correa and Slack (1994) and Slack (2005), and applying these to the specific context of kit preparation. Previous findings on flexibility related to kit preparation, for example as reported by Brynzér and Johansson (1995) and Hanson et al. (2011), do not result from research specifically aimed at this relationship, but rather from observations of studies with other aims. A finding that seems somewhat surprising is that the modern technology, e.g. pick-to-light systems, may delimit flexibility by introducing requirements on changes both in the information data bases and in the physical system. This echoes the statement by Park (2012, pp. 9-10) with respect to automation, who states, 'Proper automation has several advantages. [...] But it usually requires a substantial investment. Furthermore, it is inflexible, i.e., it is more difficult to reconfigure the system to adapt to new business environments'.

5.1.2. How design aspects govern kit quality (RQ2)

This section discusses the results presented in Subchapter 4.2, which answer Research Question 2: 'How is kit quality governed by kit preparation design aspects?'.

Discussion of work organisation and kit quality

The thesis' results related to work organisation concern the picker's job role. In Paper II, it was found that pickers who understand assembly procedures and product structures are better at picking correct and non-defective components. To improve these skills, training programs could involve assembly work practice or at least incorporate explanations of the intended use of components in the assembly process.

Pickers' knowledge of assembly procedures has been deemed important for kit quality by several authors (e.g. Glock et al., 2017; Grosse et al., 2015; Hanson and Brolin, 2013; Brynzér and Johansson, 1995). Paper II adds further empirical grounding and explanations of how these skills and knowledge relate to kit quality.

The mechanisms by which knowledge of assembly procedures and product structures can support kit quality in kit preparation seem to extend beyond the kit preparation's structural components. It is typical in literature to view the picking information system as capable of providing all the necessary information for correct and high-quality picking to be carried out. However, as seen from previous research and this thesis' findings, pickers' knowledge of assembly procedures and product structures can function as a fall-back option when picking information systems do not provide adequate information for correct picking.

Discussion of layout and kit quality

The results of this study show that kit error corrections can be made more swiftly and easily when kit preparation workspaces are located close to assembly processes. Furthermore, a direct line of sight between assemblers and pickers can facilitate communication when kit errors in kits are corrected.

Taking these effects into account when choosing the location of kit preparation workspaces can help achieve a smooth-running and efficient assembly processes even if kit errors are relatively frequent. These findings can involve existing or new applications for kit preparation. It may not be possible to always locate kit preparation workspaces close to the assembly area due to space limitations, but from a standpoint of making kit error corrections, the location should ideally be close and allow for direct communication and line-of-sight between pickers and assemblers.

The location of kit preparation workspaces within material flows is important for correcting kit errors once these are detected in assembly processes (Hanson, et al., 2011). The thesis adds details and explanations for how this mechanism is constituted, while also showing that the communication between teams of assemblers and pickers can facilitate quick and efficient kit error corrections.

Together with knowledge from previous research, the thesis' findings involving the relationship between layout and flexibility show that the choice of location is significant for correcting errors quickly and efficiently.

Discussion of policies and kit quality

The thesis' results relating to policies and kit quality concern both storage and batching policy.

The case studies reported in Paper II all applied the rule that similar-looking components should be stored separately to avoid components becoming confused with each other during work cycles. This was not only important for assuring that the correct components were picked from the shelves, but also for avoiding components from being restocked incorrectly if it had to be returned to storage. The rule was viewed as effective for supporting quality in the studied cases and should be simple to implement in most situations, only requiring an assessment of the component characteristics. However, the extent to which similar-looking components can be separated may be delimited in situations where it is necessary to store components at certain locations, such as when components must be picked and stacked in a certain order within kits to enable correct exposure during the assembly process.

Some authors have previously pointed to this relationship, both with respect to warehouse order picking (Grosse et al., 2015) and kit preparation (Brynzér and Johansson, 1996; Brynzér and Johansson, 1995). The thesis' findings echo these findings and contribute to these studies by adding more empirical knowledge. The thesis also adds details, for example, by highlighting that separation of similar-looking components also can support correct restocking.

The results reported in Paper II indicate that batching policies, whereby several kits are prepared at once during picking tours, introduce a risk of misplacing components among kits in the batch, something which is not an issue when kits are prepared individually. In addition, place-to confirmations prevented such errors. This is a feature of preparing kits in batches that needs to be accounted for when a batching policy is determined.

Previous research has discussed negative effects on kit quality based on batching several orders during the same picking tour (Hanson et al., 2015; Brynzér and Johansson, 1995). The thesis' findings expand on these notions, adding empirical explanations for how the relationship between batching policy and kit quality is constituted. Findings also showed that place-to confirmations are important, since they are often used in industry to support quality but have previously not received much attention in the literature.

Based on the available literature and the findings from this thesis, the policy design area presents considerations regarding both storage policy and batching policy that are important in supporting kit quality in kit preparation.

Discussion of packaging and kit quality

The thesis' results concerned with packaging and kit quality, as reported in Section 4.2.4, involve both the applied packaging for the kit container, as well as the packaging used in the storage.

The use of slots in kit containers, which are fitted for the component types, was found to benefit the kit quality by preventing that the wrong components with substantially different shapes are put into kits. Furthermore, the use of fitted slots or compartments was found beneficial from a quality standpoint, as they provide pickers with an overview of the stage in the picking tour, and empty slots indicating missing components are obvious and easy to detect.

As indicated in Chapter 2, fitted slots have been pointed out as beneficial for kit quality previously (Hanson and Brolin, 2013; Brynzér and Johansson, 1995). The thesis findings support these reports and further explain that fitted slots, as well as compartments, support tracking of the stage in the picking tour.

This thesis identified that discarding inner protective packaging, such as plastic wrapping, during picking tours can create distractions that introduce a risk for mistakes. A countermeasure, practiced by one of the cases in Paper II, involved positioning trash bins at kit preparation workspaces to reduce the disruptive influence of these activities. In situations where kit carriers are moved during picking tours, a trash bin may be readily put on the carrier itself.

Distractions during picking tours have been pointed out in literature as typical reasons why mistakes occur and, ultimately lead to kit errors (Grosse et al., 2015; Brynzér and Johansson, 1995). Discarding packaging may be easy to overlook when designing processes for kit preparation, but as studies show, this can compromise kit quality unless properly accounted for.

The kit container's design and the types of packaging applied in the storage are associated with several quality-related effects. Such aspects need to be accounted for not only with respect to kit preparation, but since the packaging design area has close ties with other subsystems of the materials supply system as well as with assembly (see Chapter 2), it is also beneficial to account for these when considering design options for packaging in materials supply and assembly systems.

Discussion of equipment and kit quality

While the relationship between equipment and quality has not been explicitly studied in this thesis, some reflections with respect to this relationship can be made in light of the present research.

The storage racks applied in the experiments, reported in Papers III and IV, had to be configured so that components were presented to the pickers in an effective way. To this end, the shelves were configured to have a tilt, which was increased according to the shelf height, so that the components within the plastic boxes were visible to the pickers. The results related to storage policy and kit quality, as described in Section 4.2.3, indicated that storing similar-looking components next to each other presents a risk of mistaking components. It is hence plausible that the way in which components are presented during picking affects kit quality.

The question of whether there is a relationship between how components are presented and the quality associated with picking of components has been asked before in the context of assembly workstation design (see Finnsgård, 2013), although it has yet to be answered. While the thesis cannot present conclusive evidence that this relationship exists in kit preparation, the findings indicate that a relationship might exist, and, hence, the question also deserves consideration in context of kit preparation.

Discussion of picking information and kit quality

The thesis' results show that picking information systems play a multi-purpose role in supporting kit quality.

One role is to support kit quality during picking tours by conveying information to pickers. Here, the findings from the case research reported in Paper II shows that indicating only the next activity to be performed in pick-by-light systems, as opposed to presenting all pick tasks associated with the picking tour at once, can be beneficial from a quality standpoint.

Several researchers have indicated that the way in which the picking information is designed is important for quality in kit preparation (Hanson et al., 2017; Brynzér and Johansson, 1995) and order picking (Grosse et al., 2015; Guo et al., 2015). The thesis adds to the previous knowledge by indicating that the sequence by which order lines are presented can be important to quality.

Another role that the findings from the case research in Paper II identified is that the picking information system allows pickers to confirm and receive feedback on completed activities by use of confirmation methods. With confirmations, pickers are given immediate feedback on the activities they perform and can thereby correct mistakes during picking tours, which supports kit quality.

Confirmation methods have received little attention in previous research, but have been acknowledged for their role with respect to quality in warehouse order picking (e.g. Andriolo et al., 2016; Battini et al., 2015). The experiments in Papers III and IV did not study the extent to which confirmation methods affect kit quality, owing to too few kit errors being observed to conduct a meaningful statistical analysis. However, both papers add descriptions to the literature for how various types of confirmation methods, for example voice-commands or RFID-wristbands, can be used for pick-from and place-to confirmations.

A third role that the thesis identified is to help the process deal with variability up and downstream in the materials flow, for example by reminding pickers to supplement components that were running short during the work cycle or by quickly accommodating unplanned changes from assembly processes to avoid errors.

While the importance of dealing with material shortages and unplanned changes have been emphasised as important concerns for kit preparation (e.g. Hanson et al., 2011; Brynzér and Johansson, 1995), the picking information system has not been highlighted as a means for dealing with these issues. The thesis thereby highlights a role of the picking information system that has not been acknowledged in previous research.

As stated in Chapter 2, the picking information system often has a central role in kit quality associated with kit preparation (Hanson et al., 2017; Grosse et al., 2015; Brynzér and Johansson, 1995), but literature is scarce regarding what this role consists of. The thesis contributes knowledge in this respect, providing detailed descriptions related to a variety of means for information conveyance, confirmations methods and supportive functions for dealing with variabilities in materials supply and production systems.

Discussion of automation and kit quality

The results from Paper V showed the potential with respect to kit quality for automation in the sorting task with batch preparation of kits. While cobots cannot make human errors, their ability to support quality depends on the sorting information, in terms of which components should be put in each kit. Furthermore, the components that the operator feeds it must be correct and up-to-date with the requirements of the receiving process.

As has been pointed out, the many dimensions of disorder normally associated with kit preparation is an issue with respect to robotics (Öjmertz, 1998). Such characteristics of kit preparation and picking operations in general pose significant challenges for robotic picking. However, as some researchers have already shown, the challenges are well on their way to being dealt with (Boudella, et al, 2018; Boudella, et al, 2016).

As acknowledged in Paper V, there is a potential for automation in quality inspection, for example vision-based inspection, that may support detection of errors that have occurred in earlier steps in materials flows. Such a system was considered in Paper V, and while this can support detection of quality-related issues, it also depends upon the components to be presented in a way that the system can carry out the necessary analyses. Such systems would be useful when robots carry out picking, but could also be effective support in fully manual processes.

Making use of vision-based and automatic quality inspection is common in other fields, for example for inspection of food products (Brosnan and Sun, 2004), bore holes (Biegelbauer and Vincze, 2006) and welding defects (Shafeeka et al., 2004). A significant difference with kit preparation is that the object recognition is complex as components typically are randomly oriented and often are stuck together with other components, making them difficult to identify. This has been referred to as the ‘bin picking’ problem within the literature (Martinez et al., 2015), and there are ongoing research efforts for developing solutions to handle this problem (Pérez et al., 2016).

Automation of picking and sorting supports kit quality by removing the risk of human errors. While this has long been discussed in the context of kit preparation (see e.g. Johansson, 1991; Sellers and Nof, 1989), the available solutions have mostly required a complete overhaul of the kit preparation design compared to manual setups, and the automated designs have been rigid and inflexible. The available knowledge from previous research, (e.g. Boudella et al., 2018), and the findings of the thesis, show that new applications have become more conceivable as more lightweight and flexible robotics are developed. This can help bridge the gap between theoretical potential and practical viability.

Discussion of control and kit quality

The control design area concerns rules and routines for communication between kit preparation and other subsystems in production systems.

Here, the case research reported in Paper II showed that effective error communication around kit preparation errors can help relieve assemblers of the responsibility of kit errors, as the problems are routinely reported and the needed components can be reliably resupplied. When error communication is inefficient, there is a risk that kit errors are handled ad hoc, and that they leave no trace within the system. A poor error communication is thereby a weak basis for identifying root causes and preventing kit errors from reoccurring, and routines for correcting kit errors are a key part of promoting prevention.

Routines for identifying and correcting kit preparation errors have been discussed in various studies of kit preparation (see e.g. Caputo et al., 2017a; Caputo et al., 2017b; Hanson et al., 2011). While operation planning models have been developed that involve detailed accounts of how kit errors can arise as well as the associated costs (see Caputo et al., 2017a; Caputo et al., 2017b), there is no knowledge available for how to monitor quality in industrial kit preparation. This thesis provides an account for how such routines are used in industry and highlights the typical consequences of not using them. The responsibility for detecting and dealing with kit errors is put on assemblers, which is a poor basis for dealing with kit errors proactively.

Correction of kit errors is facilitated when kit preparation workspaces are located close to assembly processes, whereas effective quality monitoring that consistently maintains records over kit errors may be more difficult to sustain. Managers must consider these effects when choosing the location of workspaces, alongside considerations of cost restrictions and capacity requirements.

The relationship between control and kit quality in kit preparation is far from fully understood in the literature. Based on the sparse knowledge that is available and the results presented in the thesis, the relationship seems to consist of the ability to monitor and correct kit errors that occur in industry.

Concluding discussion of kit quality

While kit quality associated with kit preparation has recently received attention by researchers (see e.g. Caputo et al., 2017a; Caputo et al., 2017b), the attention has been limited to theoretical approaches, and empirical investigations that address this topic have been scarce. This has been problematic since quality is a central area of performance, and unless it is operating satisfactorily, kitting becomes challenging.

The research approach adopted by this thesis contributes to literature with empirically grounded findings from case research and experiments. Furthermore, it also contributes theoretically with respect to automation. Previous understandings show quality to be about kit preparation errors and the ability to rectify these in the assembly process. The thesis builds on this understanding, presenting a variety of empirically grounded ways that kit errors can be prevented and more easily corrected.

The answer to Research Question 2 improves the understanding of how kit preparation design aspects influence kit quality by showing how design aspects can help prevent kit preparation errors and how to improve the effectiveness of correcting these errors. The results reveal, for example, that the picking information system plays an important role for quality, in terms of handling material shortages, providing feedback via confirmations and providing unambiguous instructions, and that these functions differ according to the type of picking information system used. The results of the thesis support previous research in several regards, and can also act as propositions for further research.

It was noted in Paper II that reliable statistics of kit errors were rare. The managers explained that this was because there was no need to maintain records over kit errors that could be corrected without much effort. They further indicated that the records they had were unreliable due to that kit errors were seldom reported. This is a possible reason for the scarcity of empirical studies in previous research.

The results from Papers III and IV raise the question as to how kit quality is affected by the batching policy and indicate that a single order policy with a simple picking information system may be worth considering as an alternative to order batching. Previous research seems to assume that quality is not significantly affected by the batching policy, despite practical experience suggesting otherwise.

5.1.3. How design aspects govern man-hour efficiency (RQ3)

This section discusses the results presented in Subchapter 4.3, which answer Research Question 3: ‘How is kit preparation man-hour efficiency governed by kit preparation design aspects?’.

Discussion of work organisation and man-hour efficiency

This thesis has not explicitly studied the effects of work organisation on man-hour efficiency in kit preparation, but some comments are appropriate here with respect to the experiments in Papers III and IV.

The experiments reported in Papers III and IV involved participants who were beginners in order picking and kit preparation; they participated in the experiments after only one shift of training. This was a deliberate choice, as a fair comparison was sought for picking information systems and confirmation methods, and it would be an impossible task to find participants with the same amount of experience from systems and methods. This was also justified by the fact that turnover rates in industrial order picking are typically high and pickers have little experience (Grosse and Glock, 2013).

De Vries et al. (2016) found that professional order pickers tend to outperform non-professional order pickers from a productivity standpoint, even after controlling for experience. They

recommend caution when using students in experiments. They further stress that this difference between professional and non-professional order pickers concerns absolute numbers of productivity, but that that patterns of relative productivity between different types of picking information systems generally are the same between these two categories.

The findings in Papers III and IV in terms of absolute numbers may be of less interest, in light of the above, while the comparisons made between different options for picking information systems and confirmation methods remain valid.

Discussion of layout and man-hour efficiency

The experiment reported in Paper III dealt with layout considerations related to man-hour efficiency in terms of picking density.

The results show a direct link between layout and man-hour efficiency, as longer walking distances naturally reduces the man-hour efficiency. Paper III further indicated that pick-by-voice systems and voice-confirmations (as also observed in Paper IV) perform poorly in kit preparation workspaces with higher picking density when compared with other types of systems.

Warehouse layout has received a lot of attention in the literature, as it is one of the determinants for travel distances (De Koster et al., 2007). Consideration of the layout design area and man-hour efficiency in kit preparation has been a lot less, likely because kit preparation is most often organised in compact workspaces where travelling distances are generally short (Hanson et al., 2017). However, as some researchers have pointed out (see Battini et al., 2015), some picking information systems, for example pick-by-voice, can benefit productivity-wise, from longer travelling distances, as some activities can be performed while travelling. An indication of this is seen in Paper III, where two different levels of picking density were considered. The results showed that man-hour efficiency was almost identical for pick-by-voice between the two picking density levels, while the other systems demonstrated less man-hour efficiency with lower picking density.

There appears to be a relationship between layout and man-hour efficiency of kit preparation, especially with respect to picking density. While picking density is not directly determined by the chosen layout, it is clear that the layout contributes to the picking density, and that it plays a part in determining the travel distances in kit preparation.

Discussion of policies and man-hour efficiency

The experiment reported in Paper III showed that for some applications of picking information systems, order batching in regard to man-hours can be less efficient than a single-kit approach. This is partly because confirmations must be performed when components are placed in kits with batch preparation, but this is not required with single-kit preparation. The experiment reported in Paper IV also showed that all things being equal, changing the type of confirmation used to support order batching of kits can substantially impact man-hour efficiency. The findings indicate that such considerations need to be accounted for when the order batching policy is determined.

The thesis results show previous understandings of man-hour efficiency and batching policy in a new light, by accounting for how the use of confirmation methods affect man-hour efficiency in batching policies. In previous studies that have compared single-kit and batch preparation of kits (Hanson et al., 2017; Hanson et al., 2015), confirmations have not been considered, yet these are typically applied in industry. Batching several orders during individual picking tours is generally seen to improve man-hour efficiency of kit preparation (Brynzér and Johansson, 1995), and experiments have shown that the effects on man-hour efficiency from batching or orders can be substantial (Hanson et al., 2015).

It was apparent from the studies in Papers III and IV that batch preparation of kit leads to more complex handling of components during kit preparation than a single-kit approach. This complexity

can become even greater if confirmation methods that require a lot of extra motion and activity are performed. As Paper IV showed, using confirmation methods that do not noticeably interrupt the picker, such as button-presses or RFID-scans with wristbands, may support order batching without adding to the complexity.

Discussion of packaging and man-hour efficiency

The experiment in Paper III addresses packaging with respect to man-hour efficiency. Different packaging sizes of storage packaging were used for different levels of picking density. The reasoning behind this approach was that larger sized packaging contributes to longer walking distances, thereby lowering picking density as well as man-hour efficiency. In practice, the size of storage packaging may not always be a choice owing to component characteristics or other restrictions in the material supply or production system (Hales and Andersen, 2001).

The experiments in Papers III and IV used kits with no internal structure, which meant that the pickers were completely unrestricted when placing components in kits. Although only one type of kit container design was considered in the experiments, it seems likely that those with internal structures are associated with lower man-hour efficiency, as more precision is required when components are placed in the kits. This has also been suggested in previous research (Brynzér and Johansson, 1995).

The thesis highlights two different aspects, storage packaging and kit container design, that can affect man-hour efficiency in packaging. These aspects have been considered in previous research, both in terms of the type of storage packaging used (Calzavara et al., 2017) and how the kit container is designed (Brynzér and Johansson, 1995).

Discussion of equipment and man-hour efficiency

While this thesis has not produced results that address the relationship between equipment and man-hour efficiency, the relationship has been peripheral to several of the studies that have been carried out.

Relative to the experiments reported in Papers III and IV, the kit preparation workspaces utilised in those studies involved both storage racks and kit carriers of particular designs. With respect to storage racks, one part of operationalising picking density in Paper III was to make use of different numbers of shelf levels in different sections of the workspace. By doing so, picking areas can be made more compact, reducing walking distances and consequently promoting efficiency. However, as has been discussed with respect to both flexibility and quality, it is, therefore, helpful to use shelves that can be tilted, so that components can be presented appropriately.

The kits need to be easily accessible, especially when batch preparation is conducted. The kit carrier design must be considered when the process is designed, so that pickers, either operators or robots, are not impeded when putting components into kits. The equipment governs the way components are presented to pickers, the ease by which components in the storage can be accessed and the ease by which components can be put into kits.

Discussion of picking information and man-hour efficiency

The thesis provides input into the relationship between picking information and man-hour efficiency. In one part, it addresses how types of picking information systems are affected by picking density and batch size in their impact on man-hour efficiency, as indicated in Paper III. In another part, the input consists of the role and importance of confirmation methods for man-hour efficient kit preparation, as researched in Paper IV.

The thesis' results showed that man-hour efficiency associated with the type of picking information system used depends on the applied batching policy. Here, the more complex information and the need to carry out place-to confirmations to support correct sorting with batch preparation of kits

can make it less man-hour efficient than a single-kit per picking tour approach. This was observed for the system types pick-by-light and pick-by-HUD, which applied confirmations by button-presses and single-wristband RFID-scans, respectively.

In previous research, batch preparation of kits is generally viewed as a more man-hour efficient option than single-kit preparation (Hanson et al., 2015; Brynzér and Johansson, 1995). However, these studies have not accounted for the requirement to perform confirmations during kit preparation, which is the typical approach adopted in industry. This thesis noted this absence in the literature and, although a bit surprising, showed that the effect of having to perform confirmations can be so substantial that a single-kit approach may be more efficient. If the requirement on confirmations is loosened, as with the pick-by-paper system in Paper III, the normal benefits of a batch preparation approach are, indeed, achieved. It has been pointed out by some researchers that batch preparation can be associated with more administrative work between work cycles than single-kit preparation (Brynzér and Johansson, 1995), but this thesis shows that there also is administrative work during the picking tour, which can severely affect the outcome of man-hour efficiency.

The results demonstrate that some picking information systems, for example, pick-by-light or pick-by-HUD, may not necessarily be more man-hour efficient when applied to batch preparation rather than single kit preparation, especially when the picking density is high. The type of packaging used to store components at kit preparation workspaces greatly affects the picking density that can be achieved. In this regard, using smaller packaging, as associated with smaller unit loads (Hanson and Finnsgård, 2014), can increase picking density and generally make kit preparation more man-hour efficient as the walking distances become shorter (Hanson and Medbo, 2019). At the same time, the relative benefits of man-hour efficiency from using a batch preparation approach are lessened when the picking density is higher, such as when smaller sized storage packaging is applied. Furthermore, the suitable choice of picking information system type is affected. The thesis results, hence, show an interplay between the type of picking information system used, the batching policy and the type of storage packaging.

Several authors have dealt with design and performance of kitting and order picking systems and pointed out that the picking density is a central factor for man-hour efficiency (e.g. Hanson and Medbo, 2019; Battini et al. 2015). Related to picking information systems, Battini et al. (2015) showed that some picking information systems, such as pick-by-voice, can benefit from lower picking density as some activities, such as administering voice dialogues, can be performed while travelling. The thesis findings support this notion in the context of kit preparation.

According to previous research, the picking information design area has a central role in man-hour efficiency in kit preparation (Hanson et al., 2017; Brynzér and Johansson, 1995). The relationship consists of conveying picking information about quantities and locations of components in intuitive and effective ways, to promote man-hour efficiency (Brynzér and Johansson, 1995). Studies of warehouse order picking have addressed the importance of confirmations, which are used to ensure that components are picked and sorted correctly (Battini et al., 2015). The thesis contributes to this previous knowledge by showing that confirmations plays a role for man-hour efficiency of kit preparation, and that this needs to be accounted for when choosing a picking information system. Furthermore, the presented research provides several comparative estimates of the extent to which various systems affect man-hour efficiency, including accounts of different situations in terms of batching policy and picking density.

Discussion of automation and man-hour efficiency

The automation-supported application of kit preparation in Paper V shows how automation can impact man-hour efficiency. The numerical example of the model presented in Paper V shows that the automation yields a comparable average cycle time than when a picker carries out all activities

independently. A collaborative robot handles components individually, as opposed to the operator who handles several components at once. The results indicate that the application can benefit from being used in settings where there is a high component variety. This is pertinent for managers who want to implement collaborative robots in their kit preparation.

With respect to the results in Paper V, Coelho et al. (2018) found similar productivity effects when simulating cobot-supported activities at supermarkets in production systems. Here, human workers were on average more productive, but cobots were associated with less variability and a more predictable planning environment. Boudella et al. (2018) studied robots applied to kit preparation and developed a model for assigning components between two work cells, one with an operator and one with a robot. The application studied in Paper V reverses the robot's role, by considering how it can perform the sort task, while also allowing the robot and the worker to collaborate to complete the kits.

It is often addressed in literature that kitting can be advantageous over other material supply principles when the number of component variants is high (Limère et al., 2012; Caputo and Pelagagge, 2011). The application considered in Paper V is more efficient with high component variability, and should, thereby, be suited to most situations where kitting is also deemed an effective principle.

While the concept of automation as a means for improving kit preparation man-hour efficiency has been discussed for some time (see e.g. Sellers and Nof, 1989), there have been few publications, Boudella et al. (2018) mark one exception, that present applications that do not require kit preparation to be completely reimaged. Previous research that considers collaborative automation types in kit preparation applications, whereby pickers and cobots collaborate during the work cycle, is even scarcer. The thesis has studied one such application, where the automation scope involved sorting as associated with batch preparation of kits, showing the effects on man-hour efficiency.

Discussion of control and man-hour efficiency

Control includes how kit preparation resources and capacity requirements are analysed and managed. The thesis has not directly addressed the relationship between control and man-hour efficiency, but the findings present relevant input to future research with that aim.

The literature that deals with control considers the capacity requirements, inventory levels and overall costs associated with kit preparation as part of a framework comparing kitting with other materials supply principles (see e.g. Caputo et al., 2015; Limère et al., 2012; Bozer and McGinnis, 1992). Here, the time expended on kit preparation is often modelled statically, and only one kind of design is considered (Hanson and Medbo, 2019).

The findings related to man-hour efficiency presented by the thesis, with respect to types of picking information systems, confirmation methods and collaborative robots applied in kit preparation, constitute options that can be considered in these kinds of frameworks. Furthermore, as pointed out in previous research by Hanson and Medbo (2019) and demonstrated in this thesis, man-hour efficiency in kit preparation can be highly variable and is dependent on design aspects. The thesis findings can help account for this nature of man-hour efficiency frameworks for control of kit preparation, and the thesis in this way makes a contribution to the control design area by generating applicable data.

Concluding discussion of kit preparation man-hour efficiency

This thesis has addressed man-hour efficiency by means of three focused studies that deal with the impact of types of picking information systems, confirmation methods and collaborative robots applied to kit preparation. The generated knowledge contributes to a view of man-hour efficiency as variable that depends on the choice of design aspects and their associated options. This is to some

extent in contrast to previous research in this area, which, as pointed out by Hanson and Medbo (2019), typically views kit preparation time expenditure as static and irrespective of the design.

The answer to Research Question 3 improves the understanding of how design aspects of kit preparation govern man-hour efficiency. This is achieved by presenting two experiments dealing with picking information systems, batching policy, picking density and man-hour efficiency and by presenting a mathematical model that considers man-hour efficiency of batch preparation of kits supported by a collaborative robot. The results make clear that the picking information system influences both the pickers' search time for parts and the time spent on performing confirmations during kit preparation, and that collaborative robots can support man-hour efficiency.

In regard to picking information systems, the findings with respect to the relatively new pick-by-HUD system in Paper III and the use of RFID-wristbands for confirmations in Paper IV, are considered a contribution to both practice and theory.

Paper III also reveals that batch preparation of kits is associated with a different set of requirements on the picking information system than a single-kit policy. Here, quality assurance of the placement activity, in terms of a place-to confirmation, can affect the man-hour efficiency associated with a particular picking information system design. In this regard, the answer expands the previous knowledge on man-hour efficiency of order batching in kit preparation (Hanson et al., 2017; Hanson et al., 2015), which has focused on how picking information is conveyed with order batching, while paying less attention to the impact from the type of confirmation method used.

The automation-supported application for kit preparation modelled in Paper V makes up another contribution to both theory and practice. The concept of cobots is still relatively new and very few applications have yet reached industrial implementation. The detailed models of kit preparation work tasks performed by collaborative robots and operators which the model provides, should be of interest to academics and provide a starting point for implementation in industry.

5.1.4. Overview of identified relationships between kit preparation design aspects and performance areas

The thesis has shown that there are a multitude of relationships between kit preparation design aspects and performance areas, and that there are interplays between design aspects and aspects in the context of kit preparation that influence these relationships. In this section, a summarising overview of the thesis results is presented in **Table 5.1**, highlighting the relationships identified in the thesis' results and those identified in the literature.

Table 5.1 is organised by the design areas in the far left column. In the second, third and fourth columns, the relationships between the design areas and aspects with flexibility, kit quality and man-hour efficiency are described. By means of the table, a detailed and comprehensive overview of how kit preparation design aspects govern kit preparation performance with respect to flexibility, kit quality and man-hour efficiency is provided, summarising how the thesis' purpose is addressed.

The findings summarised in **Table 5.1** are highlighted differently depending on whether the relationship stems from the literature (white), from this thesis (light grey) or from both the thesis and the literature (dark grey). The next subchapter explains the relationships between kit preparation design and performance presented in the table may be useful for theory and practice.

Table 5.1. Identified relationships from the literature (white highlighting), from the research results of the thesis (light grey highlighting) or from both (dark grey highlighting) between kit preparation design aspects and performance in terms of flexibility, kit quality and man-hour efficiency. The first column shows the design area under which the relationships have been categorized.

Design area	Flexibility impact	Kit quality impact	Man-hour efficiency impact
Work organisation	<p>Job role: Volume flexibility benefits from job roles that involve kit preparation and assembly within the same work cycle, as more opportunities for work balancing are available.</p> <p>Organisation around change: New product, modification, mix and volume flexibility benefits from organisational integration, as it affects planning and reorganisation.</p>	<p>Job role: Picking of correct and non-defective components is promoted by pickers who also perform assembly, due to better knowledge of quality requirements.</p>	<p>Job role: Man-hour efficiency is promoted when performed by pickers with knowledge and experience of how assembly should be performed.</p>
Layout	<p>Location: New product, modification, mix and volume flexibility benefit from use of locations further from assembly, as these generally come with additional floor space.</p> <p>Location: Delivery flexibility benefits from locations closer to assembly processes, due to shorter transportation distances and more control over when deliveries take place.</p>	<p>Location: Kit error corrections can be carried out more quickly and with lower costs when kit preparation workspaces are located closer to assembly processes.</p>	<p>Picking density: Man-hour efficiency is reduced by layouts with lower picking density, as picking tours have more travelling time relative to time being spent on picking activities.</p> <p>Picking density: Man-hour efficiency associated with picking information systems can be affected by the effect of picking density on travelling time in-between picks.</p>
Policies	<p>Batching policy: Delivery flexibility is reduced by larger batch sizes, as kits are tied up in kit preparation for a longer time and are, thereby, exposed to changes in production schedules.</p> <p>Storage policy: Mix flexibility is reduced by rigorous classification in storage, as reorganisation of the storage becomes necessary when the production mix changes.</p>	<p>Batching policy: Kit quality is negatively affected by batch preparation, as it introduces a risk for misplacement among kit containers (as opposed to single-kit preparation).</p> <p>Storage policy: Kit quality is promoted by separating similar-looking components in the storage, as this prevents components from being confused with each other.</p>	<p>Batching policy: Man-hour efficiency is promoted by larger batch sizes in most situations, but the relative benefits diminish when picking densities increase and when confirmation methods are used.</p> <p>Storage policy: Man-hour efficiency is promoted by storage classification according to consumption rates when kit carriers are stationary during work cycles.</p>
Packaging	<p>Kit container: New product and modification flexibility is reduced by use of fitted slots in kit containers, as the slots must be redesigned when products are introduced or modified.</p> <p>Storage packaging: New product, modification, mix and volume flexibility is promoted by use of standardised plastic boxes, which are available in a variety of sizes, as opposed to EUR-pallets; these allow for easier changes of unit load and introduction/removal of storage locations.</p>	<p>Kit container: Picking of correct types and numbers of components is promoted by fitted slots in kit containers.</p> <p>Kit container: Missing component kit errors can be prevented by use of fitted slots or standardised compartments in kit containers, as these help keep track of the next activity and make missed components obvious.</p> <p>Storage packaging: Kit quality can be negatively affected by discarding protective inner packaging and handling of empty containers during work cycles. These activities create distractions that can lead to mistakes.</p>	<p>Kit container: Man-hour efficiency is reduced by use of compartments and fitted slots in kit containers, as these increase requirements for precision when components are placed into kits.</p> <p>Storage packaging: Man-hour efficiency is reduced by use of larger sized packaging in the storage, such as EUR-pallets, as it is difficult to use in multi-level shelving and thereby contributes to lower picking density.</p>
Equipment	<p>Storage racks: Mix flexibility is promoted by use of wheel-equipped storage racks and bolt-free shelf attachments, as these facilitate reorganisations of the storage.</p> <p>Lifting supports: New product, modification, mix and volume flexibility is reduced when lifting supports are present at kit preparation workspaces, as these hinder expansion and reorganisation.</p>	<p>Storage racks: Picking of correct and non-defective components can be promoted by adjusting storage racks and shelves, such as tilting packages, to provide better access and visibility.</p> <p>Kit carrier: Kit quality is affected by the design of the kit carrier as improved visibility of, and access to kits can help prevent placement errors.</p>	<p>Storage racks: Man-hour efficiency is affected by the number of shelf levels used, as this affects picking density and, hence, travelling time during picking tours.</p> <p>Storage racks: Man-hour efficiency is affected by use of reconfigurable storage racks that e.g. allow packages to be tilted, as this improves visibility of, and access to, components.</p>

			Kit carrier: Man-hour efficiency is affected by how the kit carrier is designed, as it affects access to kits, and, thereby, the ease by which components can be placed in kit containers.
<i>Picking information</i>	System type: New product, modification, mix and volume flexibility is affected by physical components associated with picking information system types, as physical components (e.g. light indicators in pick-by-light systems) hinder expansion and reorganisation.	Information conveyance: Kit quality is affected by the sequence in which information is presented to pickers, where, in particular, only presenting the current and next picking activity at once appear to reduce ambiguities during work cycles and prevent kit errors.	System type: Man-hour efficiency is affected by the type of picking information system applied in kit preparation.
		Confirmation methods: Picking correct components and placing them correctly in kits can be promoted by using confirmation methods, due to the immediate feedback provided when a confirmation is performed.	Information conveyance: Man-hour efficiency is affected by the type of information conveyance used, as it affects the ease by which pickers receive and interpret information.
		Supportive functions: Kit quality is promoted by picking information systems with functions that help with material shortages or quickly accommodate new order information.	Confirmation methods: Man-hour efficiency benefits from use of confirmation methods that allow for pick-from confirmations to be carried out with minimal extra motion and place-to confirmations by methods that allow two simultaneous placements.
<i>Automation</i>	Automation scope: Flexibility is affected by kit preparation activities that are automated, and each situation needs to be evaluated.	Automation scope: Kit quality is promoted by automation of picking and sorting tasks, as the risk of human errors is removed from automated tasks.	Automation scope: Man-hour efficiency is affected by kit preparation activities that are automated, and each situation needs to be evaluated.
	Automation type: Flexibility is affected by the automation type used for kit preparation tasks, and different automation types affect different flexibility types.	Automation type: Kit quality is affected differently by different types of automation.	Automation type: Man-hour efficiency associated with an automation type is affected by each situation's characteristics, for example similarity between kits and the batching policy used.
<i>Control</i>	Control procedures: Flexibility can be affected by the effort involved with maintaining control procedures, for example with respect to storage assignment, batching or error communication.	Error communication: Kit quality is promoted by use of routines for identifying and correcting kit errors, as this help prevent kit errors. Work standardisation: Kit quality is promoted when pickers follow instructions in well-designed setups, while kit quality can be supported when pickers find their own ways, deviating from instructions, in poorly designed setups.	Implementation fit: Man-hour efficiency associated with automated tasks depends on how procedures for order batching, storage policy and quality control are implemented with respect to the situation's characteristics.

5.2. Supporting design and performance of kit preparation

As stated in Chapter 1, the thesis' purpose is *to contribute to the knowledge of how kit preparation design aspects govern kit preparation performance*. This purpose was chosen because of the role kit preparation plays in kitting-based materials supply with mixed-model assembly. Three research questions were formulated to target three performance areas of kit preparation, and five papers, each based on individual research studies, were written to develop answers to the research questions. The performance areas targeted by the research questions concern flexibility, kit quality and man-hour efficiency as associated with kit preparation, which are important for a kitting approach to be realised.

This subchapter discusses how the thesis addresses its stated purpose. The subchapter is divided into two sections. Section 5.2.1 presents a condensed overview of how the theoretical and practical contributions brought forth in Subchapter 5.1 contribute to the thesis' stated purpose. Section 5.2.2 then presents a discussion of the use and limitations of the thesis' findings.

5.2.1. The thesis' contribution to its purpose

The thesis' contribution to its purpose consists of three parts. In one part, it underpins and builds upon previous research that has dealt with design and performance of kit preparation. In a second part, it brings new knowledge about relationships between kit preparation design aspects and performance. The third part provides broad yet detailed knowledge with respect to existing understandings of the relationships between kit preparation design aspects and performance, owing to the wide range of methods applied in the thesis' research approach (see **Table 3.1** for an overview of the methods applied in the appended papers). In the following, these three parts are discussed at length.

With respect to the first part of the contribution, the topic deals with knowledge that is not new. Several researchers have previously dealt with design and performance of picking systems in general and with kit preparation specifically. The thesis has accounted for this, and an extensive review of the literature was conducted. Research questions, study aims and theoretical frameworks were then developed based on established knowledge. This approach has made it possible to find support for previous findings in entirely new cases and experiments, while refining and extending the previous understanding of relationships between kit preparation design aspects and performance. One example is the findings with respect to the location of kit preparation and flexibility. Here, the thesis identified and explained the multi-faceted impact of location on flexibility.

Previous research has indicated that locations further from assembly processes generally have access to more floor space, which benefits flexibility related to new product introductions and modifications, as well as volume and mix flexibility. However, the thesis' findings additionally showed that delivery flexibility is negatively affected by the same location setting, and, thereby, that there is a trade-off amongst flexibility types with respect to location. The thesis has underpinned and built upon previous knowledge, thereby contributing to the knowledge of how kit preparation design aspects govern performance.

With respect to the second part of the contribution, the thesis contributes new knowledge about kit preparation design aspects and how they impact performance. An example is the man-hour efficiency impact of confirmation methods, as identified in Papers III and IV. Here, the experiment in Paper III found that the benefits of using a batch preparation policy are affected by the design of the picking information system, particularly by the design of the confirmation method. As the thesis has shown, order batching for some designs may not be superior over a single kit policy from a man-hour efficiency standpoint, due to the additional need to perform place-to confirmations required with batch preparation. Paper IV then found that when various types of confirmation methods were applied using the same means of information conveyance, the man-hour efficiency varied substantially depending on the method used. This has received limited attention by previous research. In this way, the thesis contributes new knowledge to the literature.

With respect to the third part of the theoretical contribution, the variety of methods applied in the research has allowed for development of broad yet detailed knowledge with respect to existing understandings of the relationships between kit preparation design aspects and performance. Across the studies reported in the five appended papers in the thesis, the variety of methods has allowed the research to build on established knowledge in the literature, which at the same time have created pressing issues in practice. Examples include how design aspects impact flexibility and quality as in Papers I and II and how new phenomena, such as collaborative robots, can support man-hour efficient kit preparation in Paper V. It has also allowed for the research to deal with narrow questions and arrive at precise answers, for example by means of experiments focused on picking information systems as in Papers III and IV. The variety of methods have enabled the research area to be addressed both broadly and in-depth and to focus on topics which have scarcely been dealt

with in the past. This is a contribution to the knowledge of how kit preparation design aspects govern performance.

5.2.2. Application and limitations of the knowledge generated by the thesis

This section discusses how the knowledge generated by the thesis can be applied by researchers and practitioners. Furthermore, the section highlights limitations that must be taken into account when such knowledge is applied.

As highlighted in the theoretical framework in Chapter 2, researchers frequently emphasise that design aspects of picking systems are usually closely linked with each other, and that there are interplays between design aspects, the context and performance. This has been characterised as a complex problem (Yoon and Sharp, 1996; Bozer and McGinnis, 1992; Goetschalckx and Ashayeri, 1989).

This thesis has considered kit preparation design to be composed of design aspects, which have individual and synergistic impacts on performance, while also moderated and restricted by context. This approach has enabled the problem to be addressed in a structured manner and has allowed for relationships between design aspects and performance to be isolated and researched. The approach was inspired by previous studies that has been available on the topic (e.g. Hanson, 2012; Brynzér and Johansson, 1995) and guided by the results generated throughout the research process. The approach of using design aspects to address the purpose has brought both opportunities and limitations with respect to how the generated knowledge can be applied in theory and in practice.

Opportunities of application

The knowledge generated by the thesis consists of concise yet holistic descriptions of relationships between design aspects and performance of kit preparation. This knowledge can readily be adopted by industry with some consideration to the situation's characteristics. The knowledge can serve as input to analyses when new processes for kit preparation are designed or for improving already existing applications. For example, the knowledge can provide support to industrial engineers and facility planners for deciding where in the materials flow kit preparation workspaces should be located and what effects different options for location may bring. Other findings can be suitable for both managers and pickers to consider for existing processes, for example in terms of whether a new type of picking information system would be more suitable to implement than the currently used designs. Industrial engineers who work with kit preparation may also integrate the findings into guidelines and frameworks that may already be available in-house at companies with experience in the area, or it can provide a basis to create in-house guidelines for those with less experience.

From a theoretical standpoint, the thesis can provide input to already existing frameworks for design of picking systems. As described in Chapter 2, previous research has developed frameworks that can guide the design process of picking systems, for example the frameworks put forth by Goetschalckx and Ashayeri (1989) and Yoon and Sharp (1995). The knowledge developed in this thesis can serve as input to such frameworks, supporting a more detailed and comprehensive analysis of picking systems, by providing descriptions about design options and their impact on performance. Furthermore, a substantial body of literature deals with choice of materials supply principles, for example Limère et al. (2012), Caputo and Pelagagge (2011), and Bozer and McGinnis (1992). As pointed out when these frameworks were reviewed in Chapter 2, kit preparation is typically viewed as having fixed settings and performance effects and rarely deals with performance beyond costs and capacity requirements. As this thesis shows, the performance associated with kit preparation can be highly variable and can be influenced by a range of aspects of design and context. The thesis thus provides opportunity to integrate a more comprehensive view of kit preparation design and performance in frameworks that support selection of materials supply principles.

Limitations of application

In this thesis' research, propositions were derived from theory and then studied, which led to the results. The empirical content stems from case research and experiments. With case research, generalisations to theory are carried out analytically, by means of propositions and analytic inferences (Yin, 2009). Typically, this is also how generalisation from experiments is carried out. With mathematical modelling, such as used in Paper V, the model is developed based on theoretical propositions, and numerical examples demonstrate the empirical application. In this light, the results link back to theory by means of analytic inference from the empirical content. Thus, the findings and the generated knowledge should hence be considered valid and relevant to the extent with which the studied propositions are applicable.

The focus of this thesis is on kit preparation for materials supply by use of kitting in assembly industry and, in particular, in the automotive industry. The parts that are based on case research have derived findings, which are all from the automotive industry. The parts based on experiments and mathematical modelling have also focused on kit preparation in the automotive industry. In this way, most of the findings are conditional on the existence of a product structure and an assembly schedule, which has to be considered with respect to generalisability. However, many other types of assembly environments may present similar preconditions, for which the results should be applicable. Hopefully, from a practitioner viewpoint, the descriptions of the cases, the experiment settings and the numerical examples of the mathematical model, are sufficiently detailed to judge validity of the results in other companies and industries.

5.3. Discussion beyond the thesis scope

Building upon the discussion of contributions presented in the previous subchapters, this subchapter aims to take the discussion a step further by discussing the interplay between design aspects and performance areas, in addition to avenues of future research. The subchapter is divided into two sections. Section 5.3.1 presents a discussion of interplays, in terms of synergies and trade-offs, amongst kit preparation design aspects and performance areas. Section 5.3.2 presents a discussion of avenues for future research.

5.3.1. Interplays amongst design aspects and performance areas

The research presented in the thesis has been structured by three research questions that each address relationships between kit preparation design aspects and one of the three performance areas targeted in the research purpose statement. Owing to the way in which the research has been structured, the generated knowledge makes up a basis for revealing of interplays, in terms of synergies and trade-offs, amongst design aspects and performance areas. In the following, these synergies and trade-offs emerge when individual results with respect to different design aspects and performance areas are viewed as a whole.

There seems to be interplay with respect to location, flexibility, kit quality and man-hour efficiency. Locating a kit preparation workspace close to assembly processes, may reduce costs, as the consequences of picking errors are reduced due to the shorter distance for supplementing needed components. Meanwhile, the same location creates both trade-offs and synergies from a flexibility perspective, as it would reduce the new product, mix and volume flexibility due to less available space for extending the storage racks to make room for new storage locations. However, it would improve delivery flexibility owing to shorter transportation distances. Furthermore, from a man-hour efficiency standpoint, making use of nearby locations likely reduces the freedoms in designing the layout of the kit preparation workspace, which can negatively affect man-hour efficiency. Locations that are more remote can result in more freedom to design and thereby support man-hour efficiency.

There seems to be interplay with respect to storage policy, flexibility, kit quality and man-hour efficiency. Here, the thesis found that storage policies based on rigorous classifications generally

have less mix flexibility, as it must be arranged when production mixes change. The quality-related findings, however, suggest that some classifications, for example separating similar-looking components from each other, benefits the quality of kit preparation, as mistakes whereby components are confused with each other are less likely to occur. This is a clear trade-off between flexibility and kit quality related to the storage policy. Furthermore, the results showed that classification of the storage may be necessary in less dense picking areas in order to maintain man-hour efficiency. Oftentimes when kit carriers that remain stationary during picking tours are applied, classification is necessary to keep routes efficient and walking distances relatively short. With respect to storage policy and classification, man-hour efficiency and quality appear to be synergistic when more classification is used, while at the same time, this creates a trade-off with flexibility.

Interplay that arises from parallel considerations to several performance areas have been possible to identify in the thesis due to its multi-faceted view on performance. This is relevant both with respect to theory and to practice and may serve as input to future research studies as groundwork for hypotheses and propositions that can be evaluated in new settings and cases.

5.3.2. Discussion of avenues of future research

This section discusses avenues of future research in the area of kit preparation for materials supply by kitting.

Kit preparation design has been viewed to consist of subsystems of a particular design, for example a batching policy or a picking information system. This view, combined with a focus of studying kit preparation in its real-life context, provides a perspective on the relationships between choices among design aspects and performance. A similar perspective that links design aspects and performance as developed in this thesis could be beneficial in a larger context, such as warehouse order picking, as it provides a structure for continued research and enables opportunities for highly focused investigations that contribute to the understanding of the whole. Such research efforts could build further on previous works, such as those by Goetschalckx and Ashayeri (1989) and Yoon and Sharp (1996).

With respect to kit quality, which was addressed in Research Question 2, there was a limitation when studying the cases in Paper II with respect to obtaining precise measurements of kit errors. Had reliable records been available, it could have allowed for statistical analyses to be carried out and additional insights with respect to quality. This highlights a need for improved methods for measuring kit quality in practice. This kind of empirical data would also be useful in frameworks for planning and controlling kit preparation, such as in the frameworks by Caputo et al. (2017a) and Caputo et al. (2017b). If improved methods for measuring kit quality were available, the quality performance area could be assessed by a whole new range of methods and more knowledge of the effect on kit quality from different design options could be attained. Furthermore, reliable records over kit errors would allow for statistical analyses, whereby kit quality could be studied alongside man-hour efficiency with respect to various design options. This is an important avenue for further research.

The findings related to the influence on man-hour efficiency from picking information systems and confirmation methods raise questions about how batching policies employing higher number of kits per batch interact with various types of picking information systems. Further, as the findings indicate that order batching may have a significant influence on kit quality, further research should set out to determine the mechanics of this link and how other areas of kit preparation design, for example automation or control, may influence or moderate this link.

The cases included in Paper I did not include solutions for presenting picking information digitally, as would be possible with the HUD-system studied by Hanson et al. (2017) or the pick-by-HUD system studied in the experiment of Paper III. In light of the thesis findings, it is conceivable that

such systems can benefit flexibility when applied with kit preparation. This should be investigated in further research, and the knowledge developed by the thesis can be readily applied to find answers to such questions.

The automation-supported application in Paper V raise questions of how various forms of automation can support kit preparation. It is interesting from a general standpoint how various types of automation-based solutions, such as robot-arms, vision-systems for inspection and AGVs, and variants of these, can be used during actual live settings, with all the possible ways of applying them, and more research on this topic would be valuable.

The relationship between work schedules and deviations from these has been addressed in context of warehouse order picking by Glock et al. (2017). They determined that poorly designed systems can actually benefit from pickers having enough experience to notice and, consequently, working around flaws in the system. This is an interesting take on design and performance that should also be considered further in future research.

Action research investigations and longitudinal case studies are two other lines of research that could prove valuable for increasing the understanding of kit preparation design and performance. Here, a certain change or intervention could be monitored both in person and over time, aiming to understand enablers and barriers to kit preparation design in practice. As is often the scenario when conducting case research, only a snapshot of the operations or a narrative explaining how things got to be the way they are make up the basis. A longitudinal study, being close to the study object over a long time, would increase the richness of data and improve understanding of the great many small, but in many situations significant, variations in design affect different types of performance.

6. Conclusions

This thesis has studied kit preparation design aspects and their effects on kit preparation performance as associated with kitting-based materials supply in production systems with mixed-model assembly. The three kit preparation performance areas targeted by the thesis are flexibility, kit quality and man-hour efficiency. The industrial relevance of studying kit preparation stems from the increasing use of kit preparation in industry, which is a result of the need to better manage more component variants in production systems. Experience and guidelines for how to design these processes have been limited, and from a theoretical viewpoint, knowledge has been lacking on the relationships between kit preparation design and performance. Specifically, previous research that has treated these types of processes and simultaneously considered the three parallel performance areas has not been available.

The research in the thesis started from the existing, but scarce, knowledge on the influence of kit preparation design aspects on kit preparation performance. To complement this limited knowledge base, the thesis considered previous research from related fields, such as order picking, materials handling and manufacturing. To establish directions for the research, the thesis noted the problems as presented by industry via companies involved in the research project, alongside recommendations suggested from previous research. The needs of industry and the state of science led the research to focus on the influence from design on the flexibility, the kit quality and the man-hour efficiency associated with kit preparation, with the purpose of contributing to the knowledge of how kit preparation design aspects govern kit preparation performance.

Three research questions were formulated, each targeting one of three kit preparation performance areas captured in the thesis purpose statement, and five research papers were accordingly designed to address the research questions, focusing on the kit preparation flexibility (Paper I), the kit quality (Paper II) and the man-hour efficiency (Papers III, IV and V). The studies behind Papers I and II were designed as multiple case studies, focusing on how and why various design options influence performance. Papers III and IV were designed as experimental studies, more narrowly focusing on the influence on performance from using different types of picking information systems. Paper V was designed with a mathematical modelling approach, in order to study the potential for collaborative robots to support man-hour efficiency. Recent technology developments make this a valid and relevant area of research both from an industrial and a theoretical standpoint.

The study on flexibility performance was designed as a multiple embedded case study, in order to find ways of supporting design of flexible processes for kit preparation. The results include knowledge of the individual links between flexibility performance types and the set of design aspects that the thesis brought forth from the literature. The thesis' findings contribute to research by building on general models of flexibility from manufacturing and applying these to the specific context of kit preparation. An important observation is that modern technology in its current form and practice, such as pick-by-light systems, may delimit flexibility by being difficult to change with respect to both information data bases and the physical system.

Kit quality was studied in a similar way as flexibility. The study aimed to create an understanding of the links between kit preparation design aspects and kit error types to support kit quality. By applying a framework derived from literature describing how central kit preparation design aspects may influence kit quality associated with kit preparation, three cases of kit preparation in automotive material supply were studied in-depth. The results provide knowledge that concern, for example, the work organisation, the layout and the picking information system as applied in kit preparation and show how these aspects govern kit quality. The contribution to the literature consisted of comprehensive findings for how design aspects can be used to prevent kit errors in kit preparation and how kit error corrections can be carried out more quickly and effectively by means of kit preparation design.

The studies on man-hour efficiency, focusing on picking information systems and collaborative robots when applied to support kit preparation, make clear that technology has a great effect on outcomes of man-hour efficiency in kit preparation. These studies also point to the importance of considering the batching policy when choosing supportive technologies and indicate that large batch sizes can be problematic from a quality point of view. This is an example of trade-offs between performance areas identified in the thesis, which are interesting for further research.

The thesis contributes with broad yet detailed knowledge about relationships between kit preparation design aspects and performance. This can be used by kit preparation designers as a means to analyse and make decisions to support design and performance of kit preparation.

References

- Andriolo, A., Battini, D., Calzavara, M., Gamberi, M., Peretti, U., Persona, A., Pilati, F. and Sgarbossa, F. (2016), "New RFID pick-to-light system: operating characteristics and future potential", *International Journal of RF Technologies*, Vol. 7 No. 1, pp. 43-46.
- Baker, P. and Halim, Z. (2007), "An exploration of warehouse automation implementations: cost, service and flexibility issues", *Supply Chain Management: An International Journal*, Vol. 12 No. 2, pp. 129-138.
- Banks, J. (1998), "*Handbook of simulation: Principles, methodology, advances, applications, and practice*", John Wiley & Sons, New York.
- Baraldi, E. C. and Kaminski, P. C. (2010), "Ergonomic planned supply in an automotive assembly line", *Human factors and ergonomics in manufacturing and service industries*, Vol. 21 No. 1, pp. 104-119.
- Bartezzaghi, E. and Turco, F. (1989), "The impact of just-in-time on production system performance: an analytical framework", *International Journal of Operations and Production Management*, Vol. 9 No. 8, pp. 40-62.
- Battini, D., Calzavara, M., Persona, A. and Sgarbossa, F. (2015), "A comparative analysis of different paperless picking systems", *Industrial Management and Data Systems*, Vol. 115 No. 3, pp. 483-503.
- Battini, D., Boysen, N. and Emde, S. (2013), "Just-in-Time supermarkets for part supply in the automobile industry", *Journal of Management Control*, Vol. 24 No. 2, pp. 209-217.
- Battini, D., Faccio, M., Persona, A. and Sgarbossa, F. (2009), "Design of the optimal feeding policy in an assembly system", *International Journal of Production Economics*, Vol. 121 No. 1, pp. 233-254.
- Baudin, M. (2004), "*Lean logistics: the nuts and bolts of delivering materials and goods*", Productivity Press, New York.
- Beach, R., Muhlemann, A. P., Price, D. H. R., Paterson, A. and Sharp, J. A. (2000), "A review of manufacturing flexibility", *European Journal of Operational Research*, Vol. 122 No. 1, pp. 41-57.
- Beamon, B. M. (1999), "Measuring supply chain performance", *International Journal of Operations and Production Management*, Vol. 19 No. 3, pp. 275-292.
- Biegelbauer, G. and Vincze, M. (2006), "3D vision-guided bore inspection system", In proceedings of: Fourth IEEE International Conference on Computer Vision Systems (ICVS'06), 4-7 Jan, New York, USA.
- Boudella, M. E. A., Sahin, E. and Dallery, Y. (2018), "Kitting optimisation in just-in-time mixed-model assembly lines: assigning parts to pickers in a hybrid robot-operator kitting system", *International Journal of Production Research*, Vol. 56 No. 16, pp. 5475-5494.
- Boudella, M. E. A., Sahin, E. and Dallery, Y. (2016), "A mathematical model to assess the performance of a robotic kitting system in an assembly plant". In proceedings of the 11th International Conference on Modeling, Optimization and Simulation, Aug 2016, Montréal, Canada.
- Boysen, N., Emde, S., Hoeck, M., and Kauderer, M. (2015), "Part logistics in the automotive industry: decision problems, literature review and research agenda", *European Journal of Operational Research*, Vol. 242 No. 1, pp. 107-120.
- Bozer, Y. A. and McGinnis, L. F. (1992), "Kitting versus line stocking: a conceptual framework and a descriptive model", *International Journal of Production Economics*, Vol. 28 No. 1, pp. 1-19.

- Brosnan, T. and Sun, D.-W. (2004), "Improving quality inspection of food products by computer vision – a review", *Journal of Food Engineering*, Vol. 61 No. 1, pp. 3-16.
- Brynzér, H. and Johansson, M. I. (1996), "Storage location assignment: using the product structure to reduce order picking times", *International Journal of Production Economics*, Vol. 46-47 No. December, pp. 595-603.
- Brynzér, H. (1995), "*Evaluation of kitting systems: implications for kitting system design*", ISBN: 992-072203-0, Licentiate thesis, Chalmers University of Technology, Gothenburg, Sweden.
- Brynzér, H. and Johansson, M. I. (1995), "Design and performance of kitting and order picking systems", *International Journal of Production Economics*, Vol. 41 No. 1-3, pp. 115-125.
- Brynzér, H., Johansson, M. I. and Medbo, L. (1994), "A methodology for evaluation of order picking systems as a base for system design and managerial decisions", *International Journal of Operations and Production Management*, Vol. 14 No. 3, pp. 126-139.
- Calzavara, M., Hanson, R., Sgarbossa, F., Medbo, L. and Johansson, M. I. (2017), "Picking from pallet and picking from boxes: a time and ergonomic study", *IFAC PapersOnLine*, Vol. 50 No. 1, pp. 6888-6983.
- Caputo, A. C., Pelagagge, P. M. and Salini, P. (2018), "Selection of assembly lines feeding policies based on parts features and scenario conditions", *International Journal of Production Research*, Vol. 56 No. 3, pp. 1208-1232.
- Caputo, A. C., Pelagagge, P. M. and Salini, P. (2017a), "Modeling errors in parts supply processes for assembly lines feeding", *Industrial Management and Data Systems*, Vol. 117 No. 6, pp. 1263-1294.
- Caputo, A. C., Pelagagge, P. M. and Salini, P. (2017b), "Modelling human errors and quality issues in kitting processes for assembly lines feeding", *Computers and Industrial Engineering*, Vol. 111 No. September, pp. 492-506.
- Caputo, A. C., Pelagagge, P. M. and Salini, P. P. (2015), "A decision model for selecting parts feeding policies in assembly lines", *Industrial Management and Data Systems*, Vol. 115 No. 6, pp. 974-1003.
- Caputo, A. C., and Pelagagge, P. M. (2011), "A methodology for selecting assembly systems feeding policy", *Industrial Management and Data Systems*, Vol. 111 No. 1, pp. 84-112.
- Chan, F. T. S. and Chan, H. K. (2011), "Improving the productivity of order picking of a manual-pick and multi-level rack distribution warehouse through the implementation of class-based storage", *Expert Systems with Applications*, Vol. 38 No. 3, pp. 2686-2700.
- Chan, F. T. S., Chan, H. K. and Choy, K. L. (2006), "A systematic approach to manufacturing packaging logistics", *The International Journal of Advanced Manufacturing Technology*, Vol. 29 No. 9, pp. 1088-1101.
- Christmansson, M., Medbo, L., Hansson, G.-Å., Ohlsson, K., Unge Byström, J., Möller, T. and Forsman, M. (2002), "A case study of a principally new way of materials kitting—an evaluation of time consumption and physical workload", *International Journal of Industrial Ergonomics*, Vol. 30 No. 1, pp. 49-65.
- Coelho, F., Relvas, S. and Barbosa-Póvoa, A. P. (2018), "Simulation of an order picking system in a manufacturing supermarket using collaborative robots", In proceedings of the 32nd European Conference on Modelling and Simulation, May 22-25, Wilhelmshaven, Germany.
- Coleman, D. E. and Montgomery, D. C. (1993), "A systematic approach to planning for a designed industrial experiment", *Technometrics*, Vol. 35 No. 1, pp. 1-12.

- Correa, H. L. and Slack, N. (1994), "Framework to analyse flexibility and unplanned change in manufacturing systems", *Computer Integrated Manufacturing Systems*, Vol. 9 No 1, pp. 57-64.
- Da Silveira, G., Borenstein, D. and Fogliatto, F. S. (2001), "Mass customization: Literature review and research directions", *International Journal of Production Economics*, Vol. 72 No. 1, pp. 1-13.
- Dallari, F., Marchet, G. and Melacini, M. (2009), "Design of order picking system", *International Journal of Advanced Manufacturing Technology*, Vol. 42 No. 1-2, pp. 1-12.
- De Koster, R., Le-Duc, T. and Roodbergen, K. J. (2007), "Design and control of warehouse order-picking: a literature review", *European Journal of Operational Research*, Vol. 182 No. 2, pp. 481-501.
- De Vries, J., De Koster, R. and Stam, D. (2016), "Exploring the role of picker personality in predicting picking performance with pick by voice, pick to light and RF-terminal picking", *International Journal of Production Research*, Vol. 54 No. 8, pp. 2260-2274.
- Eisenhardt, K. (1989), "Building theories from case study research", *The Academy of Management Review*, Vol. 14 No. 4, pp. 532-550.
- Engström, T. and Medbo, P. (1997), "Data collection and analysis of manual work using video recording and personal computer techniques", *International Journal of Industrial Ergonomics*, Vol. 19 No. 4, pp. 291-298.
- Finnsgård, C. (2013), "*Materials exposure: the interface between materials supply and assembly*", ISBN 978-91-7385-954-7, PhD thesis, Chalmers University of Technology, Gothenburg, Sweden.
- Gerwin, D. (1993), "Manufacturing flexibility: a strategic perspective", *Management Science*, Vol. 39 No. 4, pp. 395-410.
- Glock, C. H., Grosse, E. H., Elbert, R. M. and Franzke, T. (2017), "Maverick picking: the impact of modifications in work schedules on manual order picking processes", *International Journal of Production Research*, Vol. 55 No. 21, pp. 6344-6360.
- Glock, C. H. and Grosse, E. H. (2012), "Storage policies and order picking strategies in U-shaped order-picking systems with a movable base", *International Journal of Production Research*, Vol. 50 No. 16, pp. 4344-4357.
- Goetschalckx, M. and Ashayeri, J. (1989), "Classification and design of order picking", *Logistics World*, Vol. 2 No. 2, pp. 99-106.
- Grosse, E. H. and Glock, C. H. (2013), "An experimental investigation of learning effects in order picking systems", *Journal of Manufacturing Technology Management*, Vol. 24 No. 6, pp. 850-872.
- Grosse, E. H., Glock, C. H. and Jaber, M. Y. (2013), "The effect of worker learning and forgetting on storage reassignment decisions in order picking systems", *Computers and Industrial Engineering*, Vol. 66 No. 4, pp. 653-662.
- Grosse, E. H., Glock, C. H., Jaber, M. Y. and Neumann, P. W. (2015), "Incorporating human factors in order picking planning models: framework and research opportunities", *International Journal of Production Research*, Vol. 53 No. 3, pp. 695-717.
- Guo, A., Wu, X., Shen, Z. and Starner, T. (2015), "Order picking with head-up displays", *Computer*, Vol. 48 No. 6, pp. 16-24.
- Guo, A., Raghu, S., Xie, X., Ismail, S., Luo, X., Simoneau, J., Gilliland, S., Baumann, H., Southern, C. and Starner, T. (2014), "A comparison of order picking assisted by head-up display (HUD), cart-mounted display (CMD), light, and paper pick list", In proceedings of ISCW, September 13-17, Seattle, USA.

- Hales, H.L. and Andersen, B.J. (2001), "Industrial engineering support for materials management". In: Zandin, K.B. (ed.) *Maynard's industrial engineering handbook*, Ch. 10.1., McGraw-Hill, New York.
- Hanson, R. (2012), "*In-plant materials supply: supporting the choice between kitting and continuous supply*", ISBN 978-91-7385-654-6, PhD thesis, Chalmers University of Technology, Gothenburg, Sweden.
- Hanson, R. and Brolin, A. (2013), "A comparison of kitting and continuous supply in in-plant materials supply", *International Journal of Production Research*, Vol. 51 No. 4, pp. 979-992.
- Hanson, R., Falkenström, W. and Miettinen, M. (2017), "Augmented reality as a means of conveying picking information in kit preparation for mixed-model assembly", *Computers and Industrial Engineering*, Vol. 113 No. November, pp. 570-575.
- Hanson, R. and Finnsgård, C. (2014), "Impact of unit load size on in-plant materials supply efficiency", *International Journal of Production Economics*, Vol. 147 No. Part A, pp. 46-52.
- Hanson, R., Johansson, M. I. and Medbo, L. (2011). "Location of kit preparation – Impact on in-plant materials supply performance", *International Journal of Industrial Engineering and Management*, Vol. 2 No. 4, pp. 123-129.
- Hanson, R. and Medbo, L. (2019), "Man-hour efficiency of manual kit preparation in the materials supply to mass-customised assembly", *International Journal of Production Research*, Vol. 57 No. 11, pp. 3735-3747.
- Hanson, R., Medbo, L. and Johansson, M. I. (2015), "Order batching and time efficiency in kit preparation", *Assembly Automation*, Vol. 35 No. 1, pp. 143-148.
- Hua, S. Y. and Johnson, D. J. (2010), "Research issues on factors influencing the choice of kitting versus line stocking", *International Journal of Production Research*, Vol. 48 No. 3, pp. 779-800.
- Johansson, E. (2006). "*Materials supply systems design during product development projects*". ISBN 91-7291-736-9, PhD thesis, Chalmers University of Technology, Gothenburg, Sweden.
- Johansson, E. and Johansson, M. I. (2006), "Materials supply systems design in product development projects", *International Journal of Operations and Production Management*, Vol. 26 No. 4, pp. 371-393
- Johansson, M. I., Wänström, C. and Medbo, L. (2012), "Manufacturing flexibility and materials supply systems", in proceedings of the 5th *Swedish Production Symposium Conference*, November, Linköping.
- Johansson, M. I. (1991), "Kitting systems for small size parts in manual assembly systems". In: Pridham, M. and O'Brien, C. (eds.) *Production research – approaching the 21st century*, Ch. 26, Taylor & Francis, London.
- Jonsson, P. and Mattsson, S.-A. (2009), "*Manufacturing planning and control*", McGraw-Hill Education, London, UK.
- Kilic, H. S. and Durmusoglu, M. B. (2015), "Advances in assembly line parts feeding policies: a literature review", *Assembly Automation*, Vol. 35 No. 1, pp. 57-68.
- Kootbally, Z., Schlenoff, C., Antonishek, B., Proctor, F., Kramer, T., Harrison, W., Downs, A. and Gupta, S. (2018), "Enabling robot agility in manufacturing kitting applications", *Integrated Computer-Aided Engineering*, Vol. 25 No. , pp. 193–212.
- Koste, L. L. and Malhotra, M. K. (1999), "A theoretical framework for analyzing the dimensions of manufacturing flexibility", *Journal of Operations Management*, Vol. 18 No. 1, pp. 75-93.

- Koste L. L., Malhotra, M. K. and Sharma, S. (2004), "Measuring dimensions of manufacturing flexibility", *Journal of Operations Management*, Vol. 22 No. 2, pp. 171-196.
- Limère, V., Landeghem, H. V. and Goetschalckx, M. (2015), "A decision model for kitting and line stocking with variable operator walking distances", *Assembly Automation*, Vol. 35 No. 1, pp. 47-56.
- Limère, V., Van Landeghem, H., Goetschalckx, M., Aghezzaf, E.-H. and McGinnis, L. F. (2012), "Optimising part feeding in the automotive assembly industry: deciding between kitting and line stocking", *International Journal of Production Research*, Vol. 50 No. 15, pp. 4046-4060.
- Lu, W., McFarlane, D., Giannakas, V. and Zhanf, Q. (2016), "An algorithm for dynamic order-picking in warehouse operations", *European Journal of Operational Research*, Vol. 248 No. 1, pp. 107-122.
- Manzini, R., Gamberi, M., Persona, A. and Regattieri, A. (2007), "Design of a class based storage picker to product order picking system", *International Journal of Advanced Manufacturing Technology*, Vol. 32 No. 7-8, pp. 811-821.
- Manzini, R., Gamberi, M. and Regattieri, A. (2005). "Design and control of a flexible order-picking system (FOPS): a new integrated approach to the implementation of an expert system", *Journal of Manufacturing Technology Management*, Vol. 16 No. 1, pp. 18-35.
- Manzini, R., Gamberi, M., Regattieri, A. and Persona, A. (2004) "Framework for designing a flexible cellular assembly system", *International Journal of Production Research*, Vol. 42 No. 17, pp. 3505-3528.
- Marchet, G., Melacini, M. and Perotti, S. (2015), "Investigating order picking system adoption: a case-study-based approach", *International Journal of Logistics Research and Applications: A Leading Journal of Supply Chain Management*, Vol. 18 No. 1, pp. 82-98.
- Martinez, C., Boca, R., Zhang, B., Chen, H. and Nidamarthi, S. (2015), "Automated bin picking system for randomly located industrial parts", *Proceedings of the 2015 IEEE International Conference on Technologies for Practical Robot Applications (TePRA)*, 11-15 May, Woburn, USA.
- Medbo, L. (2003), "Assembly work execution and materials kit functionality in parallel flow assembly systems", *International Journal of Industrial Ergonomics*, Vol. 31 No. 4, pp. 263-281.
- Öjmertz, B. (1998), "*Materials handling from a value-adding perspective*", ISBN 91-7197-713-9, PhD thesis, Chalmers University of Technology, Gothenburg, Sweden.
- Park, B. C. (2012). "Order picking: issues, systems and models", in Manzini, R. (Ed.), *Warehousing in the global supply chain*, Ch. 1, Springer-Verlag, London.
- Parker, R. P. and Wirth, A. (1999), "Manufacturing flexibility: measures and relationships", *European Journal of Operational Research*, Vol. 118 No. 3, pp. 429-449.
- Pérez, L., Rodríguez, I., Rodríguez, N., Usamentiaga, R. and García, D. F. (2016), "Robot guidance using machine vision techniques in industrial environments: a comparative review", *Sensors*, Vol. 16 No. 3, pp. 335-361.
- Pil, F. K. and Holweg, M. (2004), "Linking product variety to order-fulfilment strategies", *Interfaces*, Vol. 34 No. 5, pp. 394-403.
- Roodbergen, K. J. (2012), "Storage assignment for order picking in multiple-block warehouses", in Manzini, R. (Ed.), *Warehousing in the global supply chain*, Ch. 7, Springer-Verlag, London.
- Sadrifaridpour, B. and Wang, Y. (2018), "Collaborative assembly in hybrid manufacturing cells: an integrated framework for human-robot interaction", *IEEE Transactions on Automation Science and Engineering*, Vol. 15 No. 3, pp. 1178-1192.

- Sali, M. and Sahin, E. (2016), "Line feeding optimization for just in time assembly lines: an application to the automotive industry", *International Journal of Production Economics*, Vol. 174 No. April, pp. 54-67.
- Sali, M., Sahin, E. and Patchong, A. (2015), "An empirical assessment of the performances of three line feeding modes used in the automotive sector: line stocking vs. kitting vs. sequencing", *International Journal of Production Research*, Vol 53 No. 5, pp. 1439-1459.
- Sánchez, A. M. and Pérez, M. P. (2005), "Supply chain flexibility and firm performance", *International Journal of Operations and Production Management*, Vol. 25 No. 7, pp. 681-700.
- Schwerdtfeger, B., Reif, R., Günthner, W. A. and Klinker, G. (2011), "Pick-by-vision: there is something to pick at the end of the augmented tunnel", *Virtual Reality*, Vol. 15 No. 2-3, pp. 213-223.
- Sellers, C. J. and Nof, S. Y. (1989), "Performance analysis of robotic kitting systems", *Robotics and Computer-Integrated Manufacturing*, Vol. 6 No. 1, pp. 15-24.
- Sethi, A. K. and Sethi, S. P. (1990), "Flexibility in manufacturing: a survey", *The International Journal of Flexible Manufacturing Systems*, Vol. 2 No. 4, pp. 289-328.
- Shafeeka, H. I., Gadelmawlab, E. S., Abdel-Shafy, A. A. and Elewab, I. M. (2004), "Assessment of welding defects for gas pipeline radiographs using computer vision", *NDT and E International*, Vol. 37 No. 4, pp. 291-299.
- Staudt, F. H., Alpan, G., Di Mascolo, M. and Rodriguez, C. M. T. (2015), "Warehouse performance measurement: a literature review", *International Journal of Production Research*, Vol. 53 No. 18, pp. 5524-5544.
- Slack, N. (2005), "The flexibility of manufacturing systems". *International Journal of Operations and Production Management*, Vol. 25 No. 12, pp. 1190-1200.
- Upton, D. M. (1995), "Flexibility as process mobility: the management of plant capabilities for quick response manufacturing", *Journal of Operations Management*, Vol. 12 No. 3-4, pp. 205-224.
- Voss, C., Tsikriktsis, N. and Frohlich, M. (2002), "Case research in operations management", *International Journal of Operations and Production Management*, Vol. 22 No. 2, pp. 195-219.
- Wänström, C. and Medbo, L. (2009), "The impact of materials feeding design on assembly process performance", *Journal of Manufacturing Technology*, Vol. 20 No. 1, pp. 30-51.
- Yoon, C. S. and Sharp, G. P. (1996), "A structured procedure for analysis and design of order pick systems", *IIE Transactions*, Vol. 28 No. 5, pp. 379-389.
- Yoon, C. S. and Sharp, G. P. (1995), "Example application of the cognitive design procedure for an order pick system: Case study", *European Journal of Operational Research*, Vol. 87 No. 2, pp. 223-246.
- Yin, R. K. (2009), "Case study research: design and methods", 4th ed., Thousand Oaks, California, USA: Sage.
- Yu, M. (2008), "Enhancing warehouse performance by efficient order picking", ISBN 978-90-5892-167-3, PhD thesis, Erasmus University, Rotterdam, Netherlands.