THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Materials exposure: The interface between materials supply and assembly

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Göteborg, Sweden 2013

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ISBN 978-91-7385-954-7

Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr 3636
ISSN 0346-718X

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Printed by Chalmers Reproservice
Göteborg, Sweden 2013

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ABSTRACT

This thesis concerns the supply of components to assembly in production systems, and introduces materials exposure as the interface between materials supply systems and assembly systems. The purpose of the thesis is to explain how materials exposure influences the performance of materials supply systems and assembly systems. The supply of components is crucial for assembly, for in serving the requirements from assembly. Still, the materials supply system has to remain efficient. In this way, materials exposure impacts the performance of a production system as a whole.

The thesis is a based on five studies, all of which depart from theoretical frameworks developed from literature and empirically applied within the Swedish automotive industry. Four case studies and one experiment were conducted to answer three research questions, and the results are published in five papers.

The results of the thesis provide several theoretical and practical contributions. Both the position of the exposure and the size of the packaging for a component impact the performance of the assembly workstation performance in terms of space required, non-value-adding work, and ergonomics. Materials exposure impacts manual picking time at assembly lines, for which packaging is the most influential factor, followed by angle of exposure and height of the exposed component. Materials exposure further impacts the configuration of the in-plant materials supply system by requiring additional activities in the in-plant materials supply system, which impacts its performance. Concerning the impact of choice of packaging used in materials exposure, a model to evaluate the impact a packaging has on the performance of the materials supply system was developed. The Materials Flow Mapping methodology is another contribution that describes the activities in materials supply systems, as well as categorises the activities in material flows into materials handling, transportation, storage, and administrative activities.

This thesis explains how the materials exposure influences the performance of materials supply systems and assembly systems. It shows how materials exposure impacts the assembly system performance and the in-plant materials supply system performance, and finally, how the packaging for materials exposure impacts the performance of the materials supply systems and assembly systems. The thesis can further be used as a guide for how materials should be exposed and in the selection of packaging for materials exposure. The most beneficial managerial use would be in the design and operation of assembly systems, materials supply systems, and in particular, materials exposure.

Keywords: Materials exposure, production systems, assembly, materials supply, materials handling, packaging, lean production

List of appended papers

Paper I:

Finnsgård, C., Wänström, C., Medbo, L., Neumann, P. (2011), ”Impact of materials exposure on assembly workstation performance”. *International Journal of Production Research*, 49 (24), 7253-7274. http://dx.doi.org/10.1080/00207543.2010.503202

Paper II:

Finnsgård, C. and Wänström, C. (2013), ”Factors impacting manual picking on assembly lines: An experiment in the automotive industry”. *International Journal of Production Research*, 51 (6), 1789-1798. http://dx.doi.org/10.1080/00207543.2012.712729

Paper III:

Hanson, R. and Finnsgård, C. (2014), ”Impact of unit load size on in-plant materials supply efficiency”. *International Journal of Production Economics,* 147 (Part A), 46-52. http://dx.doi.org/10.1016/j.ijpe.2012.08.010

Paper IV:

Finnsgård, C., Medbo, L., Johansson, M. I. (2011), ”Describing and assessing performance in material flows in supply chains: a case study in the Swedish automotive industry.” *Proceedings from the 4th International Swedish Production Symposium*, s. 329-338.

Paper V:

Pålsson, H., Finnsgård, C., Wänström, C. (2013), ”Selection of packaging systems in supply chains from a sustainability perspective - the case of Volvo”. *Packaging Technology and Science*, 26 (5), 289–310. http://dx.doi.org/10.1002/pts.1979

Acknowledgements

Even if there is only my name stated on the cover of this thesis, and it is a product of my efforts, it would not have happened without the help from many others. To all of you involved, I would like to express my deepest gratitude.

I have been a part of two different research projects. The first was the Swedish Production System project – SwePS, in the MERA programme. SwePS was followed by Sustainability and cost efficiency in Supply Chains. The project was within the FFI programme.

The projects were collaborations with the participating companies, all within the automotive industry, either individually or as suppliers, and Chalmers University of Technology. The participating companies have been: AB Volvo, Volvo Cars, SAAB Automobile, Scania, Fordonskomponent gruppen (FKG, the Scandinavian automotive supplier association), and SwereaIVF. All of the involved personell in these companies deserve my gratitude. Even if you have benefited from the results of this research process, your willingness to help is very much appreciated. Some of the people I have encountered have been especially helpful: Anna Brolén, Annelie Sjölin, Petrus Dagman, Jonas Håkansson and Henrik Brynzér. You have all extended your help far beyond any expectations.

VINNOVA deserves my gratitude for making it possible by funding the SwePS and FFI projects. Many of us involved have, and will, continue to work together in new constellations.

The research enivironment with my past and present colleagues at the division of logistics and transportation can be extremely motivating. Any discussion will certainly be encouraged, digested and encountered. The attention to details is admirable at its best, and frustrating at its worst. My supervisors, Mats Johansson, Lars Medbo and Carl Wänström have been with me during this journey, for better or worse, and you deserve my gratitude.

My family has contributed greatly to making my work at all possible. My farther has been forced to read unfinished texts many times, just to be told that they have been discarded, when your feedback was ready. And still, you read the next text presented to you.

My beloved Anna, for you, words cannot express my gartidude for your help. Actually, I am gratified each day I get to share with you.

My son Carl: Pappa har äntligen skrivit färdigt sin bok – så nu kan vi leka istället...

Kullavik, december 2013

Table of contents

1 Introduction

This thesis concerns the supply of materials to assembly. The assembly takes place in a production system organised to accomplish the manufacturing operations of a company. In the case of assembly, the production system includes a materials supply system supplying components to an assembly system that assembles components into products.

The transferral of components between a materials supply system and an assembly system occurs in the *materials exposure*, which is introduced as the interface between the two sub-systems. Aspects concerning this interface and its influence on the production system's performance are explained in this thesis.

The introduction chapter presents the reader with a problem background regarding the interaction between the materials supply system and the assembly system in productions systems. Problems concerning performance within and between these systems are described. The next section introduces materials exposure, followed by the purpose of the thesis, its scope, and an outline of the thesis.

1.1 Background

The system of assembling products in a production system is termed an assembly system in this thesis, within which assembly processes take place. The system that supplies the components to be assembled is termed a materials supply system. A simple representation of a production system that contains a materials supply system and an assembly system is illustrated in Figure 1.1.

Since the early 1970s, problems in the relation between the two sub-systems have been identified, e.g., emanating from the functional division between the systems. However, in practice, efforts to overcome the problems have had little effect (Tompkins et al., 2010, p. 166).

The practical problems that are encountered in one sub-system may not be solved by improving that sub-system alone, as such improvements may disregard the overall system's performance. Schonberger (1998) stresses the necessity to use a holistic view of production systems, emphasising the flow towards customers, as opposed to other strategies that advocate specialisation, such as those proposed by e.g. Chanin et al. (1990) and Porter (1985 p. 36ff.). For example, the Toyota Production System (TPS) was developed to reduce the time between the moment when a customer orders a car and the moment the car is paid for. The objectives were producing many variants of cars (as desired by customers) at a low cost (Ohno, 1988, p. 1). As a consequence of the focus on the entire flow, TPS, and later many companies adopting lean production, strive to move away from the functional specialisation advocated by scientific management. In the 1980s and 1990s, lean production and TPS emerged as the most important paradigms for production (Hines et al., 2004; Lewis, 2000), successfully challenging accepted mass production practices (Emanuel and Palanisamy, 2000).

Compared to the assembly systems in the production systems, materials supply systems have not received sufficient attention, considering their impact on the entire production system (Gupta and Dutta, 1994), thus suggesting that more work can be done. Rubinovitz and Karni (1994) state that materials supply systems are addressed as a final stage in the development of a production system; in other words, they are not addressed until the product, assembly, and layout design has been completed, and in isolation from the overall design process. Grosse and Glock (2013) state that due to efficiency potentials in assembly systems have been widely utilised, materials supply systems show potential for further improvements in reductions of operating costs. The above statements are exemplified in the design of new manufacturing plants for automobiles, where the design of the product and the assembly systems receive first consideration (Clark and Fujimoto, 1991).

Tompkins et al. (2003) points out that, in practice, the assembly system and the materials supply system are often designed separately, with little consideration for each other, which leads to sub-optimal performance of the production system. Optimising the performance of each piece of the supply chain in isolation does not lead to a lowest-cost solution (Jones et al., 1997). A practical example is when a materials supply system is designed to deliver a component to an assembly system on a weekly basis by full truckloads, to decrease transportation cost, instead of delivering one fifth of a truckload daily to match each weekday's consumption. If this decision is taken without consideration to the resulting storage and materials handling activities at the assembly plant, a sub-optimal solution may occur. Tompkins et al. (2010) exemplifies with a transportation process optimised for high transport efficiency but using packaging that cannot be efficiently handled in the in-plant materials supply. Hence, the efficiency of a part of the materials supply system is seemingly of higher priority than the efficiency of the production system as a whole.

Contradicting the performance measurement of sub-systems, Jones et al. (1997) advocates looking at the whole chain of events. Johansson (2006) continues along these lines, stating that if requirements from the production system are not considered in a materials supply system, there is a risk of sub-optimisation within the current materials supply systems and in the design of new materials supply systems.

The performance of production systems, and the performance of the materials supply system and assembly system comprising the production system is above indicated as a problem. The next section begins this explanation by introducing the interface between a materials supply system and an assembly system. The interface between the two sub-systems and the problems associated with this interface will be explained.

1.2 Materials exposure

In a production system, the components exit the materials supply system at the point-of-delivery, where the materials supply system delivers the components to a location exposed to the assembly system (refer to Figure 1.1 for a depiction).

The interface between a materials supply system and an assembly system is termed *materials exposure*. According to Checkland (1981), an *interface* is where two systems or sub-systems interact, and transitions between the two systems occur. A *transition* can occur between sub-systems or between the system and the surrounding world (Checkland, 1981). Therefore, materials exposure is defined as the interface where components are transferred between the materials supply system and the assembly system.

In the materials exposure, the components are physically exposed to the workstation, ready to be picked by the assembly operator as part of the assembly process, preceding the assembly of the component to the assembly object.

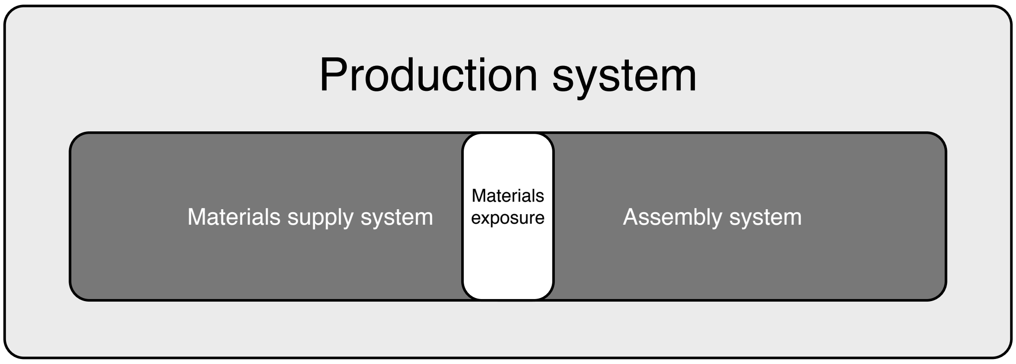

Figure 1.1. A production system containing two sub-systems, a materials supply system and an assembly system. Materials exposure as the interface between the materials supply system and the assembly system.

The design of the materials exposure impacts productivity and quality, and should aim to expose materials to the assembly operator so that the materials can be picked and assembled without delay (Wänström and Medbo, 2009). Equally the in-plant materials supply systems have to be adapted to a variety of components being the materials exposure (Limere et al., 2012). Packaging types, cover-times, volumes (of component and packaging), orientation of components are typical examples of considerations when designing the materials exposure for this purpose.

Several authors stress the potential of materials exposure to support assembly operators to perform value-adding work (Monden, 1998; Ohno, 1988; Liker, 2004). Therefore, materials should be available and exposed at the assembly workstation in a manner that aids the operators with creating value (Liker, 2004). To reduce waste, the material intended for immediate assembly should be supplied to the workstation in the rate that it is consumed. Moreover, while production engineering has always focused on process efficiency by itself, efforts under the label of lean production have further emphasised reductions in materials stored at assembly workstations (Forza, 1996; Hines et al., 2004; Hines and Rich, 1997). This has implications for materials exposure. For the materials exposure, the number of components required at an assembly workstation will compete for the same available space, and thereby considerations has to be made how components can be exposed, as well as how the materials supply system supply the components. Space along an assembly line is regarded as one of the cost drivers of assembly operations (Wild, 1975; Shtub and Dar-El, 1989). Therefore, the space used for exposing components can be expected to influence an assembly system's performance and thus the whole production system.

The amount of space used to expose components is expected to have an impact on performance of a materials supply system. Packaging is related to materials exposure, and is often used in materials supply systems to facilitate the transfer of components to assembly systems in the materials exposure. Packaging has been proven to have an impact on production system performance (Azzi et al., 2012), and is perceived as cost added rather than value added, even when its improvements to materials supply system performance are considerable (Rosenau et al., 1996; Chan et al., 2006). An example is how the choice of packaging for the materials exposure could influence performance of both the materials supply system and the assembly system. The choice of packaging will affect the packaging for the transport from the supplier, can imply extra activities affecting performance in the materials supply system, and affect performance in the assembly system.

From above, it is clear that there is evidence that materials exposure has an impact on assembly system performance. The literature above indicates that material exposure affects productivity, quality, value-adding and non-value-adding work, and the space needed at assembly workstations. However, explanations on how the materials exposure impact assembly system performance is lacking. Gunasekaran and Kobu (2007) and Battini et al. (2010) argue that more research is needed on performance aspects in materials supply systems, and especially studies that determine how to quantify the impact on performance in relation to the overall performance of production systems. Scientific contributions made on the relation between materials exposure and materials supply systems are thus limited. Hence, there is a need for explanations of how materials exposure's influence on the performance of both materials supply systems and assembly systems.

1.3 Purpose

The introduction to this thesis has shown that there is a theoretical gap in the knowledge of how materials exposure affects materials supply systems and assembly systems despite the knowledge's industrial relevance.

> *The purpose of this thesis is to explain how materials exposure influences the performance of materials supply systems and assembly systems.*

The purpose will be developed into research questions in the following chapter, each addressing specific aspects of the purpose.

1.4 Scope

The thesis includes the supply of components from suppliers to assembly workstations for mass-customised, mixed-model assembly. The focus is the production system that comprises materials supply systems, assembly systems, and the manual assembly of components into aggregated products. The supply includes discrete components, as well as raw materials, and sub-assemblies (several discrete components preassembled) if they can be used in the materials exposure in the same way as a component.

The thesis will not go further downstream in the flow of materials than the point where a component is assembled to the assembly object at the assembly workstation. The distribution of finished products to final customers lies outside the scope of this thesis.

1.5 Thesis outline

Below is a short summary of the contents of the subsequent chapters, followed by reading guidelines for those who do not have sufficient time to read the full text.

Chapter 1 (Introduction) introduces the background of materials exposure as the interface between materials supply systems and assembly systems, and provides the purpose and the scope of the thesis.

Chapter 2 (Frame of reference) provides the theoretical background, and builds the framework required to formulate the research questions.

Chapter 3 (Methodology) describes the methodology used in the research and the research process, including the case studies and experiments. It also describes the contributions of the main author and co-authors. Discussions of validity and reliability can be found in this chapter, as well.

Chapter 4 (Results) addresses the results related to each research question.

Chapter 5 (Discussion) discusses the results and contributions from theoretical and managerial perspectives as well as the contributions' relevance to other areas covered by the thesis. This chapter also suggests further research.

Chapter 6 (Conclusions) summarises the conclusions of the thesis.

2 Frame of reference

Chapter 2 presents the thesis' frame of reference. The chapter includes topics to position the research in its context and to create a basis for the discussion in Chapter 5. Furthermore, essential terms and systems treated in the thesis are explained. The chapter ends with formulating the research questions.

The chapter starts with a description of production systems and their sub-systems. As explained in Section 1.4, the thesis focuses on the materials supply system of production systems involving the assembly of products. A simple representation of how the production systems, materials supply systems, and assembly systems are connected with the flow of materials is illustrated in Figure 2.1.

The system of assembling products in a production system is termed an assembly system, and the processes within that system are designated as the assembly processes. The system that supplies the components to be assembled is labelled the materials supply system. The production system and its various sub-systems is described, as well as the interaction between them, including their interface – the materials exposure.

2.1 Production systems

A production system is a collection of processes or sub-systems that a company needs to transform an input into an output. Blackstone and Cox (2008) state that a production system, in its simplest form, is a system that accepts input and converts it into desired outputs. According to Matt (2007), production systems are collections of people, equipment, and procedures that are organised to accomplish the manufacturing operations of a company. Cochran et al. (2000) is widening the scope in the definition, stating that the term reflects the whole enterprise, comprising all the functions, activities, processes, and resources that are required to produce marketable results. Cochran et al. (2000) further state that a production system also comprises all markets, customers, and suppliers as system entities. A similar viewpoint of production systems is the Toyota Production System (TPS). As discussed in detail by Liker (2004), Monden (1998), and Ohno (1988), the TPS encompasses and concerns the whole company, its people, and its philosophies.

The system-design-influenced approaches use the terminology that is proposed in systems thinking, such as sub-systems, entities, and transitions (Checkland, 1981). The definitions below should help to clarify the way that the terms are used in this thesis.

A *system* is embodied as a set of elements connected to form a whole, and this whole possesses properties of its own in addition to the properties of its parts (Checkland, 1981). A *sub-system* is the equivalent of a system, but the former is contained within a larger system (Checkland, 1981). A *transition* can occur between sub-systems or between the system and the surrounding world. An *interface* arises where two systems or sub-systems interact; thus, an interface is the place where transitions occur. Systems and sub-systems are composed of *entities*, which are the elements that are building the systems or sub-systems. The equivalent term component is avoided in the thesis due to confusion with the components used in assembly. The term *process* generally describes deliberately defined sequences of coherent actions in time and space, and can occur within a system (Checkland, 1981; Blackstone and Cox, 2008). In addition, Juran (1988, p. 169) defined a process as a systematic series of actions directed toward the achievement of a goal.

Houshmand and Jamshidnezhad (2006) suggest that the single sub-systems within a production system are interdependent, operate under joint causation, and must be jointly designed for maximum efficiency. However, Tompkins et al. (2010) state that the assembly systems and the materials supply systems are often designed separately and in sequence rather than concurrently and jointly, which Houshmand and Jamshidnezhad assume (2006). Matt (2007) suggests that system boundaries between sub-systems in the production system, disrupt the material flows.

Ellegård et al. (1992) describe the production system in the automotive industry as having unique attributes and prerequisites that distinguish it from other production systems. For example, when Ford was implementing the paced assembly line, the company's primary concern was the manufacturing and assembly operations. Ford wanted to build on the standardisation and exchangeability of components and proposed a wide scope of the production system, including the whole supply chain, thus emphasising vertical integration (Ford, 1926, p. 38ff). Production systems designs must consider a number of variables, such as product development, production engineering, materials supply, manufacturing, marketing, and customer feedback (Ellegård et al., 1992). Ellegård et al. (1992) also suggest a model that includes the sub-systems of engineering, production engineering, materials handling, and assembly.

In summary, this thesis embraces the systems view of a production system. The systems view was chosen so that the study object – materials exposure – could be examined as the interface between materials supply systems and assembly systems; hence, the systems view is appropriate for studying the flow of materials in the sub-systems, the interface between them, and the production system as a whole. As mentioned above, descriptions of production systems often contain other sub-systems besides materials supply systems and assembly systems, but these lay outside the scope of this thesis and have little influence on the interface between materials supply systems and assembly systems.

Thus in this thesis, a production system is the system that assembles components into end products containing the two sub-systems: materials supply system and assembly system. Materials supply systems and assembly systems will be further explored in the following sections.

2.2 Materials supply systems

The system of supplying materials to an assembly system is termed a "*materials supply system*". Blackstone and Cox (2010, pp. 82, 134) define *materials systems* as connecting material flows contained in a production system, and define *supply* as the replenishment of a component. Johansson (2006, p. 1) defines a materials supply system as follows:

> *"The materials supply system is the system that supplies materials from suppliers through the focal company's production system to industrial buyers. The materials supply system thus comprises materials flow between as well as within plants and includes both physical flows and their planning and control."*

In this thesis the materials supply systems end at the materials exposure, as the component at that point will be transferred via the interface to the assembly system.

A materials supply system realises a materials flow through various activities and aided by resources needed for the activities. It includes materials handling activities, storage activities, transportation activities, and manufacturing planning & control activities (Battini et al., 2009; Baudin, 2004; Ellis et al., 2010; Limère et al., 2012). Examples of resources used in the flow of materials are operators, materials handling and storage equipment, and packaging.

The four categories of activities in the materials supply system and packaging will each be defined and explained below.

Materials handling includes handling components and aims to change the disorder of components by picking, positioning, orienting, sorting, and gathering (Öjmertz, 1998). Materials handling activities that achieve the change of disorder are described as "lifting and putting down as well as packing materials" (Johansson, 2006, p.12). In this thesis *materials handling activities* concern only the physical handling of components, as opposed to other uses of the term "materials handling" that imply a wider scope of the term (e.g., found in Bozer, 2001, p. 1504; Kulwiec, 1985, p. 4; Tompkins et al., 2010, p. 176). To differentiate *transportation activities* from *materials handling activities*, this thesis does not use *materials handling activities* to refer to relocating components from one place to another, for *transportation activities* serves this purpose. Examples of resources used for *materials handling activities* are forklifts, lifting aids, pallet jacks, and operators.

Storage of components is an activity in the materials supply system and concerns, for instance, storing in buffers, supermarkets, and inbound warehouses. For a description of different aspects of storage, refer to Gu et al. (2007) for warehouse operations, van den Berg et al. (1999) for warehouse management, Emde and Boysen (2012) for locating storage, Gagliardi et al. (2012) for AS/RS systems, and de Koster et al. (2007) for the design and control of warehousing.

Transportation is the movement of components for the purpose of relocating components from one place to another. Transportation activities can occur both within a production plant (i.e., in-plant) and between plants (i.e., externally). Sjöstedt (2005, p. 7) defines transportation as "the administration of the change of address including the boarding (loading) and deboarding (unloading) of vehicles and vessels, unless these operations are separately modelled." As Sjöstedt (2005) has recommended, the material handling activities of loading and unloading should be separately studied if the refinement of the study so suggests, hence their separation in this thesis. Therefore, transportation activities are often preceded and followed by materials handling activities. Sjöstedt's (2005) definition of transportation includes vehicles and vessels as the resources necessary for performing transportation activities; vehicles include trucks, trains, and ships, as well as smaller resources (mainly used in-plant) such as forklift trucks, tugger trains, pallet jacks, carts, automated guided vehicles, and pulleys. For a more comprehensive description of different types of external transportation, refer to Coyle et al. (2000). Resources designed for materials handling purposes, such as gravity racks, can also perform transportation activities. Operators can also perform transportation activities. For some components, or for packaging with components, it is possible for an operator to manually carry components from one address to another, thus transportation only using human resources is also possible. To differentiate transportation activities from materials handling activities in this thesis, it has been conceived that materials handling activities do not change the address for the components as transportation activities do, thus the purpose of the activity determines whether the activity qualifies as one of either materials handling or transportation. In-depth descriptions of the transportation activities included in this thesis will be provided as they occur.

Manufacturing planning and control activities include all activities in the materials flow that govern what and when to order as well as the initiation and control of material flows. *Manufacturing planning and control* is a term usually used for defining the planning and controlling of all aspects of manufacturing (Vollmann et al., 2005, p. 1). The associated activities in the materials supply system that are directly connected to the materials flow for executing and controlling flows of materials are mostly of an administrative character, such as scanning bar codes on bins and pallets, handling of kanban cards, and ordering materials by either pushing a button or entering information into a computer terminal. The administrative activities are different in character to the other three categories of activities, for they do not necessarily affect the individual component. An administrative activity can be performed without moving the address of the component and without physically handling or affecting the storage of the component.

Packaging will be included for further study in this thesis, since the resource packaging can be used in materials exposure to expose components. Packaging can also be used for facilitating, handling, and storage components, for the actual object being handled and stored, and for exposing the components (Anthony, 1985; Livingstone and Sparks, 1994; Lockamy, 1995; Robertson, 1990).

Packaging facilitates the activities in a materials supply system. For example, packaging can hold several components together so that they can easily be transported together. At a general level, Prendergast and Pitt (1996) identify three main functions of packaging: the protective function, the functions of attractiveness and usability, and the function of facilitation. There can be several levels of packaging (e.g., primary, secondary, etc.) that possess different functions, such as protecting a product or facilitating its transport. In addition to aiding transportation, packaging can also facilitate storage (e.g., smaller containers stored on pallets in a high-bay storage). Manufacturing, planning, and control can be facilitated by the use of packaging as a kanban signal or by carrying information to facilitate the administrative activities. According to Anthony (1985), a communication function of packaging refers to packaging's ability to contribute to the execution and control of the materials flow without the need to investigate each individual component.

2.3 Assembly systems

As a sub-system in a production system, an *assembly system* includes all the processes of assembling the products made in the production system (Bellgran, 1998). Assembly systems also include all actions and supporting functions that make the assembly processes operational (Cochran et al., 2000; Ellegård et al., 1992).

The input into an assembly system is the components from a materials supply system, and the output is the components aggregated into the desired output in the shape of higher-level components made available for further use downstream in the production system, or in the shape of end products.

In the mass, customised, mixed-model assembly of complex and discrete products, the principal system and normal modus operandi is an assembly line (Alford et al., 2000; Gardner, 2003; Wild, 1975, 1995).

An assembly line is defined (Blackstone and Cox, 2008, p. 7) as:

> *"an assembly process in which equipment and work centres are laid out to follow the sequence in which raw materials and parts are assembled."*

According to Wild (1975), the various types of an assembly line can be categorised according to the model mix, with *single models*, *mixed models* (several models assembled on the same line, for example, with or without sequence control), and *multi-models* (models produced in batches).

Only designated, specific operations take place at each workstation, which covers a specified area and known work content. Components are assembled into an *assembly object*, which will become an *end product* as a result of a series of assembly operations. The components aggregated are considered an end product when they require no further processing in that facility (Bozer and McGinnis, 1992, 1984). Another designation of a workstation that seems to be increasingly used by practitioners, from a materials flow perspective, is *point-of-use*.

According to Liker (2004 p.30), all manual activities at a workstation fall into one of two categories: the operations that add value to the end product, *value-adding* activities, and those operations that do not add value to the end product, *non-value-adding* activities. Hines and Rich (1997) proposed that there are necessary non-value-adding activities that cannot be omitted. The contribution that an operation makes to the final usefulness and value of the product, according to the customers, is the value-adding activity (Liker, 2004; Christopher, 1998). In manual assembly processes, the only possible value-adding activity is the actual assembly of components to the assembly object. In the most stringent interpretation, value-adding activities constitute a very small portion of time. One example is the assembly of a bolt, where the value-adding time is only the time when the bolt is actually turned towards the tightening torque.

2.4 Materials exposure

Materials exposure is in Section 1.2 introduced as the interface between a materials supply system and an assembly system, as depicted in Figure 1.1. In addition, Figure 2.1 depicts materials exposure, a materials supply system, an assembly system, and the materials flow. Materials exposure will be further discussed below.

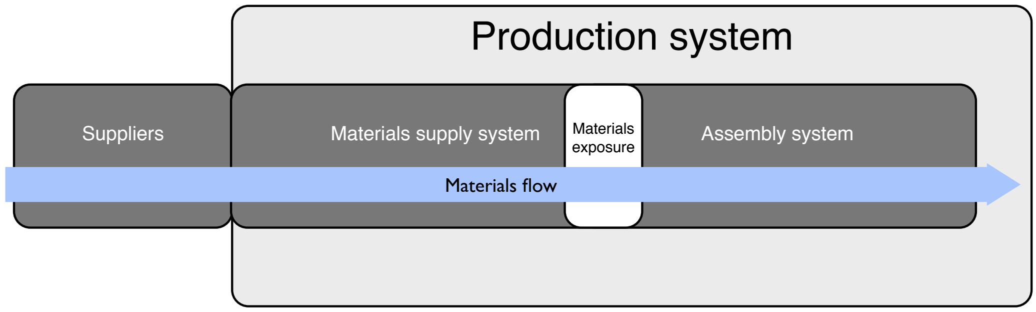

Figure 2.1. Materials exposure as the interface between a materials supply system and an assembly system

Exposure is generally defined as making something visible, typically by uncovering it or leaving it uncovered (New Oxford American Dictionary, 2005). In fact, this standard description suitably describes what is desired in the materials exposure. The word exposure explains, according to Wänström and Medbo (2009), how a component should be unpacked and ready for consumption within a short time span. In previous literature, the terms *parts presentation* (Baudin, 2002, 2004) and *parts display* (Hanson, 2012) have sometimes been used to describe the exposure of components. The expression "border of the line" is used by some researchers (e.g. Limère et al., 2012, p. 4048), for describing the entire physical border between the materials supply system on the outside and the assembly line on the inside.

As defined in the introduction section of the thesis, the materials exposure transfers the components in the materials flow between the materials supply system and the assembly system.

The components are exposed to a consuming assembly process. In this thesis, the term *materials exposure* refers to how components are physically exposed towards an assembly system and ready to be picked for assembly.

The position of an exposed component relative to the assembly object is an important feature of the materials exposure, as well as the height of the exposure (Arnström, 1981; Jones and Battieste, 2004; Petersen et al., 2005). The packaging is part of the materials exposure if the components are exposed in the packaging. If the materials exposure is facilitated by the use of equipment, such as pallet racks, gravity flow racks, or equipment used to hang components for exposure, then the equipment is included in the materials exposure.

The density of the exposure (i.e., the number of components exposed in a given area) should be considered (Jones & Battieste, 2004; Karwowski and Rodrick, 2001) regarding how the materials could be exposed to the assembly workstation. The density will affect materials exposure, such as the space needed (the appropriate number of different components needs to be exposed) and how ergonomic aspects (how different components are exposed to the assembly operator) are valued.

Materials exposure can be realised in a variety of ways that affects visibility and facilitate picking, which include angling of the exposed materials towards the assembly operator (Jones and Battieste, 2004; Trilogiq, 2006), using a vertical offset in the exposure of materials (Ciriello, 2001), and using equipment to facilitate picking from exposed positions, such as pallets on rolling extenders (Arnström, 1981; Neumann and Medbo, 2010).

A components packaging can be large in relation to the component, containing a large number of the same component. A component that is exposed in the back and on the bottom of a EUR-pallet is very differently exposed compared with a component that is exposed as high as possible and at the front of the pallet, closest to the assembly workstation (Neumann and Medbo, 2010).

Storage equipment, such as pallet racks and gravity flow racks (Battini et al., 2009; Battini et al., 2010; Bozer and Ciemnoczolowski, 2013; Limère et al., 2012) positioned along the assembly workstation, can act as the materials exposure. Materials supply operators are loading components, with or without packaging, into the racks. Components are then stored in the racks until they are exposed to the assembly system and finally picked by an assembly operator from the exposed position.

2.5 Research questions

A basic model of a production system (Figure 2.1) has been used to design the framework of the research in this thesis. In Section 2.2 it was argued that the materials flow includes materials handling activities, storage activities, transportation activities, and manufacturing planning & control activities. For materials exposure as the interface between a materials supply system and an assembly system, Figure 2.2 depicts materials exposure with the activities in the materials flow. This model helps to explain how materials exposure acts as the interface between materials supply systems and assembly systems.

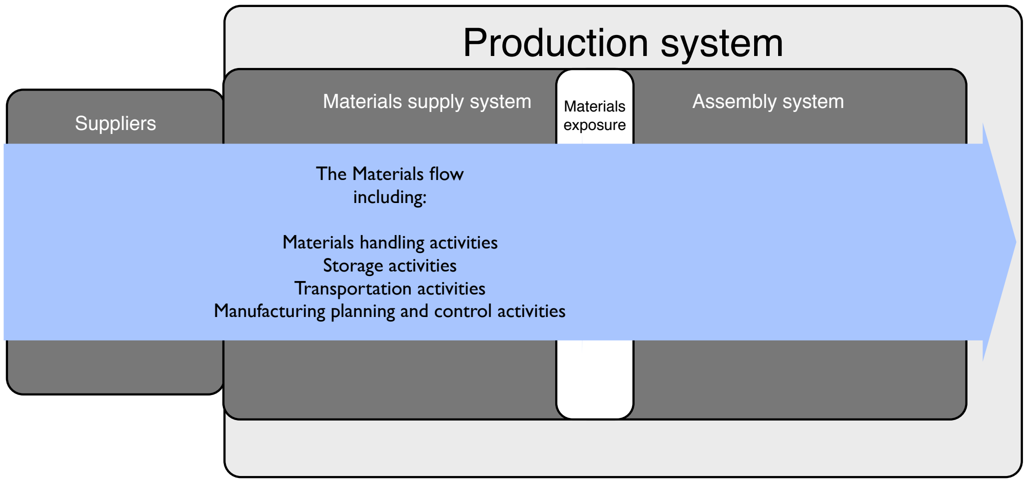

Figure 2.2. Materials exposure as the interface between a materials supply system and an assembly system, including the activities of materials handling, storage, transportation, and manufacturing planning and control

The purpose of this thesis, as stated in the introduction, is to explain how materials exposure influences the performance of the materials supply systems and assembly systems. Three research questions will be developed in this section to support the fulfilment of the purpose.

The first research question addresses assembly systems and the impact that materials exposure has on assembly workstation performance. The question starts from the materials exposure and focuses on the impact downstream. The second research question moves upstream from the materials exposure to the in-plant materials supply system that provides components to the materials exposure. The third research question asks how packaging for materials exposure impacts the performance of materials supply systems. The research question follows the entire materials flow between suppliers to the assembly system by focusing on the performance impact in the materials supply system.

2.5.1 Research question one

Assembly is often distributed over several workstations where a number of operations are performed. The assembly workstations can be part of an assembly line, covering a certain area and specific work content (Gosh and Gagnon, 1989).

At an assembly workstation, the transition of materials in the interface between a materials supply system and an assembly system starts when the components supplied by the materials supply system are delivered to the materials exposure, and ends when picked by an assembly operator. Before the transition is completed, storage of components can occur in the interface, and the storage might be in additional containers in flow-racks or pallets positioned at the workstation.

Once components are at the materials exposure at an assembly workstation, no further activity exists in a materials supply system, and these components are ready to be consumed. The next activity in the materials flow begins in the assembly process: the picking of the component. During this step, the assembly operator retrieves the component from the exposed position.

A materials supply system and an assembly system are likely to have different priorities with regard to exposure at the assembly workstation, contributing to sub-optimisations for the assembly system. For instance, a materials supply system can deliver a week's worth of consumption of components in large batches. Unfortunately, the assembly system would then be forced to handle a large amount of inventory close to the assembly process and thus would require space at the assembly workstation, and indicating that space requirements can be impacted by the materials exposure. Limère et al. (2012) describe how the exposure of all components required to assemble multiple product variants at the same assembly workstations would occupy expensive workstation space, which is a cost driver of assembly operations (Wild, 1975; Shtub and Dar-El, 1989).

Limère et al. (2012) point out that mastering the problem by adjusting materials supply to assembly requirements is one key to gaining competitive advantage. The materials supply system is likely to prioritize ensuring that components are available for the assembly system (often expressed in the number of components available in the materials exposure), whereas the aim of the assembly system might be to reduce the amount of non-value-adding work for the assembly operator. In turn, the reduction of non-value-adding work might be in opposition to suitable delivery frequencies or packaging choices for transportation in the materials supply system. The packaging used for materials exposure will affect the time that components are exposed at the assembly workstation. The components can be exposed in a multitude of smaller packages with fewer components per packaging or in larger packages with more components per packaging. The packaging size is deemed to affect the picking time for the component, so the size will likely influence the assembly station's performance, as shown by Wänström and Medbo (2009) and Neumann and Medbo (2010).

Non-vale-adding work at an assembly workstation contribute to balancing losses, handling losses, and system losses (Wild, 1975). An assembly workstation that assembles variants of a product can be used to illustrate these problems. Two variants of a component in different packaging and at different exposure locations will create non-value-adding work for the operators, such as walking to and picking up the components. Consequently, the non-value-adding work will be different for the components, and the time consumption for these non-value-adding activities will be impacted by materials exposure, as implied by several authors (Baudin, 2002; Baudin, 2004; Bicheno, 2004; Boysen et al., 2008; Connor, 2001; Liker, 2004; Wänström and Medbo, 2009). However, these authors indicate merely that an impact non-value-adding work for the assembly operator can occur; they do not quantify the size of the impact.

A variety of non-value-adding activities affect assembly workstation performance (Boysen et al., 2008). First, balancing loss occurs when there is a difference in the time required to walk back and forth to the exposed components for the different variants. The difference causes the processing time at the assembly workstation to be inconsistent between the variants (Battini et al., 2007). Second, handling loss occurs when the picking time for the components being exposed differently contributes to increased handling losses for those components that are exposed less favourably (Wagner et al., 2009). Third, system loss occurs when additional time is allocated to the workstations, for extra time to address variations in time required for the assembly operators to not disturb the flow of the assembly system. Thus, materials exposure can be expected to impact balancing, handling, and system losses.

Several authors insist that ergonomics impacts the performance of assembly operations (Dempsey and Mathiassen, 2006; Neumann and Medbo, 2010; Wagner et al., 2009). However, quantifications of the materials exposure impact on performance of the assembly system regarding ergonomics needs to be addressed. The impact of materials exposure on ergonomics at assembly workstations could be further explored based on what Neumann and Medbo (2010) accomplished in their comparison of different materials exposure alternatives during the design stage.

The problems described above are indications of that materials exposure impact the performance of assembly workstations and assembly systems: it affects non-value-adding-work, affects the space required for exposure, and affects the ergonomics for assembly operators. Thus, the question that arises is how the output of materials supply systems — materials exposure, affects assembly workstation performance. Research question one is formulated as follows.

RQ1:

> *"How does materials exposure impact assembly workstation performance in terms of space, non-value-adding work, and ergonomics?"*

2.5.2 Research question two

Several authors have stressed that processes within a materials supply system should not be designed in isolation; rather, the overall performance of the production system should be emphasised so that sub-optimisation for the production system is avoided (e.g., Kulwiec, 1985 p. 4; Wu, 1994; Jones et al., 1997; Cochran et al., 2000; Johansson et al., 2006).

In-plant materials supply systems must cope with diverse requirements, such as the different packaging favoured by purchasing, materials supply, and assembly. Materials supply might favour larger packaging due to higher load factors in transportation, resulting in lower transportation costs (Baraldi and Kaminski, 2010). In contrast, assembly might prefer smaller packaging for materials exposure to fit more variants of components close to assembly workstations. The implications for in-plant materials supply systems are that they need to be configured to be able to adapt to several different types of packaging for materials exposure (Battini et al., 2009; Limère et al., 2012).

Assembly systems have recently been requiring smaller packaging exposed at assembly workstations (Wänström and Medbo, 2009). The change in packaging for materials exposure requires in-plant materials supply systems to adapt to such packaging, e.g., by using tugger trains instead of forklifts (Battini et al., 2009; Limère et al., 2012).

The materials handling activities include moving materials in and out of storage, and feeding packaging into racks that are designed to expose the materials at assembly workstations. Handling of packaging that has been emptied (either the disposal of one-way packaging or the return of returnable packaging), and handling different packaging types, will require different material handling activities.

A change in the packaging used for materials exposure also requires in-plant materials supply systems to use different storage activities and resources (Emde and Boysen, 2012; Gu et al., 2007). The changes in the packaging used for materials exposure also require different transportation activities for delivering components. Moreover, different equipment for transportation might be needed between each location, since the packaging used for transportation and for exposing the materials might not be the same (Battini et al., 2009).

The use of no packaging at all to expose the components might reduce the amount of non-value-adding work in the assembly system (Hanson, 2011). However, the absence of packaging will require more from the in-plant materials supply systems, such as materials handling activities when the materials handling operator places the components individually at an assembly workstation. Further, to expose the materials without packaging at an assembly workstation, the storage of components requires space for storage to be made available else ware in an in-plant materials supply system, as the packaging used for external transport and in the in-plant materials supply system has to be stored some ware. The in-plant transportation also has to be adopted, to be able to either transport the components without packaging to the materials exposure, or transport the packaging holding the components to the materials exposure and then supply the component without this packaging. Equally, the extra activities will require additional manufacturing planning and control activities.

Kitting has in recent years been widely introduced in mass customised assembly environments (Hanson, 2012) and is another example of how the in-plant materials supply system is affected by a change in the packaging used for materials exposure. A kit is "a specific collection of components and/or subassemblies that together, (i.e., in the same container) and combined with other kits (if any) support one or more assembly operations for a given product" (Bozer and McGinnis, 1984, p. 3). Kitting is introduced to improve the performance of the assembly workstation (Bozer and McGinnis, 1992). However, kitting as a method of exposure also requires different activities from an in-plant materials supply system, and therefore requires different man-hours and resources, such as different equipment. As Limère et al. (2012) point out, kitting neglects the preparation and resources that an in-plant materials supply system needs.

The problems described above indicate that materials exposure impacts the performance of in-plant materials supply systems, for it affects the resources required to perform the supply of components to assembly. The problems described above also indicated that the man-hours and equipment necessary in the in-plant materials supply system can both be affected by materials exposure. The question that thus arises concerns how the output of materials supply systems — materials exposure, affect the performance of the in-plant materials supply system. Hence, research question number two is formulated as follows.

RQ2:

> *"How does materials exposure impact the performance of in-plant materials supply systems in terms of man-hour consumption and equipment required?"*

2.5.3 Research question three

Packaging design has traditionally had a subordinate role among product development and production systems design even though its impact on supply chain performance can be substantial (Azzi et al., 2012). Considerable time and cost savings can be obtained by adjusting the packaging system to the assembly situation at hand and to the components used (Harit et al., 1997). The packaging used to expose the materials can be expected to impact transportation costs, both in-plant and for external transports from suppliers to assembly plants. Different packaging will require different transportation activities and resources in materials supply systems. An impact on materials handling is also to be expected if the packaging used to expose the materials is changed. Different materials handling activities and resources are required to handle different packaging. Changing the packaging to expose components will likely affect the materials supply system to fulfil assembly system requirements, and in turn, expected to impact cost and thus performance of the materials supply system. The current problem that needs to be addressed is quantifying the performance impact on the materials supply system by the packaging used for the materials exposure.

Packaging is often perceived as a cost, with considerable effects on supply chain performance (Azzi et al., 2012; Rosenau et al., 1996; Chan et al., 2006), and might disregard the facilitating properties that the packaging can have in the materials supply system. Thus, a well-suited packaging might reduce the cost impact, but the impact on materials supply system performance is un-clear. Current models for packaging in manufacturing companies usually do not reflect the whole supply chain, leading to sub-optimisation (Tompkins et al., 2010). Much of this partial design comes from the models not having a wide enough scope, i.e., does not include enough parameters from the production system. Better packaging designs could help system designers to avoid sub-optimisation, because the packaging interacts with both materials supply systems and assembly systems during the flow of materials throughout the supply chain (Lockamy, 1995; Twede, 1992).

Using larger packaging, such as pallets, can result in a more cost-efficient materials supply, because less materials handling is required for the same number of components (Hales and Andersen, 2001; Neumann and Medbo, 2009). A common practice is to use pallets for transporting components from suppliers to an assembly plant, with an in-plant materials supply system re-packs the components into smaller packaging to adjust to the requirements from the assembly system. Due to this re-packing, the materials flow is designed with additional material handling activities and with additional manufacturing planning and control activities that are needed to control the extra activities in the in-plant materials supply system.

Azzi et al. (2012) state a lack of research that considers criteria to compare trade-offs for alternative packaging as well as a lack of research that considers both performance and environmental sustainability issues (such as CO_2 usage). An example is the use of returnable packaging. Companies use returnable packaging, as opposed to using one-way packaging that is disposed of or recycled after their first use. The impact of these packaging systems on materials supply system performance could be very influential.

From a materials supply system perspective, packaging affects every materials supply system activity, including the performance of storage, transport, and materials handling activities (Ballou, 2004; Bowersox, Closs, and Cooper, 2002; Saghir, 2004). Consequently, packaging has a great impact on materials supply system costs (Ebeling, 1990; Lancioni and Chandran, 1990). For instance, its shape and dimension alter cube utilisation efficiency in transport according to the number of components that can fit in the packaging. In addition, the choice of material of the packaging influences waste handling and recycling (and thus the cost and environmental performance).

The problems described above indicate that the packaging used for materials exposure impacts the performance of materials supply systems by affecting the activities and resources needed, the costs, and the environmental performance. The question that thus arises concerns how the packaging for materials exposure affects the performance of materials supply systems. Research question three is formulated as follows.

RQ3:

> *"How does the packaging for materials exposure impact the performance of materials supply systems?"*

3 Methodology

This chapter describes the research process and methodology used in the thesis, including the research strategy, studies, papers, cases, and experiments as well as validity and reliability. The overall aim of this chapter is to describe how the purpose of the thesis is addressed by answering research questions with the appropriate methodologies.

3.1 Research process

This thesis summarises the research on how materials exposure influences the performance of materials supply systems and assembly systems. The outcomes of the studies are described in papers that were presented at conferences and later submitted to, and published in scientific journals. This cover paper is the final stage of the research process, and it compiles the results from the research process to fulfil the purpose of the thesis.

The research process started in February 2007 as a part of the SwePS (Swedish Production System) project. The SwePS project formed part of the research programme titled Manufacturing Engineering Research Area (MERA), and the project aimed to strengthen operations in the production systems of the participating companies. To achieve this aim, part of SwePS explored how materials supply systems could use the principles of lean production in a Swedish context.

SwePS comprised 14 studies, and the results of four contribute to this thesis. Studies I and II were both performed and finished within the SwePS project. The results of Study I were presented in a conference paper, and a developed version of the paper was published (appended as Paper I). The findings from Study I indicated that there was a need to study further the picking time for assemblers, which initiated Study II. The results of Study II were presented in a conference paper and then in a published paper (appended Paper II). For Study III, data regarding the original materials exposure were collected during the SwePS project, but the major part of the study was performed during 2010-2011. A licentiate thesis (Finnsgård, 2009) was presented, including three papers. Two of them are included in this thesis, i.e. Paper I and Paper II, as further developed and journal-published versions.

A new project followed, which was entitled Sustainability and Cost Efficiency in Supply Chains. The project was performed within the FFI research programme (Strategic Vehicle Research and Innovation, Fordonsstrategisk Forskning och Innovation in Swedish), and ran between 2009 and 2013. The purpose of the project was to understand how to design lean and sustainable supply chains in order to support lean production processes. The project was funded by VINNOVA and comprised 10 studies, with results from three contributing to this thesis. Study III continued with the data collection initiated in the SwePS project, and the results were presented in a conference paper and later in a published journal paper (appended as Paper III). The study was initiated by the further research suggestions from Study I, which indicated that the in-plant materials supply would be affected by materials exposure. Study IV developed a methodology to map materials flows. The results were presented in a conference paper. Study V was conducted within the FFI project to develop a theoretical model that assists companies in selecting packaging for inbound supply from suppliers. This study utilised the materials flow mapping methodology developed in Study IV. Likewise, the results from Study V were presented in a conference paper and thereafter developed into a published journal paper (appended as Paper V).

3.2 Research strategy

To attain knowledge of how materials exposure influences the performance of the materials supply system and the assembly system, five studies were designed. The results from these studies are presented in the appended papers in the thesis (Papers I to V). Each of these studies and their corresponding papers were designed to contribute to fulfilling the purpose of the thesis as a whole, by answering the research questions described in chapter two, as shown in Figure 3.1. The authors' responsibilities in the papers are explained in Section 3.3, and methodological issues for the studies are explained in Section 3.4. The answers to the research questions are provided in Chapter 4.

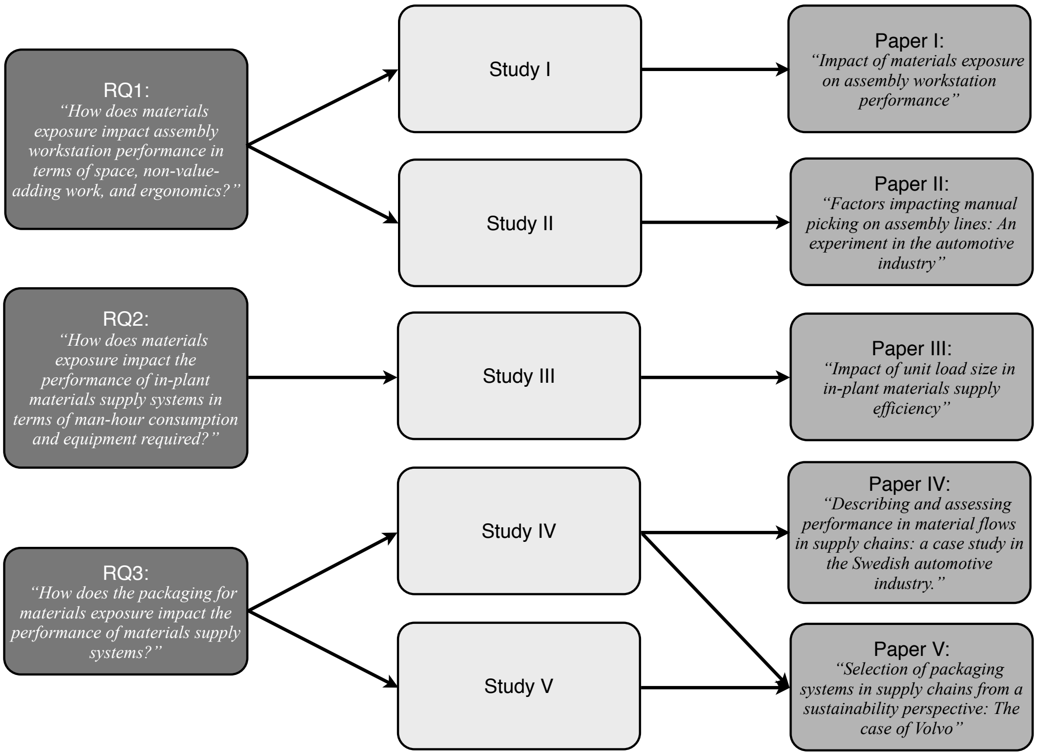

Figure 3.1. The relation between the three research questions, the five studies, and the corresponding papers of the thesis

Deduction has been the major approach in this thesis, using literature and existing knowledge as the base when formulating the research questions. All the case studies, the experiment and the development of theoretical models are built on a theoretical background.

A deductive standpoint, or the mental process through which valid conclusions can be logically deduced from valid premises (Smith, 1998), was chosen for creating frameworks from theory (Studies I–V), for testing those frameworks (Studies I, III, IV, and V), and for testing a hypothesis (Study II). Hereby, the research in the studies goes from theoretical to empirical, as is the case when using a deductive strategy, with the problem formulation connecting the theory through the empirical research (Grønmo, 2006).

A combination of deductive and inductive approaches, known as systematic combining (Dubois and Gadde, 2002), can also be used. Systematic combining stresses the simultaneous evolvement of the theoretical framework, empirical world, and cases. It also allows theory to be developed through in-depth insights into empirical phenomena and their contexts. In short, researchers can use systematic combining to make new insights about existing phenomena by examining problems from a new perspective (Kovács and Spens, 2005). In this research, the empirical world and cases have had an impact on the problem formulation, prompting the author to focus on theory development rather than on theory generation (Dubois and Gadde, 2002; Eisenhardt, 1989).

Two primary research designs were used: case study and experimental design. The design of the case studies will be discussed below, as it is used in four of the studies. The experimental research design will be discussed in Section 3.4.2, as it is used in Study II alone.

3.2.1 Case study research design

Case studies were chosen as the main research design in Study I, III, IV, and V. For Study II, which features the experiment with picking time, the case study design from previous studies contributed to formulating the hypothesis.

The local research environment, which contains strong traditions in case study research design, will most likely have influenced the choices above.

A case study is the preferred strategy when asking "who or why" research questions, and when the researcher cannot control the events or phenomena, and the focus is on contemporary phenomena with some real-life context (Yin, 2003). This was the situation in Studies I and III. Voss (2011) describes the case study method as empirical research that uses data from case studies as its basis, and these data either stand alone or are triangulated with data from other sources, as they were in Study III. Eisenhardt (1989) pinpoints three strengths of the case study: it creates novel theory, it can test emerging theories, and the theories that it confirms are likely to be empirically valid, as was tested in Studies IV and V, confirming the empirical validity of both. Conducting a case study is an iterative process (Eisenhardt, 1989) and commonly used in the research field of operations management, because case studies provide unique means of developing theory by utilising in-depth insights into empirical phenomena and their contexts (Dubois and Gadde, 2002), as in Study IV.

Theory development is an essential part of the case study methodology, regardless of whether the purpose of the study is to develop or to test theory (Yin, 2003). Both theory development and theory testing can be found in Studies III, IV, and V. In Study III, the theory development addressed how to evaluate the impact of materials exposure on the in-plant materials supply system performance, which was then tested in the case study. In Study IV, a methodology was developed to describe the activities in material flows between suppliers and the assembly system of a receiving company. This methodology was then tested in a case study, and applied in order to attain the necessary data in Study V. Study V developed a theoretical model that helps companies to select packaging for materials supply systems based on their evaluations of the packages' performance.

Study I, on the other hand, involves mostly theory testing rather than theory generation. The case study in Study I was mainly a holistic single-case study

(Yin, 2003), evaluating three assembly workstations at an assembly line to assess workstation performance and its relation to materials exposure at these workstations. Hence, an embedded single case study design was used, providing three cases for the unit of analysis.

3.3 Papers

The responsibilities of the authors in the five papers are outlined in Table 3.1.

Table 3.1: Authors' responsibilities for the five papers

	First author	Second author	Third author	Fourth author
Paper I	Christian Finnsgård	Carl Wänström	Lars Medbo	Patrick Neumann
Respon-sibilities	Design, main data collection, analysis of the results, and main writing of the paper.	Participated in the design of the study, data collection, analysis of the results, and in the writing of the paper.	Participated in the design of the study, data collection, and the writing of the paper.	Participated in the writing of the paper and in the analysis as an expert in ergonomics.
Paper II	Christian Finnsgård	Carl Wänström	-	-
Respon-sibilities	Design, data collection, main analysis of the results, and main writing of the paper.	Participated in the design of the study, the data collection, and in the writing of the paper.	-	-
Paper III	Robin Hanson	Christian Finnsgård	-	-
Respon-sibilities	Jointly planned the design of the study and jointly performed the analysis. Participated in data collection. Main responsible party for writing the paper.	Jointly planned the design of the study and jointly performed the analysis. Responsible for the data collection. Participated in the writing of the paper.	-	-
Paper IV	Christian Finnsgård	Lars Medbo	Mats Johansson	-
Respon-sibilities	Design, data collection, analysis of the results, and main writing of the paper.	Participated in the design of the study, the data collection, and in the writing of the paper.	Participated in the data collection, and in the writing of the paper.	-
Paper V	Henrik Pålsson	Christian Finnsgård	Carl Wänström	-
Respon-sibilities	Jointly planned the design of the study and jointly performed the analysis. Main responsible party for writing the paper.	Jointly planned the design of the study and jointly performed the analysis. Responsible for the data collection and calculations. Participated in the writing of the paper.	Jointly planned the design of the study and jointly performed the analysis. Participated in the writing of the paper.	-

3.4 Methods used in the papers

This section covers the methodological choices made in each study, including case selection.

3.4.1 Methods used in Study I

Studies I and II aim to answer research question one: how materials exposure impacts assembly workstation performance. Study I is descriptive, with the unit of analysis being assembly workstation performance in terms of space, non-value-adding work, and ergonomics. A case study was suitable for Study I, because it enabled the measuring of the impact on assembly workstation performance for two ways of exposing components in a real-life situation at three assembly workstations. Contextual factors that could influence the unit of analysis were also of interest, further promoting the use of a case study.

The empirical data are based on an embedded case study performed in cooperation with a Swedish company (Volvo Powertrain, Skövde plant). The company was selected among the companies that were participating in the SwePS project at the time of the study. The prerequisite in the case selection was that the company had a mixed model assembly. The assembly plant was about to change its materials exposure and was willing to participate in the case study. During the case study, the assembly lines operated normally at the designated pace. During data collection, only experienced staff operated the workstation. These were the same personnel that would normally operate the workstation.

Three assembly workstations at two assembly lines were studied. The selection of assembly workstations was made together with plant personnel (a project group including production engineers, materials handling personnel, assembly operators, first line managers, and logistics engineers). The redesign was made with the objective to expose components close to the assembly object while still using the existing infrastructure at the assembly workstation. The schematic layout of one of the workstations studied is presented in Figures 3.2-3.4.

The redesign was carried out during a period when the assembly line was running at full takt. To reduce start-up effects in the data, the researchers commenced the video observations one week after the redesign was implemented.

The space requirement was determined by use of two measures. First, the occupied floor space, referable to facility layout considerations. Second, the vertical area facing the assembly line for the purpose of representing the area of materials exposure, the "wall" of materials exposed to the assembly operator.

To measure the impact of the implemented changes on assembly workstation performance, the comparison was made between the exposure offered by wooden pallets with frames to the exposure offered by plastic containers, as seen in Figures 3.2-3.4.

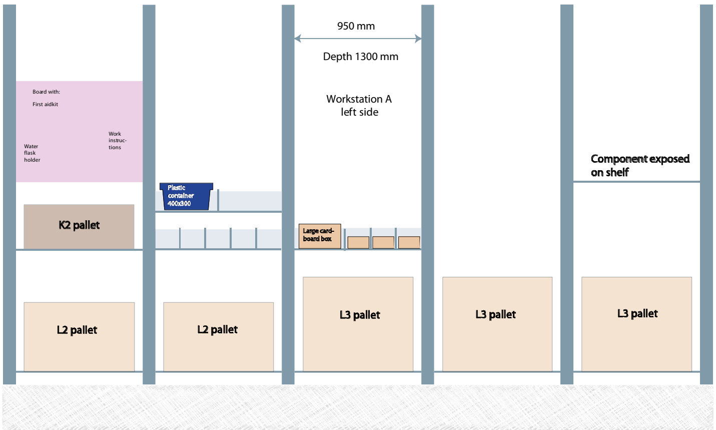

Figure 3.2. Schematic picture of workstation A before the redesign, left side

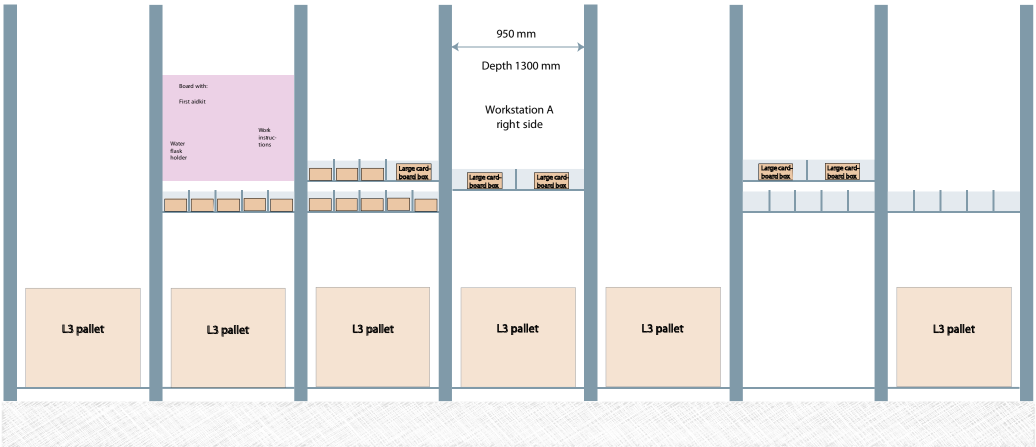

Figure 3.3. Schematic picture of workstation A before the redesign, right side

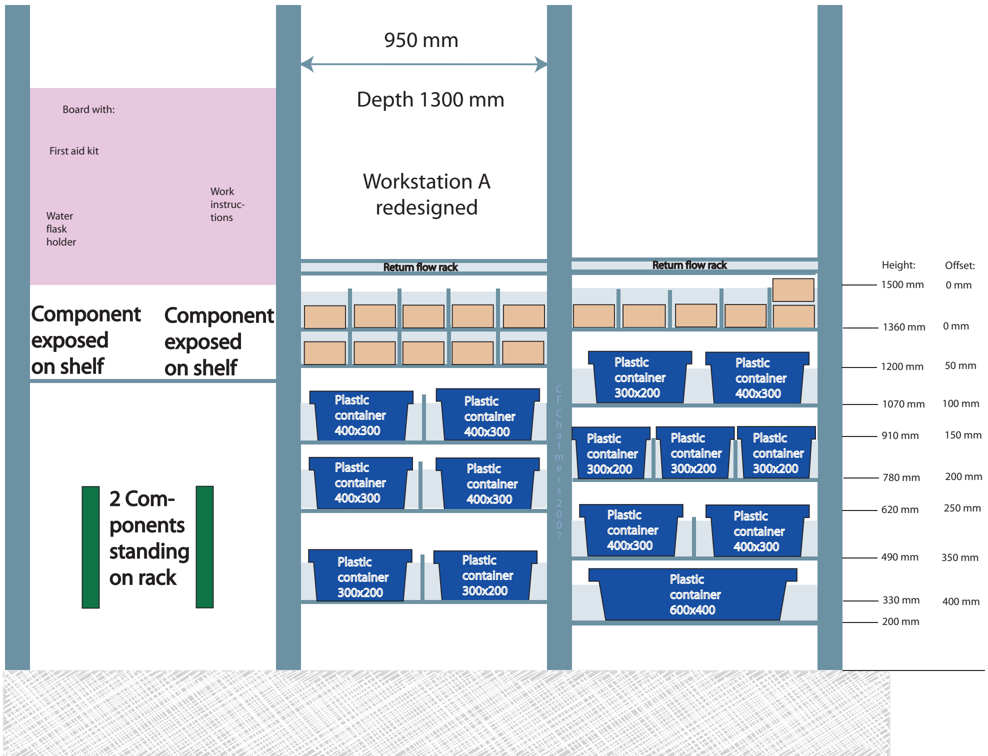

Figure 3.4. Schematic picture of workstation A after the redesign

The number of components and their packaging at the three workstations are provided in Table 3.2.

Table 3.2. Number of components exposed at the three workstations in total and in different packaging for materials exposure. The figures refer to the left and right sides of the assembly line.

	Workstation A left/right	Workstation A right	Workstation B left/right	Workstation B right	Workstation C left/right	Workstation C right
	Current	Redesigned	Current	Redesigned	Current	Redesigned
Total no. of components	11 / 24	35	0 / 23	24	20 / 11	31
Pallet	5 / 6	0	0 / 4	0	2 / 2	0
Pallet, half size	0 / 1	0	0 / 0	0	4 / 4	0
Plastic container, 800x600mm	0 / 0	1	0 / 0	1	0 / 0	0
Plastic container, 400x600mm	1 / 0	7	0 / 6	9	0 / 2	4
Plastic container, 300x400mm	0 / 0	6	0 / 0	1	0 / 0	9
Large cardboard box	1 / 4	0	0 / 0	0	0 / 0	0
Small cardboard box	3 / 13	17	0 / 13	13	12 / 5	17
No packaging used	1 / 0	4	0 / 0	0	0 / 0	1

To replicate the operators' walking patterns, with the purpose of measuring the walking distance between the exposed components and the assembly object and visualise the walking path, spaghetti diagrams were made on work cycles. The work cycles (see Figures 4.1 and 4.2) with the average cycle time closest to average for each product variant for assembly workstation A were visualised in the spaghetti diagrams (the methodology for creating spaghetti diagrams were made as described by Liker (2004) and Dennis (2002)). The sequential order of the workstation activities in the work cycles were very similar between the product variants.

The impact on ergonomics was measured with three variables: exposure position, back bend, and shoulder-arm raise. The three variables are included in the VASA model, a method of measuring the impact of on ergonomics including materials exposure factors. It is accepted in the Swedish industry and is applied by Volvo Powertrain, Skövde (Backman, 2008). It measures the height of the exposed materials, dividing it into three categories (red, yellow, and green) depending on ergonomic impact (Figure 3.5). Measurements were made in the actual setting.

Figure 3.5. The schematic plan of the VASA model, coding exposure positions as green, yellow, and red (including the height from the floor and depth at the different levels)

Work positions were measured using the same video recordings of the work cycles as for the analysis of non-vale-adding work. Frequencies per hour for back bending and upper-arm raising were counted, because these postures, and their frequency are associated with injuries to the lower back and shoulder-neck region, respectively according to the VASA model.

3.4.2 Methods used in Study II

Study II aims at answering research question one together with Study I, with Study II looking in depth at assemblers' picking time, as part of the term *non-value-adding work* that was used in Study I. Thus, the picking time is the unit of analysis in Study II, which examines what materials exposure factors affect picking time at the assembly workstation. Therefore, Study II is explanatory, and the experimental research design is favourable when control over variables is desired. It could be argued that a case study would be suitable, but to be able to explain the causal relationship, the choice was made to perform an experiment.

For the experiment in Study II, the setting could just as easily have been a laboratory setting, but the economic downturn during the fall of 2008 made the factory at Volvo Powertrain (Skövde plant) available to the researchers due to production halts in the assembly plants. Both timing and suitability were contributing factors (more so than cost and resource issues) to the selection of a company setting over performing the experiment in a laboratory setting, as the opportunity to host the experiment at an actual assembly line presented several advantages. It was still possible to control the variables for the experiment, but it was advantageous compared to a laboratory setting, because the same assembly operators who worked at the assembly line were able to take part in the experiment.

An experiment is a way of artificially replicating the idea of a closed system (Smith, 1998). In contrast to case studies, experiments are well suited when there is control over behavioural events (Yin, 2003). The experiment in Study II exemplifies how the control of the experimental setting was implemented in the design of the experiment. One of the components was to be assembled with bolts to the assembly object. In the experiment, the bolts were available at the assembly object, controlling the activities to the desired sequence walking-picking-walking-assembly. Whereas in a case study, the assembly operator would most likely pick these bolts before or after the component was picked, with the activity sequence walking-picking-picking-walking-assembly, and thus faulting the design of the study. A true, classical scientific experiment requires that the researcher will be able to manipulate the independent variable of the research hypothesis in order to observe the influence of particular variables upon the dependent variable under examination (Croom, 2009).

In the experiment, the system boundary was the components exposed in the materials exposure and when the component was assembled to the assembly object. Schematic depictions of the experimental setting are provided in Figures 3.6 and 3.7. The red line marks where the start and stop of the picking activity occurred. When the hand of the assembly operator passed the red line moving towards the exposed component the picking activity started, and when the hand passed the red line with a component, the activity stopped.

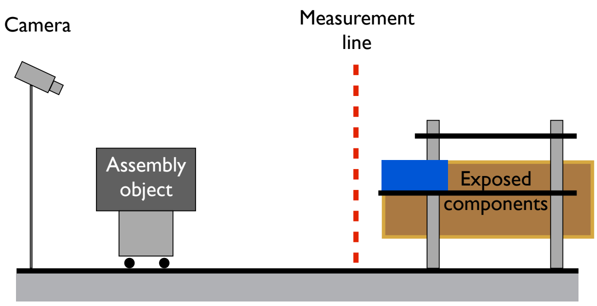

Figure 3.6. A schematic depiction, viewed sideways along the assembly line, of the experimental setting used in the experiment in Study II. The depiction shows the experimental setting and components exposed in two different packaging with vertical offset and at the low level in height of the exposed component.

Inside the system boundary, all variables were controlled and free from interference. The major argument in favour of selecting an experimental format was the ambition to make more generalisable conclusions regarding what factors impact the picking time.

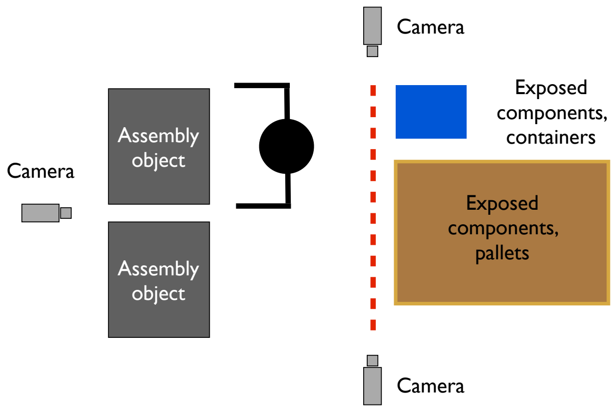

Figure 3.7. A schematic depiction, seen from above, of the experimental setting used in the experiment in Study II

The experiment in Study II employed a full factorial design comprising seven factors at two levels each (see Box et al., 1978). The measured dependent variable was the picking time, which was influenced by seven factors in how components were exposed. Testing of the seven factors deduced from theory required 128 experiments (a two-level factorial experimental design requires 2^7 experiments) to test the complete set of circumstances. An effect in the test of a factor is the response as one moves from a low level to a high level of a factor (Box et al., 1978). The outcome of the analysis is the size of the factors, i.e. how much the factors affect the manual picking time. Complete experiments include the interaction of factors to create factors that are more significant than other individual factors. Operationalisation of the low and high levels for the factors presents considerable challenges in deciding which levels to chose (refer to Table 3.3 for the factors used and their levels).

Table 3.3. Factors used in the experiment and operationalisation of the levels

Category	*Factor*	*Coding in experiment*	*Low level (–)*	*High level (+)*
Materials exposure	*F2 – Offset in vertical distance*	B	0 cm	50% of packaging
	F3 – The angle of exposure of a materials container	C	3°	30°
	F4 – Sideway positioning of a part	D	0°	30°
	F5 – The height available to pick	E	Possible to pick 1 part	Full packaging height
	F7 – The height of the exposed materials container	G	80cm above floor level	140cm above floor level
Packaging	*F6 – The packaging used to expose a part*	F	Small bin	Pallet with 3 collars
Part	*F1 – Part size*	A	Small	Large

3.4.3 Methods used in Study III

Study III was conducted to answer research question two: how materials exposure impacts an in-plant materials supply system's performance in terms of man-hour consumption and equipment required. Thus, the performance of the in-plant materials supply system and how that performance is influenced by materials exposure are the units of analysis in the study.

A case study design was regarded appropriate in that a case study could attain data on the effects caused by contextual factors that might otherwise be lost. In this case, the company's main aim for redesigning the materials exposure was to reduce the space required for the assembly workstations and to reduce non-value-adding work.

The same company and the same assembly line as in Study I was selected.

Figure 3.8 shows the original and redesigned materials exposure. The same original materials exposure was used as in Study I. However, the redesigned materials exposure differed, as the company in the case had rebuilt the entire assembly lines according to the results from Study I, at the time the redesigned materials exposure was studied in Study III.

For each of the three assembly stations that were studied, Table 3.4 lists the types of packaging used for materials exposure and the number of components supplied in each type of packaging, both before and after the transition to smaller packaging.

Table 3.4 Components in different packages at the assembly workstations

	Assembly station A left/right		Assembly station B left/right		Assembly station C left/right	
	Original	Re-designed	Original	Re-designed	Original	Re-designed
Total no. of components	11 / 24	9/32	0 / 23	26	20 / 11	20/12
Pallet	5/6	1/1	0/4	0	2/2	0/2
Pallet, half size	0/1	2/0	0/0	0	4/4	0/0
Plastic container, 600 x 200 mm	0/0	0/0	0/0	2	0/0	0/0
Plastic container, 400 x 600 mm	1/0	2/0	0/6	3	0/2	1/2
Plastic container, 300 x 400 mm	0/0	0/6	0/0	3	0/0	10/3
Large cardboard box	1/4	0/4	0/0	1	0/0	0/0
Small cardboard box	3/13	3/14	0/13	13	12/5	6/4
Small plastic bin	0/0	1/4	0/0	2	0/0	2/1
No packaging used (hanging Minomi)	1/0	0/3	0/0	2	0/0	1/0

Note: The figures refer to the left and right sides of the assembly line facing downstream. Differences in the total number of components before and after the re-design occur due to rebalancing of work tasks between assembly stations. Furthermore, the materials delivered in the small cardboard boxes are not included in the study, as they were not affected by the redesign, i.e. the in-plant materials supply remained the same.

Figure 3.8. On the right is a photo of the redesigned materials exposure applied by the case company primarily based on plastic containers in gravity-flow racks, and on the left is the original materials exposure primarily based on wooden pallets with wooden frames in pallet racks.

3.4.4 Methods used in Study IV

Study IV helped to answer research question three, which asks how the packaging for materials exposure impacts the performance of materials supply systems.

A case study was used to evaluate the developed methodology. The unit of analysis in the study is the materials flow of from the supplier to the assembly workstation. Therefore, the case will consist of several case companies, and the unit of analysis is the flow itself.

Study IV covered three companies so that the study could follow the flow of components. The assembly company was SAAB Automobile, a player in the automotive industry. The materials flow ending at SAAB Automobile was used to evaluate the methodology. One original equipment manufacturers (OEM) supplier, TI Automotive, and a logistics service provider, TT AB, participated.

The case selection was made on the basis of selecting a vehicle manufacturer and a type of component (bundles of brake pipes and fuel pipes; for a picture of this component, refer to Figure 3.9). The materials flow would be possible to study again by selecting the same type of component.

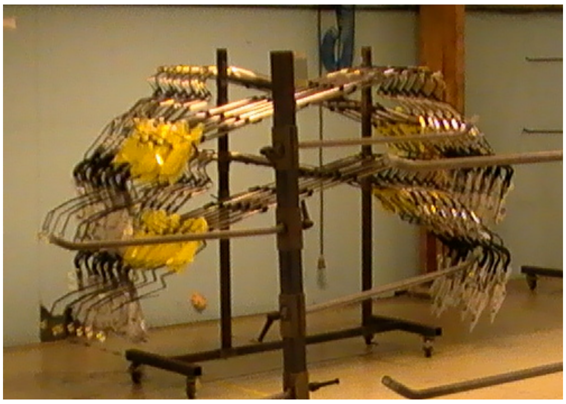

Figure 3.9. A picture of a component studied in Study IV

The case companies were selected from the companies that were participating in the FFI-project at the time of the study, with the exception of the OEM and LSP. The latter two were chosen based on what company was supplying the chosen component.

In the case, the materials flow involved SAAB Automobile and the final assembly of components to cars at an assembly workstation. The studied flow started at the last manufacturing operation at the supplier and ended with the materials being exposed at the final assembly station, with all activities within the selected scope in the flow included. Refer to Figure 3.10 for a simple schematic depiction of the flow.

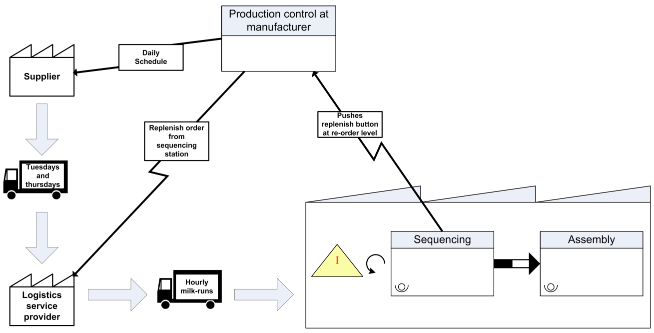

Figure 3.10. A simple overview of the materials flow of the studied component group in the SAAB Automobile case.

3.4.5 Methods used in Study V

Study V, which examines the packaging for materials exposure, aims at answering research question three. The study is descriptive, with the unit of analysis being the packaging for materials exposure. The study deducted a theoretical model from literature, to evaluate how the packing selection for the materials exposure influences the performance of the materials supply system in terms of economic (cost) and environmental (CO_2) criteria. A case study was considered suitable for testing the developed model. The methodology developed in Study IV was used to evaluate the impact of the choice of packaging on the performance in materials flow.

Environmental and economic factors were reviewed using the structure and analysis schemes suggested by Swales and Feak (2000, pp. 150-153). To follow these schemes, they were colour coded and arranged the factors found in the references in two columns: one for economic factors and one for environmental factors. The factors were sorted and rearranged, and colour coding helped identifying the source of each factor. Eighteen environmental and 27 economic factors were identified from the literature. To create criteria, factors with similar focus areas were grouped together in clusters. From the factors, this clustering created five environmental and six economic criteria.

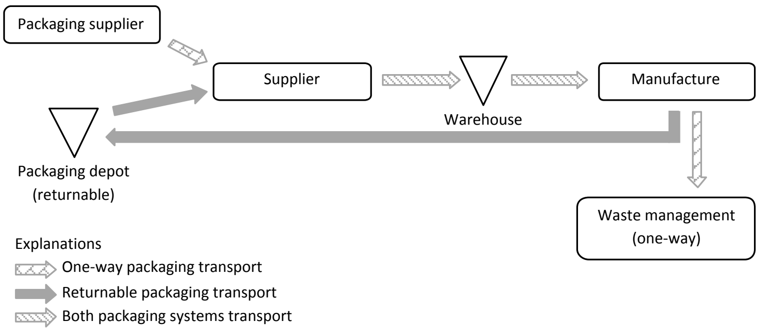

Figure 3.11. Illustration of the two supply chains observed in the case study

The case studied was of a flow of a cable harness from the supplier in Bursa, Turkey, to the final assembly plant of Volvo Car Corporation (VCC) in Gothenburg, Sweden. The principal flow of components is illustrated in Figure 3.11, with Volvo Logistics as a supplier of the logistics services and the packaging to VCC. VCC suggested a new type of packaging, and it was possible to study the development and design made by VLC of the new packaging. Therefore, the flow of materials for the new packaging for the materials exposure was a suitable case, comparing the present packaging with the new alternative packaging Figure 3.12 shows the two packaging compared in the case.

Figure 3.12. To the left: the re-usable plastic packaging used in the case. To the right: the developed one-way cardboard packaging.

3.5 Data collection and analysis

Diverse forms of data collection have been employed in accordance with the type of research design used to answer the research questions. This section will comment on these data collection techniques.

Arbnor and Bjerke (1994) categorise data collection according to whether the data have already been collected (secondary data) or whether it must be collected from new sources (primary data). Both primary and secondary data are used in the studies, as indicated in Table 3.5. Six sources of evidence are suggested by Yin (2003): documentation, archival records, interviews, direct observations, participant observation, and physical artefacts. Table 3.5 shows how these were used in the thesis.

Table 3.5. Type of study, data used, data collection techniques, and analyses in the studies

	Study I	Study II	Study III	Study IV	Study V
Type of research design					
- **Experiment**	-	X	-	-	-
- **Case study**	X	-	X	X	X
Data collection					
- **Primary**	X	X	X	X	X
- **Secondary**	-	X	X	X	X
Sources of evidence					
- **Archival records**	-	-	X	-	-
- **Documentation**	X	X	X	-	-
- **Interviews**	X	X	X	X	X
- **Direct observations of**					
- **assembly workstation**	X	X	X	X	X
- **layout**	X	X	X	X	X
- **meetings, administration**	X	-	X	-	-
- **production flow**	X	-	-	X	X
- **materials supply**	X	-	X	X	X
- **using video**	X	X	-	X	X
- **Participant observations**	X	X	-	X	X
- **Physical artefacts**	-	X	-	-	X
Analysis of data					
- **Quantitative analysis**	X	X	X	X	X
- **Qualitative analysis**	X	X	X	X	X
- **Video analysis**	X	X	-	X	X
- **Factorial design analysis of data**	-	X	-	-	-

One type of direct observation – video-recording – was used in all of the studies except in Study III, and will be discussed in detail here. Video-aided observations were used to gather a permanent record of the activities occurring at the assembly workstation for Studies I and II. The video footage was then used in the analysis to determine the workstation performance in terms of non-value-adding activities and ergonomics. In Study II, the footage was used to determine the picking time. The data collection in Study II was very similar to that in Study I, with the difference being that only picking time was analysed in Study II. Two of the main advantages of video-recorded observations are that the assembly operator at the workstation is less disturbed by the researchers and that the observations can take place in the normal environment (Kadefors and Forsman, 2000; Wallén, 1996). Video observations can also strengthen the collection of other primary data (Arbnor and Bjerke, 1994), such as in Studies IV and V about data in the material flows.

Figure 3.13 shows the experimental setting in Study II.

Figure 3.13. A photo showing one of the stationary cameras and the gravity flow racks used in the experiment in Study II

To measure the assembly workstation activities, a video-recording method (Engström and Medbo, 1997; Wänström and Medbo, 2009) that had been developed for measuring assembly system activities was used. The use of video filmed directly at workplaces has become common for recording postures and kinematic analysis of movements (Örtengren, 1997). Furthermore, video is excellent for evaluating the time taken for different work movements. The use of video observations also makes highly detailed time-motion studies possible.

The experiment in Study II was recorded using synchronised video equipment from three different angles (Figure 3.7). In Study I, before the redesign, the footage was recorded using a single handheld camera. After the redesign, it was recorded with a single stationary camera. As a result of the use of handheld cameras, four work cycles had to be omitted from the analysis. The omitted work cycles were incomplete, because the camera operator had missed the footage of pieces of activities at the assembly workstation. Another issue is the interference with the operator's work that can have an impact on his/her performance and behaviour.

In all studies, the workers union and the individuals were asked beforehand if they would volunteer for the study, considering that they were to be recorded by video.

The use of video observations with the researcher present also provides the opportunity for the researcher to pose questions to the operators. The preferred methodology would be to use a combination of stationary and movable cameras, in order not to disturb activities while still having the footage from the stationary camera for the unit of analysis.

The resulting video footage from Studies I and II was analysed using ATM 3.0, a highly sensitive video motion analysis tool (frame by frame, 25 frames per second). This tool is especially useful for evaluating different production system designs (Forsman et al., 2002). The analysis includes all work cycle activities divided into categories as shown in Table 4.2.

Interviews were conducted in Studies I, III, IV, and V. Interviews were also conducted during Study II, but used as a complementary way of gaining knowledge about the unit of analysis rather than collecting data per se, to become familiar with the processes and operations of the case company.

Physical artefacts (such as the components and test jigs used in the experiments) were collected in Study II, and the experimental settings should be possible to replicate. In Study V, the cardboard packaging was collected and stored for future replicability should the packaging become discontinued.

3.6 Validity and reliability

This section will address the research quality in terms of validity and reliability.

Validity can be estimated in three dimensions: *construct validity*, *internal validity*, and *external validity* (Voss, 2009; Yin, 2003). Each is described below. Table 3.6 lists tactics that can be used to improve reliability and validity in case study research, and describes to what extent the tactics have been used in the present research.

Table 3.6. Tactics for improving case study research (adapted from Yin, 2003). Study II is not included, because it is not a case study.

Test	Case study tactic	Phase of research in which tactic is used	Used in this research?			
			Study I	Study III	Study IV	Study V
Construct validity	• Use multiple sources of evidence	Data collection	X	X	X	X
	• Establish a chain of evidence	Data collection	-	X	-	X
	• Have key informants review draft case study report	Composition	X	X	X	X
Internal validity	• Do pattern matching	Data analysis	X	X	-	X
	• Do explanation building	Data analysis	X	X	-	-
	• Address rival explanations	Data analysis	X	X	X	X
	• Use logic models	Data analysis	X	X	-	-
External validity	• Use theory in single-case studies	Research design	X	X	X	X
	• Use replication logic in multiple-case studies	Research design	X	X	-	-
Reliability	• Use case study protocol	Data analysis	X	X	X	X
	• Develop case study database	Data analysis	X	X	X	X

3.6.1 Construct validity

Construct validity is the extent to which a correct operational measure for the concepts being studied has been established (Voss, 2009; Yin, 2003). Construct validity relates to research objectivity and neutrality (Reige, 2003)

For Study I, multiple sources of evidence were used. The use of time measurement for assembly workstation activities is an established method for evaluating workstation performance (Wild, 1975). Furthermore, the data collection built on previous work in this field to design their methodology for measuring time and for measuring and evaluating ergonomics and space (Engström and Medbo, 1997; Wänström and Medbo, 2009). A complete set of data were initially collected and analysed, but had to be replicated due to a computer malfunction. This improved the construct validity, because the data collection had to be repeated and analysed again, providing opportunities for feedback from the case company.

For Study II, the experiment measuring the impact on picking time provided good construct validity with a well-established method for measuring assembly workstation activities.

For Study III, multiple sources of evidence were used, with data collected from direct observations, from archival data, and interviews. In conjunction with the subsequent follow-up with the case company after the experiment, additional interviews were performed to obtain feedback on the results. The chain of evidence was strengthened by the duration of the study, allowing the participants to reflect upon the results.

The development of a methodology was the main purpose of Study IV. The materials flow in the case was mapped together with the personnel from the case companies, so it was possible for the key informants to follow the case study continuously. This improved the construct validity, as the personnel participating in the case posted more questions about the material flow as the flow was studied.

Study V's main purpose was developing a model to evaluate performance, and the case was used to verify and test the model. The model was based on literature and previous research, and had its base in many theoretical sources. Hence, it can be argued that the correct operational measures were taken to ensure a good fit by using multiple sources of evidence in building the model. Verification of the model was made in co-operation with the participating case companies, and these companies had opportunities to provide feedback that strengthened the model.

In all of the studies, the continuous contact with the participating companies' personnel and the professional and academic network at seminars, workshops, project meetings, and academic and professional conferences provided plentiful opportunities for feedback.

3.6.2 Internal validity

Internal validity is the extent to which a causal relationship can be established whereby certain conditions are shown to lead to each other, as distinguished from spurious relationships (Voss, 2009; Yin, 2003). Due to its connection to causality, internal validity is more important to explanatory case studies than to other types of studies (Riege, 2003; Yin, 2003).

The experiment in Study II was designed and implemented to achieve high internal validity by establishing causal relationships using a factorial design. For Studies I, III, IV, and V, several measures were undertaken to strengthen the internal validity (Table 3.6). If the methodology developed in Study IV had been available to Study III, then Study III would most likely have produced more detailed results, facilitating the description of how the material flows was configured.

Pattern matching is comparing empirically-based patterns with patterns that have been predicted by previous studies (Yin, 2003). In Study I, pattern matching was performed against earlier studies in the field, specifically a modelled study with results that had not been verified in empirical settings (see Wänström and Medbo, 2009). A good match was found. Logic models were used to explain some of the results gained from the study, such as differences in walking speed and walking distances. Logic models were also used in Study III to explain the results attained in the case. The use of comparisons within cases of two measurements before and after redesigns in Studies I and III should strengthen the casual relationships and thus increase internal validity.

3.6.3 External validity

External validity is knowing whether a study's findings can be generalised beyond the immediate case study (Voss, 2009; Yin, 2003) or, as Bryman and Bell (2009) put it, whether they can be generalised outside the specific context of the study. Moreover, findings can be categorised into *analytical* or *statistical* generalisations (Yin, 2003). All of the studies in this thesis offer both types of generalisations with the exception of Study II, which features only statistical data. However, Study II's statistical generalisability gives it high external validity. All generalisations in the other papers must be based on analytical generalisation, and, as such, each generalisation needs to be motivated. Theoretical sampling in theory building has been sought after instead of statistical generalisability in this thesis, so the cases were selected for theoretical rather than statistical reasons (Schroder et al., 2008).

Tactics to strengthen external validity include using theory in single case studies and using replication logic in multiple case studies (Yin, 2003). Both theory and logic have been used extensively in the present five studies. In Studies I and III, theory was used to build a foundation for the cases, and the authors used an embedded case study design so that they could study several workstations within the cases. In Studies IV and V, the case studies were performed similarly by building a theoretical foundation for the cases, but with the aim to evaluate a methodology and a model.

All papers appended to this thesis that use the case study methodology have adopted a deductive approach based on theory that is not limited to the cases or to the automotive industry (as all cases are from within the automotive industry). Therefore, the results from these studies are not necessarily limited to either the cases or the automotive industry, which might have been the situation with an inductive approach. The generalisability of the thesis and the papers will be discussed in Chapter 5.

3.6.4 Reliability

Reliability is the extent to which a study's operations can be repeated with the same results (Voss, 2009; Yin, 2003) and the consistency of the measures (Hair et al., 2010). According to Miles and Huberman (1994), the underlying issue is whether the process of the study is consistent and reasonably stable over time and across researchers and methods.

For Studies I and III, which were case studies, the replicability is uncertain regarding the outcome levels in different replications. However, the same results would be expected if the same changes and influences were replicated in other materials supply systems, so the results are reliable.

In Studies IV and V, the purpose was to develop a methodology and a model, respectively. The methodologies are expected to be replicable, based on the same models on the same literature, and easily available. The cases were included to validate the usefulness of the methodologies. A study of a materials flow is more uncertain and might be exposed to the same type of problem as the two case studies in Studies I and III if replicated in the future with new contextual conditions and new results in a new data collection. The methodology in Study IV was developed and used in many other settings and for different material flows after the case study presented in the paper, so the replicability has already been proven. The model developed in Study V has since been used by the companies in the case study as well as by students, and has lead to other research projects.

In all of the studies, databases were developed and stored. The studies are documented in full with case study protocols and video recordings that are available for further analysis with the purpose of providing reliability. Based on the way the studies were conducted, they will all be replicable, given the same preconditions, thus providing good theoretical replicability and reliability.

For the experiment in Study II, replicability can be expected with the same results, supported by the controlled environment and experimental conditions.

4 Results

This chapter presents the results linked to the research questions of the thesis that were presented in the frame of reference chapter. The following sections provide a selection of the results of the respective papers.

4.1 How materials exposure impacted assembly workstation performance

How materials exposure impacted assembly workstation performance was analysed on three dimensions: space requirements, non-value-adding work, and ergonomics. Each set of results on the respective dimensions is provided below under its corresponding heading.

4.1.1 Space

In Study I, Volvo Powertrain redesigned the materials exposure for the assembly workstations at one of their assembly lines. The redesigned materials exposure was intended to reduce the space required for materials exposure at the assembly workstations. The means to achieve this was using smaller packaging for the same components. The reduced packaging size made it possible to expose all components on one side of the assembly workstations, in all three assembly workstations studied.

In the original system, the three stations combined used a total of 24 pallet sections, equalling 25.2 m in length, in the storage racks at the assembly line. After the redesign, a total of eight pallet sections were required for the same components along the assembly line. The floor space requirement was reduced by 67%, and the area exposed towards the operator was reduced by 76%. For details regarding the distribution among the stations, please see Table 4.1. For workstations A and C, the redesigned materials exposure used 3.15 m each (for workstation A, refer to Figure 3.4); workstation B occupied a length of 2.1 m (for figures of workstations B and C, refer to Paper I). This gave a total length of 8.4 m for the three workstations in the redesigned system. The length of the workstations will have an impact on the walking paths and the time that the assembly operator uses to walk to obtain materials, as will be referenced in the next section.

Table 4.1: Impact of materials exposure on space requirements at the assembly workstations

		Original	Redesigned	Results
Workstation length	Total	25.2 m	8.4 m	
Floor space required for materials exposure at the workstation (m^2) (Horizontal plane)	Stn A	16.38 m^2	4.10 m^2	−75%
	Stn B	5.46 m^2	2.73 m^2	−50%
	Stn C	10.92 m^2	4.10 m^2	−63%
Exposure area required for materials exposure towards line (m^2) (Vertical plane)	Stn A	17.95 m^2	4.41 m^2	−75%
	Stn B	6.62 m^2	2.10 m^2	−68%
	Stn C	11.60 m^2	2.09 m^2	−82%

4.1.2 Non-value-adding work

The impact of materials exposure on non-value-adding work required further refinement of the different assembly workstation activities than has been done in existing literature. To answer research question one, it was necessary to differentiate between value adding and non-value-adding activities, as the non-value-adding activities were to be further studied.

The analysis framework in Table 4.2 is based on the categorisation of Jonsson et al. (2004) and the performance factors suggested by Wild (1975). Compared to Jonsson et al. (2004), the framework is further developed and adapted for materials exposure with further divisions of the non-value-adding work into materials handling work and other miscellaneous work. The activities are refined into more detailed activities in a framework used to categorise the activities in Study I and the experiment in Study II.

The 27 identified activities were firstly divided into value-adding and non-value-adding activities, depending on whether they added value to the assembly object. In assembly operations, only two value-adding activities occur: assembly and pre-assembly. The non-value-adding activities are further divided into materials handling activities and miscellaneous activities. The materials handling activities are separated due to their connection to the materials exposure. The materials handling activities include walking to and from the materials, picking items from differently exposed materials, picking preparation, package handling, and line feeding activities performed by the assembly operator. The miscellaneous activities include all other types of activities, such as moving or repositioning the assembly object, tool handling, reporting to MPC systems, reading specifications, and waiting. The complete list of the analysis framework for assembly workstation activities that was identified in this study is provided in Table 4.2 with short descriptions of how the activities were used in Studies I and II.

Table 4.2: The analysis framework for assembly workstation activities categorised into value-adding and non-value-adding activities, the latter with 25 subcategories

		Activity	Short description
Value - adding	Assembly		Assembly work
	Preassembly		Assembly work performed away from the assembly object
Non-value-adding work	Materials handling	Walking for materials	Walking for materials or components 1) Walk towards main assembly object with material or components to assemble 2) Walk from the main assembly object to fetch the component or material to assemble 3) Walk between different material racks or boxes to pick or preassemble components 4) Walk with subassemblies to or from main assembly object or preassembly station
		Picking from pallet	Picking component, material or subassembly from standard wooden pallet, in full- or half-size. With or without one or more frames.
		Picking from container	Picking from container (plastic or large cardboard box)
		Picking small materials	Picking from small (cardboard or plastic) box (nuts and bolts)
		Picking hanging or racked materials	Picking materials hanging or standing in racks
		Picking or placing on assembly object	Picking from all types of racks where materials or components are hung for convenience for picking by operator
		Picking from mobile rack	Picking from material racks that are not fixed
		Picking from sequence-sorted rack/container etc.	Dependent on the situation and exposure
		Picking or moving preassembly	Handling of preassemblies
		Packaging handling	Handling of packaging and waste material, recycling
		Line feeding	Assembly operator refilling materials in the materials exposure
		Pick preparation	Including some kind of setting, moving, removing, temporarily changing location, or sorting of the components in or in front of the box or rack for ease of picking of components or materials
	Miscellaneous	Moving or picking preassembled materials	Handling or moving preassemblies to an intermediate position
		Positioning of assembly object	Positioning assembly object to enable assembly
		Move assembly object	Moving assembly object (or AGV)
		Tool handling	Fetching, placing, retrieving or preparing tools
		Reporting to system	Reporting to IT system or ordering new materials
		Reading specifications	Operator reading specifications during assembly
		Checking	Checking the assembly object, all quality assurance work
		Walking	Walking other than walking for materials
		Waiting	Waiting and not performing any work
		Adjustments	Adjustments and reworking comprises repeat work done to clear or correct work that was initially carried out incorrectly
		Q and A	Questioning and answering between colleagues
		Miscellaneous	Everything that does not fit into the specified activities here
		Waste	Included in the video recordings, but not for analysis (such as breaks or talking to film crew or researchers)

Picking and walking, which are both non-value-adding work activities, were studied in further detail to answer the research question. Picking and walking were chosen for further study, because they are non-value-adding work affected by materials exposure. Walking for materials covers the assembly operator's movement to and from the exposed materials, and the walking distance from the assembly object is dependent on materials exposure. The operator has to pick the components from the exposed position and walk back to the assembly object.

In Study I, the activity Walking for materials was analysed to compile spaghetti diagrams for assembly workstation A to illustrate the walking patterns in the original and redesigned workstations. To pick materials for assembly from the storage racks, the assembly operator has to leave the assembly object and walk to the exposed material, pick the component and return to the assembly object. Two aspects of walking were studied: walking time and walking distance. The walking distance and walking path for the two product variants at assembly workstation A is depicted in Figure 4.1 and 4.2.

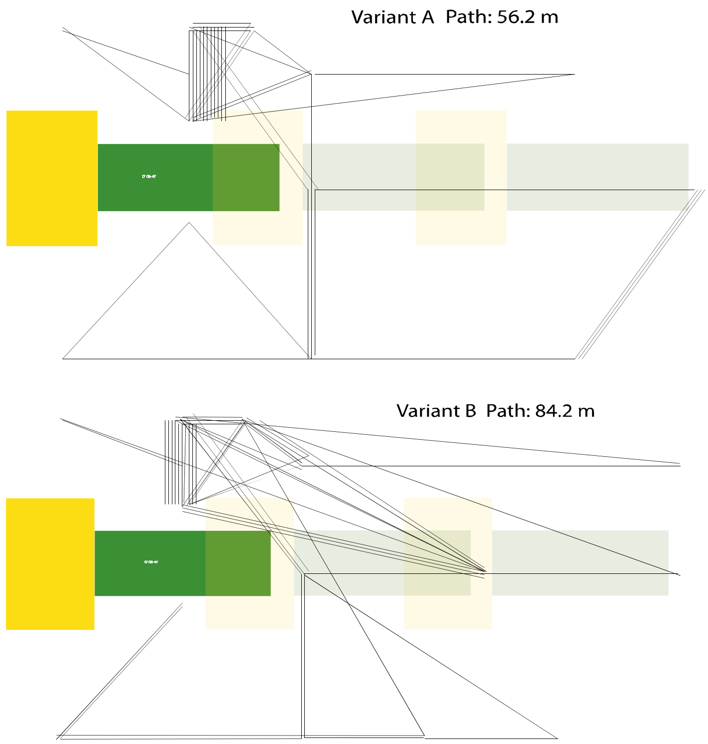

Figure 4.1. Walking paths before the materials exposure redesign for the two major product variants assembled. Before the redesign there was a difference between product variants; after there was no difference.

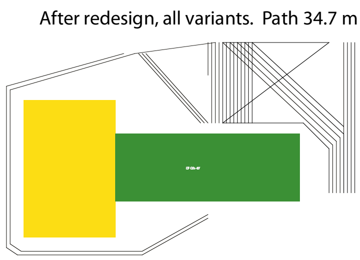

Figure 4.2. Walking path after the redesign. No difference between product variants.

After the redesign, there was no difference in walking patterns between the major product variants. The results for walking time and walking distance are provided below in Table 4.3: walking time decreased by 33%, and the walking distance decreased by an average of 52%.

Table 4.3: Impact of materials exposure on non-value-adding work

			Original	Redesigned	Difference
Materials handling	Walking distance in metres for assembly workstation A	Variant A	56.2 m	34.7 m	
		Variant B	84.2 m	34.7 m	
		Average	72 m	34.7 m	−52%
	Walking for materials time				– 33%
	Picking time, pallets		3.1 (sec)	-	
	Picking time, container		3.2 (sec)	1.6 (sec)	– 50%
	Total, all materials handling activities				−23%
All non-value-adding					−20%

Picking time was further analysed according to differences in picking from different packaging types. After the redesign of materials exposure, no pallets remained. The picking time for components in pallets before the redesign was, on average, 3.1 seconds. After the redesign, no pallets remained and the same components were stored in plastic containers, resulting in an average picking time of 1.6 seconds. Before the redesign, the picking time for components in containers was 3.2 seconds, so also this time was greatly affected by the redesigned materials exposure. The reason was that the components originally were exposed in high locations and in cardboard boxes with lids, requiring extra handling activities each time they were picked. After the redesign, the exposure of the components provided better conditions for assembly workstation performance. Several materials exposure factors changed in the redesign: exposure height, packaging, and sideways positioning, all of which reduced the picking time by 50% due to the improved materials exposure.

Study I showed that materials exposure had a considerable impact on the non-value-adding part of the assembly operator s' work. For the redesigned materials exposure, the time for non-value-adding work decreased by 20.4% compared to the original situation. The total materials handling time of the non-value-adding work decreased by 23% (see Table 4.3).

As a result of the redesign, the materials handling time (including picking time and walking time) for the operator could be reduced by 23% and the total non-value-adding work by 20%.

Study I showed that the materials exposure affected the picking time, and thereby the non-value-adding work. However, the study could not explain what factors affected the picking time and thus illuminated the need for further research. For this purpose, Study II was designed.

The experiment in Study II was designed to explain what factors impact the manual picking time on assembly lines. The experiment included seven factors at two levels, and is explained in section 3.4.2. The data in Study II were analysed to determine the major effects and the effect interactions between the factors on all levels. The average picking time was 1.98 seconds over the 128 experiments and included 1170 occurrences of picking. The work-cycle was walking-picking-walking-assembly. The results from the experiment are summarised in Table 4.4, in order by size of effect.

The main effects revealed by the experiment are shown in Table 4.4, stating the effect as well as the direction and size of the effect on picking time. Packaging was found to have the greatest impact on picking time, with an effect of +0.717 seconds. The angle of exposure was the second most influential factor on picking time, with an effect of –0.278 seconds. Two examples of packaging are provided in Figure 4.3, and a picture and a schematic depiction of an angled exposure appear in Figure 4.4.

Figure 4.3. Two types of packaging used in the experiment, here exemplified by the exposure of the same component

Figure 4.4. On the left, a picture of an angled exposure; on the right, a schematic depiction of an angled exposure

The height of materials exposure was the third most influential factor of picking time, with an effect of +0.230 seconds, followed by the part size and weight, with an effect of –0.168 seconds. Examples of the larger components used in Study II's experiment are provided in Figure 4.3.

Sideways positioning of a component was the fifth most influential factor for the picking time, with an effect of +0.135 seconds. Figure 4.5 provides a schematic depiction of sideways positioning.

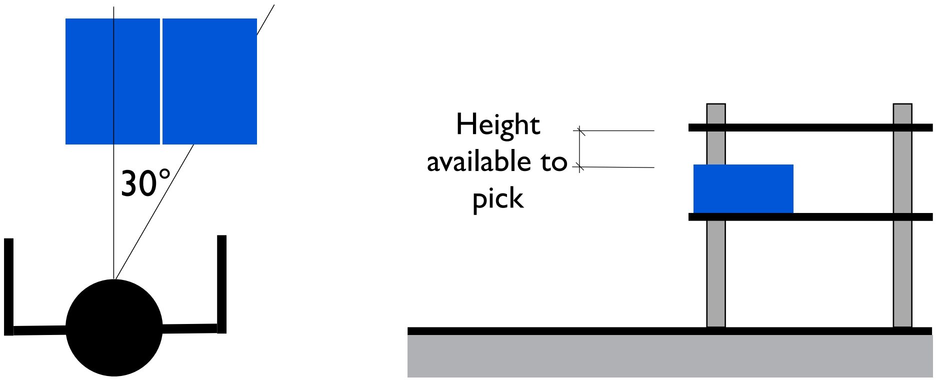

Figure 4.5. Schematic depiction of sideways positioning of a component on the left; on the right, height available to pick. For a picture, refer to Figure 3.13.

The sixth most influential factor affecting the picking time was the offset in vertical distance, with an effect size of +0.068 seconds. Vertical offset facilitates access to the components and increases the components' visibility to the assembly operator while sacrificing floor space in the horizontal plane. The vertical offset is depicted in Figure 4.6.

Figure 4.6. Vertical offset is depicted to the left and the schematic is to the right

The seventh factor included in the experiment, the height available to pick, did not appear to influence picking time. The resulting effect of –0.012 seconds was not significant in relation to the confidence interval and was thus not supported. The factor height available to pick is depicted in Figure 4.5.

The experiment tested the factors, and the results are summarised in order by size of effect in Table 4.4.

Table 4.4. The results of the factors (significant or not significant) with a confidence interval of 0.044, significant at the p < 0.05 level

Factors	Result	Size of effect (sec)
F6 – The packaging used to expose the part	Significant	+ 0.717
F3 – The materials container's angle of exposure	Significant	– 0.278
F7 – The height of a part's exposed materials container	Significant	+ 0.230
F1 – Part size and weight	Significant	– 0.168
F4 – Sideways positioning of a part	Significant	+ 0.135
F2 – Offset in vertical distance of exposure	Significant	+ 0.068
F5 – The height available to pick a part	Not significant	– 0.012

The factor interactions that were found to have the greatest impact on picking time are provided in Table 4.5 in order of effect size. The first four factor interactions all contained the factor packaging. The combination of part size and packaging was the largest, with an effect of –0.233 seconds. The implications of the factor interactions will be discussed in chapter five.

Table 4.5. Factor interactions, significant at the p<0.05 level, and with an effect of > 0.1 seconds. For the complete list of factor interactions, please refer to Paper II.

Factor interactions	Result	Size of the effect (seconds)
AF – Part size & packaging	Significant	– 0.233
CDFG – Angle of exposure & sideways & packaging & height	Significant	+ 0.188
FG – Packaging & height	Significant	– 0.188
CF – Angle of exposure & packaging	Significant	– 0.163
AD – Part size & sideways	Significant	– 0.136
BCEF – Offset & angle of exposure & height to pick & packaging	Significant	+ 0.118
DF – Sideways & packaging	Significant	+ 0.117
CDG – Angle of exposure & sideways & height	Significant	+ 0.114

4.1.3 Ergonomics

In Study I, the impact of materials exposure on ergonomics at the assembly workstation was measured. Before the materials exposure was redesigned, 45 components were exposed in the red zone, which is the least favoured exposure according to the VASA model. The yellow zone contained 42 components, which has slightly better exposure. The green zone, which is the preferred exposure, contained only four components.

In the redesigned system, only four components remained in the red zone, representing a 92% decrease.

Twenty-nine components were exposed in the yellow zone, indicating a 31% decrease.

The number of exposed components in the green zone increased from four to 58, thereby increasing by 1350%.

For a summary of the case study's results on ergonomics, refer to Table 4.6. For a depiction of a workstation from the case with the green, yellow, and red zones displayed, refer to Figures 4.7 and 4.8.

Table 4.6: Impact of materials exposure on assembly workstation performance in terms of ergonomics

		Original	Redesigned	Results
Work positions during picking	Back, >45° bend forward (frequency/hour)	85	8	−91%
	Shoulder, arm >90° raise in upper arm (frequency/hour)	230	0	−100%
VASA model	Red zone (number of components in the zone)	45	4	−92%
	Yellow zone (number of components in the zone)	42	29	−31%
	Green zone (number of components in the zone)	4	58	+1350%

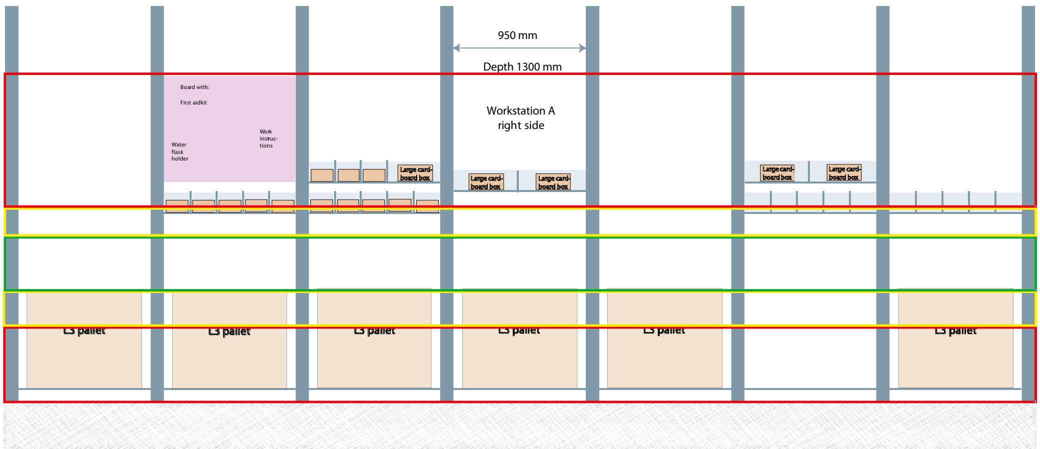

Figure 4.7. A depiction of one side of a workstation before the materials exposure redesign with the green, yellow, and red zones displayed. No components were exposed in the green zone at this workstation.

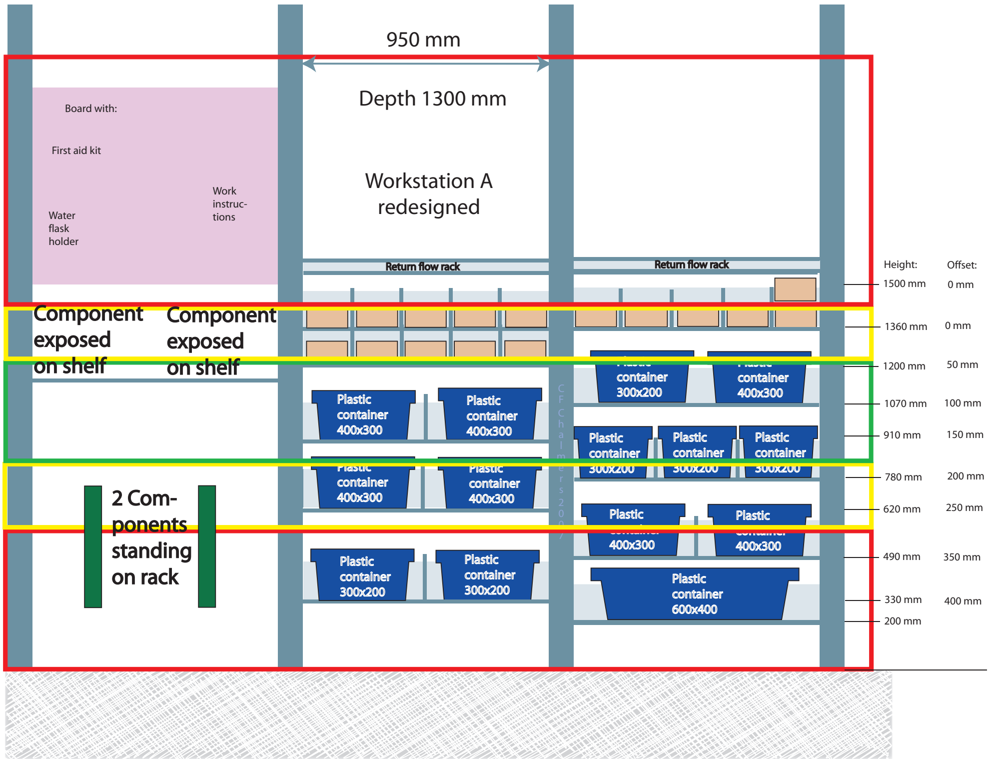

Figure 4.8. A depiction of the same workstation after the materials exposure was redesigned, with the green, yellow, and red zones displayed. Several components are exposed in the green zone.

The work positions during the work cycles were also analysed. Before the materials exposure redesign, 85 occurrences per hour of forward trunk flexion postures beyond 45° existed. The redesigned system had nine occurrences per hour of these potentially harmful body movements, accounting for a 91% reduction.

For upper-arm raises of more than 90° from horizontal, the original system had 230 occurrences per hour, whereas the redesigned system had none. This indicates an elimination of an ergonomically unbeneficial body movement, improving ergonomics.

4.1.4 Summary of the results for research question one

This section revealed how materials exposure impacted assembly workstation performance in terms of space, non-value-adding work, and ergonomics.

The impact on the three dimensions was illustrated in a case study in which the materials exposure was redesigned. The new design reduced the space needed to expose the components by 67%, so it impacted space requirements at the assembly workstation. In addition, the new design decreased the non-value-adding work by 20%. As a part of non-value-adding work, picking was studied further to explain what factors impact picking times, with packaging being the most influential factor. A further five factors had a significant effect on the picking time: angle of exposure, height of the materials exposure, part size and weight, sideways positioning of components, and offset in vertical distance. Thus, the experiment explained how the factors impacted the picking time at an assembly workstation.

Ergonomics was impacted by the materials exposure. The new design greatly improved ergonomics for the assembly operators by exposing more components in ergonomically preferred positions. In fact, the new design almost eliminated potentially harmful body movements.

4.2 How materials exposure impacts the performance of in-plant materials supply systems

The impact of materials exposure on performance of the in-plant materials supply system, in terms of man-hour consumption and equipment required, was analysed together with how materials exposure affected the in-plant materials supply configuration and, thus, indirectly affected the in-plant materials supply performance.

The case study in Study III focused on a redesigned materials exposure at three assembly lines. The study focused on the man-hour consumption of the in-plant materials supply, because man-hour consumption is closely related to the operational costs of the system. The in-plant materials supply system's configuration (materials handling equipment and delivery routing) was also studied, including the required equipment to conduct the in-plant materials supply.

The case company redesigned the materials exposure of its assembly lines, and thereafter adjusted the in-plant materials supply system accordingly. The man-hour usage and required equipment had to change after the materials exposure was redesigned, to improve delivery precision and decrease material shortages. In the redesigned system, the delivery performance and material shortages at the assembly lines had improved as a consequence of the redesign. As concerns assembly, the redesign of the materials exposure enabled the company to reduce its workforce by 13.5 assembly operators.

Before the redesign, pallets were delivered to the assembly workstations by forklift trucks, combined with a conveyer system and an AS/RS. Figure 4.9 provides a depiction of how these deliveries were performed. A total of five forklift trucks were used to serve the three assembly lines.

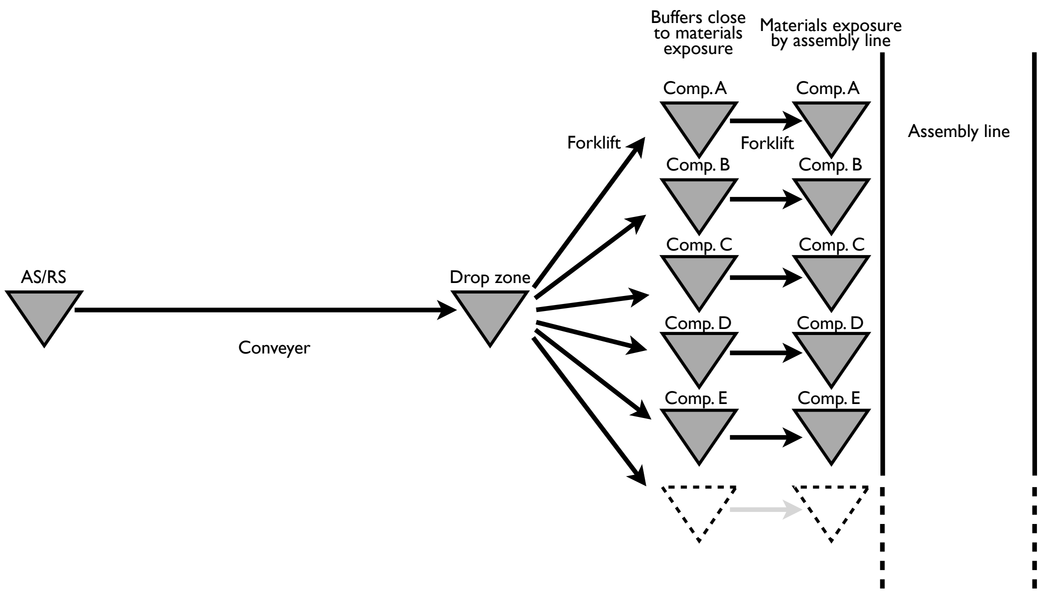

Figure 4.9. Deliveries with forklifts (large packaging, i.e., pallets with frames)

Ordering replenishments of components was a major problem before the in-plant materials supply system was redesigned. The variation in the order backlog of the AS/RS caused severe capacity problems for the conveyer that was delivering pallets from the AS/RS to the three pallet drop zones, which, in turn, resulted in unpredictable delivery precision and delayed delivery of components due to large variations in the lead time, and thereby delaying delivery of components. Additional man-hour consumption was required among the forklift operators as the queues caused additional handling.

Sixteen per cent of the packaging used to supply the components were plastic or cardboard containers that were manually handled to and from vehicles and to the exposed locations. A visual depiction of the mix of packaging used for materials exposure is provided in Figure 4.10. The plastic and cardboard containers were supplied by the use of small electric trucks with a platform, transporting a small number of various types of containers on each delivery round.
After the redesign, only 6% of the components were supplied to the assembly workstations in wooden pallets with frames, compared to 31% before the redesign. The proportion of components supplied in smaller packaging increased to 48%, compared to 16% before the redesign. Six per cent of the components were supplied without packaging (1% before the redesign), and 40% of them were supplied in small cardboard packaging (52% before the redesign).

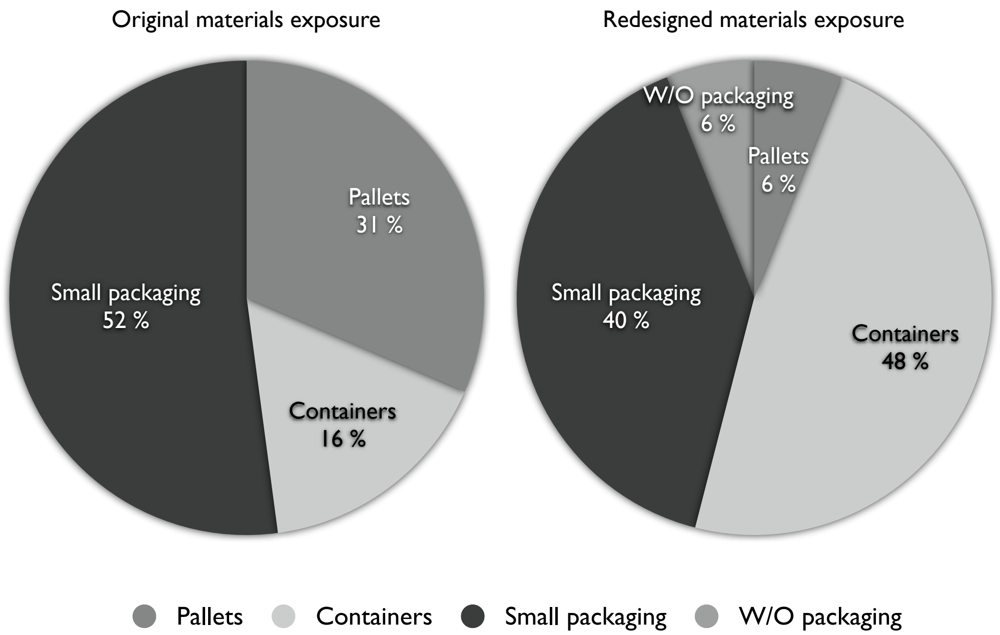

Figure 4.10. The mix of packaging used for materials exposure

Tugger trains performed the majority of the in-plant materials supply after materials exposure was redesigned, as depicted in Figure 4.11.

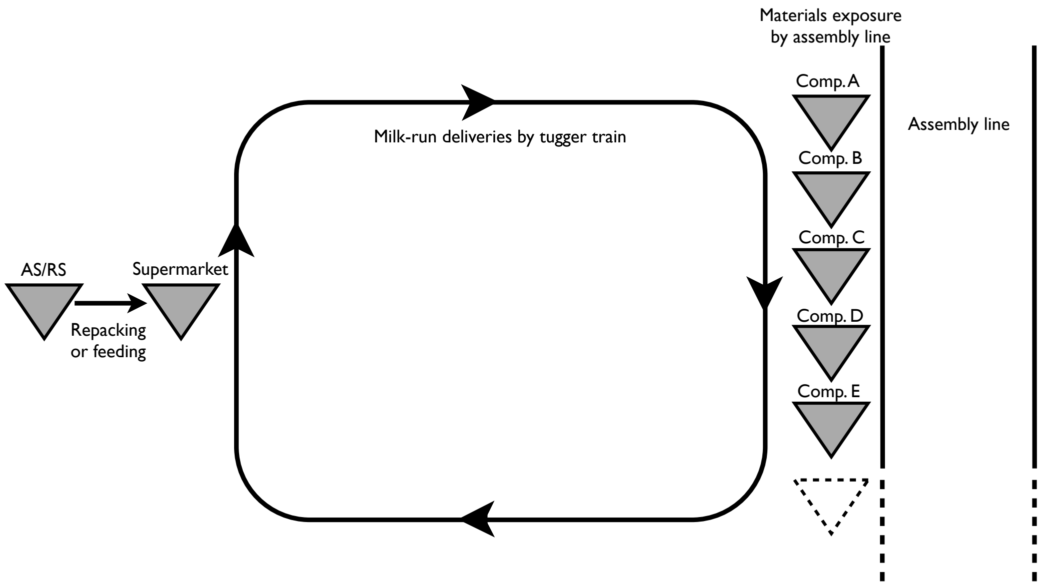

Figure 4.11. Deliveries with a milk-run approach (small packaging, containers and components without packaging) after repacking them in the redesigned system

Following the materials exposure redesign, the use of sequenced deliveries was introduced to the assembly line. The sequencing was made in-plant. The company also introduced repacking to maintain the packaging for external transportation from the suppliers.

After the redesign, the in-plant materials supply workforce to the three assembly lines had increased by 13 operators. The man-hour consumption, number of forklift trucks, and number of tugger trains in the original and in the redesigned system are summarised in Table 4.7. The redesign did not change the number of operators required to actually deliver the components to the assembly line. Instead, the additional operators were occupied in the preparation of the deliveries, either to repack components into smaller packaging or to prepare sequenced deliveries to the assembly lines.

The resources needed to perform the deliveries differed slightly between the original and redesigned systems. Two forklift trucks were decommissioned, reducing the materials supply system's costs for forklift trucks. A different type of tugger train was employed instead of the small electric trucks with a fixed platform that was being used in the original system, and to replace the two eliminated forklift trucks. The new type towed the carts, and used fixed shelves on the carts. All of the tugger trains were cheaper pieces of equipment than the forklift trucks, thus reducing the system's costs. The AS/RS system and conveyer systems used for pallets were still required, as these systems were used to deliver the remaining pallets. Also, the company anticipated a lower cost for the future, because the lower utilisation of the systems would lower the maintenance and repair costs, but this was not possible to verify or quantify within the case study.

Table 4.7. Summary of the case study results

		Original	Redesigned	Results
Man-hour consumption	Assembly operators			−13.5
	Materials handling operators			+13
	- for deliveries			±0
	- for sequencing and repacking			+13
	Total operators in in-plant materials supply system and assembly system			– 0.5
Required equipment in the in-plant materials supply system	Fork lift trucks	5	3	−2
	Tugger trains and other smaller vehicles used			
	- Tugger trains	1	3	+2
	- Small electric trucks with a fixed platform	3	1	–2
	- Total tugger trains			±0

Research question two, regarding the impact of materials exposure on the performance of in-plant materials supply systems in terms of man-hour usage and required equipment, was answered in this section. Materials exposure has an effect on the in-plant materials supply system's performance by impacting the in-plant materials supply system's configuration, which, in turn, has an impact on its performance. Materials exposure impacted the in-plant materials supply system by affecting several requirements regarding the packaging used for materials exposure and thus affecting the system's resources and activities. The configurations of the equipment for handling and transporting components depended on the way the components were exposed, so the performance of the in-plant materials supply system was affected by the materials exposure.

As a result of the redesign, there was an increase in the number of operators (13 were added) in the in-plant materials supply system. All of the additional operators worked with materials handling activities to repack and prepare deliveries to the materials exposure. In contrast, the same number of operators were used to deliver the components, even if the redesigned materials exposure increased the number of packaging that had to be delivered.

Therefore, the materials exposure affected the in-plant materials supply system's performance by impacting the configuration of the in-plant materials supply system and the man-hours, resources, and activities required to fulfil the system's requirements.

4.3 How the packaging for materials exposure impacted the performance of the materials supply systems

How the packaging for the materials exposure impacted the performance of the materials supply system was determined by a packaging evaluation model described in section 4.3.2. The framework for how to use the model for packaging evaluation is provided in Figure 4.12.

To achieve this it was necessary to develop a methodology to describe activities in material flows presented in section 4.3.1.

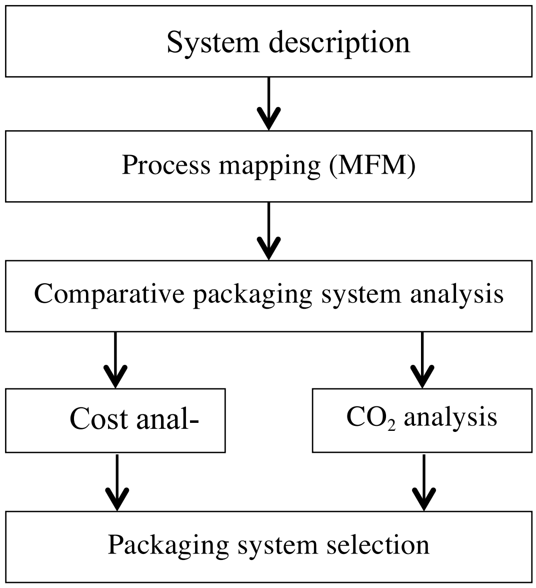

Figure 4.12. Framework for the use of the packaging evaluation model

4.3.1 Material flow mapping

A material flow mapping methodology (MFM) is presented in this section. The MFM includes measurements specified at materials supply system activities materials handling, transportation, storage, and administrative activities.

The proposed methodology to compile materials flow maps follows the procedure below:

Decide on the study object: The scope of the study is important to specify from the beginning as it sets the studied flow (i.e. the included supply chain) and the requirements that comes from the end user and might affect the design of the materials flow.

Data collection: The data collection should start by follow the flow downstream, to get an overview. It is an easier starting point to first follow the flow downstream, and in a second stage follow the flow upstream from the point-of-use. The methodology suggests following one individual identified component. The data collection should follow the component without interfering the materials supply system activities. Use of standardised data sheets for activities could be of use, an example is provided in Figure 4.13.

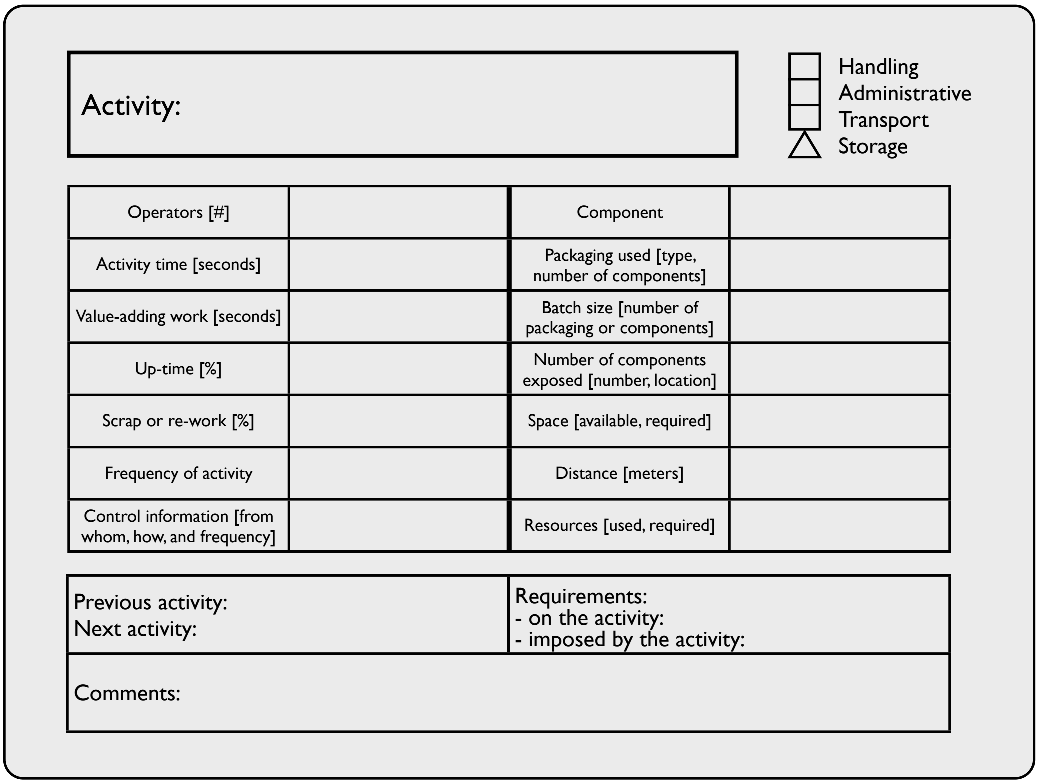

Figure 4.13. An example of a data sheet that can be used to collect data about activities in material flows

In following the individual component, it is preferred to record the entire flow by video and all included activities. An uninterrupted video recording will also provide timing for all activities of the materials flow. If interrupted, it is important to record all discrete activities affecting the component, including materials handling, transportation, storage and administrative activities along the flow. Resources used by the activities such as equipment, packaging, and operator, should be noted. Operators and managers along the flow, should be interviewed to identify requirements that have an effect on the flow design (both current and future). Try ascertaining any process descriptions available about the activities, but stay resilient not avoiding from direct observations as the premier data collection method.

Compilation of data collection: The analysis should be preceded a visualising of the flow in a schematic picture, in order to map the configuration of the activities.

Analysis of video material: The role of the video material is to construct the MFM flow as well as all activities as they occurred. The time required for each activity should be determined.

Compile the MFM: The compilation of the MFM should include all relevant data collected, such as identified requirements and process descriptions. The MFM should present the map of the activities describing the configuration of the activities in the materials supply systems.

HATS analysis: Perform an analysis of the MFM and denominate the activities handling, administration, transport and, storage. Summarise the HATS data such as the number of activities, total and average time required for the categories.

Re-iterate: Discuss with involved actors and validate the compiled MFM and reiterate data collection for activities needing further data collection.

The MFM methodology was tested in a case involving a three-tier supply chain in the Swedish automotive industry.

Data were collected, as the MFM methodology suggests, by mapping the flow of materials from the designated starting-point, which was the end of manufacturing at the supplier, to the point were materials are exposed to the assembler at the assembly line of the car manufacturer. Data was gathered on the individual processes and operations occurring along the flow.

An excerpt of the MFM from the case is provided in Figure 4.14. The figure showing the map is not detailed enough to elaborate on the contents of the map, but provide some insights into the data gathered. Further, the HATS analysis presented in Table 4.8 provided some interesting results based on the map. The results show that it takes 47 activities to move a component of about 1 kg the 64 km from the supplier to the assembly line of the customer, via the warehouse of the logistics provider. The flow was designed so that it at least took two days for a component to reach the assembly station after finishing the manufacturing at the supplier. Materials are pushed in the flow, and manufactured against a daily updated delivery schedule. The supplier pushes materials out to the logistics service provider, who in turn receives a pull signal from the car manufacturer and being connected to the sequencing station at the assembly line.

Table 4.8. A compilation of the HATS-analysis in the case. Note that transportation average time in the case analysis only included in-plant transports.

Performance measurement	**Number of processes** *[number of]*	**Average time** *[seconds]*
Handling	11	185
Administration	18	161
Transport	11	44
Storage	7	N/A
Total	47	

Considering that the components are pulled in segments of the flow, and that the lead-time is possible to measure in days, components in the flow with a manufacturing date at the supplier more than two years before was found. Storage data gathered in the MFM is included in the map. A total of 1451 individual components were stored in the flow at the time of the mapping. The takt time at the car manufacturer was 135 seconds. Assembly worked in one shift at 7.5 hours per day. Assuming that the deviation from the dimensioned storage and the actual assembly mix does not deviate too much. This gives that the current storage, at the time of the case study, had a run-out time of 54,4 hours of production, or 7,25 days, including all 7 storage points and is thus, the average throughput time from supplier to assembler.

The MFM methodology was useful in describing the flow of the materials from the supplier to the assembly line, and was able to visualise the activities and the configuration of the activities in a way that the supplier, logistics service provider and assembly plant managers had not been able to grasp before. The methodology described material handling, storage, transportation and, administrative activities.

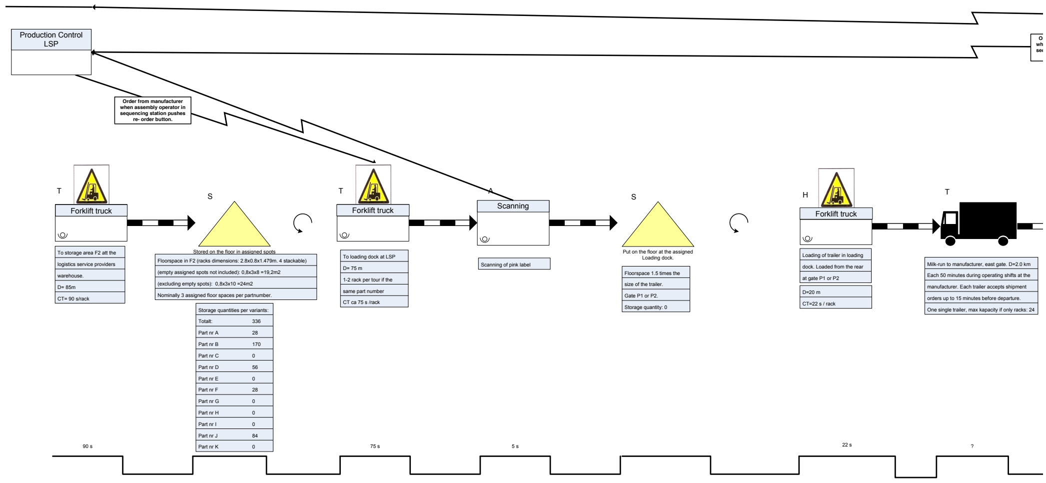

Figure 4.14. An excerpt of the MFM from the case

In summary, it was possible to apply the MFM methodology in the case study. The case showed how it was possible to conduct the steps of the methodology. The outcome of the case study was the Materials Flow Map, including HATS data for the materials flow. The MFM was successful in identifying activities, collecting relevant data about the activities and that the activities were distinguishable according to the HATS taxonomy. The data collected for the activities differed between the different categories of activities. In analysing the materials flow and compiling the MFM the configuration of the flow was visualised, resulting in a useful description of the materials flow in the case.

4.3.2 Theoretical model for packaging selection

A model for explaining how the packaging for materials exposure impacts the performance of materials supply systems was developed. The model structures a systematic comparison between different packaging systems in environmental and economic criteria.

In total, 18 environmental and 27 economic factors were identified from literature. To create criteria for packaging evaluation, factors with similar focus areas were grouped together in criteria. Out of the total number of factors, the clustering created five environmental criteria and six economic criteria, as summarised in Table 4.9. For each criterion, the table states the references from which it was derived.

Table 4.9. Theoretical model for packaging selection, structuring environmental and economic criteria for packaging

Environmental criteria	Economic criteria
Packaging fill rate Lai et al., 2008; Svanes et al., 2010; Wal-Mart, 2012	**Packaging fill rate** Lai et al., 2008; Olsmats and Dominic, 2003; Svanes et al., 2010; Wal-Mart, 2012
Packaging material Faruk et al., 2001; Lai et al., 2008; Matthews, 2004; Svanes et al., 2010; Wal-Mart, 2012	**Packaging material** Lai et al., 2008; Matthews, 2004; Olsmats and Dominic, 2003; Svanes et al., 2010; Twede and Clarke, 2004; Wal-Mart, 2012

Transport Faruk et al., 2001; Kroon and Vrijens, 1995; Lai et al., 2008; Twede and Clarke, 2004; Wu and Dunn, 1995; Wal-Mart, 2012	**Transport** Faruk et al., 2001; Kroon and Vrijens, 1995; Lai et al., 2008; Olsmats and Dominic, 2003; Twede and Clarke, 2004; Wu and Dunn, 1995; Wal-Mart, 2012
Material handling Lai et al., 2008; Matthews, 2004; Wu and Dunn, 1995	**Material handling** Lai et al., 2008; Matthews, 2004; Olsmats and Dominic, 2003; Svanes et al., 2010; Twede and Clarke, 2004; Wu and Dunn, 1995
Waste handling Faruk et al., 2001; Lai et al., 2008; Lee and Xu, 2004; Olsmats and Dominic, 2003; Svanes et al., 2010; Twede and Clarke, 2004; Wu and Dunn, 1995	**Waste handling** Faruk et al., 2001; Lai et al., 2008; Olsmats and Dominic, 2003; Svanes et al., 2010; Twede and Clarke, 2004; Wu and Dunn, 1995
	Administration Kroon and Vrijens, 1995; Twede and Clarke, 2004

The economic and environmental criteria are the basis of the model. Environmental calculations are based on CO2 emissions, and economic calculations are based on costs. In order to obtain comparative figures for different types of packaging, calculations are presented per component. This is obtained from aggregated figures for several components, such as for packaging containing more than one component, unit loads, or transports, which should be divided into the effect from each component by dividing the aggregated figure by the number of components. Each criterion will be explained below.

Packaging fill rate[1] criterion

The basis of the evaluation model is the packaging that is used in the supply chain. The packaging fill rate refers to the total fill rate in the packaging system (i.e., the number of components in each packaging). The packaging fill rate is a measurement that has implications for a number of environmental and economic criteria, and is calculated as support information. The packaging fill rate is the same for both environmental and economic criteria, but could vary for different parts of the supply chain. Refer to Table 4.10 for the packaging fill rate criterion.

Table 4.10. Factors covered by the packaging fill rate criterion

Packaging fill rate	CO_2 driver	Cost driver
Degree of filling in *primary packaging* Svanes et al., 2010; Olsmats and Dominic, 2003; Wal-Mart, 2012	%	%
Degree of filling in *secondary packaging* Svanes et al., 2010; Olsmats and Dominic, 2003; Wal-Mart, 2012	%	%
Degree of filling on *load carrier* (pallet) Svanes et al., 2010; Olsmats and Dominic, 2003; Wal-Mart, 2012	%	%

Packaging material criterion

Packaging material refers to the environmental and economic impacts of producing packaging and any additional necessary material, such as stretch film or intermediate layers of corrugated board (Table 4.11).

[1] Packaging fill rate refers to utilisation rate, not to be confused with fill rate as a measure of service level, as often used in MPC literature.

Table 4.11. Factors covered by the packaging material criterion

Packaging material	CO_2 driver	Cost driver
Packaging material (material type and material weight) Svanes et al., 2010; Olsmats and Dominic, 2003; Lee and Xu, 2004; Lai et al., 2008; Wal-Mart, 2012	N/A	€/kg
Extra packaging material (e.g., stretch film) Lee and Xu, 2004; Mathews, 2004	CO_2/kg	€/unit
Material type Faruk et al., 2001; Wal-Mart, 2012	CO_2/kg	N/A
Weight of a box	Kg	N/A
Primary energy use in packaging production and utilisation Svanes et al., 2010	CO_2/packaging	N/A
Packaging investment Twede and Clark, 2004	N/A	€

Transport criterion

Transport is used in several parts of the supply chain. The factors that one would use to determine the environmental and economic impacts of packaging are similar to the ones that one would use for the transport criterion (see Table 4.12). The total impact depends on the mode of transport, which determines the CO_2 and cost intensity per km, shipping distance, and packaging fill rate.

Table 4.12. Factors covered by the transport criterion

Transport	CO_2 driver	Cost driver
Mode of transport Faruk et al., 2001; Olsmats and Dominic, 2003; Lee and Xu, 2004; Lai et al., 2008; Kroon and Vrijens, 1995; Wu and Dunn, 1995	CO_2/km	€/km
Shipping distance (incl. material distance) Faruk et al., 2001; Twede and Clark, 2004; Olsmats and Dominic, 2003; Lee and Xu, 2004; Lai et al., 2008; Kroon and Vrijens, 1995; Wu and Dunn, 1995; Wal-Mart, 2012	km	km
Packaging fill rate (see Table 4.9)	%	%
Empty running Twede and Clark, 2004	km	N/A
Empty running/Backhaul management Twede and Clark, 2004; Wu and Dunn, 1995	km	km
Equivalent max. capacity in transport (no. of packages)	No.	No.

Materials handling criterion

Materials handling involves emissions and costs that differ according to the packaging system; see Table 4.13.

Table 4.13. Factors covered by the materials handling criterion

Materials handling	CO_2 driver	Cost driver
Materials handling Olsmats and Dominic, 2003; Lai et al., 2008; Wu and Dunn, 1995	CO_2/h	N/A
Warehouse space needed Mathews, 2004; Lai et al., 2008; Wu and Dunn, 1995)	CO_2/h	N/A
Handling and other operational efficiencies Twede and Clark, 2004	N/A	€/h
Extra handling/Material handling Svanes et al., 2010; Twede and Clark, 2004; Wu and Dunn, 1995	N/A	€/h
Cost of sorting Mathews, 2004	N/A	€/h
Packing process Svanes et al., 2010; Olsmats and Dominic, 2003; Lai et al., 2008	N/A	€/h

Waste handling criterion

The waste handling criterion covers waste, recycling, and reuse of packaging systems as well as product shrinkage due to insufficient packaging; see Table 4.14.

Table 4.14. Factors covered by the waste handling criterion

Waste handling	CO_2 driver	Cost driver
Cleaning/Reuse Faruk et al., 2001; Twede and Clark, 2004; Lai et al., 2008	CO_2/h	€/h
Loss of packaging Svanes et al., 2010	N/A	€/packaging
Recycling Faruk et al., 2001; Twede and Clark, 2004; Olsmats and Dominic, 2003; Lee and Xu, 2004; Lai et al., 2008	CO_2/h	N/A
Shipments of packaging waste Lai et al., 2008; Wu and Dunn, 1995	CO_2/km	€/km
Packaging waste Svanes et al., 2010; Olsmats and Dominic, 2003; Lai et al., 2008	CO_2/kg	€/kg
Product shrinkage Svanes et al., 2010; Olsmats and Dominic, 2003	CO_2/component	€/component

Administration criterion

This criterion is considered to only have a financial impact on returnable packaging systems. It includes the administration of managing a system as well as having a system for different types of fees (Table 4.15).

Table 4.15. Factors covered by the administration criterion

Administration	Cost driver
Container management/Administration Twede and Clark, 2004; Kroon and Vrijens, 1995	No. of packaging variants, no. of packages, no. of actors involved, etc.
Service, distribution, and collection fees Kroon and Vrijens, 1995	No. of packages

Results of calculations in the case study

The case in Study V studied a flow of a cable harness from the supplier in Bursa, Turkey, to the final assembly plant of Volvo Car Corporation (VCC) in Gothenburg, Sweden. The principal flow of components is illustrated in Figure 3.11, with Volvo Logistics as a supplier of the logistics services and the packaging to VCC. The study compared a one-way packaging and a returnable packaging,

Transport is the largest contributor to CO_2 emissions in the case in Study V. Irrespective of the type of packaging used, the suppliers send the same number of components. Therefore, the difference in emissions comes from the difference in components' density in the packaging. In this case, the one-way packaging accommodates 15 components, and the returnable packaging accommodates 12 components due to its conical shape. This design is needed for volume efficiency in the return flow (i.e., it needs to be nestable).

The results of the packaging evaluation model show that the one-way packaging system caused the lowest level of CO_2 emissions for the supply of the studied component. The difference in CO_2 emissions per component supplied is 208 g in favour of the one-way packaging system; see Table 4.16.

Table 4.16. Relative carbon emissions and costs per component for returnable packaging compared to one-way packaging in the case. A positive number indicates increased costs or increased CO_2 emissions for the returnable packaging.

Summary of CO_2 emissions and costs	Returnable compared to one-way packaging (g CO_2)	Returnable compared to one-way packaging (€)
Inbound	**+116**	**–0.03**
- Packaging material	–28	–0.09
- Transport *Packaging supplier – Supplier*	144	+0.06
Physical movement of goods using packaging	**+76**	**+0.28**
- Transport *Supplier – VCC*	76	0.03
- Materials handling	0	0.25
Outbound	**+16**	**+0.04**
- Waste handling	16	0.04
- Transport of empty packaging	0	N/A
Administration	N/A	**+0.08**
Comparative CO_2 emissions/costs per component	**+208**	**+0.37**

The cost calculations show that the cost of supplying the components in one-way packaging is lower than the cost of using returnable packaging. The cost of using the returnable packaging is €0.37 more per component consumed than if using the one-way packaging.

The main difference in the physical movement of goods with packaging is the cost of materials handling. The use of the MFM methodology showed that there was a simpler flow of materials for the one-way packaging in-plant at VCC. The use of the MFM methodology showed that each one-way packaging required 63 seconds less work per packaging in the in-plant delivery of components to the assembly line, compared with the returnable packaging. This difference was not known to VCC and was revealed by the use of the methodology.

4.3.3 Summary of the results for research question three

Section 4.3 answered research question three, which sought to explain how the packaging for materials exposure impacts the performance of the materials supply system. Whilst research question two focused on the in-plant materials supply system, question three focused on the whole materials flow and on the packaging in particular. The answer of the research question began with an introduction of a methodology for describing material flows, called Materials Flow Mapping. The methodology contributed to the answer the third research question, by describing activities in material flows, mapping and categorising the activities and ascertaining the data for required for determining the performance in terms of CO_2 emissions and cost attributed to each component in the materials supply system. The MFM methodology was a necessary step to answering the third research question, and the methodology was used to attain input for the model to compare how different packaging for materials exposure impact the performance of materials supply systems in the flow of materials to the exposed location at the assembly workstation.

The proposed evaluation model aims to assist companies with the selection of packaging for use in the materials exposure. The model can be used to determine how a packaging's economic criteria (i.e., packaging fill rate, packaging material, transport, material handling, waste handling, administration), in terms of cost measured in cost, and environmental criteria (i.e., packaging fill rate, packaging material, transport, material handling, waste handling), in terms of CO_2 emissions, impact the performance of a materials supply system.

5 Discussion

This chapter discusses the research results, starting with discussions about the results for each research question. It continues with the practical implications and generalisability of the research and ends with suggestions for further research.

5.1 How materials exposure impacts assembly workstation performance

This section discusses the results related to research question one (i.e., the results addressed in Section 4.1). Based on the results from Studies I and II, it can be established that materials exposure influences the performance of the assembly system in terms of space, non-value-adding work, and ergonomics, , each of which will be discussed below in subsections 5.1.1 to 5.1.3, respectively.

5.1.1 Impact in terms of space

In Study I the company reduced the floor space used along the assembly line to less than a third of the previously required space. Freed space increases flexibility so that a company may either more easily introduce new products (Wild, 1975) or increase its volume flexibility and product mix-flexibility (Hua and Johnson, 2010). According to Slack et al. (2007), flexibility is included in the definition of performance, along with quality, speed, dependability, and cost.

The ability to expose many variants of a component is arguably a performance measure of flexibility; Persona et al. (2007) have described this ability as responsiveness to demand changes, which Limère et al. (2012) subsequently confirmed. In Study I the original system's potential to introduce new components was limited and required considerable effort in reconfiguring the materials exposure. As several authors have indicated, the cost of space for assembly lines can be high (Shtub and Dar-El, 1989; Wild, 1975), and the results from Study I show that the materials exposure greatly affected the amount of space required at the assembly line. In Study I the freed space after the redesign was used for staff meetings, morning briefings, and breaks. Later, after the redesign of the entire assembly line, a whole line section was devoted to meetings and team activities for the staff. The freed space could as well be used for other value-adding activities or to relocate materials supply system activities closer to the assembly line.

5.1.2 Impact in terms of non-value-adding work

The reduction in walking distance that resulted from the redesigned materials exposure in Study I was 52%. The exposed components required less space in the flow racks, therefore the components could be exposed closer to the assembly object, which shortened the walking distance for the assembly operator. The components and assembly objects remained the same at the assembly workstations. However, with less non-value-adding work and equal value-adding work (the value-adding work changed by < 1%), the assembly operators at the three redesigned assembly workstations initially walked more slowly, but this effect could be suspected not last after the entire line would be re-balanced.

While operating with its original materials exposure design, due to restrictions in terms of cycle time, the company in Study I had to control the sequence in which product variants were manufactured. These restrictions emanated from differences in the location of components in the materials exposure for the different product variants, which resulted in different materials handling time. The explanation is provided in Figure 4.1, which shows that walking distances were much greater for product variant B, which contributed to more non-value-adding work. After the materials exposure was redesigned, the differences in the time required to assemble product variants were eliminated, so fewer constraints limited the final assembly schedule. The change therefore improved the company's flexibility, because it could plan the production schedule by considering fewer constraints and make customer-ordered scheduling with as levelled production as possible. The constraint on the schedule-mix was reduced due to less variation between the assembly objects. Thus, the initial materials exposure had a negative impact on assembly workstation performance by creating time differences between variants that had the same amount of value-adding work.

According to the results from Study I and the experiment in Study II, materials exposure influenced the operator's picking time. In Study I picking time was halved by changing the packaging to a smaller container instead of a wooden pallet with frames, complementing the results from the experiment in Study II suggest that materials exposure significantly impacts the manual picking time in an assembly situation. These findings support earlier work by Wänström and Medbo (2009) and Neumann and Medbo (2010), who both categorised picking locations in pallets into different sections with associated differences in picking times. The reduction in size of the packaging reduced the variance in picking time, making it possible for companies to better estimate picking times during the design and operation of the assembly systems. These findings are supported by Battini et al. (2007), who concluded that less time variations decreased losses.

All tested factors in Study II were supported by the experiment except for the height available to pick, as illustrated in Table 4.4. The packaging used to expose components was shown to be the most important factor. In this sense, larger packaging increases the distance between the packaging's edge and the component, which lengthens the distance needed to reach the component. In large packaging, there is also a higher risk that layers of components can get stuck to each other while being picked. By contrast, smaller packaging brings the products closer to the edge but usually contain fewer components. Packaging can also possess other properties that affect the exposure, such as edges (i.e., of different shapes and sizes, both of which affect exposure) and closures. Lids and closures affected the non-value-adding work category pick preparation in Study I, and in this case, the picking time was doubled when the assembly operator had to open the packaging each time a component needed to be picked.

The factor interactions provided in Table 4.5 show that the four largest interactions included packaging. The influence from the size of the effect of the packaging affects the size of the interactions between the following factors: angle of exposure, sideway positioning, part size, and exposure height. Exposure angle and height can easily be expected to interact, because packaging that is angled toward the picker is better exposed toward the picker, demonstrating that using the best angle becomes more important as the exposure height increases.

The factor effect of the height available for picking was clearly not significant. By contrast, the literature maintains that the factor height available to pick is important; Jones and Battieste (2004) have indicated that shelf dimensions should be spacious enough to allow easy picking, while Karwowski and Rodrick

(2001) have indicated that horizontal barriers have an impact on picking performance. Further investigations could thus be beneficial to establishing this factor's importance. A possible explanation for the effect of the factor not being supported in the experiment is the inappropriate choice of values for the low or high levels, which do not differentiate picking conditions. The levels could have been set too generously to the point at which they had no effect on the picking operator's ability to pick (i.e., too high or too low) and therefore did not affect the picking time, thus rendering it insignificant in the experiment. The other factors in the experimental design were based on industry standards, whereas no such standard was found for the height available to pick.

The results explain what factors impact picking time at assembly lines and are thus useful for designing manual picking operations at both assembly lines and in other situations in which discrete manual picking occurs, such as order picking or bench assembly. Order picking has several similarities to picking at assembly lines, especially when it is conducted as picker-to-part, for the picker moves to the stored component in order to retrieve it (de Koster et al., 2007). The picking situation then resembles an assembly operator's picking components exposed at an assembly line, although the assembly operator repeats the picking activity of the same components more frequently. The literature review of de Koster et al. (2007) rehearsed how previous research had focused both on routing and on the principles of how the picker gets to the exposed position of the component to be picked, and this thesis supports these ideas with findings regarding how materials exposure impacts the picking time when a picker is at an exposed component. The contribution about what factors impact manual picking at assembly lines also complements previous work on picking time by explaining the factors of materials exposure. Previous contributions on picking time have focused on picking times from pallets (Arnström, 1981; Neumann and Medbo, 2010), though the contribution here is applicable to other smaller packaging and materials exposure conditions. The manual picking times for picking from smaller bins is an important finding that contributes to previous work about motion and time studies, such as performed by Barnes (1980).

5.1.3 Impact in terms of ergonomics

In Study I the workstations were redesigned with space as the primary consideration. The company could have prioritised differently during the redesign, such as by considering ergonomics first. Nevertheless, some of the largest improvements were ergonomic, including a 92% reduction in potentially harmful picking activities and an almost complete elimination of body movements that put the picker at risk for back and shoulder injuries, according to the VASA-model used by the company in the study. The results from the study thus clearly showed that materials exposure impacted the assembly workstation in terms of ergonomics.

However, the literature has also indicated a risk in redesigning an assembly operator's work. New activities might not contribute to overall better conditions for the operator, because time is a critical aspect of repetitive strain injuries (Wells et al., 2007). If the time gains from reduced manual materials handling are simply used to increase the time spent on assembly work, then the operator potentially faces an increased risk of repetitive strain injury. Previous research at the company in Study I showed that over 60% of the assembly operators reported pain in the hand and wrist (Neumann et al., 2006); it was not, however, clarified whether this resulted from material handling or assembly activities. This dynamic has been named the ‘ergonomics pitfall’ (Westgaard and Winkel, 1996), which does not, however, justify retaining ergonomically unsound tasks.

For the redesigned materials exposure in Study I, the assembly operators had to reach out less, so they did not need to raise their arms or bend their backs as frequently when picking. The redesigned materials exposure thus also affected assembly workstation performance in terms of ergonomics. The findings regarding ergonomics add to the findings of Dempsey and Mathiassen (2006) and Wagner et al. (2009), who both commented that quantifications of the impact on performance of the assembly system were important. These studies, however, focused on movements and injury risks coupled with ergonomics instead of the performance of the assembly system.

5.1.4 Performance of the assembly workstation and the assembly system as a whole

The results showed that materials exposure had an impact on the non-value-adding portion of the operator’s work. By using a better-suited materials exposure in the studied case, the company could reduce the materials handling time for the assembly operators by 23% and the total non-value-adding work by 20% at the workstations included in the study. As will be discussed below, the practical implications of these results have large implications for assembly systems.

For the assembly system as a whole, the decrease of 20% in non-value-adding assembly work made rebalancing necessary to achieve the full effect on assembly line performance. For workstation A, the assembly operator completed assembly objects well in advance of the cycle time; hence, losses were incurred since the next assembly object was not yet available. The operator had to wait for the next assembly objects to arrive at the assembly workstation but did not work any faster. The assembly lines in the original system employed 45 operators per shift, implying a possible reduction of 11 operators after a redesign and a rebalancing of the whole line, as shown by the results.

Based on the case study’s results, the company planned and executed a redesign of the final assembly lines that introduced the changes suggested by the study for all assembly lines. During the summer of 2008, the company rebuilt the assembly lines during a three-week production break. After the subsequent rebalancing of the assembly lines, the company demonstrated a general increase of more than 20% in line performance; September 2008 exhibited the highest monthly engine production on record for the company—an increase that would have been impossible before materials exposure was redesigned (Dahlquist, 2009). Being able to reduce the number of assembly operators without affecting the output and with little need for investment indicates the industrial relevance of the results.

In retrospect, the economic downturn affected the company during the last months of 2008, so the company reduced the number of assembly operators instead of increasing the output. By comparing the results from Study I with the results from Study III, at the same assembly lines the total reduction in assembly operators was 13.5 operators, showing that both the ongoing improvements to materials exposure and the rebalancing of the assembly lines was continuously beneficial. Moreover, if the company desired an increase in production volume, then it could use the improved performance to meet these goals as well. Hence, flexibility was also increased.

To summarise, the findings showed how materials exposure impacts assembly workstation performance in terms of space, non-value-adding work, and ergonomics. Materials exposure's effect on assembly workstation performance has large industrial relevance, since an individual assembly operator may perform the non-value-adding activities several thousand times per shift – making improvements relevant.

5.2 How materials exposure impacts the performance of in-plant materials supply systems

This section discusses the results related to research question two. The discussion will include the results addressed in Section 4.2, which describes how materials exposure impacts the performance of in-plant materials supply systems.

Study III showed that materials exposure influenced both the in-plant materials supply system's configuration and the in-plant materials supply system's performance. It also revealed how the configuration of the in-plant materials supply system needs to be determined in order to also determine the impact that materials exposure has on the in-plant materials supply system.

Study III measured the resources used to run the in-plant materials supply system. In the case in Study III, the packaging contained on average fewer components after materials exposure had been redesigned, though the number of packaging and packaging types carried in each delivery run increased in the in-plant materials supply. The components were mostly delivered by tugger trains, as per to a milk-run approach in which a number of packaging types are transported together (see Figure 4.11).

The redesigned materials exposure added 13 operators to the materials supply system. However, it is important to recognise that the in-plant transportation activities did not cause an increase in the number of operators. Instead, this increase was due to the materials handling activities preparing deliveries, which includes both the repacking of components into smaller packaging, the sequencing of components, and kit preparation. Therefore, even though the average packaging size was reduced, the deliveries did not use more man-hours for transportation activities. It is not the packaging size that determines the frequency of the transport, as it is still possible to consolidate the deliveries with smaller packaging into the same number of transports. This result is important, for it is sometimes believed that fewer, larger deliveries will always cost less. However, this thesis proved that it is possible to deliver the same components in smaller packaging at a similar or lower number of man-hours and resources used. Previous research by Hales and Andersen (2001) and Baudin (2004) indicated that different resources were required, though neither of these studies investigated the impact of resources on performance.

In Study III the redesign of materials exposure affected the configuration of the in-plant material supply system. Before the redesign, many components were exposed in pallets and delivered by forklift trucks. After the redesign, however, most components were exposed in smaller plastic containers, which were unsuitable to deliver by forklift trucks. Instead, they were delivered by tugger trains operating in milk-runs that pulled carts with shelves carrying the smaller plastic containers. The redesigned materials exposure thus caused a change in the configuration of the in-plant materials supply.

Battini et al. (2009) mentioned that components can be moved to the assembly workstation in one of three ways (i.e., pallet, trolley, or kit), though they did not study the actual performance (i.e., man-hours needed) for the configurations in the in-plant materials supply. Other studies, such as those by Battini et al. (2010) and Emde and Boysen (2012), focused on the configuration of the in-plant materials supply system. Although they studied the localisation problem of activities in the in-plant materials supply system, both studies omitted the performance in terms of the man-hours used. Boysen et al. (2012b) studied the supply of sequenced products to assembly lines but also included the configuration of the in-plant materials supply system and did not consider the performance in terms of the man-hour consumption. By contrast, Faccio et al. (2013) investigated the number of man-hours needed to supply a mixed-model assembly line, though they examined only the man-hours in order to optimise the number of kanbans in the system.

In the redesigned system in Study III, the tugger train had the same start and finish location for all components and stopped at the components' exposed locations at the assembly line. In this sense, all tugger trains followed the same basic routing and timetable, whereas the forklift trucks employed a taxi style of operations in which they were on call to be assigned a transport task.

The number of forklift trucks was reduced from five to three by the redesign. The decrease in the number of forklift trucks was not proportional to the reduction in the number of pallets used in the materials exposure. While the number of components exposed in pallets decreased by 81%, the forklift trucks only decreased in number by 40%. Hence, an even lower utilisation rate could be expected for the forklift trucks. As a result of the redesign, further adjustments to suit the new capacity requirements should be possible. This possibility indicates the need for the in-plant materials supply system to be able to cope with all packaging types used in materials exposure. Even if there were only one pallet left, one forklift truck would be required to transport and handle that single pallet. As long as the materials exposure uses a packaging requiring a resource to transport and handle that type of packaging, the in-plant materials supply system has to be configured accordingly. Each individual packaging and the mix of all packaging will both affect how the dimensions of the in-plant materials supply system can be modified.

The redesigned materials exposure considerably increased the number of operators preparing materials deliveries (i.e., repacking, kitting, and sequencing) in the in-plant materials supply system. Even so, the savings in man-hour consumption in assembly exceeded the increase in materials supply. The results from Study III matched or slightly outperformed the results from Study I, which had indicated a 20% increase in overall performance for assembly workstations, which resulted in a possible reduction of assembly operators by 11 operators. In Study III, the actual outcome of the change for the same assembly system was a decrease of 13.5 assembly operators, while the number of in-plant materials supply system operators increased by 13 operators. Since the company is situated in Sweden, where operators have a similar wage rate (Edin & Zetterberg, 1992), it and other companies there have no incentive to redistribute tasks between assembly and materials supply operators based on salary and wage costs.

In this case the increase in the number of operators required to perform the in-plant materials supply was entirely linked to the preparation of deliveries and not to the deliveries themselves. A way to avoid repacking into smaller packaging is to arrange for the suppliers to deliver components to the plant in the packaging that is used for exposing the components. The case company stated that a solution like this had been considered but rejected due to pre-existing supplier contracts specifying the packaging. Another factor considered was an expected under-utilisation of volume in the transport vehicles from the suppliers to the plant.

For the in-plant materials supply, storing components in buffers creates additional activities under the categories of material handling, storage, transportation, and manufacturing, planning, and control (Caputo and Pelagagge, 2011). For example, exchanging pallets at the assembly workstations caused several problems, including the question of who should empty the old pallet if components still remained there. In this case, either the forklift truck driver or the assembly operator must empty the old pallet and place any remaining components into the new pallet, which invariably results in additional activities. However, the redesign employed a system for the components not exposed in pallets in which the assembly operator simply returned the empty container in a gravity flow rack from the inside of the assembly line. The use of flow racks and plastic containers eliminates the problem of additional activities that arises when a forklift truck driver must both exchange pallets and transfer remaining components to the new pallet. The smaller packaging in the flow of materials, makes it possible to handle the packaging and components manually.

A major theoretical and practical contribution of this thesis is that the performance of the in-plant materials supply system is not proportional to the packaging size used for exposing components. However, there can be differences in the configuration of the in-plant materials supply systems required for delivering components to materials exposure. Another contribution is that an increased delivery frequency does not necessarily increase the man-hours required to perform the in-plant materials supply.

Research question two, which addressed how materials exposure impacts the performance of in-plant materials supply systems, was answered by showing how material exposure impacted the in-plant materials supply system and its performance. The materials exposure affected the in-plant materials supply system's performance by impacting the configuration of the in-plant materials supply system, as well as the man-hours and equipment needed for the system to operate.

It can be concluded that the efficiency of in-plant deliveries does not need to be negatively affected by a redesign that uses smaller packaging. The presumption that supplying smaller packaging to materials exposure would be costlier due to different configurations and resources was thus proven false.

5.3 How the packaging for materials exposure impacts the performance of materials supply systems

This section discusses the results of research question three (i.e., presented in Section 4.3) regarding how the packaging for materials exposure impacts the performance of materials supply systems. The section starts by discussing the developed methodology for material flow mapping (MFM) and continues with discussions of how this methodology was used in a model to evaluate how the packaging for materials exposure impacts performance. The section ends by discussing the packaging selection model.

In Study IV the MFM methodology was developed to describe activities in material flows. To answer research question three, this methodology provided the necessary means to evaluate how the packaging for materials exposure impacts the performance of materials supply systems. The MFM methodology also made it possible to describe the material flow in terms of the HATS taxonomy summarising materials handling, storage, transportation, and administration activities. The taxonomy aids in visualising the flow in a comprehensible way.

Study IV illustrated the usefulness of the methodology in a material flow between a supplier and the assembly workstation for the final assembly at the vehicle assembly plant.

In Study IV components were supplied in sequence to the assembly workstation, because the workstation did not have enough space available to expose all variants of the component. The sequencing was made inside the final assembly plant at SAAB Automobile. During the data collection for the mapping, personnel from SAAB, the logistics service provider, and the supplier participated and observed the sequencing operations. Before the MFM methodology was applied, there was no transparency between the parts of the material flow; neither of the personnel participating knew of the activities outside of their own operations. The MFM methodology ultimately illustrated the realised design of the material flow.

In Studies IV and V, the steps of the MFM methodology were performed as suggested. In this methodology, no variations in activity times are considered, and preconditions at each mapping opportunity will affect the outcome. Thereby, the MFM methodology shares a caracteristics with the VSM methodology: using snapshots of actual figures and activities as measurement tools (Brunt, 2000). Snapshots do not display the utilisation of shared resources, because the mapping covers only one flow. By contrast, a materials supply system can contain many material flows, and the situation for the whole materials supply system might differ and remain unidentified by the MFM methodology.

The cases clarified the need for knowledge of why each activity occurs in order to construct a material flow map. Particular knowledge of the control of the flow is necessary to understand the relations between the activities constituting the flow. In this sense, the MFM methodology is a contribution that can be used as a means to improve the performance of materials supply systems.

The MFM methodology was developed to describe activities in material flows between suppliers and assembly, but it is by no means limited to this scope. The methodology is useful for analysing material flows containing materials handling, transportation, storage, and administration activities and is therefore usable well beyond the scope of this thesis. According to the HATS taxonomy with four types of activities, the division of activities in material flows is both a theoretical and a managerial contribution.

Research question three addressed how the packaging for materials exposure impacts the performance of materials supply systems. While the MFM methodology was developed to describe activities in the material flow, the packaging selection model can be used to examine the selection of the packaging used for materials exposure and the impact on the performance of the materials supply system. Compared to other models suitable for packaging selection, the presented model is more comprehensive, for it combines economic and environmental criteria. Previous research on the selection of packaging systems can be seen as following one of two strands. The first strand consists of research on existing packaging systems involving either economic criteria, such as the Packaging Scorecard that follows the performance of packaging in a supply chain (Olsmats and Dominic, 2003; Svanes et al. (2010), or the environmental criteria, as exemplified by LCA models (Lee and Xu, 2004; Sonneveld, 2000). The second strand consists of research on new packaging systems and focuses on the factors that companies should consider during the design phase. Examples of this stream include Bramklev (2009), who provided a model of concurrent engineering and product design; Svanes et al. (2010), who focused on sustainable packaging design; and Twede and Clake (2004), who focused on the design of returnable packaging systems.

Compared to LCA models, the model presented in Study V is far less time-consuming to apply and constitutes a major contribution by its inclusion of both environmental and economic factors.

The model was developed to both compare two or more packaging systems and simplify the required data collection. However, the model can also be used to compare more packaging systems. The inclusion of more packaging systems is only limited regarding the amount of data that can be collected. The model stipulates what is required to compare different types of packaging systems. In Paper V the purpose of the case study was to compare two different packaging systems. However, the model can also be used to attain the data necessary to describe and compare whole material flows in terms of the packaging's impact on the performance of the materials supply system.

The contributions from the model are in line with Azzi et al. (2012), who suggested valuable future contributions to the research of packaging. First, Azzi et al. (2012) stipulated the criteria and procedures needed to be weighed against each other, thus suggesting that packaging logistics can be integrated for a holistic view of the supply chain that could be used to assess the performance of the packaging configuration. Second, Azzi et al. (2012) also suggested that models combining criteria of sustainability, logistics, and ergonomics are required. The packaging selection model has contributed to the first two areas, and Section 5.4 addresses how ergonomics can be integrated into further research.

Limitations in utilising the model include collecting the data for future flows. The data collection for future flows may be difficult to perform, for it relies on uncertain data. This limitation is the major reason for using the model as a relative model to compare different types of packaging systems. However, the mapping of the material flow still needs to be performed in order to ascertain which activities differ among the various types of packaging. Hence, to use the packaging selection model suggested in Paper V, a methodology such as that of the MFM needs to be applied. The development of the MFM methodology thus facilitated answering research question three.

In Study V, the model was tested in a case study that compared a one-way packaging system with a returnable packaging system. In this case, both the CO_2 and the cost calculations showed that the one-way packaging system was preferable.

In Study V the model was tested in a case study that compared a one-way packaging system with a returnable packaging system. In this case both the CO_2 and cost calculations showed that the one-way packaging system was preferable.

In Study V the model for packaging selection revealed that the costs related to both materials handling and administrative activities are larger for returnable packaging than for one-way packaging. Furthermore, the case study showed potential options for cost and CO_2 reductions. Considering that packaging in general has been neglected in many industries (Field, 1998), such potential would likely be discovered in other companies as well. There have also been attempts to expand the performance measurements in materials supply systems to include environmental metrics (e.g., Shaw et al., 2010), though apart from the addition of metrics, attempts developing models have been scarce. Azzi et al. (2012) pinpoint the lack of research on combining performance issues with environmental sustainability issues, such as CO_2 usage, which has heavily gained importance as a performance measure in production (e.g. Hu et al., 2011).

In Study V the company representatives believed that they used the most environmentally friendly package due to its reusability. The result showed that it is important to gather knowledge of the actual situation, and the developed model provided these possibilities. Herein lies an important practical contribution of the model. When the model was presented to the manager responsible for packaging at the major case company, the manager commented that it was the first time that he had encountered a model that combines cost and environmental criteria. By using the model, adopted practices could be challenged by comparing facts about cost and CO_2 emissions for different packages that have been selected or considered for use in materials exposure.

The model can be used for material flows, in which it is possible to attain information about the flow of materials and the packaging systems involved. Therefore, the model's applicability is neither limited to the automotive industry nor to materials supply to assembly, since the focus is on the material flow. The model is limited, however, in that it requires the packaging systems to be defined before the comparison is made. In this sense, the model does not suggest optimal packaging by any means; it simply compares the chosen packaging systems.

The industrial relevance of the model is easily explained. In companies that assemble products, almost all components use packaging in some form in the materials supply systems, so the suggested model for evaluating the packaging's impact on the performance of the materials supply system can be useful.

Research question three, which addressed how the packaging for materials exposure impacts the performance of materials supply systems, was answered by developing a methodology to describe activities in material flows. The MFM methodology was the first major contribution, and a packaging selection model was the second. The methodology contributed to describing material flows and the activities (i.e., materials handling, transportation, storage, and administration activities) in a material flow. The MFM methodology was also useful in providing input for the packaging selection model, because the latter was designed to compare the impacts of different packaging on a material supply system's performance.

Materials exposure thus has an impact on material supply system performance, which is both identifiable and quantifiable by using the MFM methodology and the packaging selection model.

5.4 Further research

This section proposes further research, on the basis of the results of this thesis. Some of the proposals are deepened continuations of the studies performed here, some are widening of the scope, some are new aspects, and some are addressing limitations in the present research.

Regarding assembly workstation performance, investigations of materials exposure's impact on product quality would be interesting. Quality is indicated as an important performance measure (Slack et al., 2007), and was not included in the thesis, motivating further research. Does materials exposure have an impact on product quality? For example, does an increased proportion of value-adding work, due to a materials exposure reducing non-value-adding work, impact product quality?

The choices of the number of factors to include, and the number of experiments required in Study II also present opportunities for further research. In selecting the factors to include, choices were made, limiting the results from the study. With additional time and resources for the experiment, further factors could have been included. Further studies could determine which packaging properties impact picking time and time for pick prepartion. Study I showed how materials exposure impacted non-value-adding work, so further explanations with case studies regarding the factors that had an impact on the non-value-adding work would be beneficial. Each factor in the experiment in Study II could be further examined in case studies, further explaining how each factor affect the performance of assembly workstation performance. Separating the factor 'part size and weight' into the factors 'component size' and 'component weight' would have improved the results of the study, because they might differ for other types of components. The experiment covered manual picking with one hand; that is, the components were so small that they could be picked with one hand. In cases where the component is so large that it cannot be picked with one hand, conditions might differ, therefore motivating further research.

The factor of height available to pick was not supported in the experiment on picking time. Further studies are desirable to study materials exposure with a high density of exposed components, as an increased density will reduce the height available to pick. If the height available to pick does not impact picking time for assembly operators, considerable space savings could be achieved.

In the experiment in Study II, 128 experiments were conducted with different experimental conditions. Each of these conditions and the resulting picking time was stored in a database. The purpose for that study was to explain what factors impact picking time. However, all the 128 experimental settings provide practical contributions with the picking time for that actual setting for use in designing materials exposure in industry.

Picking of small components might require special attention by an assembly operator in order to pick only one, or a designated number, of components. This attention to precision might have an impact on the picking time and would benefit from further research.

The effects of a materials exposure without packaging could be studied further as well, because the conditions for the exposure different compared to an exposure in packaging. Studies of components exposed without packaging could explore whether gains made in assembly counteract the extra activities required in the in-plant materials supply system.

Kitting was only briefly discussed in this thesis. Kitting is a way of exposing components, so the materials exposure connections with kitting could be further studied. Kitting could, for instance, be used to further decrease the space required for materials exposure, and have an impact on assembly workstation performance. Further studies using the contributions, such as the impact on space requirements, non-value-adding work and ergonomics, from this thesis could explore whether the gains made in assembly could counteract the extra activities required in the materials supply system.

The results of this thesis primarily involve cases of picking in which the picker knows what component to pick. Further research could include cases in which the picker is not as accustomed to what to pick, i.e., situations that require supporting information on what to pick, such as in the preparation of kits, were errors in the preparation can affect the performance of the kitting process (Caputo and Pelagagge, 2011).

Further extensions of the studies on picking time could include more ergonomics-related aspects. The height of the exposure, and angle of exposure impact the picking time, and how these two factors affect ergonomics for the picker merit further studies. Ergonomics, for example, can be studied in relation to the other contributions made in this thesis, comparing impact on performance with impact in ergonomics.

A shift in materials supply systems toward using smaller packaging increases the possibilities to use manual materials handling in-plant. Therefore, it would be beneficial to add ergonomics to both the developed materials flow mapping methodology and to the model evaluating the packaging selection for material flows. With more kitting used, preparation for kitting, and sequencing will most likely affect the ergonomic impact in materials supply systems. Hence, ergonomics could be added as a data to collect for the MFM methodology.

Manual handling of smaller packaging will also affect the configuration of the in-plant materials supply system as studied in Study III. The frame of reference developed for non-value-adding work for assembly operators (table 4.2) could be developed for studying the materials exposure on the in-plant materials supply side, i.e. in the feeding of the components into the materials exposure.

6 Conclusions

This thesis concerns the supply of components to assembly in production systems, and introduces materials exposure as the interface between materials supply systems and assembly systems. The purpose of the thesis is to explain how materials exposure influences the performance of materials supply systems and assembly systems. For companies assembling components into products, the supply of components is crucial for the operation of the assembly process, for it creates conditions both for the efficiency at the assembly workstation (e.g., in terms of the amount of non-value-adding work) and conditions for the operator in terms of ergonomics. At the same time, the materials supply system has to be efficient in its operation in order to keep costs of operation low. In this way, materials exposure impacts the performance of a production system as a whole.

The thesis is based on five studies, all of which depart from theoretical frameworks developed from literature and applied in five empirical studies performed within the Swedish automotive industry. Four case studies and one experiment were conducted. The studies aided in answering three research questions, and the results from the studies are published in five papers.

Research question one sought to explain how materials exposure impacted assembly workstation performance in terms of space, non-value-adding work, and ergonomics.

In studying how materials exposure impacts assembly workstation performance in terms of space, the packaging used to expose the component and the mix of components in materials exposure both impact space requirements. The size of the packaging is very influential on the space requirements for materials exposure. If smaller packaging is used in materials exposure, both the number of different components and the amount of components can be exposed in less space. If multiple product variants are assembled, the impact becomes more evident as more components require space in the materials exposure.

Considering the common use of the EUR-pallets as packaging in assembly systems, a case study showed a considerable reduction in workstation space requirements. In the case study a change of the materials exposure that used smaller packaging impacted the space required to expose the components with a reduction of 67%. The reduction meant that the materials exposure no longer was the limitation for space requirements at the assembly line. It can thus be concluded that the contribution regarding how materials exposure impacts assembly workstation in terms of space is that suitable materials exposure can reduce the space required for assembly workstations.

In studying non-value-adding work for the assembly operator, a contribution was the development of a new taxonomy for non-value-adding work for assembly operators. The taxonomy is developed from previous work and based on assembly operator's work in picking components for assembly. The taxonomy divides the assembly operator's work in two value-adding and 25 non-value-adding categories of work. The non-value-adding categories are further divided according to whether they consider material handling related work.

The results from the case study show three reasons for why materials exposure impacts non-value-adding work at assembly workstations.

The position of the exposure of a component impacts the performance of the assembly workstation. The position of the component in the materials exposure affected the walking time for the assembly operator when retrieving the component for assembly at the assembly object. The impact on assembly workstation performance is that the walking time for the assembly operator contributed to non-value-adding time for the assembly operator.

The size of the packaging used to expose components in the materials exposure has an impact on assembly workstation performance. The packaging used to expose the component impacts the time used by an assembly operator to retrieve a component from the materials exposure, which is measured as the picking time. The picking time contributes to the non-value-adding work for the assembly operator and thereby impacts assembly workstation performance.

The non-value-adding work 'pick preparation' is affected in several ways by how components are exposed. The design of the packaging used to expose components has an impact on assembly workstation performance. Packaging used to expose components can have lids and closures, thus causing the assembly operator to perform additional non-value-adding activities prior to being able to pick the component from the packaging. The way that components are exposed inside the packaging causes the assembly operator to perform additional non-value-adding activities, such as sorting components for ease of picking.

It can thus be concluded that the case contributed a detailed description of the large potential for reducing non-value-adding work for assembly workstations by considering the impact from materials exposure. A contribution from the case study is the three reasons for why materials exposure impacts non-value-adding work at assembly workstations. In the case study the non-value-adding work was reduced by 20%. The entire line was subsequently rebuilt, which resulted in a 20% productivity increase for the whole assembly line and thus showed the practical implications of the contributions.

A theoretical contribution is what factors impact picking times. The non-value-adding activity picking was further studied in an experiment to explain what factors impact manual picking at assembly workstations. The packaging was found to be the most influential factor. Five more factors had a significant effect on the picking time: angle of exposure, height of the materials exposure, component size and weight, sideways positioning of components, and offset in vertical distance. From the experiment it is thus determined what materials exposure factors have an impact on the manual picking time at an assembly workstation, which contributes new theoretical knowledge with large practical implications as how to design materials exposure.

The results from the case study also show how materials exposure impacts assembly workstation performance in terms of ergonomics. Using smaller packaging to expose the components makes it possible to expose components more favourably from an ergonomic point-of-view. The way components are exposed can thereby be designed to avoid picking components from an ergonomically unfavourably position. In the case study a change of the materials exposure caused a 92% reduction in potentially harmful body movements. As a contribution based on the above, it can be concluded that a materials exposure that reduces non-value-adding work and a materials exposure that favours better ergonomics for the assembly operator will not oppose each other.

Research question two sought to explain how the materials exposure impacts the performance of in-plant materials supply systems in terms of man-hour usage and required equipment.

Materials exposure affects both the packaging and the mix of packaging that has to be delivered by the in-plant materials supply system to materials exposure. The in-plant materials supply system therefore needs the appropriate equipment to be able to deliver the requested mix of packaging used in materials exposure. Herein lies the special case of components exposed without packaging, which require further equipment and activities in the in-plant materials supply system. The use of additional new packaging also implies that an increased number of different packaging can be handled by the in-plant materials supply system, if previously used packaging is not completely removed from the materials exposure or the in-plant materials supply system. Therefore, it can be concluded that different packaging and the mix of packaging used in the materials exposure require different activities in the in-plant materials supply system by requiring resources such as operators and equipment.

Materials exposure using sequenced components or kitting requires the in-plant materials supply system to perform additional and different activities in the in-plant materials supply system such as repacking, kit-preparation, and sequencing of the components. Repacking can occur when components arrive from suppliers in a packaging different from the packaging used in materials exposure. Materials exposure affects the activities for the in-plant materials supply system in how the components are delivered to materials exposure.

The contribution is thus that materials exposure impacts the configuration of the in-plant materials supply system, which in turn impacts its performance. In a case study changes in materials exposure impacted the in-plant materials supply system. The equipment for handling components and the in-plant transportation of components depended on the way the components were exposed. Materials exposure impacted the number of operators and therefore the man-hours required, and the equipment needed to perform the in-plant materials supply system.

Research question three sought to explain how the packaging for materials exposure impacts the performance of materials supply systems.

The model to evaluate the impact a packaging used in the materials exposure has on the performance of the materials supply system is a theoretical contribution. The model determines the impact on the performance of the material supply system in a systematic comparison between different packaging systems in environmental criteria based on CO_2 emissions (i.e., packaging fill rate, packaging material, transport, material handling, and waste handling), and economic criteria based on costs (i.e., packaging fill rate, packaging material, transport, material handling, waste handling, and administration).

In a case study the model was used to compare two different packaging systems by showing the performance impact of a one-way packaging and a returnable packaging in cost and CO_2 emissions. It can be concluded that the model was useful in determining how the packaging for the materials exposure impacts the performance of the materials supply system.

The Materials Flow Mapping methodology (MFM) is a theoretical contribution. The methodology aided in answering the third research question, by describing the activities in materials supply systems. The MFM methodology maps and categorises activities in material flows into materials handling, transportation, storage, and administrative activities. The categorisation facilitated the data collection by categorising the activities, in order to determine the performance in terms of CO_2 emissions and cost per component in the packaging selection model.

The MFM methodology was proven useful in two case studies describing the activities in the materials supply systems. In these cases the activities were identified and categorised and the configurations of the activities the materials supply systems were determined. The methodology visualised the material flows and showed improvement potentials for the involved companies and the performance of their materials supply systems, thus showing the practical relevance of the methodology.

From all of the above, it can be concluded that this thesis has explained how materials exposure influences the performance of materials supply systems and assembly systems. The thesis has shown how materials exposure impacts the assembly system performance, the in-plant materials supply system performance, and finally the packaging for materials exposures' impact on the performance of materials supply systems and assembly systems.

The thesis can be used as a way to improve, develop, and design production systems by using knowledge of how materials exposure impacts materials supply systems and assembly systems. The thesis can further be used as a guide for how materials should be exposed and in the selection of packaging for materials exposure. The most beneficial managerial use would be in the design and operation of assembly systems, materials supply systems and, in particular, materials exposure.

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Appended papers

Paper I:

Finnsgård, C., Wänström, C., Medbo, L., Neumann, P. (2011), ”Impact of materials exposure on assembly workstation performance”. *International Journal of Production Research*, 49 (24), 7253-7274. http://dx.doi.org/10.1080/00207543.2010.503202

Paper II:

Finnsgård, C. and Wänström, C. (2013), ”Factors impacting manual picking on assembly lines: An experiment in the automotive industry”. *International Journal of Production Research*, 51 (6), 1789-1798. http://dx.doi.org/10.1080/00207543.2012.712729

Paper III:

Hanson, R. and Finnsgård, C. (2014), ”Impact of unit load size on in-plant materials supply efficiency”. *International Journal of Production Economics,* 147 (Part A), 46-52.
http://dx.doi.org/10.1016/j.ijpe.2012.08.010

Paper IV:

Finnsgård, C., Medbo, L., Johansson, M. I. (2011), ”Describing and assessing performance in material flows in supply chains: a case study in the Swedish automotive industry.” *Proceedings from the 4th International Swedish Production Symposium*, s. 329-338.

Paper V:

Pålsson, H., Finnsgård, C., Wänström, C. (2013), ”Selection of packaging systems in supply chains from a sustainability perspective - the case of Volvo”. *Packaging Technology and Science*, 26 (5), 289–310. http://dx.doi.org/10.1002/pts.1979