THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

On the link between materials preparation design and performance

PATRIK FAGER

Department of Technology Management and Economics
Division of Supply and Operations Management

CHALMERS UNIVERSITY OF TECHNOLOGY

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Division of Supply and Operations Management
Department of Technology Management and Economics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

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Patrik Fager
Department of Technology Management and Economics
Chalmers University of Technology

ABSTRACT

Materials preparation is used in materials supply systems to arrange materials in accordance with the requirements from the assembly. Kitting and sequence based materials supply are two examples of when materials preparation is used in industry, where different part variants are collected to packages intended for one or multiple assembly objects.

The use of materials preparation in industry is increasing along with the increasing amount of part variants in need of handling in the production system, while knowledge on how the materials preparation should be designed in regard to the materials preparation performance objectives of quality, flexibility and time efficiency, needs further research. In addition, rapid developments in information technology calls for new research in terms of how the new technology fits in the materials preparation process.

The purpose of the thesis is to expand knowledge of how the desired performance of materials preparation in terms of flexibility, quality, and time efficiency influences the design of materials preparation. In the thesis, results are presented from literature studies, two multiple case studies and an experiment. The results presented focus on how options in the materials preparation design influence the materials preparation performance.

An experiment, focusing time efficiency, together with two case studies on flexibility and quality performance, respectively forms the empirical basis of a framework for how the performance requirements influence the materials preparation design, in terms of the links between the studied design variables and the performance requirements. The framework also considers the materials preparation context and trade-offs in the materials preparation design in regard to the three performance requirements.

The thesis contributes to practice by providing guidance to the materials preparation designer in terms of the performance to expect when choosing among options of the materials preparation design variables. The theoretical contribution of the thesis pertains to the developed framework that describes the relation between materials preparation design and performance.

Key words: Materials kitting, Part sequencing, Order picking, Information systems, Production systems, Assembly industry

List of appended papers

Paper I:

Fager P., Hanson, R., Johansson, M. I., and Medbo L. (2016). *"Flexibility of kitting processes in production systems".* Working paper to be submitted to the *International Journal of Production Economics.*

An earlier version of this paper was published in the Proceedings of the 19th EurOMA Conference, 28-30 June 2015, Neuchâtel.

Paper II:

Fager P., Johansson, M. I., and Medbo, L. (2014). *"Quality problems in materials kit preparation"*. Published in the *Proceedings of the 7th Swedish Production Symposium Conference*, 16-18 September 2014, Gothenburg.

Paper III:

Fager P., Hanson R., Medbo L., and Johansson M. I. (2016) *"Time efficiency of information systems in materials kit preparation",* Working paper to be submitted to the *International Journal of Production Economics*.

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The researcher's contribution to the papers

PAPER	FIRST AUTHOR	SECOND AUTHORS	RESPONSIBILITIES
I	Patrik Fager	Robin Hanson, Mats I. Johansson and Lars Medbo	The paper planning was done by the first author, under advisement of the other authors. The first author was responsible for the data collection, supported by the other authors. The first author did the larger part of the writing, developing drafts for all sections that were then discussed and improved jointly. The analysis was conducted by the first author and discussed between all authors to arrive at the final analysis and conclusions.
II	Patrik Fager	Mats I. Johansson and Lars Medbo	The paper planning was done by the first author, under advisement of the other authors. The first author was responsible for the data collection in all cases, supported by the other authors. The writing of the version submitted to the SPS-conference was done by the first author under advisement of the other authors.
III	Patrik Fager	Robin Hanson, Lars Medbo, Mats I. Johansson	The paper planning was done by the first author, under advisement from the other authors. The first author wrote the full paper which was discussed and revised together with the other authors. The analysis was conducted by the first author and discussed between all authors to arrive at the final results and conclusions.

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1 Introduction

This thesis addresses the preparation of kits- and sequence-deliveries for assembly in production systems, chiefly in terms of how the design of the preparation process, aimed at fulfilling the requirements set by assembly, effect the performance of the preparation process. It specifically focuses on the performance in terms of quality, flexibility, and time efficiency.

In this first chapter, Section 1.1 introduces the background of the problem, from which the purpose and scope of the thesis derive, as outlined in Section 1.2. Then, Section 1.3 articulates the three research questions that have guided the research. Section 1.4 presents an overview of the contents of the thesis.

1.1 Background

Given the high degree of end-product customisation in the assembly industry - which, in the automotive industry, can theoretically result in car models with billions of different variants (Pil and Holweg, 2004) - the array of part variants require efficient and reliable logistics operations in production systems (Boysen et al., 2015). As product life cycles become shorter (Chen et al., 2012), thereby causing a continuously changing assortment of part variants, corresponding production systems need to be able to provide customers with products that meet their exact requirements on time. In that sense, such a responsive production system requires the flexibility of the production system, as well as flexibility of the materials supply subsystem (Holweg, 2005). To that end, one approach acknowledged for improving flexibility in assembly systems is the use of kitting materials supply for assembly (Caputo and Pelagagge, 2011; Hanson and Brolin, 2013). Another such approach is sequenced deliveries of part variants to assembly. To enable kitting-based and sequenced materials supply, materials preparation in the materials supply system is necessary.

This thesis introduces the term *materials preparation* to encapsulate materials handling operations and processes in supply systems that configure materials according to assembly requirements, as detailed in Section 2.1. Two examples of materials preparation are kitting and sequencing processes, as elaborated in Section 2.2, both of which are commonly used in industrial environments in which part variant counts are high. Two common reasons for introducing kitting or sequencing are, one, to improve space utilisation in assembly lines by presenting materials in heterogeneous packaging (Limère et al., 2012) and, two, to improve assembly efficiency by reducing the time spent searching for parts (Hanson and Brolin, 2013). Another reasons is to facilitate the cognitive process of the assembler, thereby assuring the correct parts being assembled (Medbo, 2003).

However, to realise those benefits, materials preparation needs to operate at expected performance levels and meet the requirements posed by assembly. To this end, choosing the design of processes for materials preparation by adjusting certain design variables is crucial, and has to consider the context in which the design is deployed and the performance that it can yield.

1.1.1 Performance issues in materials preparation

In industry, knowledge about what performance can be expected from adjustments to materials preparation design variables, at least beyond in-house experiences, is rarely available to materials preparation designers. Many examples of materials preparation are observable in industries that simultaneously face difficulties with adapting to changing requirements from production systems, especially regarding quality-related problems with prepared materials and inefficient order picking operations. In turn, those issues impose performance requirements on the materials preparation process in terms of flexibility, quality, and time efficiency.

Flexibility. In the preparation of materials supplied for assembly, the management of part variants is located to the specific preparation areas, which can improve supply flexibility since changes to order content can be made by simply updating picking information (Caputo and Pelagagge, 2011). However, for the materials preparation process to fulfil its role of improving the flexibility of the production system, it needs to be able to adapt to changing requirements in the production system, which requires flexibility in the materials preparation process itself. Research has identified that need, particularly when comparing materials kitting to alternative materials supply methods, and has called for factors that determine the flexibility of materials preparation to be investigated (Hua and Johnson, 2010).

Quality. Since materials preparation by definition occurs prior to assembly operations (Hua and Johnson, 2010), it is crucial that the configuration of materials delivered for assembly conforms to assembly specifications, specified by both the product structure and the assembly schedule (Brynzér and Johansson, 1995). If a quality-related problem occurs in materials preparation, then necessary corrections can prolong the order delivery time, interrupt the production flow, and in the worst-case scenario, require expensive rework or even result in the delivery of the wrong product to end customers (Boysen et al., 2015). It is thus crucial that materials preparation is high quality in terms of picking accuracy and that the consequences of picking errors are minimised. Previous research has linked materials preparation design to quality, for example, in terms of the type of information system used in order-picking processes (Battini et al., 2015), the location of the preparation area for kitting processes (Hanson et al., 2011) and the influence of human factors in order-picking system design (Grosse et al., 2015). However, quality in order-picking operations is far from fully understood, and further research on the topic has been recommended (Grosse et al., 2015).

Time efficiency. Using materials preparation instead of materials supply methods for delivering packages with homogenous contents (containing a single part number) to assembly (for example, line stocking or continuous supply) introduces extra materials handling operations into the material flow (Limère, 2012) that has received great criticism in discussions of kitting as an alternative materials supply method (Bozer and McGinnis, 1992). However, the additional materials handling work introduced by kitting, as well as other types of materials preparation, can be balanced by the efficiency gained in assembly from less walking and searching during part collection (Hanson and Finnsgård, 2014). As such, improving the time efficiency of materials preparation is central to improving overall production system efficiency when using materials preparation. Further, new developments in information technology have enabled new alternatives among picking information systems, for example, solutions involving wearable computing (Reif et al., 2009) and scanning technology (Battini et al, 2015). In terms of wearable computing, smart glasses are visual interfaces now available to display virtual (Guo et al., 2015) or augmented picking information (Schwerdtfeger et al., 2011), thereby providing workers with updated information in real time during picking tours. In terms of scanning technology, solutions based upon radio frequency identification (RFID) are becoming increasingly reliable at lower costs and thereby approaching viability in industrial operations (Battini et al., 2015) as alternatives to traditional barcodes and checklists. In effect, many new applications have emerged, which in itself motivates new research on how those technologies compare to established ones in terms of performance, as the picking information is known to be important for both time efficiency and quality (Brynzér and Johansson, 1995). Knowledge on how choices in the design of the picking information system influence time efficiency, then, becomes a most relevant aspect for making sound decisions.

1.2 Purpose and scope of the thesis

1.2.1 Purpose

In industry, generally little, if any, knowledge is available to materials preparation designers that extends beyond in-house experiences with how materials preparation should be designed to meet performance requirements. As demonstrated in the background of the problem, some research has been conducted that links materials preparation design to materials preparation performance (e.g., Brynzér, 1995), but knowledge on designing materials preparation to achieve satisfactory performance remains limited, thereby calling for research to resolve performance issues. As indicated in this section, such knowledge concerns links between materials preparation design and expected levels of flexibility, quality, and time efficiency, especially in light of new technological developments. By expanding knowledge on links between materials preparation design and performance, and building upon groundwork established by earlier research, more informed decisions about materials preparation design can be made and the resolution of the aforementioned performance issues more likely.

Since materials handling research has strong links to practice, in which production standards, management policy, technology, society and culture are continuously developing, new preconditions for materials handling and preparation design arise that research has to capture, analyse, and understand. That understanding should derive from perspectives on how new developments can be situated amid previously developed knowledge, as well as in terms of how previously developed knowledge fits into changed preconditions presented by practice.

Progress in fields related to materials handling and materials preparation - for example, order picking for assembly - should also be understood in terms of their generalisability to materials preparation. Any commonalities among the fields can, and arguably should, be exploited and integrated to further the overall development of knowledge. It is in that light which this thesis aims to make a contribution. As Figure 1.1 illustrates, *the purpose of the thesis is to expand knowledge of how the desired performance of materials preparation in terms of flexibility, quality, and time efficiency influences the design of materials preparation.*

This formulation of the purpose reflects the problem of the designer of the materials preparation process in industry, when faced with the task of, for example, improving the quality performance of a process in operation, or when having the task of designing a materials preparation process performing at a certain level in terms of time efficiency.

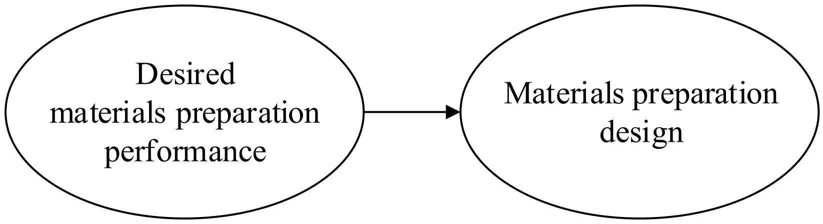

Figure 1.1. Purpose of the thesis

1.2.2 Scope

This thesis addresses materials preparation for kit- and sequence-based materials supply to mass-customised, mixed-model, and manual assembly systems - that is, assembly systems in which multiple end product variants are produced in a mixed sequence derived from customer demand.

In this thesis, *materials* refers to parts and subassemblies used in the assembly of end products, whereas *materials preparation* refers to materials handling activities conducted in order to configure materials in accordance with requirements posed by the assembly system. By contrast, *materials preparation process* refers to the complete sequence of activities during which materials are configured, the elements in the materials handling system that connects the materials preparation activities and makes the sequence possible, and the layout and equipment of the physical areas in the materials supply chain in which the activities takes place. The materials preparation processes considered in the thesis do not necessarily occur in the same facility as the final assembly, but necessarily occur in the materials supply system that precedes assembly in the entire production system.

The thesis exclusively treats options for materials preparation design variables and their influence on materials preparation performance in terms of flexibility, quality, and time efficiency. The variables considered here concern equipment, operations, and principles of materials preparation. At the same time, the thesis does not treat the design process itself - that is, the methods and procedures by which materials preparation should be designed.

In terms of Goetschalckx and Ashayeri's framework (1989) for classifying order-picking systems, this thesis considers only manual materials preparation, in which workers provide both power and control. It also considers only two-dimensional storage - that is, storage in locations determined according to the two coordinates of the row, or shelf level, and the column - meaning only preparation within a single aisle. In terms of zoning policy, the thesis accounts for materials preparation in a single zone only, for orders completed by individual workers.

In terms of interface with the production system, the thesis considers the requirements of interface between materials preparation and assembly, as well as the interface between the replenishment function of the warehouse and materials preparation. It also accounts for the planning interface within the overall planning system of the production system, as well as the management interface between materials preparation and the production system.

1.3 Research questions

Three research questions have structured the research conducted for this thesis, largely to align the work with the purpose presented in section 1.2. An argument of relevance accompanies each research question presented here in order to give the reader an overview of the relevance of each question. Further details concerning the relevance of each question appear in the theoretical framework described in Chapter 2.

All three research questions have two aspects in common. First, each question reflects the link between materials preparation design and a specific performance dimension. Second, the relation of design and performance as expressed in the questions reverses how the link is expressed in the purpose of the thesis. This reversal is intentional and reveals the difference between results derived as answers to the research question and the intentions regarding the use of these results, as expressed in the purpose of the thesis. While the purpose reflects the problem of which design leads to certain performance, or how materials preparation should be designed to improve the performance of materials preparation, it is more natural to put research questions relying on empirical data as how the design variables influence performance, and design research studies accordingly.

Results from answering the three research questions thereby constitute a set of links for how materials preparation design influences materials preparation performance. Once knowledge attained from answering each of the three questions is synthesised, the resulting frameworks for each of the three performance objectives will facilitate the understanding of how performance influences design. In that way, results derived from the research questions is intended to function beyond the thesis. This reversal is further commented on at the end of this section, its motivations explained in the description of the method in Chapter 3, and its effects discussed in Chapter 6.

1.3.1 Research Question 1

A common reason for introducing materials preparation is to improve the flexibility of the production system. When the primary driver for using materials preparation is to improve the flexibility of that system, it is necessary for the materials preparation process to also be flexible for materials preparation to fulfil its role in the system. Although the concept of flexibility and its meaning in materials preparation is explained in detail in Chapter 2, it should be stated that the need to understand how options of design variables in the design of materials preparation determine the flexibility of materials preparation has been expressed in previous research on kitting by Hua and Johnson (2010), but mainly as a means to compare alternative materials supply methods. The first research question targets the link between materials preparation design and its flexibility, formulated as:

Research Question 1:
How does materials preparation design influence the flexibility of materials preparation?

1.3.2 Research Question 2

Another reason for introducing materials preparation into the production system is to improve the quality of assembly operations (Caputo and Pelagagge, 2011). It is therefore crucial that prepared materials supplied to assembly conform to product specifications stated in the bill of materials and the production schedule, in order to not disrupt production and so that materials preparation can realise the effects expected. Materials preparation quality - that is, the degree of conformance between prepared materials and assembly requirements - is thus another crucial aspect of the role of materials preparation in production systems.

Although quality has received a fair amount of attention in research on order picking and materials handling, the focus has tended to be the cost of overcoming picking errors, in which quality is a cost factor in computational cost models (e.g. Caputo et al., 2015; Battini et al., 2015). More rarely has the influence of design on quality been considered in a sense that clarifies how design variable options influence quality and how that link is constituted. Despite a foundation for that line of reasoning - for example, the oft-cited study by Brynzér and Johansson (1995) - more research in that direction is necessary.

Studies that investigate the influence of aspects of order-picking design on order-picking quality have been suggested (Grosse et al., 2015). Regarding kitting, Hua and Johnson (2010) has particularly recommended research on how factors in kitting process design affect kitting quality. The quality outcome of materials preparation is thus the focus of the second research question:

Research Question 2:
How does the materials preparation design influence the quality outcome of materials preparation?

1.3.3 Research Question 3

Previous research has shown that the total man-hour consumption, in both the assembly and supply of materials, of using materials preparation in materials supply systems can be similar to that of using other methods (Hanson and Finnsgård, 2014). This is the case when the time spent on extra materials handling activities for materials preparation is counterbalanced by efficiency gained in assembly from using materials preparation in the materials supply. It is thus crucial that materials preparation is performed efficiently, to realise benefits achieved in assembly.

A few studies have addressed process design variables in relation to time efficiency of materials preparation, for example, that using order batching improves the efficiency of kit preparation given the possibility of picking parts for multiple orders at once (Hanson et al., 2015). However, new developments in information technology have made new picking information systems available - for example, pick-by-vision (Schwerdtfeger et al., 2011) and RFID-based confirmation of picking operations (Battini et al., 2015). Such systems have demonstrated potential for higher time efficiency in order-picking scenarios (Guo et al., 2015), though its potential for materials preparation types such as kitting remains unclear. Therefore, the target of the third research question is the effect of the design of materials preparation on its time efficiency, particularly concerning the effect of the picking information system:

Research Question 3:
To what extent does the picking information system influence the time efficiency of materials preparation?

1.3.4 Conceptual framework of the thesis

The conceptual framework in Figure 1.2 illustrates how the research questions relate to the purpose of the thesis. The solid black arrows indicate the direction of the influence between design and performance in terms of the research questions, whereas the hollow white arrow shows the direction considered in the purpose of the thesis. In the framework, the context is included to illustrate the influence of context on the performance and design of materials preparation, as indicated with dashed arrows.

The specific meaning of *materials preparation design* in Figure 1.2 might differ depending on which performance objective is considered, since only some design variables might be relevant to the particular performance objective.

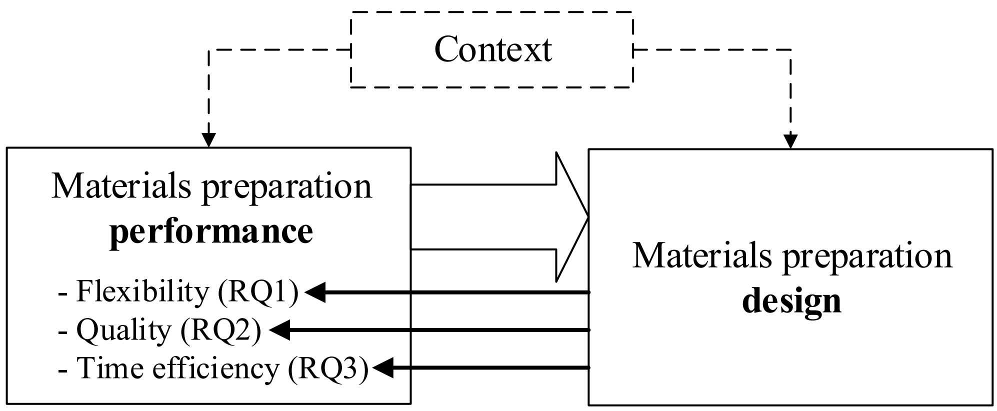

Figure 1.2. The conceptual framework of the thesis

1.4 Outline of the thesis

Chapter 1 presents the background of the thesis, including the problem addressed, the purpose and scope of the thesis, its three research questions, and its conceptual framework.

To explain the theoretical framework of the thesis, Chapter 2 is organised around four primary topics: the materials preparation design framework, materials preparation performance, materials preparation design variables, and the synthesis of those elements in the theoretical framework of the thesis.

Chapter 3 describes the research method of the thesis, and discusses the quality of the research conducted to answer the three research questions.

Chapter 4 briefly summarises the three appended papers for the reader's reference.

Chapter 5 presents the results of the thesis, in terms of the answers to the three research questions.

Chapter 6 discusses the results in terms of their contributions to the research purpose, generalisability, as well as outlining directions for further research.

The final chapter of the thesis, Chapter 7, presents the conclusions of the research.

2 Theoretical framework

This chapter presents the theoretical framework of the thesis. Section 2.1 defines the term “materials preparation design” and derives from literature the design framework used in the thesis. Section 2.2 presents examples of materials preparation in industry. Sections 2.3 and 2.4 define the two central terms of the thesis, *materials preparation performance* and *materials preparation design variables*, and link the terms to theory. Thereafter, Section 2.5 defines the term *materials preparation context* and explains how the context is treated in the thesis. Finally, Section 2.6 synthesises the theory presented into the complete conceptual framework used in the thesis, combining the design framework derived in Section 2.1 with the framework derived for the performance in Section 2.3, the framework derived for the design variables in Section 2.4 and the framework derived for the context in Section 2.5, illustrated in Figure 2.8.

2.1 Definition of “materials preparation design”

A central term in the thesis is *materials preparation design*, a term consisting of three words, each with a specific meaning. This section aims to clarify this term by first defining the purpose of materials preparation as considered in the thesis and, then, presenting the definitions used in the thesis for the three words constituting the term. Lastly, the design framework used in the thesis is derived from literature, where after the concept of *design variable* is explained.

2.1.1 The purpose of materials preparation

The purpose of materials preparation is in this thesis stated as to configure materials in accordance with the assembly requirements, via a number of materials handling activities forming the materials preparation process. Materials handling has been defined as “… a system or combination of methods, facilities, labour, and equipment for moving, packaging, and storing of materials to meet specific objectives” (Kulwiec, 1985, p. 4). Thus, all handling activities performed on the unit load level or the individual item, for example transport and handling of a pallet, or the orientation of materials, is part of materials handling, but not part of materials preparation. The material handling types listed by Öjmertz (1998) - picking, positioning, orienting, sorting and gathering - are used for materials preparation and applied to change the configuration of the unit loads handled in the material flow, while not being concerned with the movement of the unit loads in the materials flow.

Materials preparation is used in the materials supply system to fulfil the requirements of the assembly process. Hence, the materials preparation design is dependent on the assembly requirements, which often are formulated in order to achieve efficient and reliable assembly operations This means that the purpose of materials preparation is to support the assembly operations.

The types of activities that occur in a particular case of materials preparation depends on the requirements posed by the assembly. For example, positioning of parts or orientation of parts in the picking package during materials preparation could be required in one case, but be unnecessary in another case, in terms of the activities fulfilling requirements from the assembly. Hence, the materials preparation purpose is unique for the particular case. The relation between materials preparation and assembly is illustrated in Figure 2.1.

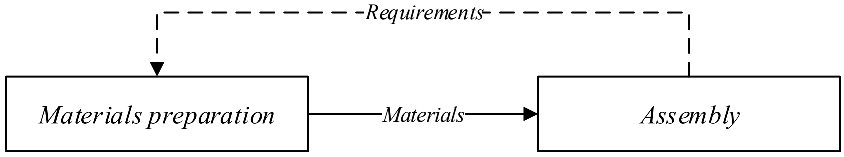

Figure 2.1. The relation between materials preparation and assembly

2.1.2 Specification of *materials*, *preparation* and *design*

The aim of this subsection is to clarify the meaning of the individual words of the central term of the thesis - *materials preparation design*.

Materials, the first word of the term, refers in this thesis to the physical parts or sub-assemblies which are to be used in the assembly of an assembly object, in line with the definitions by Bozer and McGinnis (1992). Specifically, a *part* is considered in the noun form as “a manufactured object assembled with others to make a machine” (Oxford English dictionary, 2016), which in the thesis is considered equivalent to what Bozer and McGinnis (1992, pp. 3) denote as a “component”. A *sub-assembly* is considered in its noun form as “a unit assembled separately but designed to be incorporated with other units into a larger manufactured product” (Oxford English dictionary, 2016).

Preparation, the second word of the term, is in the thesis defined as “the action or process of preparing or being prepared for use or consideration” (Oxford English dictionary, 2016). The word “process” is here defined as “a series of actions or steps taken in order to achieve a particular end” (Oxford English dictionary, 2016). In this thesis, *preparation* thus refers to the series of actions performed to configure the materials. The verb *configure* is here meant as to “arrange or put together in a particular form or configuration” (Oxford English dictionary, 2016). Thus in this thesis, *preparation* includes all, and only those, activities that are part of altering the configuration of the materials, in a manner that is in accordance with the assembly requirements on the configuration. The configuration refers to the orientation, position, etc. (Öjmertz, 1999). The meaning of “preparation” in this thesis is illustrated in Figure 2.2.

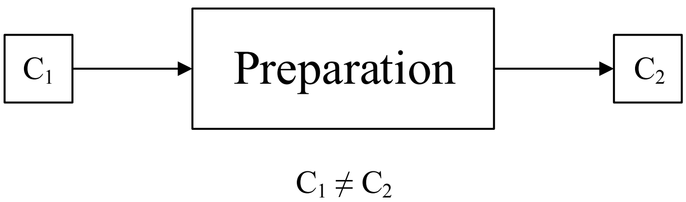

Figure 2.2. Preparation alters the configuration of materials ($C_1 \rightarrow C_2$) in the materials supply system.

Design, the third word of the term, is in the thesis considered in its noun form as "a specification of an object, manifested by some agent, intended to accomplish goals, in a particular environment, using a set of primitive components, satisfying a set of requirements, subject to some constraints" (Ralph and Wand, 2009, pp. 108). This concept is further elaborated on in the next sub-section.

2.1.3 The design framework used in the thesis

The definition of design from Ralph and Wand (2009) cited in sub-section 2.1.2 is used in this sub-section to derive the design framework used in this thesis, presented in Figure 2.4. The definition of "design" from Ralph and Wand is reproduced in Figure 2.3 for the reader's reference.

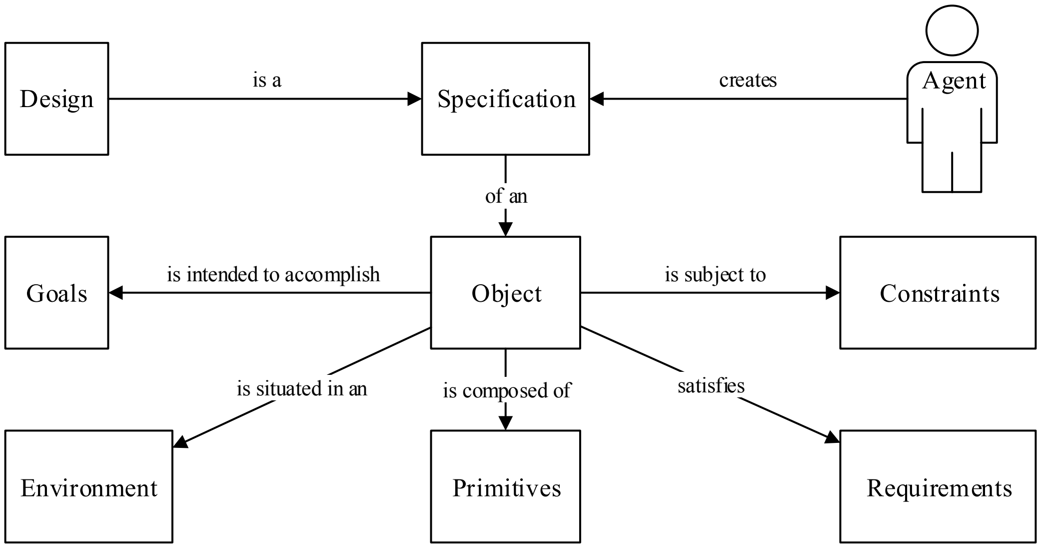

Figure 2.3. Design as a noun, from Ralph and Wand (2009)

The design object in Figure 2.3 is the entity being designed (Ralph and Wand, 2009, pp. 108). The entity being designed in this thesis is the materials preparation process, i.e., the process in which the materials preparation is conducted. The design is intended to accomplish performance goals and to fulfil the requirements stemming from the production system. The design is composed by the design primitives, which is "the set of elements from which the design object may be composed, (usually defined in terms of types of components assumed to be available)" (Ralph and Wand, 2009, pp. 108). There are two criteria for an element to be part of the design in this thesis: that the element has an influence on the materials preparation performance and that the element is subject to choice for the designer. The influence can either be direct or indirect, meaning that the element either directly influences the materials preparation performance, or it influences another element which in turn influences the materials preparation performance.

Those elements of the materials preparation process that do not influence the materials preparation performance, nor are subject to choice for the process designer, are considered as *contextual background elements* and reside outside the scope of the thesis. Those elements that neither have a direct nor indirect influence on materials preparation performance, but are subject to choice for the designer, are classified *design background elements*. Those elements of materials preparation that have either a direct or indirect influence on materials preparation performance, but are not subject to choice for the designer, are part of the materials preparation context and classified as *contextual factors*. Those elements of materials preparation that either directly or indirectly influences the materials preparation performance, and are subject to choice for the designer, are part of the materials preparation design and are classified as *design variables* in the thesis.

The contextual factors and design variables that are considered in the research are those linked to the performance objectives considered in the thesis, i.e. there may well be other design variables and contextual factors than the ones treated in this thesis that links to other performance objectives. The above reasoning is illustrated in Figure 2.4, where the cross-sections of the ellipses that contain the "contextual factors" and the "design variables" are treated in this thesis. The concept of design variables is explained in the next sub-section.

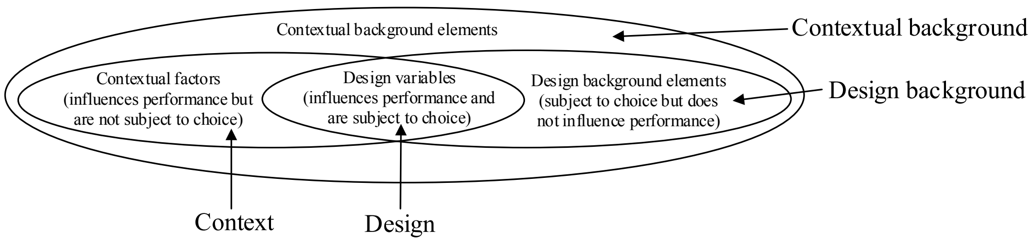

Figure 2.4. The elements of materials preparation, illustrates how the terms design and context are treated in this thesis.

2.1.4 The concept of "design variables"

A variable (noun) is "an element, feature, or factor that is liable to vary or change" (Oxford English dictionary, 2016). A materials preparation design variable is an element of the materials preparation design that either directly or indirectly influences the materials preparation performance, and is subject to choice for the materials preparation designer. To comprehend this definition, it is necessary to consider both that the requirements "has significance for the materials preparation performance" and "can be changed by the process designer".

For an element of materials preparation to have significance for the materials preparation performance, an alteration of the element must yield a change in the materials preparation performance. If the alteration of an element does not yield a change in performance, the element is not a design variable, neither is it a contextual factor. If the alteration of an element yields a change in performance, but is outside the circle of influence for the designer, the element is part of the materials preparation context. A design variable, or a context element, can be of three kinds - categorical, continuous or nominal. In case of a categorical variable, two values may yield the same performance, but as long as one of the values yield another performance than the rest, the variable is considered a design variable or as part of the context.

Concerning the materials preparation designer, this title may in practice not be restricted to a single process manager, but rather concerns the possibilities of changing the process for the specific case. Thus, the border between design and context may in practice shift slightly between cases, where a design variable for one case is a context factor for another. The criterion for an element to be subject to choice for the designer also concerns the feasibility of changing the element. For example, if a company is undergoing a major reorganisation, there may be more, or less, design variables in the materials preparation design than if the process is in steady state operation. Further, the time perspective is crucial, where a certain element may be subject to choice for the designer over a longer time horizon, but part of the context if considered in the short term.

2.2 Materials preparation types

The two types of materials preparation focused on in this thesis are the materials preparation conducted for enabling the materials supply methods of kitting and sequencing. These are defined and explained in this section, together with repacking, which is third type of materials preparation that is not specifically treated in this thesis, but is included in this section in order to highlight the unifying characteristics between different materials preparation types.

There is a distinction made in this section between the materials preparation and the materials supply method. In order to avoid confusion in this section, it is stated already here that the materials preparation of the materials kitting supply method – hereafter labelled kitting, in short - is denoted *kit preparation* in this thesis. The materials preparation of the materials supply method sequencing is denoted *parts sequencing* in this thesis. These terms are further clarified in sections 2.2.1 to 2.2.3.

2.2.1 Kit preparation and the materials kitting supply method

Kit preparation is the process of collecting parts designated for a particular assembly object into a single unit load that then is delivered to assembly (Johansson, 1991) and has been described as an assembly operation where all but the final step, the assembly, is performed (Brynzér, 1995). *Kit preparation* is in this thesis considered to be equivalent with the term *kit assembly*, that has been defined as the "operation where all the components and/or subassemblies that are required for a particular kit type are physically placed (sometimes in specific positions) in the appropriate kit container" (Bozer and McGinnis, 1992, pp. 3). In the materials flow, kitting is thus "the practice of delivering materials to the shop floor in predetermined quantities that are placed together in specific containers" (Bozer and McGinnis, 1992, pp. 1). The distinction used in this thesis is hence that the kit preparation is the materials preparation that is used to enable the materials kitting supply method.

Kit preparation can be performed manually, semi-automatically or fully automatically (Brynzér and Johansson, 1995). This thesis deals only with manual kit preparation. In manual kit preparation, the operator picks parts from storage locations and places the parts in a kit package. The information on which parts are required for a specific kit is provided by the picking information system.

Kit preparation can be conducted at different locations in the materials supply system and by different categories of personnel. For example, the kit assembly can be conducted by the assembly operator close to the assembly line as part of the assembly work, or can be conducted by a logistics operator that works exclusively with materials preparation in a warehouse (Brynzér and Johansson, 1995).

2.2.2 Part sequencing and the materials sequencing supply method

The second type of materials supply method enabled by materials preparation, often used as an alternative to kitting in environments where the number of variants per part type is high, is sequence-based materials supply (Boysen et al., 2009; Caputo and Pelagagge, 2011). Sequence-based materials supply has been treated far less than kit-based materials supply in the literature, in terms of the effects on the materials handling and assembly systems, although examples exist in for example Mathisson-Öjmertz and Johansson (2000), and in terms of definitions. Part sequencing is the materials preparation process that organizes part variants of a part type for multiple assembly objects in accordance with the assembly schedule. In contrast to kitting, the packages generated in part sequencing normally contains only a single or few different part types. As kitting conventionally is defined as the collection of multiple parts for a single assembly object, sequencing is instead the collection of variants for several consecutive assembly objects.

2.3 Materials preparation performance

This section presents the perspective on materials preparation performance used in the thesis, which is a synthesis from three different, but related, knowledge areas: order picking, manufacturing and materials handling. These three knowledge areas provide a good starting point to derive the materials preparation performance framework from, as the activities with which the areas are concerned are similar in many regards. This section starts with a discussion of perspectives on performance in order picking, manufacturing and materials handling, that concludes in the synthesis of the performance framework for materials preparation used in the thesis consisting of the three performance objectives: flexibility, quality and time efficiency. Then, the three performance objectives are treated separately, in terms of the definitions and measures used in the thesis (sub-sections 2.3.2 to 2.3.4).

2.3.1 Synthesis of the performance framework of the thesis

Operational performance in order picking is concerned with the productivity and the quality of the order picking system (Park, 2012). Productivity is a performance measure of a system, generally defined as the ratio of system output to system input. Examples of productivity measures include labour productivity, for example the ratio of completed order lines per man hour and storage density, for example the ratio of storage capacity to the floor space used. The degree to which the customer requirements are met cannot be determined from the productivity measures, but is the purpose of the quality measures. Park (2012) states that quality in the order picking system is determined from the customer experience. Quality measures are hence the performance measures that are directly relevant to customer service, of which the two most important are the system cycle time and the picking accuracy (Park, 2012). The system cycle time is the elapsed time between the order release and the order completion, which is crucial for the customers, as it to a large extent determines the lead time from order placement to order receipt for the customer (Park, 2012). The picking accuracy is the percentage of order lines completed without error and is directly relevant for the customer service level.

The performance objectives for manufacturing operations are concerned with increasing the competitiveness of the business and with improving the customer experience (Slack et al., 2010). Slack et al. (2010) specifies five operations performance objectives - quality, speed, dependability, flexibility and cost. According to Slack et al. (2010), the quality objective is concerned with providing the customer with error-free goods and services that conforms to the customer expectations. The speed objective is concerned with shortening the time from the customer request is received until the request is fulfilled. The dependability is concerned with keeping delivery promises towards the customer. Flexibility is concerned with being able to adapt to changing circumstances, or to provide customers with individual treatment, both in terms of the range of alternatives and in regards to the time at which any changes can be accommodated. The cost objective is concerned with producing the goods or services at a cost level that allows a return to the organisation, while providing the goods or services at a reasonable price on the market. According to Slack et al. (2010), the five operations performance objectives are interrelated. For example, improvements in regards to the quality objective benefits the cost objective, by reducing the costs of correcting mistakes, and the dependability objective, by keeping the customer promise of delivering error-free products. Improvement in regard to flexibility improves the response speed of operations, saves time, and maintains the dependability of the operation when changes are made. In general, improvement in regards to any of the performance objectives quality, speed, dependability and flexibility, improves the cost performance objective.

In kitting operations, two performance objectives that have been emphasised in previous literature are the picking accuracy, i.e., the percentage of error-free order lines, and time efficiency, the ratio of necessary work content to total work content (Brynzér and Johansson, 1995).

From the literature on order picking, manufacturing and materials handling performance, it seems that performance in in these knowledge areas to some extent is concerned with the amount of output attained from a given amount of input, i.e. efficiency, and partly with the degree to which customer requirements are met, i.e. effectiveness. As materials preparation is part of the production system that is assessed by the manufacturing performance objectives, and is concerned with similar activities to those in order picking and materials handling, a framework for studying the materials preparation performance should reflect these three perspectives. As the purpose of materials preparation is to arrange materials in accordance with the requirements from the assembly. The assembly hence is the customer of materials preparation and an appropriate materials preparation performance definition should consider the amount of input required to meet the assembly requirements and the degree to which these requirements are met.

The picking efficiency performance objective used by Brynzér and Johansson (1995) appears to capture parts of the productivity aspect associated with order picking performance, where a more time efficient materials preparation will consume less resources to achieve the same level of output, while also capturing the speed and cost aspects associated with operations and manufacturing performance. The picking efficiency performance objective also aligns with the system cycle time emphasised by Park (2012) as an important quality measure in order picking systems. Picking efficiency, in this thesis labelled as *time efficiency*, is hence one of the chosen performance objectives of materials preparation in the thesis.

Quality, in terms of the degree to which customer expectations are met, is similarly defined for materials handling, order picking, manufacturing operations, and would in terms of the materials preparation purpose be the degree to which the assembly requirements are met. Achieving high quality in materials preparation then, implies conformance to the requirements from the assembly and, thus, that the materials are correctly configured. On this note, the picking accuracy as used by Brynzér and Johansson (1995) is crucial and will affect dependability and cost performances of the materials preparation. *Quality* is therefore chosen as a performance objective for materials preparation in the thesis.

As was stated in the introduction, there is a trend of an increasing number of part variants in production systems that stems from the increasing degree of customisation of end products. The materials preparation must be able to accommodate this requirement from the production system. Therefore, the materials preparation flexibility is chosen as one of the performance objectives in the thesis.

In summary, literature on performance in materials handling, order picking and manufacturing performance presents similar performance considerations. Time efficiency, in terms of the amount of time spent for completing a set amount of work; quality, in terms of picking accuracy, and flexibility, in terms of the ability to accommodate changing requirements, are the three performance objectives that are focused in this thesis. These three performance objectives are treated separately in sections 2.3.2 to 2.3.4.

2.3.2 Materials preparation flexibility

2.3.2.1 Definitions of flexibility

Flexibility has been defined as the ability of a system to respond effectively to changing circumstances (Mandelbaum, 1978) and as the ability of a system to change or react with little penalty in time, effort, cost or performance (Upton, 1995). Flexibility thus concerns both the circumstance that necessitate the system to change, and the penalty of changing the system. Circumstances that generate requirements for flexibility arise from the need of a system to manage environmental uncertainty and enabling variability of outputs (Correa, 1992; De Toni and Tonchia, 1999). For a production system, production flexibility refers to the ability of the individual manufacturing resources (Slack, 2005), including the material handling units (Sethi and Sethi, 1990; Sánchez and Pérez, 2006), to manage environmental uncertainty and variability of outputs. Specifically, ability in this context refers to the effort exerted when changing either structural or infrastructural resources (Correa, 1992). Thus, the perspective maintained in this thesis is to consider the flexibility of materials preparation process, i.e., the work station or preparation area at which the materials preparation occurs.

2.3.2.2 Dimensions of flexibility

Literature appears consistent on the notion that a single measure is insufficient for modelling flexibility (Mandelbaum, 1978; Slack, 2005; Vokurka and O'Leary-Kelly, 2011), and that there is a distinction between dimensions of flexibility and types of flexibility (Slack, 2005; Parker and Wirth, 1999). *Dimensions of flexibility* reflects different measures of the flexibility types, and has been described as the "characteristic coordinates which help describe the nature of the flexibility types" (Parker and Wirth, 1999, pp. 430). In this thesis, the distinction between the two dimensions range and response (Slack, 1983), is focused due to its frequent use in other works on flexibility (see e.g. Upton (1995) or Koste et al. (2004)). Accordingly, range flexibility reflects the capability range or the range of states which the system can adopt over a longer time horizon, while response flexibility reflects the effort, in terms of cost or time, of making changes within the capability range over a shorter time horizon (Slack, 2005). Slack (2005) emphasize that changes in the short-term are nearly always concerned with improving system response in terms of cost or time, or both.

2.3.2.3 Measures of flexibility

In a materials preparation process, the range flexibility would represent the number of part variants that can be accommodated by the process, since this ability would determine the range of outputs, in terms of the theoretical number of packages with different contents. However, as previous research has shown (e.g. Hanson, 2012), only a selection of part types and variants are assigned to a single materials preparation process, why the absolute number of part types and variants managed in the single materials preparation process might be of less interest, as the absolute count is not an end goal in itself. Instead, what is of interest would be the amount of part types and variants that can be managed given some constraints as for example floor space, operator count or the information system characteristics. This would provide insight of what is possible with a given set of resources. However, if instead the response dimension is considered, constraints in terms of floor space, operator count or information system characteristics would change the response if the capability range is exceeded. Thus, from studying the response flexibility, it would be possible to attain indications on how the range flexibility is constituted, while the other way around would not. Therefore, the flexibility dimension focused in this thesis is the response dimension.

Different types of environmental uncertainty, i.e. the stimuli acting on the system, and variability of outputs, i.e. the range of products produced by the production system and the variation of this output over time, sets requirements for different types of flexibility (Correa, 1992; Gerwin, 1993). However, types of production flexibility are diverse and scattered in literature, where up to 15 different types (Vokurka and O'Leary-Kelly, 2000) and over 50 different terms can be identified for various flexibility types, and identical terms used by different authors can have different meanings (Sethi and Sethi, 1990). The particular flexibility types to consider when assessing flexibility can be selected from the objective which the flexibility type fulfils, i.e., the uncertainty or variability which it manages (Beach, 2000; Gerwin, 1983). Flexibility can thus be examined from focusing on the system's capability of overcoming known or unknown changes in the environment (Gupta and Goyal, 1989), and measured by the effort, in terms of cost or time, from overcoming those changes (Sethi and Sethi, 1990). Of interest in this thesis, is how the materials preparation process manage uncertainties and variability in regard to the requirements stemming from the production system..

Changes in production systems, thus necessitating flexibility, includes new product introductions (Koste and Malhotra, 1999; Slack, 2005), engineering changes of existing products and parts (Gerwin, 1993; Koste and Malhotra, 1999), alterations of the product mix (Koste and Malhotra, 1999; Slack, 2005), changes in production volume or production rate (Bertezzagi and Turco 1989; Slack, 2005), and changes in the delivery schedule (Beamon, 1999; Slack, 2005). Each of these changes are of relevance for the materials preparation process in fulfilling its role in the production system, as indicated by previous studies on flexibility in materials handling and supply chain management (for example Wänström and Medbo, 2009); Hanson et al., 2011; Johansson et al., 2012). Table 2.1 presents the flexibility types focused in the thesis and the corresponding changes in the production system which is managed by each flexibility type.

Table 2.1. Overview of the flexibility types considered in the thesis

Flexibility type	Change in production system	Definition used in the thesis
New product	Product introductions	Slack (2005): *The ability to modify products or introduce novel products*
Modification	Engineering changes	Gerwin (1987): *The ability to accommodate design changes*
Mix	Product mix changes	Slack (2005): *The ability to change the ratio of different products*
Volume	Production rate changes	Slack (2005): *The ability to change the level of output*
Delivery	Late schedule changes	Slack (2005): *The ability to change planned or assumed delivery dates*

Based on the work of Correa and Slack (1994), flexibility is in this thesis considered as a modifier of the relation between *changes in requirements* for the kitting process, resulting from the changes in the production system listed in Table 2.1, and the *effort for required actions* exerted when adapting the process to the new requirements, measured in cost and time.

2.3.3 Materials preparation quality

2.3.3.1 Definitions of quality

The definition of quality may vary depending on the discipline, and may also vary between functions within the same company (Garvin, 1984). For example, the transcendent approach of defining quality, adopted within philosophy, views quality as an “innate excellence” (Garvin, 1984, p. 25) that can be appreciated but not quantified. The product-based definition used within economics, considers quality to be the quantity of some attribute of the product (Garvin, 1984). Further, Garvin (1984) states that the marketing department at a company may regard the customer as the judge of what is to be considered high or low quality, meanwhile the manufacturing department is more concerned with whether the produced goods conforms to the specification.

In order picking, Park (2012, p. 11) uses a broader definition of quality for warehousing operations, where quality is the “perception of the degree to which the system meets the customer’s expectations”, which can be evaluated by the two quality measures: system cycle time and picking accuracy. From the perspective of materials preparation, which has the assembly as the customer, the assessment of what constitutes high or low quality may, in the context of production systems, be considered as less concerned with the assemblers’ perception of the prepared materials, but more so with whether the prepared materials conform to specification derived from the bill of materials and the assembly schedule. On this note, the definition that originates in manufacturing, i.e. that quality is the degree of conformance to a specification (Garvin, 1984), is central to materials preparation. However, Garvin (1984) further explains that the value-based approach to defining quality further considers the conformance in regards to the cost of achieving the particular conformance level, so that a very high conformance level achieved at very high cost is valued the same as a reasonable conformance level achieved at a reasonable cost. The value-based definition of quality is what is focused in this thesis.

2.3.3.2 Dimensions of quality

The motive for conforming to the specification in the first place within manufacturing, is most often to reduce the total cost of the manufacturing operations, where rework, line stoppages or even erroneous end products, all eventually incur additional costs (Garvin, 1984). Preventive measures such as investments in error proofing technology, quality controls or rapid response support services are often motivated by their cost benefits in reducing the amount errors and their associated consequences (Garvin, 1984). Also for the materials preparation process, which produce packages with prepared materials for assembly, the quality dimension is not solely concerned with providing the assembly with error free prepared materials, but also concerned with ensuring that any detrimental error that may eventually occur, is taken care of in an efficient way. Thereby, there are two quality dimension that are of concern to this thesis: conformance quality and serviceability quality. The former is the conformance in regards to the specification, which is considered in light of the value-based approach to quality explained in section 2.3.3.1, while the latter is the speed and of correcting any errors (Garvin, 1984), in the prepared materials.

2.3.3.3 Types and measures of quality

During materials preparation in kitting and in order picking systems, picking errors is the strongest contributor to lowering the conformance quality level (Brynzér and Johansson, 1995; Grosse et al., 2015). In order picking, Grosse (2015) denotes quality as the percentage of picking errors to total volume, while Brynzér and Johansson (1995) instead uses the term picking accuracy, the percentage of correctly executed order lines to total order line executed to assess the conformance quality. These two terms obviously presents the same data, but in two different ways. Sousa and Voss (2002) states that the specific quality measures employed must be adapted for the particular context. From the perspective of conformance quality in materials preparation, the picking accuracy terminology is used in this thesis, as an increase in picking accuracy would mean a proportional increase in conformance quality, in relation to the costs for achieving the particular picking accuracy. In addition to the conformance quality, materials preparation quality also entails the serviceability quality, in terms of the degree to which any errors can be rectified at minimal cost to the overall system.

2.3.4 Materials preparation time efficiency

2.3.4.1 Definitions of time efficiency

In literature on manufacturing performance, time has been considered to hold the potential for competitive advantage (Neely et al., 1995) and to be equivalent with money (Stalk, 1988). In order picking, travel time and route optimisation are two central research streams (De Koster et al., 2007), which both focusing the reduction of time spent on the order picking activities, i.e. to improve the ratio of the direct picking time to the total time of the picking tour. As materials preparation function is highly similar to order picking, but often on smaller scale, the proportion of work content which adheres to the materials preparation purpose, i.e. to arrange materials in accordance with the requirements from assembly, is likewise desirable to increase.

2.3.4.2 Measures of time efficiency

From the previous sub-section it can be concluded that time efficiency should be assessed from the time spent on completing a specified content of work. In materials preparation, this would refer to fulfilling a customer request or completing an order line as part of a customer request. Of course, there are other activities associated with the materials preparation than the actual preparation work content, but, the focus of this thesis is time efficiency in regards to the actual preparation work, while associated work time is considered as part of the context, as far as time efficiency is concerned.

2.4 Materials preparation design variables

The purpose of this thesis, stated in section 1.2, concerns the knowledge on materials preparation design in relation to performance and the design must be understood in terms of the options of the design variables and their link to the materials preparation performance. Hence, the aim of this section is to present the theoretical basis concerning materials preparation design variables as derived from previous literature, in addition to introducing the reader to the details which are focused in this research. This section first presents a discussion on categorisations of design variables for order picking and kitting systems in previous research, that is used to synthesise the categorisation of materials preparation design variables used in the thesis (sub-section 2.4.1). Then, the design variables, organised as broader design areas were each design area entails a number of design variables, are defined and discussed in terms of the identified links to performance in previous research (sub-sections 2.4.2 to 2.4.7).

2.4.1 Categorisation of materials preparation design variables

2.4.1.1 Order picking system design

Literature on specific aspects in the design of order picking systems is rich, but less so in terms of holistic design frameworks, which has been attributed to the strongly interdependent nature of the main order picking design areas (De Koster et al., 2007). However, one holistic design framework for order picking systems is available from Goetschalckx and Ashayeri (1989), denoted the systematic planning and designing procedure for order picking systems (SYD-OPS). While the entirety of the SYD-OPS is outside the scope of this thesis, the framework that the procedure builds on is relevant to materials preparation design. To begin with, the framework is based on a categorisation of the aspects in order picking system that the design procedure aims to define. The concepts in focus in SYD-OPS are distinguished as part of either the external strategies, i.e. the policies concerned with the strategy of the company, or the internal strategies, i.e., the policies concerned with the organisation and management of the order picking system. The external strategies are not designed by the SYD-OPS, but are the constraints that must be considered when designing the internal strategies. In terms of the design framework used in this thesis, presented in Section 2.1, the internal strategies can be regarded as part of the materials preparation design, as the internal strategies can be regarded as within the scope of the designer, while the external strategies are part of the context. Goetchalckx and Ashayeri (1989) classifies the internal strategies by five criteria: policy level, command cycle, dimensionality of the warehouse, mechanisation level and information availability.

The command cycle relates to automatic and semi-automatic order picking systems (De Koster et al., 2007) and is thereby outside the scope of this thesis. The mechanisation level of the warehouse is only considered at the manual level in the thesis, i.e., shelf picking as denoted by Goetschalckx and Ashayeri (1989). The warehouse dimensionality, i.e. the number of coordinates determining the location of an item, can also be considered as less applicable to the thesis, as only dimensions is considered, i.e., the item location is given by the shelf level and the column. The information availability describes whether all picking information is available before the picking tour is initiated, a so-called static system, or whether the information can change during the picking tour, a so-called dynamic system (Goetschalckx and Ashayeri, 1989). For materials preparation, where the picking tour time is short and the orders often determined by the assembly schedule, the information is only of the static kind.

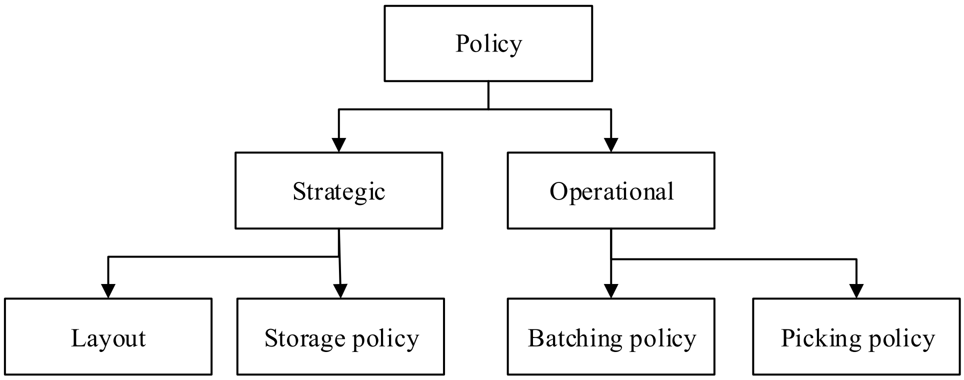

Figure 2.5. The design considerations within the policy level, from Goetschalckx and Ashayeri (1989)

The policy level, however, is applicable to materials preparation, shown in Figure 2.5. The policy level, defined as "the time scale and scope of a policy in a warehousing system" (Goetschalckx and Ashayeri, 1989, pp. 100), involves decisions on the strategic and the operational policy levels. The strategic policy level is concerned with the warehouse layout design, comprising the decision on the size and on the location of the storage of the individual parts and the picking activities. The storage policy is concerned with the decision of where individual stock items are stored in the warehouse, partly based on the item characteristics. The operational policy level comprises the batching policy, i.e., the sequence in which several customer orders are retrieved from the warehouse and whether orders are grouped together, and the picking policy, the sequence in which individual items are retrieved for a single customer order.

2.4.1.2 Kitting system design

Brynzér (1995) studies methods for the evaluation of kitting system performance and derives six design factors of kitting systems, partly based on Goetschalckx and Ashayeri (1989), which are central for the kitting system picking efficiency. These design factors include the layout, the picking information, the equipment selection, the storage policy, the batching policy and the picking policy.

Regarding the layout design factor, Brynzér (1995) identifies the location of the kitting area in relation to the assembly line, the width and length of aisles and the location of shared equipment and areas. Concerning the picking information design factor, the picking information media and the structure of the picking information are considered important. As regards equipment selection, the two main considerations identified are the storage equipment and the picking package. The storage policy is concerned with the storage assignment policy, i.e. the logic behind the location of individual items in the storage. The batching policy refers to number of orders that are managed during a single picking tour. The picking policy is defined identically to the definition by Goetschalckx and Ashayeri (1989) and is in the kitting system concerned with the sequence in which picking locations are visited during a single tour, and whether the picking package passes through zones and, hence, is completed by different operators. As only single operator materials preparation is focused in the thesis, only the sequence with which the singular order is completed is within the scope. Therefore, the thesis does not consider the decision of whether zoning should be used or not. The framework for kitting system design in relation to picking efficiency is visualised in Figure 2.6.

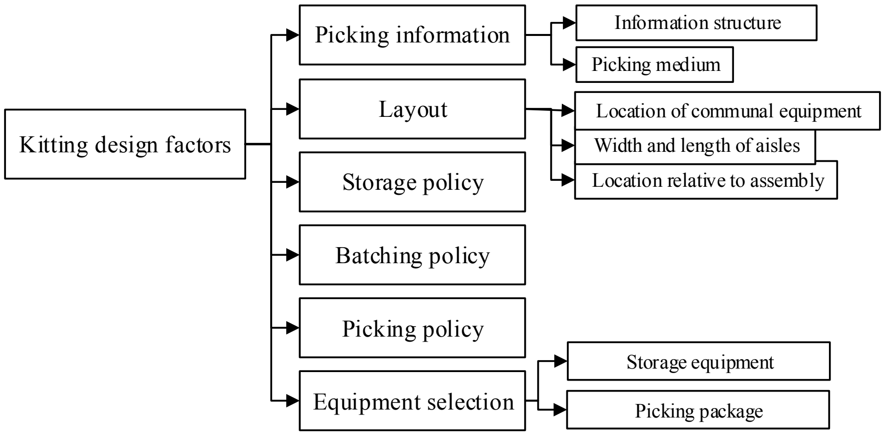

Figure 2.6. The design factors for kitting systems, by Brynzér (1995)

2.4.1.3 Assembly workstation design

A third knowledge area to consider in regards to materials preparation design is the design of assembly workstations, exhibiting many similarities with materials preparation as regards the picking operations conducted to collect parts. Wänström and Medbo (2009) identify the storage packaging as important for the flexibility in regards to handling new product introductions, and Hanson and Finnsgård (2014) find that a smaller unit load, enabled by smaller storage packaging, greatly impacts the assembly workstation performance in terms of the time spent for fetching parts. Similarly, the storage packaging type should be considered in the materials preparation design.

2.4.1.4 Synthesis into a design variables framework

From the reviewed literature on order picking system, kitting system and assembly workstation design in sections 2.4.1.1 to 2.4.1.3, the central considerations in regards to the design of materials preparation processes – the design variables - can be synthesised as shown in Figure 2.7.

The design variable part of the framework in figure 2.7 is treated in sections 2.4.2 to 2.4.7. Each design variable is treated in terms of the values the variables might assume and the influence of the variables on materials preparation performance, as identified in previous literature.

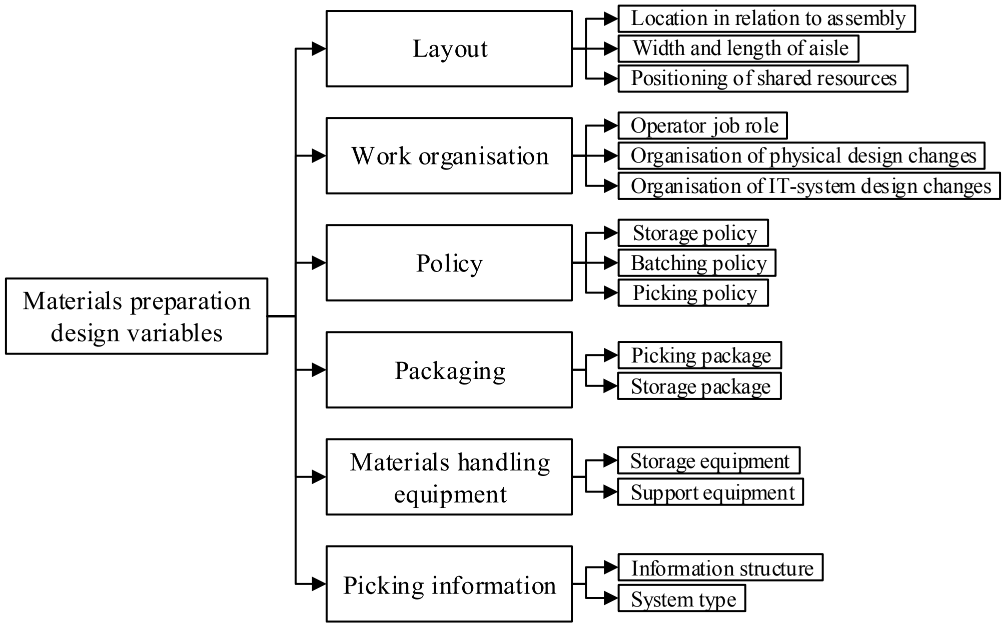

Figure 2.7. The design variables framework used in the thesis

2.4.2 Layout design

Layout design is concerned with the location of the preparation area in relation to assembly, the position of shared resources at the preparation area, and the length and width of the preparation shelves and the storage aisles (Brynzér, 1995).

The location of the preparation area in relation to assembly is a high level decision concerning the materials preparation design (Brynzér and Johansson, 1995) and is often part of the larger decision of whether to use a centralised policy, where multiple materials preparation processes are kept together in the same area, and a decentralised policy, where materials preparation is located close to assembly.

The location of the preparation area influence the options for the operator job role, where a location closer to assembly enables the assembly operator to conduct materials preparation, either individually or for the team. Further, a localisation closer to assembly enables balancing of operations between the materials preparation area and the assembly, which can reduce balancing losses in both assembly and materials preparation (Brynzér and Johansson, 1995). However, reduced balancing losses might also be achieved with a centralised policy, where work content instead can be balanced between materials preparation processes in the same department (Hanson et al., 2011). Balancing losses may rather be an issue for intermediate locations, where neither assembly nor other materials preparation processes are nearby (Hanson et al., 2011). A location farther from assembly tends to improve the flexibility of the kitting process, in terms of a higher availability of floor space that allows for extending the storage racks (Hanson et al., 2011). On this note, a location farther from assembly could also improve the opportunities for designing the process more freely, thus facilitating the design of more a more time efficient kit assembly process. Further, the response time for correcting picking errors is shorter when the preparation area is located closer to assembly, which reduces the impact of picking errors on the assembly (Hanson et al., 2011).

The layout of the preparation area sets the movement pattern of the operator in the preparation process, but also relates to several other design variables. Grosse and Glock (2013) investigates the influence of storage assignment policy on the time efficiency in U-shaped order picking areas and finds that the locations of the part numbers and the location of the picking package can influence time efficiency to a great extent. The position of shared resources in the preparation process concerns both the distances between key resources and the organisation of key resources, i.e. where the resources are located relative to one another. Previous literature has linked the position to both the time efficiency of the preparation and the quality levels of the prepared materials. In regards to time efficiency, the location of resources as for example the printer and the discarding point for empty packages, will impact the movement pattern in the preparation area during the picking tour (Brynzér, 1995). The interruptions caused by walking to the discarding point for empty packages or plastic wrapping could cause picking errors, as the operator is interrupted in the picking sequence and forgets the last step performed (Brynzér, 1995), thus impacting the quality.

In summary, the location of the preparation area has partly a direct effect on the quality, flexibility and time efficiency of the materials preparation, and partly sets the preconditions for other design variables in terms of enabling or disabling certain design variable values. The location decision is often, but not necessarily, within the scope of choice for the materials preparation designer, and is hence in this thesis considered a materials preparation design variable.

2.4.3 Work organisation

The materials preparation work organisation is concerned with the work tasks of the operator who conducts the materials preparation as well as the manner in which the management of the materials preparation are organised. These two aspects are here denoted as the operator job role and the materials preparation management. The options available for the operator job role depends to a large extent on the localisation of the materials preparation area (Brynzér and Johansson, 1995). It is generally considered that a job role where materials picking is combined with assembly work improves the picking accuracy due to that the operator knows the product structure and performing the materials preparation for own use (or for use by the team) (Brynzér and Johansson, 1995)[1]. Further, depending on how the materials preparation management is organised, aspects such as the conditions for continuous improvements (Hanson et al., 2011) as well as communication channels and the risk of interruptions (Brynzér and Johansson, 1995) could be impacted. Beyond this, literature appears scarce in regards to the influence of the management function on the materials preparation process performance and operation.

[1] The exact mechanism for the improved picking accuracy from an integrated job role between assembly and preparation is, in the author's opinion, not clear from Brynzér and Johansson (1995). It is the author's own interpretation that the improved accuracy stems from an increased sense of responsibility for, and thus a more conscientious approach to, the preparation, as the preparation is performed for the own use or for use by the team.

In summary, the work organisation is in this thesis concerned with the operator job role and the organisation of the materials preparation management. While the influence of the job role has been treated in previous research on kitting operations, the influence of the management organisation is unclear.

2.4.4 Policy

Policy in the design is concerned with the rules for determining the storage location for parts, the number of orders treated during the same picking tour, and the sequence in which parts are retrieved from the storage. These aspects are here treated as the storage policy, the batching policy and the picking policy, respectively.

The storage policy is concerned with the location of parts within the storage (Park, 2012), both in the horizontal plane, vertically (shelf level), and in relation to the storage location of other parts. According to Park (2012), there are three different types of storage policies available to warehouses: the random, the dedicated and the class-based storage policies. The random storage policy involves assigning a part number to a storage location without consideration to neither the activity nor the turnover for the part number, where the common heuristic rule is to store each new part number at the closest open location. The dedicated storage policy on the other hand use a fixed location for each part number, where a common heuristic is to organise the part numbers according to frequency, so that the part number with the highest frequency is located closest to depot. The class-based storage policy is an intermediate of the random and the dedicated storage policies, where the storage is partitioned in classes, where each class for example represent a frequency range, and the part numbers are stored randomly within each class. In contrast to the random, the dedicated and the class-based storage policies that consider the demand for a part number to be independent of the demand of other part numbers, Brynzér (1995) explain the correlated storage policy to consider the correlation in demand between part numbers, where part numbers that frequently are requested together should be stored together. In kitting processes, these correlations can be determined from the product structure (Brynzér, 1995).

In materials preparation, there are somewhat different preconditions from the more general warehousing context, due to the existence of a product structure and the dependence on the assembly schedule, which create a dependent demand among parts (Brynzér, 1995). Thus, the parts managed in the materials preparation process can be considered as more constant, in terms of the same part number being managed in the process over a longer time, than in the traditional order picking context of distribution centres. This implies that the storage assignment policy is dedicated at a given point in time. The differentiation as described by Park (2012) is rather concerned with where new part numbers should be located once they arrive to the process, and with how the location of part number should change upon changes in the demand characteristics.

The batching policy is the number of orders that are handled during a single picking tour (Brynzér and Johansson, 1995). The reason why batching policy has received significant attention in order picking is due its effect on time efficiency, where it enables parts for multiple order to be picked at once (Hanson et al, 2012). However, some literature points at that batching of orders might be associated with an increased amount of sorting and administration in kit assembly operations (Brynzér and Johansson, 1995). In order picking, batching is utilized in order to reduce the travel distance per completed order (De Koster et al., 2007).

The picking policy is concerned with the sequence in which parts are picked for a single order. This has implication for the movement across the picking area, where picking from alternate sides of the aisle can be contrasted with picking from one side at the time (Brynzér and Johansson, 1995).

In summary, the policy design variable is in this thesis concerned with the storage, batching and picking policies.

2.4.5 Packaging

The packaging used in the materials preparation is in this thesis concerned with the storage packaging type used in the material storage and the picking package to which parts are picked. The type of storage packaging that can be used is dependent on the part characteristics (Hales and Andersson, 2001), which is a contextual condition having implications for the flexibility of the preparation process. At assembly stations, Wänström and Medbo (2009) show that using smaller packaging in materials storage improves the new product, mix and volume flexibility of the materials flow, as storage locations are more easily removed or added.

The design of the picking package is very much dependent on the batching policy used, as well as the requirements posed by assembly, which is another set of contextual conditions. Brynzér (1995) identifies significant efficiency potentials from the design of the picking package, but also remarks that the design options of the picking package is to a large extent dependent on the requirements on the materials preparation from the assembly, in terms of whether the picking package uses a structured or unstructured design. A structured design of the picking package could also improve the picking accuracy, as each part type then has a specific position and a missing or erroneous part is more easily detected.

In summary, both the storage packaging and the picking package design have been identified as influential on the materials preparation performance in previous research. However, the influence on all three performance objectives treated in this thesis are not clear from previous research.

2.4.6 Materials handling equipment

The materials handling equipment design variable is concerned with the equipment types and the design of the storage, categorised as the aspects support equipment and the storage equipment. The materials handling equipment has been linked to flexibility (Chan, 2002), where for example Wänström and Medbo (2009) found that the storage rack design can influence the volume, mix and modification flexibility at assembly stations. Support equipment concerns the design of lifting devices, the design of trash bins and return trays for empty packaging that may be necessary to use due to contextual factors, as the part characteristics and the type of storage packaging used (Hales and Andersson, 2002). Although multitudes of different materials handling equipment types exist from retailers, more research is needed that compares different alternatives in regards to the impact on the materials preparation performance.

2.4.7 Picking information

The picking information concerns the information which communicates to the picker what is to be picked, where picked items should be placed, and the manner in which the picking operator confirms completed operations. The aspects concerned with the picking information include the picking information system type and the information structure. The system type includes the picking medium (Brynzér, 1995) and the technology used for confirming completed operations. The information structure is in this thesis concerned with the physical labels on the storage racks that communicates the storage location identity, the physical labels on the picking package, the interface between the picking information system in the material preparation process and the production planning system, and the design of the information that is communicated.

Brynzér and Johansson (1995) identifies several issues with how picking information is conveyed to the picking operator, in addition to how the systems used in industry are designed. Inappropriate design of picking information systems impacts picking accuracy negatively, which creates disturbances in the storehouse and the production processes (Brynzér and Johansson, 1995). As explained by Park (2012), the use of automatic presentation of information is increasing, where the developmental direction is towards hands-free and paperless systems. The primary advantage of using such systems is the facilitated search and extraction process for items from storage and the reduction of picking errors (Park, 2012). A number of different types of picking information systems are mentioned in literature, where the most common include the paper picking list, pick-by-light and pick-by-voice (Battini et al., 2015). In recent years, pick-by-vision systems based on head-up displays are also emerging as a viable alternative to the traditional systems.

In summary, the picking information is a central design area for materials preparation, because it is connecting the process to the overall production system. There are also high requirements on this design area in terms of information accuracy and information clarity towards the picking operator.

2.5 The materials preparation context

In the design framework of this thesis, a central part is the differentiation between those aspects of the materials preparation design that influence the materials preparation performance and those that does not, as well as what can be designed by the materials preparation designer. The context is outside what can effectively be influenced when designing the materials preparation, but includes those aspects that have an influence on the performance. This influence can be wither direct, in terms of directly contributing to the performance, or indirect, in terms of influencing the link between some other design variable and the performance. This types of factors are in this thesis denoted as context factors. This section aims to exemplify what context factors there might be, without explicitly defining the overall context of the materials preparation, as this is not part of the thesis purpose. The section will focus on two context factors brought forth in previous literature, these are: the part characteristics and the assembly requirements.

2.5.1 Part characteristics

The part characteristics are concerned with the size, weight, shape and fragility of parts that are picked in materials preparation. The specific part types and variants presented in a materials preparation process are determined from the evaluated benefit at the assembly line from receiving prepared materials (Hanson, 2012). The part characteristics have major implications for most design areas of materials preparation, including the storage packaging type, the picking package design, the tool types that are necessary in the process and the batching, picking and storage policies (Hales and Andersson, 2001), and is hence a crucial consideration in regards to materials preparation design.

2.5.2 Assembly requirements

In addition to the basic requirements the materials preparation process is designed to fulfil, there might also be additional requirements which would improve the utility of materials preparation as experienced in assembly. These additional requirements could include positioning or sorting of parts for easier handling of prepared materials in assembly (Öjmertz, 1998). Such requirements influences in particular the picking package design and the picking policies that can be used and should be considered in the materials preparation design.

2.6 Synthesis of the framework into a conceptual model

This section synthesises the framework that has been outlined previously in the chapter. on the link between materials preparation design and performance outlined in this chapter. This is done in the conceptual framework shown in figure 2.8. The framework is used to organise the results of the research and will be linked back to in the results chapter (chapter 5).

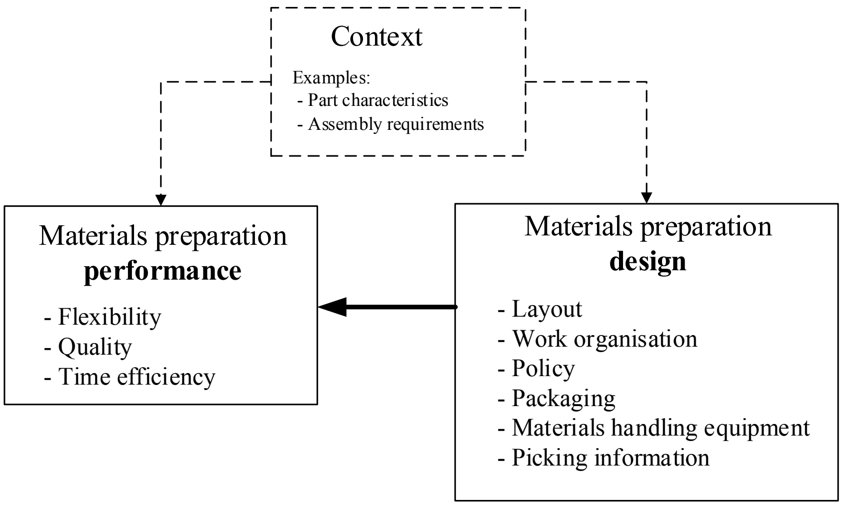

Figure 2.8. – The framework derived from previous literature on the link between the design and performance of materials preparation processes

3 Research method

This chapter describes and motivates the research methods that are used in the three appended papers. The first section describes the general research process. The second section describes the research design, in terms of the overall design used in the thesis. The third section describes the empirical studies conducted, in terms of the study design, case selection, data collection and data analysis. The fourth section discusses the validity and reliability of the three studies. The thesis builds on three separate studies that each has resulted in one paper.

3.1 The research process

The research presented in this thesis has been performed as part of a research project within the VINNOVA FFI-programme of sustainable production. The research project is a collaboration between Chalmers and Swedish industry and envelops three automotive OEMs, three suppliers to the automotive industry and a logistics service provider. The case studies selected for the studies in this thesis have been conducted at the sites of the three automotive OEMs, but from multiple sites of these OEMs. The other project parties have been involved during the formulation of the research objectives and in validation processes within the studies.

Throughout the research project and for the studies conducted, the general research process can be outlined as follows:

- Discussions with the companies, in parallel with reviews of the literature, have resulted in the problem formulation of the studies
- Continued literature review and pilot studies at the companies have concluded in the research design and the conceptual and analytical frameworks used in the studies
- Based on the conceptual and analytical frameworks, the cases for the case studies were selected (study 1 and 2) and the experimental design was specified (study 3)
- Data collection for the selected cases and experiment trials was conducted (see section 3.2 for details)
- For studies 1 and 2, preliminary analysis was conducted and missing data was supplemented
- Primary analysis was conducted, where preliminary findings were derived for all studies
- Preliminary findings were presented for and discussed with the industrial project partners
- A paper for each of the studies was written to report the findings of each study

A time line for the research process is shown in figure 3.1, showing the sequence in which the three studies were carried out and the sequence of the separate parts of each study.

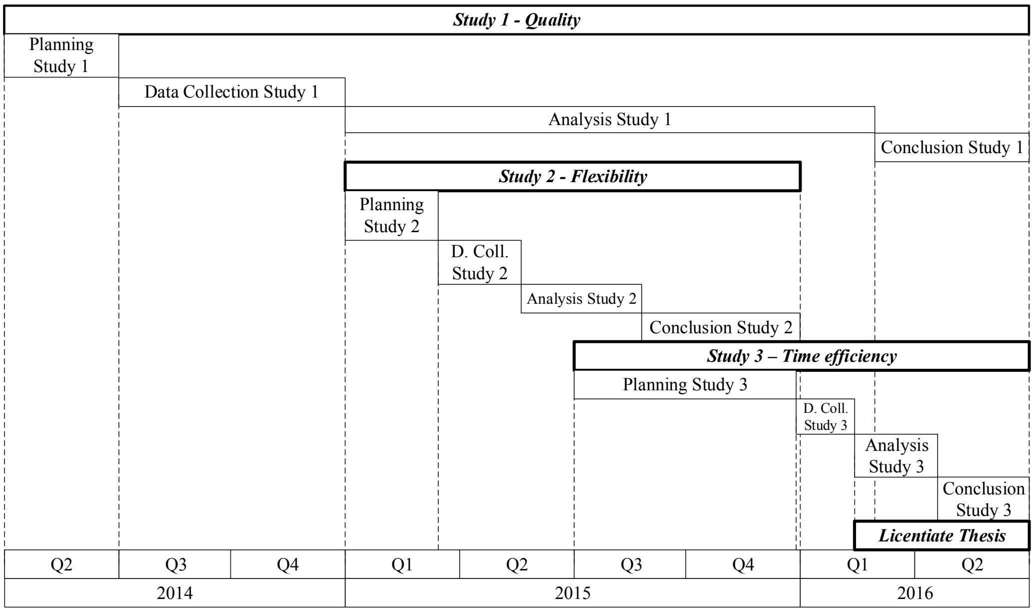

Figure 3.1. The time line for the research process

3.1.1 The formulation of the research project

At the outset of the PhD studies, the author had been employed as a research project assistant for 16 months. During the employment as research project assistant, the author's primary work tasks was to assist in two different research projects, being course assistant in master level courses, and to participate in the formulation of the application for the research project which funded the PhD studies.

Over the first two weeks of the PhD studies, the author spent time at one of the project parties' facilities, participating in kitting operations and discussing the operations with the process manager. This experience has facilitated the research work by providing a personal reference point throughout the research. Within the first month of the PhD studies, a pilot study was conducted at the project companies' facilities, having the aim of assessing the current state of the materials preparation operations at the project companies. A secondary aim was to further specify the focal areas for the research that had been formulated in the project application.

The pilot study included direct and participatory observation of materials preparation processes at the project companies, where drafts of data collection templates derived from literature were used to develop basic process descriptions. These descriptions were later used in the case selection procedure for study 1 and study 2. Over the first six months of the research project, multiple workshops were organised together with the project companies, where their expectations on the research project were matched with the outcome of studying the literature, in order to identify viable directions for the research, combining industrial and theoretical relevance.

At an early stage within the research project it was discovered that the knowledge on how to design effective materials preparation processes varied substantially between the different parties. For example, some of the project companies were working on reducing the picking error levels downwards from 22 errors per million parts picked in a highly standardised environment, while others were having trouble in properly implementing a decent picking information system. There was also a remarkable difference between the degree of detail of the guidelines used to design the materials preparation processes at the companies, ranging from global standardised and detailed guidelines, to almost ad hoc solutions on a case-by-case basis, not following any specific guidelines beyond the previous in-house experiences.

It was clear from the dialogue with the project companies, during the formulation of the research application, that the main performance areas of concern within the area of materials preparation was quality, flexibility, time efficiency, and ergonomics. The four performance areas of flexibility, quality, time efficiency and ergonomics were focused by the research project as a whole, while the author chose to focus on flexibility, quality and time efficiency in this thesis.

3.2 Empirical studies performed

This section presents the research methods used in the studies. The section is divided into the sub-sections study design, case selection, data collection and data analysis. In each sub-section, each study is described separately. The validity and reliability is treated in the next section, section 3.3.

3.2.1 Research design

Maxwell (2010) explains the research design to be the interaction between the research questions, the research goals, the conceptual framework, the research methods and the research validity. Drawing on Maxwell's framework of research design, this section presents the interaction between the components of the framework, in terms of how the research in each of the three studies was conducted.

3.2.1.1 Study I (on quality performance)

Already in the planning stage of study I, materials preparation quality was understood as a difficult phenomenon to study empirically, due to the difficulties in gathering data on picking errors, which is necessary to obtain if having a quantitative approach. This difficulty was the primary reason why the initial research focus was directed towards quality, as it was realised that knowledge was scarce both in academia and practice due to the difficulty of measuring picking errors and, hence, that an important contribution could be made. During the pilot study, records of picking errors for the case processes were difficult to obtain. Also when picking error records were available, the procedure with which the records were established were often unclear, making it questionable what the records actually showed. Therefore, a purely quantitative approach focusing on picking error records was not deemed feasible and it was realised that more knowledge on the nature of the quality phenomenon was needed. The choice here was to use case research, in order to also capture qualitative aspects about the quality phenomenon.

Previous research on quality in picking operations is mostly concerned with the cost of quality problems, accounted for by a cost factor in a larger evaluative model (see for example Caputo and Pelagagge, 2015). However, as discussed by Grosse (2015), the relation between picking errors and the order picking system design is not well understood in literature, apart from some observations on the subject in for example Brynzér and Johansson (1995), but in these cases as part of a broader scope. On this note, the intention was to investigate the phenomenon further and a multiple embedded case study was chosen, as this would allow for the influence of multiple design variables on the quality outcome to be studied. As it was discovered at an early stage in the study that complete and reliable picking error records was difficult to attain, the focus was shifted to the outcome of root-cause analyses that had been conducted in the studied cases upon detecting a problem with the prepared materials at the assembly line. This meant that while the complete record of picking errors were unavailable, there was still experience available in terms of adjusting and improving the processes to improve the quality outcome. Hence, the study shifted focus from comparing materials preparation processes based on picking error records to a focus on the experiences from working with improvements to prevent picking errors. On this note, the embedded case study forming study I was designed. This data was the basis for the paper presented at the SPS conference in September 2014 that is appended in the thesis.

The intention for the rework of the conference paper appended in the thesis into a journal ready paper, is to reduce the number of cases included from nine to four, and to add a new case, that will result in a total of five cases in the revised version. The primary reason for this measure is the overlap between the cases, in terms of the replication logic, in the version of the paper appended in the thesis. From a cross-case analysis point of view, the cases that are taken away adds little value to the conclusions. At the same time, the reduction of cases will allow for a more refined analysis for each case in the paper, enabling a higher level of clarity in the results. The addition of the new case is done to allow for a better fit with the replication logic used for deriving the conclusions from the cross-case analysis.

3.2.1.2 Study II (on flexibility performance)

The second topic identified to address was flexibility. The issue, as stated by the project companies, was that floor space was limiting the use of materials preparation, where current materials preparation designs required too much space in relation to the amount of part numbers each preparation process managed, i.e., the processes lacked the necessary flexibility to handle the part numbers. Hence, the aim expressed by the companies was to understand how the materials preparation should be designed to manage more part numbers for the same amount of floor space, i.e. how the process could be made more flexible in terms of production volume and mix. It was also observed during the pilot study that the picking information system at some of the project companies were not up to date with the current bill of materials, leading experienced picking operators to neglect the information system and, instead, pick from experience. Obviously, the risk for picking errors was high when the order contents changed, which was indicated by the very high picking error levels observed in the picking error records available. It was at this point proposed that the updating of picking information was avoided due to a lack of flexibility in the materials preparation processes, i.e., it was too difficult, or time-consuming, to update the picking information according to changes in the bill-of-materials or the assembly process and keep the picking information up to date with the requirements on the materials preparation from the production system.

These two starting points - the ability to handle more part numbers on the same amount of floor space and the ability to keep the materials preparation up to date with the requirements from the production system - indicated that a flexibility focused study could make a contribution to practice. When reviewing literature on flexibility for materials preparation, previous research rarely focused on flexibility for any type of picking operations, apart from considering a single design variable (e.g. Hanson et al., 2013), or as part of a larger reasoning on the effects of kitting as a materials supply method (e.g. Caputo and Pelagagge, 2011). Overall, literature was unclear on what flexibility meant for materials preparation and how the design influenced the flexibility. Therefore, the intention was to derive a framework for how flexibility could be assessed for materials preparation processes and to learn how the design influenced the flexibility, why a case research approach was chosen.

From studying literature on primarily manufacturing and materials supply flexibility, a model for how to assess flexibility was derived, focusing on the cost and time requirements for changing the preparation process to adapt to new production system requirements, see Section 2.3.2 for details. The application of the model to the 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 model could be refined, given the data that had been collected, where in particular the mechanism of flexibility could be explained in greater detail. This was the primary aim during the revision of the paper into the version appended in this thesis.

3.2.1.3 Study III (on time efficiency)

The third focus in the research was directed towards the time efficiency when using different picking information systems. The focus was established during the pilot study and the project workshops, where the project companies expressed concern about what picking information to use in which environment and how emerging technologies, as for example head-up displays and RFID scanning devices, performed in materials preparation. Requests for comparisons between alternative picking system designs was also apparent in literature, for example Hua and Johnson (2010) and Grosse et al. (2015). Hence, there was a potential for both a practical and a theoretical contribution from comparing different picking information systems.

It was realised during the planning of this study that a different approach than for the quality and flexibility focused studies was required in order to make an accurate comparison. In particular, a controlled environment was deemed necessary in order to compare alternate designs accurately. 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 the companies and participants involved and installing the equipment. Once everything was in place, the actual data collection was completed during three full days of trails.

3.2.2 Case selection

In common for both case research and experiments is that generalisation from any findings to theoretical propositions is done analytically, as opposed to statistically (Yin, 2003). To enable analytical generalisation in multiple case studies, cases should be selected based on a replication logic (Voss et al., 2002). This section describes how replication logic was used in the case selection procedure in study I and study II, and further explains how the experimental design in study III was selected and defined.

3.2.2.1 Study I and study II

Studies I and II followed a similar procedure for the case selection process. For both studies, an initial literature study was performed that led to the development of the study frameworks. In both studies, the frameworks contained the design variables to be studied and the relevant values of the variables. Based on the frameworks, the cases were selected from reviewing the materials preparation process descriptions developed during the pilot study. Based on these process descriptions, replication logic was used to select appropriate case processes for each of the two studies.

In study I, nine cases were selected based on a replication logic, where the the picking information system type was prioritised (for details, see appended paper II). The four case processes at company A were located in the same department, nearby one another, which allowed for four different process designs to be studied that differed little in terms of the context. Thus, a comparison between the different design variable options could be isolated. The three case processes at company B were not located nearby one another, but as the cases were within the same production system, the context was also similar for the cases at company B. The two case processes at company C was located next to assembly and in a separate department, respectively, but as for cases at company B, the context was similar for the cases at company C, why the influence of the design variables could be isolated to an extent. The cases were selected in order to differ in their design according to the framework, why different quality outcomes were expected, i.e. a theoretical replication (Yin, 2003).

In study II, the theoretical framework was based on design variables identified as central for flexibility in literature, derived from a literature study on kitting, order picking and manufacturing (for details, see appended paper I). The cases were chosen based on theoretical replication logic, in terms of each case exhibiting a unique characteristic among the selected. For example, Case A had a stationary rack design with few components per kit and high number of kits per picking package, in addition to a high number of product variants at the preparation area, and used a pick-by-voice system with finger scanning. An even more complex scenario was found in case B, which had a fewer number of kits per picking package, although still many in comparison to the other cases, but a higher number of components per kit and used a pick-by-light and place-by-light system for picking information. Cases A and B had roughly the same number of part variants at the preparation area. Case C, in contrast to cases A and B, had relatively few parts per kit and kits per picking package, but used a pick-by-light system as primary picking information. The reader is referred to the appended paper, paper I, for more details concerning the case selection.

3.2.2.2 Study III

During the design of the experiment, the strategy was to arrange the experiment set-ups as close as possible to real-life industrial processes that in the pilot study was assessed as exhibiting high performance. Further, in a parallel study that was ongoing within the research project, case research was used to determine the influence of the design variables of kit preparation processes on the time efficiency performance, that comprised 15 cases (Hanson and Medbo, 2015). This study provided further guidance on an appropriate design of the experiment, where those design variable values that was identified as having a positive influence on the time efficiency was used as input to the experimental design. Lastly, the experience from similar studies within the research group was another input. The resulting experimental 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 processes.

3.2.3 Data collection

According to Yin (2003), there are six sources of evidence in case research, of which three has been used in studies I and II: archival records, interviews and direct observation. This section describes these three data collection methods used in the studies, as well as how the data collection was performed in the experiment. The reader is referred to the appended papers for further details.

3.2.3.1 Study I and study II

The data collected from the cases in study I include interviews with managers of the processes and logistics team leaders, direct observation of the cases as well as excerpts from root-cause analyses of picking errors, which are considered as archival records. Study II used similar types of data as study I, including interviews with managers for the case processes, excerpts from projects for redesigning the case processes, here denoted as archival records, as well as direct observation.

An extensive literature review was conducted at the outset of both study I and study II. This led to a conceptual framework from which a research protocol and a data collection template could be derived. The focus when developing the data collection template was to include both hard aspects, in terms of sizes and counts, as well as soft aspects, in terms of how the work was conducted and perceived. In a way, the data collection template can be said to have included both exploratory parts and confirmatory parts, which yielded rich as well as precise data. The interviewees were identified with support from the key informants, which were connected to the research project. Each interview was preceded by a visit to the facility where the processes were observed and the majority of the descriptive aspects of the protocol could be completed. Any unresolved aspect of the descriptions was resolved during the interviews. During the interviews, the author and at least one more researcher were present. For all interviews, the author led the interview and the other researchers kept track of the conversation and emphasized 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 missing parts detected were supplemented on short notice over telephone.

The sites accommodating the cases were visited for direct observation at the outset of each study, after the framework derived from literature had reached consistency so that the lines of inquiry were known. During the observation, an observation template was used to ensure that the descriptive data concerning the design variables were captured. As emphasised by Yin (2003), 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. During the observations, notes were taken and any questions about the operation of the processes were answered by the process managers and team leaders that guided the visits. At those sites were permission was attained, the cases were video recorded. Additionally, many photographs were taken during the visit for later reference, in regards to layout and specific values of the design variables. However, due to the nature of quality problems, being rare and thus impossible to plan to observe, the information gathered during the visit rather concerned the operation of the processes and not necessarily the quality phenomenon per se. It should also be noted that at this stage of the study, the specific cases to be included in the papers had not yet been selected, but the same types of information were gathered for all processes observed.

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 (2003), interviews should be conducted with the purpose of the inquiry in mind. In this case, 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 more focused on the parts of the framework that were less certain, in terms of being based mostly on theory rather than the understanding attained during the initial visits, could be employed for the interviews, where an interview template guided the conversation. The interview template was sent to all interviewees on beforehand with a request to review the questions before the interview. This enabled a focused approach during the interview, yet the questions on the template were ensured to all 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 how the process functioned without being led towards a certain answer, thus strengthening the internal validity (Yin, 2003).

3.2.3.2 Study III

The data collection for study III was conducted in a laboratory environment. Given the topic of research question III, the focused measure was the time required to complete one picking tour. To extract the time from the trials, video recording was used, which 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 picking accuracy to be evaluated. The reader is referred to the appended paper III for more details on the data collection in study III.

3.2.4 Data analysis

The two case studies – Study I and II – both employed within- and cross-case analyses to derive the study conclusions. In accordance with Yin (2003), the within case analyses built on pattern matching between the case data and the theoretical frameworks developed. From the conclusions drawn in the within-case analyses, cross-case synthesis was used to derive the study conclusions. The experiment focused a single dependent variable - the time for conducting the picking operations - from which statistical analyses of the independent samples yielded the study findings. This section further describes the analysis procedures used in the each of the three studies.

3.2.4.1 Study I and study II

The data analysis for studies I and II were conducted in three stages. The first stage begun right after the data had been collected, where the data was preliminary matched to the framework to see if any vacancies existed, which was supplemented as described in section 2.3.3. The second stage was a more detailed analysis of how the data matched the framework. This stage consisted of two parts. The first part was the within-case analysis, where each case was analysed separate from the other cases in terms of the study framework. Then, in the second part, the separate analyses of the different cases were compared and the influence from the design variable on the studied performance could be derived in the cross-case synthesis. The results from the second stage were then discussed with the project companies, including the companies at which the studies were conducted, yielding further refinement of the results, and then presented at conferences for additional insights. At this point, the third stage of analysis begun, where the frameworks were revised based on the insights provided by industry and academia, yielding the versions of the papers appended in this thesis.

3.2.4.2 Study III

The data analysis for study III was more straightforward compared with the two first studies, considering the quantitative data in terms of time measurements of the picking times. After extracting the times for each individual picking tour, organized per operator and system, using video-analysis software, data sets with differences between the respective picking information systems were calculated. These data sets were then analysed using independent samples t-tests in SPSS, with the null hypothesis of no difference.

3.3 Validity and reliability

To assess the validity and reliability of the research, the framework from Yin (2003) is used, which has been recommended by for example Voss et al. (2002) for evaluating the validity and reliability in case research. Yin's framework is also used to assess the validity and reliability of the experiment in study III. The framework consists of the criteria construct validity, internal validity, external validity and reliability. This section is structured by these four criteria and treats studies I, II and III, one criteria at a time.

3.3.1 Construct validity

The definition of construct validity used in this thesis is expressed as "the extent to which we establish correct operational measures for the concepts being studied" (Voss et al., 2002, pp. 211). According to Yin (2003), construct validity implies that case research use multiple sources of evidence in order for the evidence to converge on the line of inquiry (Yin, 2003). The convergence is ensured from maintaining a "chain of evidence", in terms of the data being traceable over time and that the sequence in which the data is collected is recorded, to ensure that no evidence is lost or neglected, and from having key informants review drafts of the case study report. Voss et al. (2002) also suggests that observations should be made about whether the predictions for the relationships to other variables can be confirmed, to ensure construct validity.

3.3.1.1 Studies I and II

In terms of establishing a chain of evidence, a similar procedure was used for studies I and II. For both studies, case descriptions were developed after the direct observation, notes and video recordings had been collected during the site visits. All interviews were voice recorded and transcribed within a week after each interview. Archival records and supplementary documentation from the company were sent by email or received in conjunction with the interviews, and was archived together with the other case data. In this manner, a case research database was established for each study. Key informants were asked to review the drafts of the case study reports via e-mail and the comments received provided refinements to the study conclusions. The conclusions have at several occasions been presented for and approved by project company representatives, including the companies at which the studies were performed, and the key informants for each case.

3.3.1.2 Study III

Study III used an experimental design in a laboratory setting, which may raise concern regarding construct validity. To ensure that the setting represented a real kit preparation process in industry, three measures were used. First, the research group's previous experience of kit preparation process design facilitated the decision-making on the appropriate settings. Second, the parallel case study on kit preparation time efficiency in the research group made large amounts of data from various kit preparation systems available, enabling details regarding the experiment setup to be reviewed and assessed in terms of representativeness for real kit preparation processes. Third, a continuous dialogue was upheld with the project companies. When needed, they provided drawings for equipment, layout schemes and answers to any other questions regarding real-life settings on short notice. Further, the project company representatives also reviewed and approved the design during a project workshop organised in the laboratory.

3.3.2 Internal validity

Internal validity is according to Voss et al. (2002, pp. 211) "the extent to which we can establish a causal relationship, whereby certain conditions are shown to lead to other conditions, as distinguished from spurious relationships". Yin (2003) proposes four approaches to ensure internal validity: pattern matching, explanation building, addressing rival explanations and using logic models.

3.3.2.1 Studies I and II

Yin (2003, pp. 36) explains that case studies involve an inference every time an event cannot directly be observed and that inferences of this kind must in some way be ensured to be correct in order for the study to show internal validity. Both study I and study II does rely on inferences made on events that could not directly be observed, for example the picking errors in study I and the changes made to the case processes in study II.

In study I, the internal validity was considered by focusing the interviews on the root-cause analyses that had previously been conducted at the case processes. However, the problem does to some extent persist, in terms of the root-cause analyses also being inferences to the actual events, i.e., the picking error. However together with the insights from the interviews, the theoretical framework derived from literature, the direct observation of the processes, and the picking error records, provided multiple perspectives on the causal links addressed in the study, why the findings could be distinguished from spurious relationships. Considering the collected data, in particular the incomplete picking error records for some of the cases, the intention with the study design was not to make a statistical inference from the cases, but rather an analytical research approach was used where the reviewed picking error records contributed to the estimation of the quality construct, rather than determining it. The estimation of the quality construct in the particular case was hence the combined estimate from the interviews and the archival records collected, which together with the pattern matching, with literature, and the cross-case comparisons, strengthens the internal validity.

In study II, the cost and time estimates for making the necessary changes to the processes are inferences to events which could not be observed directly. However, similar to study I, the pattern matching with the framework derived from literature, the cross-case comparisons and the additional insights gained during the interviews from discussing the actual mechanisms behind the changes in detail, strengthens the internal validity of the study.

3.3.2.2 Study III

As the experiment was conducted in a laboratory environment, where full control of the settings was possible, the settings could be adjusted to be in accordance with the study aim. Hence, a high internal validity could be achieved.

3.3.3 External validity

External validity is concerned with the generalisability of the findings beyond the immediate case study. External validity may be problematic for case studies, as each case exists in its own unique context. One approach for improving the external validity in case research is to use replication logic in multiple case studies (Yin, 2003).

3.3.3.1 Studies I and II

Replication logic was used both in studies I and II, which was enabled by the study designs. In both study I and study II, the design variables were embedded in each case, which allowed for a replication logic to be used for the respective design variable. The replication logic used, together with the pattern matching with the theoretical framework used in the within-case analyses, strengthens the external validity of the conclusions in studies I and II.

3.3.3.2 Study III

The laboratory setting for the experiment in study III, as opposed to an industrial setting, makes the external validity questionable. However, as discussed in section 3.3.1.2 in regards to the construct validity, the consideration taken to previous literature, the rich data available from the parallel case study and the continuous dialogue with and the review by the project companies, strengthens the external validity of the study.

3.3.4 Reliability

The reliability of research is concerned with whether the same findings and conclusions could be arrived at if the study was to be replicated by another researcher. Yin (2003) emphasise that it is the replicability of analysing the same case one more time and arriving at the same conclusions that is the concern in case research, rather than conducting another case study and arriving at the same conclusions. To ensure reliability in case research, a case research protocol should be used and case research database should be maintained (Yin, 2003).

3.3.4.1 Studies I and II

As was described in section 3.3.1.1 concerning the construct validity, a case research data base was carefully maintained in both study I and study II, where the data collection procedures as well as the actual data was thoroughly documented, in terms of recordings and transcriptions of the interviews, note summaries of each site visit and direct observation as well as time and activity logs of the research work. The studies also used a case research protocol, which was realized by the use of the data collection templates for collecting the data in each case, which then served as the criteria according to which the data was collected, which strengthened the reliability of studies I and II.

3.3.4.2 Study III

The detailed knowledge and control of the factors in the studied case in the experiment allowed for a detailed understanding of the conditions during which the data was collected, that when combined with the documentation of the procedures and notes taken during the experiment, ensured the reliability of the data. The understanding of the conditions during which the data was collected was facilitated by the interviews with the participants, where for example the previous experience of logistics work was discussed, the personality tests and the preceding training sessions. Also, the warm up rounds with the video cameras recording allowed the participants to become acquainted with being video recorded before the actual measurements were started, which reduced the influence on the behaviour once the actual measurements were started.

4 Summary of papers

This chapter aims to summarise the three appended papers in order to provide the reader with an overview of the appended papers. The reader is referred to the appended papers for more details.

4.1 Paper I – Flexibility of kitting processes in production systems

Paper I studies the flexibility of materials preparation processes in kitting and sequence based materials supply to automotive assembly systems. Flexibility is in the paper defined as the ability of the materials preparation process to adapt to the changing requirements in the production system, where flexibility is assessed from the cost and time expenditures for making the necessary changes. The empirical basis of the paper is an embedded multiple case study of five materials preparation processes in automotive materials supply. The paper derives an operationalisation of flexibility for materials preparation processes, which is used to assess the flexibility for each case in a within-case analysis. Then, the influence of the studied design variables on the materials preparation flexibility is synthesised in a cross-case analysis. It is learned from the paper that the picking information system type, the work organisation around physical and IT-system changes, the storage packaging type, the picking package design and the storage assignment policy have significant influence on the flexibility of the materials preparation process. Further, it also learned that the floor space around the preparation area, empty storage locations in the storage racks and excess shift capacities are contextual factors that influence the materials preparation process' ability to manage changing requirements in the production system.

4.2 Paper II – Quality problems in materials kit preparation

Paper II studies the influence of materials preparation design variables on the materials preparation quality. The empirical basis of the paper is an embedded multiple case study, comprising nine cases of materials preparation for kitting and sequence based materials supply to automotive assembly systems. The data collected for the cases includes interview data from interviews with managers for the case processes and logistics team leaders, direct observation of the cases processes, excerpts from root-cause analyses of picking errors reported by the assembly system and pick-error records for the cases where such records were available. The study uses a conceptual framework, derived from literature on quality in order picking, kitting and assembly operations, to analyse each case in within case analysis, where the influence from the focused design variables on the picking error types is derived for each case. Then, the cases are compared in a cross-case analysis, where the different values of the design variables in the cases and their corresponding influence on the quality performance is synthesised into the results framework.

4.3 Paper III – Time efficiency of picking information systems in materials kit preparation

Paper III studies the influence of the picking information system on the time efficiency in kit preparation. The empirical basis of the paper is an experiment study performed in a laboratory environment where four principally different picking information systems are compared based on time efficiency for two different batching policies. In addition to the time efficiency, the number of incorrectly executed order lines was determined for each picking information system type in each of the batching policies. The paper finds that the confirmation in the picking and placing operations can influence the time efficiency of the kit preparation and indicates that while batching may improve the time efficiency if the confirmation is carefully designed, batching may also compromise the picking accuracy due to the multiple placement locations.

5 Results

This chapter presents the results of the thesis as responses to the research questions. The chapter is structured by the responses to each research question, where Section 5.1 provides the response to research question 1, Section 5.2 provides the response to research question 2 and Section 5.3 provides the response to research question 3. For reference, the research questions are restated at the beginning of the section were the response to the respective research question is provided.

In this thesis, the empirical studies performed equals the number of papers, where one study is reported in one paper. The responses to the research questions is either made directly by one of the papers or from a synthesis of the papers and the theoretical framework in the cover paper. Specifically, research question 1 is responded to by Paper I synthesised with the theoretical framework in the cover paper. Research question 2 is responded to by a synthesis of Paper II, Paper III and the theoretical framework in the cover Paper. The synthesis for answering research question 2 is presented in Section 5.2 in this chapter. Research question 3 is responded to by Paper III only. The relations between the 3 studies, the 3 papers, the 3 research questions and the theoretical framework in the cover paper is illustrated in Figure 5.1.

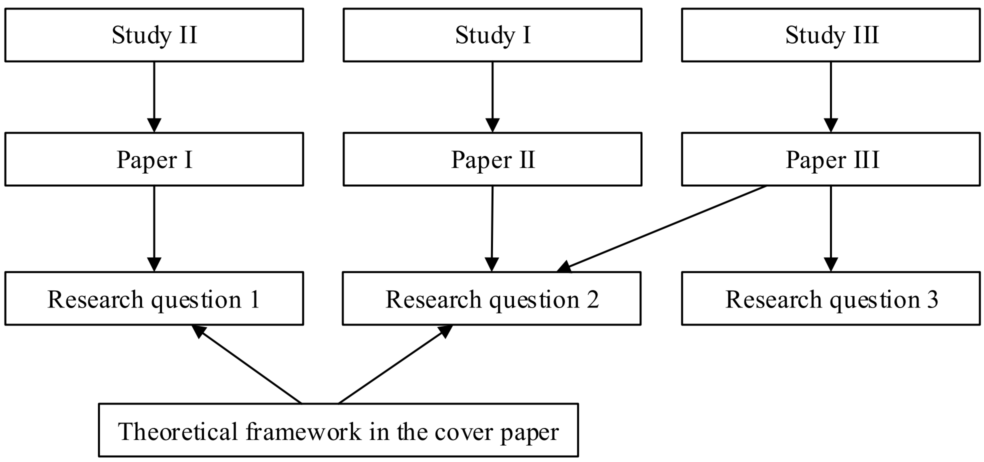

Figure 5.1. The relation between the studies, papers, research questions and the theoretical framework in the cover paper

The theoretical framework in the cover paper, developed in Chapter 2, is used to structure the answer to research questions 1 and 2 in Section 5.1 and 5.2, respectively. For the reader's reference, the part of the framework concerning the design variables, depicted in Figure 2.7, is restated here in Figure 5.2.

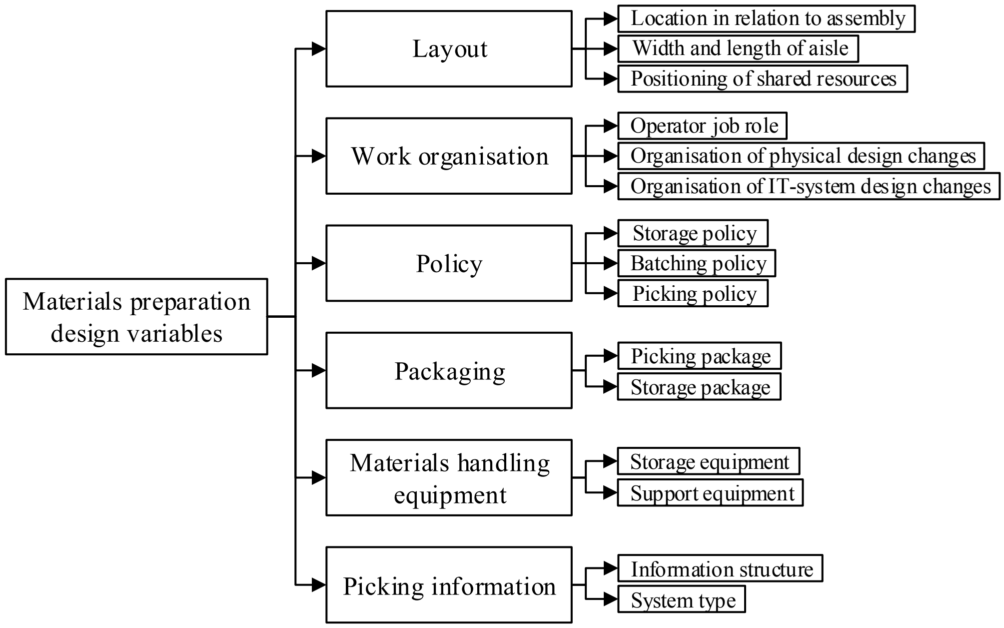

Figure 5.2. The design variables framework used in the thesis

5.1 The influence of materials preparation design on materials preparation flexibility

Research question 1 concerns the influence of the materials preparation design on the materials preparation flexibility and is restated here for reference:

Research question 1:
How does the materials preparation design influence the materials preparation flexibility?

This question is responded to by a synthesis of the theoretical framework in Chapter 2 with Paper I. In Paper I, a framework over the links between design variables and flexibility was developed based on literature and a multiple case study. The aspects to the design variables that are considered in Paper I are:

- The location of the preparation area
- The layout of the preparation area (the storage assignment policy)
- The work organisation around physical- and IT-system changes
- The operator job role
- The storage packaging type
- The materials handling equipment (lifting supports and storage rack design)
- The picking information system type

Additionally, a number of context factors were identified to influence the materials preparation flexibility:

- Floor space availability around the preparation area
- The part characteristics, in terms of size and weight

Flexibility is in this thesis defined as the ability of the materials preparation process to adapt to changing requirements in the production system. The conceptual framework developed in Paper I for how the materials preparation design influence the materials preparation flexibility, and the role of flexibility in regards to the ability of the materials preparation process to handle changed requirements in the production system, is shown in Figure 5.3.

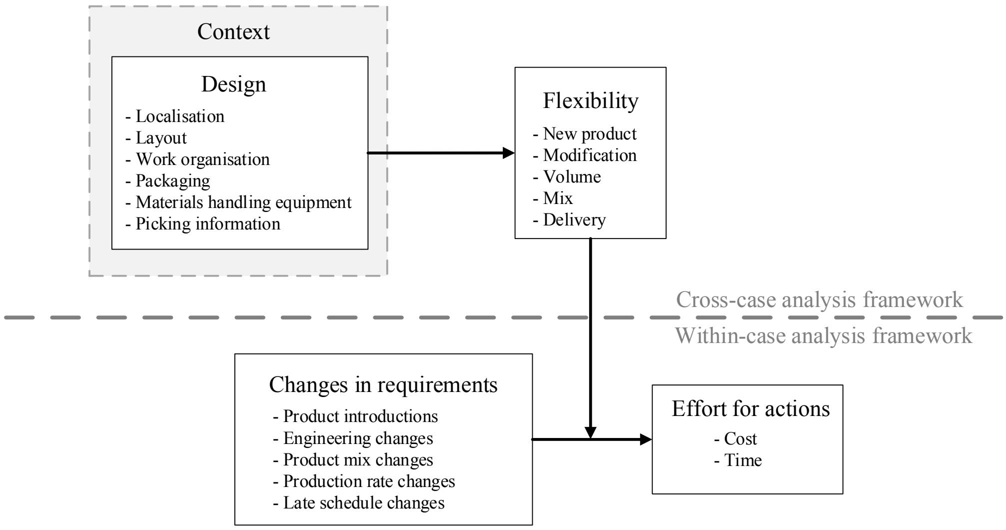

Figure 5.3. The conceptual framework developed in Paper I for how the materials preparation design influence the materials preparation flexibility

5.1.1 Layout

Paper I found the influences presented in Table 5.1 from the location relative to assembly on the materials preparation flexibility.

Table 5.1. The influence of the location in relation to assembly on the flexibility

Design variable	Flexibility type	Direction of influence	Description of influence	Contextual influence
Localisation: Distance to point-of-delivery	New product	Positive with increasing distance	Floor space to make room for more part numbers is more likely to be available farther away from the point-of-delivery (observed in cases A and E)	*Floor-space availability:* Necessary for extending the depth of storage for more part numbers (all cases) or more inventory (case B)
	Modification			
	Mix			
	Volume			
	Delivery	Negative with increasing distance to point of delivery	Long distances from point of delivery requires delivery batch to be ready when tugger-train arrives (case E)	(Not observed)

Paper I did not identify any influence from the position of key resources at the preparation area on the flexibility, nor from the length and width of the picking aisle. However, the absence of observed influence from these design variables in Paper I does not equate that there is no influence, but the absence rather indicates that within the scope of Paper I, no influences could be identified.

5.1.2 Work organisation

Paper I found the influences from the influence from the work organisation on the materials preparation flexibility shown in Table 5.2.

Table 5.2. The influence from the work organisation design area on the materials preparation flexibility

Design variable	Flexibility type	Direction of influence	Description of influence	Contextual influence
Work organisation: Organisation around physical- and IT-system design changes	New product Modification Mix Volume	Positive with increasing organisational integration	Process engineers manage changes as part of daily work (high flexibility: cases A, B, C); in-house firm is available on short notice but requires job-specification (medium flexibility: cases D, E); external contractor availability requires at least mid-term forward planning (low flexibility: case C)	(Not observed)
Work organisation: Job role integration	Volume	Positive with increasing job role integration	If assemblers perform picking, re-balancing is facilitated if production volumes change (case D)	(Not observed)

5.1.3 Policy

The storage policy was in Paper I found to have influence on the materials preparation flexibility shown in Table 5.3.

Table 5.3. The influence from the storage policy on the materials preparation flexibility

Design variable	Flexibility type	Direction of influence	Description of influence	Contextual influence
Layout: Storage assignment policy	Mix	Negative with increasing classification	Part numbers change classification due to variability in demand and thus have to be rearranged (cases A, C, E)	(Not observed)

Paper I did not identify an influence on flexibility from the batching policy. This means that within the scope of the study, no influence could be observed. In previous, Brynzér and Johansson (1995) have for example pointed out that the longer batching time horizon that is required when batching kits may impair the flexibility of handling late order changes. However, in the cases included in the study, the picking information was received by the information system at the preparation areas in advance that this never was perceived as a problem. From a theoretical perspective however, it could be though that batching policies where comparatively extreme numbers of kits are prepared at once, could make the batching time horizon problematic.

Paper I did not identify an influence from the picking policy on the flexibility, However, the absence of observed influence does not equate that there is no influence, rather that no influence could be observed within the scope of Paper I.

5.1.4 Packaging

The packaging design area was in paper I found to have influence on the materials preparation flexibility shown in Table 5.4.

Table 5.4. The influence from the packaging on the materials preparation flexibility

Design variable	Flexibility type	Direction of influence	Description of influence	Contextual influence
Packaging: Storage package	New product	Negative with increasing packaging size	Boxes require comparatively small storage space (cases A, B, D)	*Part characteristics (Part size*): Large parts requires large packaging (all cases).
	Modification		Pallets require comparatively large storage space (all cases)	
	Mix		Addition of a box picking location is likely possible without reconstruction (cases A, B, D)	
			Addition of a pallet picking location is unlikely possible without reconstruction (all cases)	
Packaging: Picking package	New product	Negative with increasing customisation	Customisation to existing part types compromises additions of new part types (cases C, D, E)	(Not observed)
	Modification			
	Volume			

5.1.5 Materials handling equipment

Paper I found the influences included in Table 5.5 from the materials handling equipment on the materials preparation flexibility.

Table 5.5. The influence of the materials handling equipment on the flexibility

Design variable	Flexibility type	Direction of influence	Description of influence	Contextual influence
Materials handling equipment: Lifting support	New product	Negative with increasing mechanisation	Significant costs if changes have to be made (cases D, E)	*Part characteristics (Part weight):* Heavy parts requires lifting support (cases D and E)
	Modification			
	Mix			
Materials handling equipment: Storage rack design	Volume	Positive with increasing re-configurability	Wheel-based racks and shelf-attachments without bolts facilitate smaller redesigns of storage racks (cases A, B)	(Not observed)
	Mix			

5.1.6 Picking information

The picking information design is in this thesis concerned with the information structure and the system type design variables. Paper I found the influence from the picking information system type on the flexibility shown in Table 5.6.

Table 5.6. The influence of the picking information design area on the flexibility

Design variable	Flexibility type	Direction of influence	Description of influence	Contextual influence
Picking information: System type	New product	Negative with increasing automation (moderated by organisation around IT-system changes)	Printed labels require links between location and new part numbers (high flexibility: case E); pick-by-voice requires management of validation codes (medium flexibility: case A); pick-by-light requires cables, light-indicators and links to light-indicators for new part numbers (low flexibility: cases B, C, D)	(Not observed)
	Modification			
	Mix			

Within the scope of Paper I, an influence of the picking information structure on the flexibility was not observed.

5.2 The influence of materials preparation design on materials preparation quality

Research question 2 concerns the influence on materials preparation quality from the materials preparation design variables and is in thesis responded to by a synthesis of the theoretical framework in Chapter 2, with Papers II and III. For reference, the research question is restated here:

Research question 2:
How does the materials preparation design influence the materials preparation quality?

The part of the response to research question 2 provided by Paper II concerns the influence on quality from the design variables:

- Position of key resources at the preparation area (layout),
- The operator job role,
- The storage policy,
- The picking package design,
- The picking information system type, and
- The picking information structure

The conceptual framework used in Paper II to analyse the cases in the within-case analysis considered the situations in which quality problems occurred (denoted as causes of quality problems in Paper II), the types of quality problems that the situation enabled and the design variable values and context factors that enabled the situation to occur (these design variable values and context factors are in Paper II treated under the same heading as determinants of quality problems). The conceptual framework used in Paper II is shown in Figure 5.4.

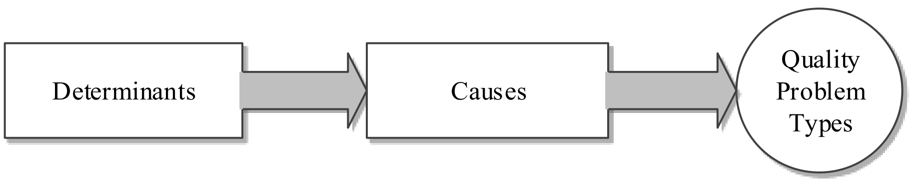

Figure 5.4. The conceptual framework used in Paper II to analyse the cases

As the design variables and context factors were treated under the same heading in Paper II, the results in this section are based on an additional analysis of the findings in Paper II, which involved separating the design variables from the context factors, the result of which are presented in this chapter.

The contribution in the response to research question 2 from Paper III, consists in the influence on the materials preparation quality from:

- The picking information system type, and
- The batching policy

As a result of the additional analysis performed on the results in Paper II, a number of context factors that have a direct influence on the materials preparation quality have also been identified from Paper II. These context factors include:

- The reliability of the materials supply to the preparation area,
- The reliability of the material deliveries from the preparation area,
- Disturbances to the picking work from informal communication
- Part characteristics (fragility and size)

The influences from the design variables and context factors identified in Papers II and III, which were listed above, are reported in sections 5.2.1 to 5.2.6.

5.2.1 Layout

The position of the discarding point for empty packaging or internal packaging at the preparation area, was found to influence the risk for quality problems occurring in Paper II. This influence is shown in table 5.7.

Table 5.7. The influence of the layout design area on the materials preparation quality.

Design variable	Associated cause	Associated quality problem type	Influence from other design variables or context
Position of key resources at the preparation area	Operator forgets next picking operation due to intermittent handling of packaging, particularly if long walks to discard point	Incorrect part Superfluous part Insufficient no. of parts Interchanged parts	Storage packaging type (design variable)

5.2.2 Work organisation

The job role of the operator, in terms of the responsibilities for delivering the prepared materials to assembly, was found to influence the materials preparation quality by increasing the risk of delivering prepared materials with missing parts in Paper II. This influence is described in table 5.8.

Table 5.8. The identified influence of the work organisation on the quality outcome.

Design variable	Associated cause	Associated quality problem type	Influence from other design variables or context
The operator job role	Operator works ahead of tact resulting in shortage, order is then completed with parts missing, but is delivered to assembly by another materials handling operator	Missing part	No. of picking packages in material flow (context)

5.2.3 Policy

The storage policy was in Paper II found to influence the risk of incorrect parts being included in the kits. The influence of the storage policy on the materials preparation quality is shown in table 5.9.

Table 5.9. The influence of storage policy on the materials preparation quality

Design variable	Associated cause	Associated quality problem type	Influence from other design variables or context
Storage policy	Mixed pallet contents due to incorrect return of parts to storage packaging	Incorrect part	Similarity between parts (context)
	Picking from incorrect container, due to similar parts are stored closely	Incorrect part	Similarity between parts (context)

The results in Paper III indicate that the additional placement locations that comes from using a multi batch policy enables placement errors, which can have influence the materials preparation quality. This was also supported by the results in Paper II, as shown in Table 5.11.

The results in Papers II and III did not identify an influence of the picking policy on the materials preparation quality. However, this does not discount the existence of such an influence, but only indicates that the influence could not be identified under the premises of Papers II and III.

5.2.4 Packaging

The packaging, in terms of the picking package design, was in Paper II found to influence the materials preparation quality as described in Table 5.10.

Table 5.10. The influence of the packaging design on the quality outcome

Design variable	Associated cause	Associated quality problem type	Influence from other design variables or context
Picking package design	The batch is completed backwards, hence delivered out of sequence within the batch	Incorrectly sequenced kits or picking packages	Non observed
	Parts can be collected from incorrect kit during assembly, due to presence of several kits in the picking package	Incorrect component	Reliability of final assembly (context)
	Incorrect assumption of kit being complete as parts are already apparent in kit	Insufficient number of parts	No. of parts in the kit (context)

5.2.5 Picking information

Paper II identified the picking information structure and system type to have the influence on the materials preparation quality shown in Table 5.11.

Table 5.11. The influence of the picking information design on the quality

Design variable	Associated cause	Associated quality problem type	Influence from other design variables or context
Picking information system type	Complex situation when using paper picking lists, hence cognitive misinterpretation	Incorrect parts	No. of part numbers at kitting station (context)
	The operator assumes incorrect number of parts due to an order of regular parts in non-standard quantity	Superfluous parts	Non observed
		Insufficient no. parts	
Picking information structure	Two part numbers are placed at each other's destination, not prohibited by picking information system	Interchanged parts	Batching policy (design)
	An incorrect part is collected due to ambiguous light indicator positioning	Incorrect part	Non observed

The observed picking error rates in Paper III further indicates that picking information system types placement confirmation, in multi kit batching policies, could reduce the amount of quality problems in kit preparation. This result can be linked to both the picking information structure and the system type, as an information system type can use different types of confirmation technology.

5.2.6 Context influence

In the additional analysis conducted in the cover paper of the results from Paper II, a number of contextual factors were identified to have a direct influence on the materials preparation quality. These are shown in Table 5.12.

Table 5.12. The direct influence of contextual factors on the quality outcome

Context factor	Associated cause	Associated quality problem type
Reliability of materials supply to kitting process	Incorrect mark-up or packaging from supplier	Incorrect component
	Incorrect replenishment to kitting process	Incorrect component
	Delayed supply to kitting process, hence parts are unavailable during kitting cycle	Known omitted component
		Missing component
		Kit supply lateness
Reliability of materials supply to assembly	Picking packages are retrieved and delivered out of sequence	Incorrectly sequenced kits or picking packages
	Materials supply retrieves packages from assembly with parts remaining, unaware of contents, or assembly operator neglects certain components upon non-recognition	Missing component
Informal communication	Operator forgets next picking operation due to interruptive communication	Incorrect component
Part characteristics	Fragile components can be damaged during picking, transport or assembly	Damaged component
	Small components more difficult to identify	Incorrect component

5.3 The extent of influence of the picking information system type on the materials preparation time efficiency

Research question 3, that concerns the extent of the influence from the picking information system on the materials preparation time efficiency, is responded to directly by Paper III. For reference, the research question is restated here:

Research question 3:
To what extent does the materials preparation picking information system influence the materials preparation time efficiency?

The response to research question 3 is given in terms of two typical kit preparation batching policies, as the difference in time efficiency between four principally different picking information system types: Pick-by-list, Pick-by-light, Pick-by-vision and Pick-by-voice. Table 5.13 shows the extent of influence on the time efficiency of the picking information system types in a 1 kit batching policy, while Table 5.14 shows the same in a 4 kit batching policy.

Table 5.13. The comparison of the four systems within the single kit policy, in seconds per picked part

System	Compared to…	Mean diff.	Sig.	L. bound (95% CI)	U. bound (95% CI)
Pick-by-List					
	Pick-by-Light	0,749	p<0,001	0,615	0,882
	Pick-by-Vision	0,261	0,016	0,05	0,471
	Pick-by-Voice	-0,945	p<0,001	-1,225	-0,664
Pick-by-Light					
	Pick-by-Vision	-0,479	p<0,001	-0,665	-0,293
	Pick-by-Voice	-1,682	p<0,001	-1,916	-1,448
Pick-by-Vision					
	Pick-by-Voice	-1,205	p<0,001	-1,505	-0,906

Table 5.14. The comparison of the four systems within the 4 kit policy, in seconds per picked part

System	Compared to…	Mean diff.	Sig.	L. bound (95% CI)	U. bound (95% CI)
Pick-by-List					
	Pick-by-Light	-0,968	p<0,001	-1,075	-0,861
	Pick-by-Vision	-1,392	p<0,001	-1,524	-1,260
	Pick-by-Voice	-1,944	p<0,001	-2,139	-1,749
Pick-by-Light					
	Pick-by-Vision	-0,416	p<0,001	-0,528	-0,305
	Pick-by-Voice	-0,976	p<0,001	-1,131	-0,821
Pick-by-Vision					
	Pick-by-Voice	-0,562	p<0,001	-0,735	-0,390

6 Discussion and further research

The results presented in chapter 5 are in this chapter discussed in terms of their contribution to the research purpose and in terms of their generalisability. Further, the chapter discusses the limitations of the research, as well as directions for further research.

6.1 Discussion of the contribution of the thesis

As can be acknowledged by reviewing the research purpose and the research questions, each research question adheres to the same logic, where each question targets to answer the question of how a particular design influences performance. The research purpose, on the other hand, is formulated in reverse in terms of the direction of influence between the design and the performance. That is, the purpose aims to treat the problem of which design can be used to reach a desired performance. In each study, the specific influence from the design on the performance objective was identified. Then, for the two case studies, the similarities and differences from the cases were identified in cross-case analyses and the results reconnected with previous research, which then yielded the study conclusions. These study conclusions can be regarded as the improved understanding on how the design influences the performance objective. When this knowledge is used in industry, it will be used for providing answers to questions like: “if I want my materials preparation to perform well in regards to quality, how should I then design my process”? The knowledge from the individual studies then give guidance in how the desired performance influences the materials preparation design.

The answer to research question 1 improves the understanding of how the materials preparation design influence the flexibility of materials preparation, by showing how the values of the design variables influence the ability of the materials preparation to manage changes in the requirements from the production system. It is clear from the results that is not only important how the work is organised in regards to the materials preparation operations, but also how the work is organised in regards to maintaining the operations, in terms of how to manage the necessary changes to the physical system and the IT-system.

The findings, and the resulting framework developed in Paper 1, contributes to research by building on general models of flexibility from manufacturing, e.g. Correa (1992) and Slack (2005) and applying them to the specific context of materials preparation. Previous findings on flexibility in this context, for example Brynzér and Johansson (1995) and Hanson et al. (2011), do not result from research specifically aimed at this relation, but provide some scattered observations and propositions. A finding that seems somewhat surprising is that the modern technologies, 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 confirms the statement by Park (2012, pp. 9-10), stating that “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”.

The answer to research question 2 improves the understanding of how the materials preparation design influence the quality outcome of materials preparation, by showing how the values of the design variables contribute to situations that results in quality problems of the prepared materials. The results reveal that the work organisation in terms of the responsibilities that are assigned to the job role for the delivery of the prepared materials may lead to misunderstandings between operators when the materials are delivered to assembly, if the materials are awaiting supplementation due to material shortages at the preparation area during the picking tour. In regards to such misunderstandings, the picking information system, in terms of additional functionalities related to the procedures for handling shortage of material in the preparation process can remove risk of the misunderstandings having a detrimental effect on the system. Such functionality differs between different types of picking information systems. The results from the case study supports previous research in several regards, for example in terms of the effect on the quality outcome from disturbances to the picking sequence stemming from empty packaging handling that for example was observed by Brynzér and Johansson (1995).

As for the quality area, the more comprehensive results on causes to quality problems in the materials preparation context, further traced back to the design variables, contributes to previous research. While authors like Garvin (1984) and Grosse et al. (2015) treats quality as it pertains to manufacturing and order picking respectively, the result from Paper II contributes comprehensive results focused on the materials preparation context, covering the design variables identified as important from theory. Hereby, the tables in Section 5.2 can together be seen as a framework that could guide practitioners when designing materials preparation systems, or re-designing current systems in order to improve quality outcome. The relations pointed at in the results can also act as propositions for further research.

The results from Paper III raise the question on how the quality outcome is affected by the batching policy and indicate that a single order policy with a simple picking information system may be worthy of consideration as an alternative to order batching by support of an advanced picking information system. Previous research seems to assume that quality is not significantly affected by the batching policy.

The answer to research question 3 improves the understanding of the extent to which the picking information system influence the time efficiency of materials preparation, by presenting a comparison of the time efficiency achieved from using four different picking information systems in kit preparation, for two different batching policies. The results make clear that the picking information system influence both the pickers' search time for parts and the picking confirmation function. The inclusion of the recently developed pick-by-vision type of system, and the use of RFID bracelet confirmation in the comparison is considered a contribution to both practice and theory. For example, in their concluding remarks after comparing four picking information systems in an order picking context, Guo et al. (2015) ask the question "how will including pick-confirming sensors or a button push affect accuracy and speed relative to the pick-by-HUD method?". An educated response to this question can be formulated based on the results from Paper III, which exemplifies the theoretical contribution of Paper III.

The result of Paper III also reveals that the multi-kit order batching policy presents a different set of requirements on the picking information system than does a single order policy, where the quality assurance of the placement operation, in terms of a placement confirmation, to a great extent determine the time efficiency of a particular information system design. In this regard, the answer expands previous knowledge on the time efficiency of order batching in materials preparation (Hanson et al., 2015) by explaining how the efficiency potentials from batching may be realised with consideration taken to the picking information system design.

The answers to the three research questions shows how the materials preparation design influence the materials preparation flexibility, quality and time efficiency, which leads to an improved understanding of the performance to be expected from selecting different values of the materials preparation design variables. For example, from selecting a location of the preparation area closer to the line, the quality costs may be expected to be reduced compared with a location in a separate department, as the consequences of picking errors are reduced due to the shorter distance for supplementing the correct part, while the same location from a flexibility perspective would reduce the new product, mix and volume flexibility due the less space available for extending the storage racks to make room for new storage locations. Similarly, while a multi batching policy would improve the time efficiency of the preparation, the requirements on quality assurance at the same time increases in terms of the placement confirmation, which if the design is not carefully considered, could offset the time efficiency that may be expected to be gained from batching based on previous studies, for example Hanson et al. (2015). Another example of a trade-off found (Paper I) is that a dedicated storage policy, that often is introduced to improve the time efficiency of the picking work or is advantageous from a walking distance perspective when having stationary picking packages, reduces the flexibility of managing changes in the production mix. Such trade-offs, that arise from consideration to several performance objectives, have been possible to identify in the thesis due to the multi-faceted view on performance employed. The awareness of such trade-offs is an important contribution to practice, and may serve as.

Many of the detailed findings have been acknowledged in previous research, and the findings in this thesis contribute refinements and extensions to the established knowledge. For example, the study concerning time efficiency when using different types of picking information systems in materials kit preparation (Paper III), found that the benefits of using a multi kit batching policy is heavily influenced by the design of the picking information system, in particular the design of the picking confirmation function. The multi kit policy may for some design options not even be superior over a single kit policy, due to the additional administration required in the multi kit policy. Previous research seems to assume a general benefit in terms of time efficiency when using a multi kit policy.

In regards to the research purpose to expand the knowledge of how the desired performance of materials preparation in terms of flexibility, quality, and time efficiency influences the design of materials preparation - the results presented can be used as a guide for the materials preparation designer when selecting the values of the materials preparation design variables, by showing how the choices may impact the performance. In this way, the particular performance of materials preparation that is desired by the materials preparation designer will influence the selection of the values of the design variables.

6.2 Discussion of the generalisability of the results

The focus in this thesis is on materials preparation for materials supply by use of kitting and sequencing in assembly industry, and in particular in the automotive industry. Most of the thesis findings are conditional on the existence of a product structure and an assembly schedule, which has to be considered in regards to the generalisability of the results. The empirical content on which this thesis is based stems from case research and from an experiment, for which the main approach for generalisation is analytic generalisation to theory by means of propositions (Yin, 2003). In the thesis, propositions were derived from theory and studied in the research, which lead to the results. By means of analytic inference from the empirical content, the thesis results thus links back to theory and, hence, should be considered valid and relevant to the extent with which the studied propositions are applicable. Although the thesis is based on case research, where findings are derived within the boundaries of the case characteristics, and an experiment focusing on materials preparation in the automotive industry setting, many other types of assembly environments may present similar preconditions, for which the results of the thesis should be applicable. Hopefully, from a practitioner viewpoint, the descriptions of the cases and the experiment settings are detailed enough to judge validity of the results in other companies and industries.

6.3 Further research

An aspect of this thesis, which is less common in literature, is the view of the materials preparation design as constituted by subsystems of a particular design, e.g. the batching policy or the picking information system. This view, combined with a focus of studying materials preparation in its real-life context, provides a perspective on the links between a certain choice in the design and the expected performance outcome. A similar framework on the link between design variables and performance as is developed in this thesis could be beneficial to have available in a larger context, of for example order picking, as the framework developed by the thesis provides a structure for continued research, enables opportunities for highly focused investigations that contribute to the understanding of the whole.

In regards to materials preparation for materials supply by means of kitting and sequencing, the thesis lays a foundation for interesting opportunities for further research. For example, regarding the materials preparation quality outcome, is treated in paper II, there was a limitation in regards to obtaining precise measures of the picking accuracy. This points at the need for improved methods for measuring the quality outcome in practice. If improved methods for measuring the quality outcome would be available, the picking accuracy could better be assessed and more knowledge on the quality outcome from different design options could be attained.

Concerning materials preparation flexibility, response flexibility was focused in the thesis (Paper I). As was explained in sub-section 2.3.2, the results provided by thesis in regards to response flexibility could be used in further research on how the range flexibility is influenced by the materials preparation design. A good starting point for research in regards to range flexibility, could be to evaluate different principal designs in regards to their range flexibility and, from this, derive new principal designs that can handle more part variants on a fixed amount of floor-space. In regards to range flexibility, a broader scope than in this thesis could extend the knowledge developed, where for example multi-aisle layout concepts could be evaluated in simulation-based studies, or that the unit of analysis in case research is set to be a whole materials preparation department where then the range of part numbers that can be managed in the department can be evaluated.

The findings in regards to the influence on time efficiency of different picking information system for multi kit batching policies raises two questions. One, how combinations of different picking information technologies may influence the time efficiency and, two, how batching policies employing higher number of kits in the batch interacts with the picking information system in terms of time efficiency. Further, as the findings indicate that order batching may have a significant influence on the materials preparation quality outcome, further research should set out to determine how this link is constituted and how other materials preparation design variables, for example the materials handling equipment or the layout, may influence or moderate this link.

Another line of research that could prove valuable for the link between materials preparation and performance would be action research investigations or longitudinal case studies, where a certain change is monitored both in person and over time. Because it is often the scenario when conducting case research that only a snapshot of the operations is attained or a narrative explaining how things got to be the way they are. A longitudinal study, being close to the study object over a long time, would increase the richness of data and increase understanding of the great many small, but in many cases important, variations in design that affect the different types of performance.

7 Conclusions

This thesis has studied the link between the design and performance of materials preparation for kit- and sequence-deliveries for assembly in production systems. The three perspectives of performance applied in the thesis is flexibility, quality, and time efficiency. The industrial relevance of studying materials preparation stems from the increasing use of materials preparation in industry, which is a result of the need to better manage the increasing amount of part variants in the production system, while experience and guidelines for how to design these processes are limited. From a theoretical viewpoint, knowledge is lacking on the links above, specifically treating this type of processes and simultaneously considering the three parallel performance objectives.

The research in the thesis started from the existing, but scarce, knowledge on the influence of the materials preparation design on the materials preparation performance, but in addition including previous research from related fields of knowledge, e.g. order picking, manufacturing performance, and manufacturing flexibility, and took note of the problems as presented by industry. This was done by means of the companies involved in the research project of which the author was part, and by means of recommended research directions from previous research. The needs of the industry and the state of science led the research to focus on the influence from design on the flexibility, the quality and the time efficiency, with the purpose of expanding the knowledge on the desired performance of materials preparation, in terms of these performance areas, influence the design of materials preparation.

Three research questions were formulated in order to align the research with the research purpose, and three studies were accordingly designed to address the research questions, focusing on the materials preparation quality (Study I), flexibility (Study II), and the time efficiency (Study III), respectively. Study I and II were designed as multiple case studies, focusing how and why various design options influence performance. Study III was designed as an experimental study, more narrowly focusing the influence on performance from using different types of picking information systems. Recent technology developments make this a valid area of research both from an industrial and a theoretical perspective.

The study on quality performance was designed as a multiple embedded case study in order to improve the understanding how the materials preparation design, in interaction with the materials preparation context, may cause different types of quality problems. From applying a framework derived from literature, describing how the materials preparation design variables may influence the quality outcome of materials preparation, nine cases of materials preparation in automotive materials supply were studied. The results provide knowledge, for example, the work organisation, the layout and the picking information system have an influence on the materials preparation quality outcome.

Flexibility performance was studied in a similar way. The result of this study includes knowledge of the individual links between flexibility performance and the set of design variables identified in the thesis, and contributes to research by building on general models of flexibility from manufacturing, applying them to the specific context of materials preparation. An important observation is modern technologies in its current form and practice, 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. As for the quality area, the more comprehensive results on causes to quality problems in the materials preparation context, further traced back to the design variables, contributes to previous research.

The study on time efficiency, focusing the picking information system, make clear that the picking information system influence both the pickers' search time for parts and the picking confirmation function. It also points at the importance of considering the batching policy when designing the information system, and indicate that multi kit batching policies are more problematic from a quality point of view. This is an example of trade-offs between performance objectives identified in the thesis, which are interesting for further research. In addition, further research could include the possibilities and design options of automated functions within the process, the inclusion of range flexibility, and quantitate studies on the quality outcome from various design options.

The thesis contributes to practice by providing guidance to the materials preparation designer in terms of the performance to expect when choosing among options of the materials preparation design variables. The theoretical contribution of the thesis pertains to the developed framework that describes the relation between materials preparation design and performance.

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