Design of Materials Preparation Processes

Public report

Project within Hållbar produktionsteknik

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Content

1. Summary

The project "Design of Materials Preparation Processes" deals with materials preparation as a means for the production system to manage the increasing numbers of component variants, which is an ever growing challenge in modern assembly operations. Materials preparation is a term introduced by the project, referring to materials handling operations in supply systems that configure materials according to assembly requirements—to enable supply to assembly by kitting or sequenced deliveries. To be effective, materials preparation must be designed so that it can be performed with high levels of flexibility, quality, time efficiency and ergonomics, at low cost. The use of materials preparation is increasing, but the knowledge on how to design the materials preparation in order to achieve desired levels of performance is limited, both in literature and in practice. On these grounds, the purpose of the research project is stated as: *to expand knowledge of how the desired performance of materials preparation, in terms of flexibility, quality, time efficiency, and ergonomics, influences the design of materials preparation*, which reflects the problem of the designer of the materials preparation process in industry. The project addresses materials preparation for kit- and sequence-based materials supply to mass-customised, mixed-model, and manual assembly systems. Six research questions were formulated to address the project purpose, each question focusing a particular link between variables in the materials preparation design and one or more of the materials preparation performance objectives. Phase 1 of the project involved workshops and study visits for clarifying the propositions which the project sought to address. Phase 2 involved three deep multiple case studies—studying flexibility, quality and time efficiency—and phase 3 utilised experiments to address narrow but important relations between the materials preparation design and performance. Phase 4 involved summary, conceptualisation and dissemination of the derived knowledge.

The objectives which were specified as different deliverables in the project application were achieved over the course of the project. The answer to research question 1 shows how the values of the design variables influence the flexibility of the materials preparation, where the resulting framework is useful for practitioners to assess flexibility and for academics to account for flexibility when studying trade-offs for design decisions. The answer to research question 2 support previous research in several regards, for example in terms of the effect on the quality outcome from disturbances stemming from empty packaging handling. Answering research question 3 revealed aspects of critical importance to the time efficiency of materials preparation systems, including aspects in both the design and the context. The answer to research question 4 demonstrated that batch preparation can offer significant benefits in terms of time efficiency, while the answer to research question 5 showed the extent to which the type of picking information system influences time efficiency. Answering research question 6 showed the influence of materials exposure on the picking time and ergonomics.

All studies were performed collaboratively between practitioners and researchers, why the results were automatically implemented in the project companies' activities, as well as communicated to both students and professionals through courses at Chalmers. There has been and still is a great interest for the problem area that the project addressed. Throughout the project, the research considered the problems experienced in industry by means of the companies involved in the research project, together with recommended research directions from previous research. The findings of the research project contributes to practice by providing guidance to the materials preparation designer in terms of the performance to expect when choosing among options of the materials preparation design variables. The theoretical contribution of the project pertains to the developed frameworks that describes the relations between materials preparation design and performance. Future research efforts should focus methods for measuring the quality outcome in practice, which if available, would allow more knowledge on the quality outcome from different design options to be attained. Two other interesting questions for future research regards how combinations of different picking information technologies may influence the performance and how batching policies employing higher number of packages in the batch interacts with the picking information system in the effect on performance. The frameworks developed by the current project would serve well to such ends.

2. Sammanfattning på svenska

Bakgrund, syfte och forskningsfrågor
Projektet "Utformning av effektiva materialkonfigureringsprocesser" behandlar materialpreparering som ett sätt för materialförsörjningssystemet att förbättra produktionssystemens förmåga och flexibilitet. Detta är nödvändigt i dagens produktionssystem för att antalet produkter och komponentvarianter, som ständigt ökar (Boysen et al., 2015), ska kunna hanteras effektivt. Materialpreparering är en term som introduceras av projektet för materialhanteringsoperationer och processer i försörjningssystem som konfigurerar material enligt monteringens krav för att möjliggöra materialförsörjning till montering genom t.ex. kittning (Caputo och Pelagagge, 2011, Hanson and Brolin, 2013) eller sekvenserade leveranser. För att vara hållbar och effektiv måste materialprepareringen utformas så att den kan utföras med hög grad av flexibilitet, kvalitet, tidseffektivitet och ergonomi till en låg kostnad. Även om användningen av materialpreparering i produktionssystem ökar, är kunskapen om hur materialprepareringen ska utformas för att uppnå önskade prestationsnivåer begränsad, både i litteratur och i praktiken, varför syftet med detta forskningsprojekt anges till:

... att öka kunskapen om hur den önskade prestationen av materialpreparering, vad gäller flexibilitet, kvalitet, tidseffektivitet, ergonomi och kostnad, påverkar utformningen av materialprepareringen.

Syftet återspeglar problemet som designern av materialprepareringsprocessen möter i industrin när uppgiften är att till exempel förbättra kvalitetsprestanda för en process redan i drift eller när uppgiften är att designa en materialprepareringsprocess som utförs vid en viss nivå när det gäller tidseffektivitet. Projektet behandlar materialpreparering för kit- och sekvensbaserad materialförsörjning till monteringssystem för manuell, blandad och storskalig produktion—det vill säga monteringssystem där flera slutproduktsvarianter produceras i en blandad sekvens utifrån kundernas efterfrågan. Projektet behandlar alternativ för materialprepareringens designvariabler och deras inverkan på materialprepareringens prestanda vad gäller flexibilitet, kvalitet, tidseffektivitet, ergonomi och kostnad.

För att uppfylla och svara mot projektets syfte formulerades sex forskningsfrågor som användes som en vägledning genom hela projektet. Forskningsfrågorna var:

Forskningsfråga 1: Hur påverkar materialprepareringens utformning flexibiliteten i materialberedningen?

Forskningsfråga 2: Hur påverkar materialprepareringens utformning kvalitetsutfallet av materialprepareringen?

Forskningsfråga 3: Vilka designvariabler avgör tidseffektiviteten i materialprepareringsprocesser?

Forskningsfråga 4: Påverkas tidseffektiviteten vid materialplockning av batchning, jämfört med förberedelse av ett kit i taget?

Forskningsfråga 5: I vilken utsträckning påverkar plockinformationssystemet tidseffektiviteten vid materialpreparering?

Forskningsfråga 6: Hur påverkar tidseffektiviteten och den fysiska arbetsbelastningen av komponenternas presentation, vad gäller förpackningens storlek, förpackningens höjd och huruvida förpackningens öppning lutas mot plockaren eller ej?

Metod

Projektet genomfördes i fyra faser. Fas 1 innefattade projektets uppstart genom workshops och studiebesök, för att förtydliga de frågor som projektgruppen enat om att behandla. Fas 2 involverade tre djupgående flerfallstudier, som inriktades på hur utformningen av materialprepareringen påverkar tre prestationsmål—flexibilitet, kvalitet och tidseffektivitet—som saknade tillräcklig behandling i tidigare litteratur för projektets ändamål. I synnerhet behandlade de fallstudier som utfördes i fas 2 forskningsfrågor 1, 2 och 3 och genererade propositioner studerades vidare i fas 3. Fas 3 innebar en uppsättning mer fokuserade studier, där experiment var den huvudsakliga metoden, vilka behandlade smala men viktiga relationer mellan materialprepareringens utformning och prestation. Dessa relationer gällde inverkan av batching och plockinformationssystemet på tidseffektivitet, samt effekten av plockhöjd, förpackningsstorlek och förpackningens lutning, på ergonomi och tidseffektivitet, vilka identifierades i fas 1 och 2 av projektet som centrala relationer. Specifikt behandlade fas 3 forskningsfrågor 4, 5 och 6. Fas 4 involverade sammanställning, konceptualisering och spridning av den utvecklade kunskapen från forskningsstudierna, varvid resultaten användes för att bidra till projektets syfte.

Måluppfyllelse och resultat

Att härleda svar på forskningsfrågorna innebar parallellt att en uppsättning mål som angavs i projektansökan (Dnr: 2013-05626) uppnåddes. Målen för projektet i projektansökan organiserades i fem arbetspaket med fem milstolpar, vilka redogörs för nedan:

- Milstolpe 1 gällde utveckling av en kategorisering av materialprepareringsprocesser i nuvarande materialförsörjningssystem, vilket uppnåddes under fas 1 av projektet.

- Milstolpe 2 gällde utveckling av metoder för att bedöma kvalitetsresultat och utveckcling av en modell som operationalirar flexibilitet, vilket uppnåddes under fas 2 i projektet.

- Milstolpe 3 gällde utvecklingen av en modell som beskriver hur olika faktorer i ett materialförsörjningssystem påverkar valet av materialprepareringsdesign, som uppnåddes under fas 2, 3 och 4 i projektet.

- Milstolpe 4 modifieraded som konsekvens av en förändring av arbetspaketsledare för arbetspaket 4, vilket innebar att fokus ändrades från lokalisering till att effektivitet och ergonomi vid plockning. Den nya målsättningen för milstolpe 4 gällde utvecklingen av en modell för hur materialexponeringen i plockområdet skulle utformas för optimal ergonomi och tidseffektivitet, vilket uppnåddes under fas 3 i projektet.

- Milstolpe 5 gällde utvecklingen av en handbok för hur materialprepareringens utformning väljs i olika typer av materialförsörjningssystem, vilket uppnåddes under fas 4 i projektet.

Sammanfattningsvis, med endast mindre ändringar, uppnåddes leverablerna för de olika arbetspaketen under projektets gång. Svaren på de enskilda forskningsfrågorna sammanfattas nedan.

Svaret på forskningsfråga 1 ökar förståelsen för hur materialprepareringens utformning påverkar flexibiliteten i materialprepareringen genom att visa hur värdena på designvariablerna påverkar materialprepareringens förmåga att hantera förändringar i kraven från produktionssystemet. Resultaten är användbara både för ingenjörer som arbetar med utformning och drift av materialprepareringsprocesser för att bedöma flexibilitetseffekten av olika designmöjligheter, samt för akademin när det gäller att beakta flexibilitet när avvägningar för designbeslut studeras.

Svaret på forskningsfråga 2 ökar förståelsen för hur materialprepareringens utformning påverkar kvalitetsutfallet vid materialpreparering, genom att visa hur värdena på designvariablerna bidrar till situationer som leder till kvalitetsproblem. Resultaten stöder tidigare forskning i flera avseenden, till exempel när det gäller effekten på kvalitetsutfallet från störningar som härrör från tomförpackningshantering som till exempel observerades av Brynzér och Johansson (1995).

Forskningsfråga 3 i projektet fokuserade på sambandet mellan materialpreparationsdesign och tidseffektivitet, vilket behandlades i en flerfallstudie av 15 fall, där varje fall utgjordes av en arbetsstation för materialspreparering i bilindustrin. Aspekter av avgörande betydelse för tidseffetkiviteten hos materialprepareringsprocesser identifierades, inklusive aspekter av både designen och kontexten för systemen.

Batchingens relation till tidseffektivitet i kitpreparering var fokuset för forskningsfråga 4. Resultaten från två experiment visade att batchning kan ge betydande fördelar när det gäller tidseffektivitet. I båda experimenten var plockningstiden signifikant kortare för batchning än för preparering av ett kit åt gången.

Svaret på forskningsfråga 5 ökar förståelsen för omfattningen av plockningsinformationssystemets påverkan på tidseffektiviteten vid materialpreparering, genom att presentera en jämförelse av tidseffektiviteten i kitpreparering som uppnås genom användning av fyra olika plockningsinformationssystem för två olika batch storlekar. Resultaten klargör att plockningsinformationssystemet påverkar både plockarens söktid för komponenter och pekar på betydelsen av systemens plockbekräftelsefunktion.

Plockning från lutande och horisontellt placerade förpackningar studerades i två olika experiment vid projektföretag, samt i en labstudie vid Padua University, där varje studie behandlade olika aspekter av forskningsfråga 6. Sammantaget visar resultaten att när det gäller plockningstid är plockning från en lutad förpackning fördelaktig i jämförelse med att plocka från en horisontell, samt att arbetsbelastningen kan variera stort beroende på vilken position den plockade komponenten ligger på i förpackningen.

I förhållande till projektets syfte kan de presenterade resultaten användas som en guide för materialprepareringsdesignern när värdena för designvariablerna väljs för materialprepareringen, genom att påvisa hur valen kan påverka prestationen. På detta sätt påverkar den specifika prestationen av materialprepareringen som önskas av materialprepareringsdesignern valet av värdena för designvariablerna.

Spridning av projektresultaten

I och med att genomförandet av projektet har baserats på fallstudier och experiment som utförts tillsammans med praktiker och forskare, har resultaten automatiskt implementerats i företagens verksamhet under projektets gång. Genom projektmöten har resultaten från olika studier diskuterats inom projektgruppen. Vidare har projektet utnyttjat sin webbportal för att kontinuerligt sprida resultat, som olika parter genererat, inom projektgruppen. Projektresultaten har fortlöpande förmedlats till eleverna på Chalmers genom olika kurser inom kandidat- och masters-programmen, samt för proffesionella inom näringslivet genom Chalmers Professional Education.

Intresset för projektets problemområden, som påvisats vid exempelvis branschkonferenser och mässor, har varit och är fortfarande stort. Två anledningar att intresset är så pass stort är säkerligen att många företag upplever osäkerhet om hur det ökande antalet produktvarianter bör hanteras och att nya tekniker som kan stödja materialhanteringsprocesser framträder i rask takt. Utvecklingen av demonstratorn för plockinformationssystem, som företag och andra organisationer har tillgång till framöver, var en konsekvens av det uppvisade intresset.

Slutsatser och fortsatt forskning

Detta projekt har studerat sambandet mellan utformning och prestation för materialpreparering för kit- och sekvenserade leveranser till montering i produktionssystem. De fyra perspektiv på prestanda som tillämpats i projektet är flexibilitet, kvalitet, tidseffektivitet, ergonomi och kostnad. Den industriella relevansen av att studera materialpreparing grundas i den ökande användningen av materialpreparering inom industrin, vilket är ett resultat av behovet av att bättre kunna hantera den ökande mängden produktvarianter i produktionssystemet, medan erfarenhet och riktlinjer för hur man utformar dessa processer har varit begränsad. Under hela projektet beaktade forskningen problemen som upplevs av industrin genom de företag som deltar i forskningsprojektet och med hjälp av rekommenderade forskningsspår i tidigare forskning. Industrins behov och vetenskapsläget medförde att forskningen fokuserade på inflytandet från designen på flexibilitet, kvalitet, tidseffektivitet, ergonomi och kostnad, med syftet att utöka kunskapen om hur den önskade prestationen av materialpreparering, vad gäller dessa prestandaområden, påverkar utformningen av materialprepareringen.

Sex forskningsfrågor formulerades för att likrikta forskningen med syftet, där forskningsstudierna utformades för att behandla forskningsfrågorna. Tre studier har utformats som flerfallstudier med fokus på hur och varför olika designalternativ påverkar flexibilitet, kvalitet och tidseffektivitet. Fem studier har utformats som experimentella studier, vilka fokuserat på inverkan på prestationen från att använda olika typer av plockningsinformationssystem, från olika batchningssprinciper och från olika sätt att presentera materialet för plockaren. Resultaten från forskningsprojektet bidrar till industrin genom att ge vägledning till materialprepareringsdesignern när det gäller vilken prestation som går att förvänta sig val görs mellan alternativ för designvariablerna i materialprepareringen. Projektets teoretiska bidrag avser de utvecklade ramverken som beskriver relationerna mellan materialprepareringens design och prestation.

Projektet lägger även en grund för intressanta möjligheter till fortsatt forskning. Exempelvis pekar projektresultatet på behovet av förbättrade metoder för att mäta kvalitetsresultatet i praktiken, vilka om de var implementerade skulle innebära att plockriktigheten bättre kunde bedömas och mer kunskap om kvalitetsutfallet från olika designalternativ skulle erhållas. Resultaten med avseende på påverkan på tidseffektivitet från olika plockningsinformationssystem och för batchningsprincipen ger upphov till de två frågorna (1) hur kombinationer av olika informationstekniker kan påverka tidseffektiviteten och (2) hur batchingsprinciper med ett större antal leveranse interagerar med plockningsinformationssystemet när det gäller tidseffektivitet. Andra forskningsinriktningar som kunde vara värdefulla är aktionsforskning eller longitudinella fallstudier, eftersom att traditionell fallstudier oftast bara ger ögonblicksbild av verksamheten eller en berättelse som förklarar hur sakerna blev som de är. En longitudinell studie kan öka detaljeringsgraden av insamlad data, samt öka förståelsen för de många många små, men i många fall viktiga, variationerna i utformning påverkar olika typer av prestationsmått. De ramverk som utvecklats av det aktuella projektet skulle fungera bra för sådana ändamål.

3. Background

The project “Design of Materials Preparation Processes” deals with materials preparation as a means for the materials supply system to effectively manage the increasing degree of end-product customisation in the assembly industry - which, in the automotive industry, can theoretically result in car models with billions of different variants (Pil and Holweg, 2004). For the materials supply system, increasing customisation of end-products result in increasing numbers of component variants that require efficient and reliable logistics operations (Boysen et al., 2015). Shortening product life cycles (Chen et al., 2012) causes the assortment of component variants to continuously change, why the production system must be responsive for being able to provide customers with products that meet their exact requirements on time, which requires flexibility of the production system.

To achieve flexibility of the production system, flexibility of the materials supply subsystem is needed (Holweg, 2005). To that end, one approach acknowledged for improving flexibility in assembly systems is the use of kitting materials supply for assembly (Caputo and Pelagagge, 2011; Hanson and Brolin, 2013). Another such approach is sequenced deliveries of part variants to assembly. To enable kitting-based and sequenced materials supply, materials preparation in the materials supply system is necessary. To be effective however, the materials preparation must be designed so that it can be performed with high levels of flexibility, quality, efficiency and ergonomics, at a low cost. Albeit the use of materials preparation in production systems is increasing, the knowledge on how to design the materials preparation in order to achieve the desired levels of performance is today very limited.

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

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

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

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

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

Time efficiency. Using materials preparation instead of materials supply methods for delivering packages with homogenous contents (containing a single part number) to assembly (for example, line stocking or continuous supply) introduces extra materials handling operations into the material flow (Limère, 2012) that has received great criticism in discussions of kitting as an alternative materials supply method (Bozer and McGinnis, 1992). However, the additional materials handling work introduced by kitting, as well as other types of materials preparation, can be balanced by the efficiency gained in assembly from less walking and searching during part collection (Hanson and Finnsgård, 2014). As such, improving the time efficiency of materials preparation is central to improving overall production system efficiency when using materials preparation.

A few studies have addressed the impact on time-efficiency from some factors in the materials preparation design, e.g. in kit preparation processes (Brynzér and Johansson, 1995), but previous research is on the whole unclear on which factors in the materials preparation design that govern the materials preparation time efficiency. Due to the importance of time-efficiency for making the materials preparation an effective solution for dealing with increasing numbers if component variants in the materials supply system, knowledge of which factors in the materials preparation design that impact the time-efficiency is needed.

One factor that has been repeatedly pointed out as crucial for time-efficiency in both kit preparation (Brynzér and Johansson, 1995) and in order picking (Battini et al., 2015), is the picking information system. In recent years, new developments in information technology have enabled new alternatives among picking information systems, for example, solutions involving wearable computing (Reif et al., 2009) and scanning technology (Battini et al, 2015). In terms of wearable computing, smart glasses are visual interfaces now available to display picking information based in augmented reality (Guo et al., 2015) or mixed-reality (Schwerdtfeger et al., 2011), thereby providing workers with updated information in real time during picking tours. In terms of scanning technology, solutions based upon radio frequency identification (RFID) are becoming increasingly reliable at lower costs and thereby approaching viability in industrial operations (Battini et al., 2015) as alternatives to traditional barcodes and checklists. In effect, many new applications have emerged, which in itself motivates new research on how those technologies compare to established ones in terms of performance, as the picking information is known to be important for both time efficiency and quality (Brynzér and Johansson, 1995). Knowledge on how choices in the design of the picking information system influence time efficiency, then, becomes a most relevant aspect for making sound decisions.

Ergonomics. From a working environment and ergonomics perspective, manual material handling is one of the most widely studied risk factors for musculoskeletal disorders (MSDs) such as low back pain – the world's most expensive work place injury (Bernard 1997). Previous research in Swedish industry has shown that the selection and implementation of material supply strategy has substantial impact on the biomechanical loads on the operator and hence their risk of musculoskeletal injury (Neumann et al. 2006). It is thus crucial to understand and account for the impact of the materials preparation design on ergonomics, to achieve a safe and sustainable work environment, when striving for high levels of flexibility, quality and time efficiency.

4. Purpose, research questions and method

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

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

4.1. Purpose and scope

Progress in fields related to materials handling and materials preparation - for example, order picking for assembly - should also be understood in terms of their generalisability to materials preparation. Any commonalities among the fields can, and arguably should, be exploited and integrated to further the overall development of knowledge. It is in that light which this project aims to make a contribution. As Figure 4.1 illustrates, *the purpose of the research project is to expand knowledge of how the desired performance of materials preparation, in terms of flexibility, quality, time efficiency, and ergonomics, influences the design of materials preparation.*

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

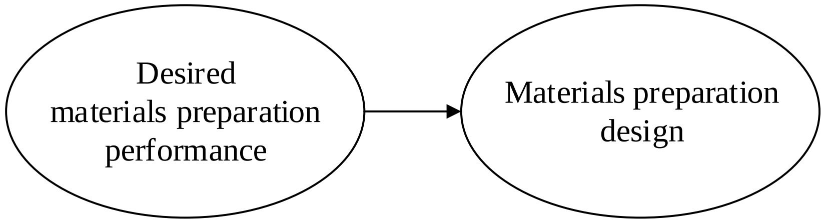

Figure 4.1. Purpose of the research project

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

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

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

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

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

4.2. Research questions

Six research questions have structured the research conducted for this project, largely to align the work with the purpose presented in section 3.1. An argument of relevance accompanies each research question presented here in order to give the reader an overview of the relevance of each question.

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

Results from answering the three research questions thereby constitute a set of links for how materials preparation design influences materials preparation performance. Once knowledge attained from answering each of the three questions is synthesised, the resulting frameworks for each of the four performance objectives will facilitate the understanding of how performance influences design. In that way, results derived from the research questions is intended to function beyond the project.

4.2.1. Research Question 1 - Flexibility

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

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

4.2.2. Research Question 2 - Quality

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

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

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

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

4.2.3. Research Question 3 – Time efficiency

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

A few studies have addressed process design variables in relation to time efficiency of materials preparation, for example, that using order batching improves the efficiency of kit preparation given the possibility of picking parts for multiple orders at once (Hanson et al., 2015). However, a complete framework that encapsulates the factors that govern the time-efficiency in materials preparation processes is yet to be derived. Without a holistic knowledge of the design variables that govern materials preparation time-efficiency, the materials preparation designer is left with fragmented knowledge that may risk leading to decision that sub-optimise the materials preparation performance. Hence, research question 3 relates to time-efficiency and is expressed as:

Research question 3:
Which design variables govern time-efficiency in materials preparation processes?

4.2.4. Research Question 4 – Order batching

A factor often attributed as key for time efficiency in order picking (De Koster et al., 2007) and in kit preparation (Brynzér and Johansson, 1995) is the order batching policy. Preparing kits in batches can potentially increase man-hour efficiency by reducing both travel distances and direct picking times, but can also increase the amount of sorting and administration compared to making one kit at a time. Within companies that apply kitting, both batch preparation and preparing one kit at a time are common approaches, and no consensus seems to exist regarding the benefits, drawbacks or applicability associated with either method. Therefore, research question 4 was formulated as:

Research question 4:
Is time efficiency of the picking affected by the use of batch preparation, compared to preparation of one kit at a time?

4.2.5. Research Question 5 – Picking information systems

On a more specific note in regards to time-efficiency, new developments in information technology have made new picking information systems available - for example, pick-by-vision (Schwerdtfeger et al., 2011) and RFID-based confirmation of picking operations (Battini et al., 2015). Such systems have demonstrated potential for higher time efficiency in order-picking scenarios (Guo et al., 2015), though its potential for materials preparation types such as kitting remains unclear. Therefore, the target of the fifth research question of the project was the effect of the picking information system design on materials preparation on time efficiency:

Research Question 5:
To what extent does the picking information system influence the time efficiency of materials preparation?

4.2.6. Research Question 6 – Picking height, packaging tilt and size

From a working environment and ergonomics perspective, manual material handling is one of the most widely studied risk factors for musculoskeletal disorders (MSDs) such as low back pain – the world's most expensive work place injury (Bernard 1997). Previous research in Swedish industry has shown that the selection and implementation of material supply strategy has substantial impact on the biomechanical loads on the operator and hence their risk of musculoskeletal injury (Neumann et al. 2006). It is thus crucial to understand and account for the impact of the materials preparation design on ergonomics, to achieve a safe and sustainable work environment, when striving for high levels of flexibility, quality and time efficiency.

Previous studies have highlighted that the design of picking operations can affect both time efficiency (Finnsgård et al. 2011; Finnsgård and Wänström 2013) and physical workload (Neumann and Medbo 2010). In this context, it has been indicated that time efficiency of picking can be improved if the packaging picked from is tilted towards the picker (Finnsgård and Wänström 2013). However, no studies have been found that fully address the variations in time and workload in the context of picking from large containers. Therefore, research question 6 was formulated as follows:

Research Question 6:
How does the time efficiency and physical workload relate to the presentation of components, in terms of containers size, container height, and whether or not the container is tilted towards the picker?

In many situations, using small unit loads is either infeasible or not cost efficient, and consequently, picking from large containers is common. Finnsgård and Wänström (2013) found that tilting the container towards the picker can reduce picking time. However, not only average time consumption is of importance, but also potential variations in time consumption. In manual picking from large containers, it seems that both time consumption and physical workload will vary depending on the position of the components within the container (Neumann and Medbo, 2010). Variations in time consumption could, in turn, result in time losses when a fixed takt time determines the work pace, as it may then be difficult to properly balance the workload. Variations in physical workload are also problematic and it is important to consider not only the average load, but also the maximum load, when operations are designed. This is especially important as it is often large, heavy components that are presented in large containers.

4.3. Method

The project was organised in four distinct phases. Phase 1 involved the initiation of the project through workshops and study visits, performed in order to clarify the propositions which the project group agreed to address. Phase 2 involved three deep case studies, targeting how the design of materials preparation influenced three of the performance objectives within the project scope which lacked sufficient treatment in previous literature.

Phase 3 involved a set of more focused studies, utilising experiments to address narrow but important relations between the materials preparation design and performance, which had been identified in phases 1 and 2 of the project. Phase 4 involved summary, conceptualisation and dissemination of the derived knowledge from the research studies, utilising the results to make contributions to the research purpose. In the forthcoming subsections, each of the four phases are described in more detail.

4.3.1. Phase 1 – Project initiation

Phase 1 involved initiating the project by specifying the aim of the project and the problems which should be addressed, as well as what contributions to the project purpose each involved party could make—in terms of cases for case studies, study objects, competencies, experiences and networks. This initial phase consisted of workshops involving all project parties, where problems which the companies experienced regarding their own materials preparation were raised and compared with problems raised by other project parties and with the ongoing discussion in literature. An emphasis was placed on laying ground for potential collaborations between project parties for treating more practical problems that could not be addressed by the project as whole, as these problems were only experienced by some of the parties. Further, the initial phase involved study visits to each of the participating companies, both by the researchers and by representatives from the other parties. During these study visits, the current practice of the materials preparation processes was mapped and the problems raised during the workshops could be studied in detail. Study visits to international sites were also performed during phase 1, both by individual parties involved in the project as well as constellations of the entire project group, aiming to visit and learn from state-of-the-art materials preparation design. Examples of sites visited include Scania's operations in Sao Paolo, operations of Volvo Car Corporation in Chengdu and Schenker's operations in Leipzig.

The outcome of the initial phase was a set of propositions for further research—the research questions presented in the previous section—which the project then agreed to address. The first phase also initiated the collection of guidelines from the individual project parties for how to design materials preparation processes. These guidelines were organised in a document which was circulated among the project parties for continual updating as the project progressed, in order to eventually evolve into the project handbook—the final deliverable of the project.

4.3.2. Phase 2 – Case research

In *phase 2,* three deep case studies were performed on basis of the propositions developed during phase 1, targeting research questions 1, 2 and 3. The idea behind this approach was to establish holistic frameworks for understanding *how* the materials preparation design influenced the three performance objectives flexibility (research question 1), quality (research question 2) and time efficiency (research question 3). The performance objective of ergonomics was not targeted in this manner, as substantial and consistent literature was found within related areas, e.g. assembly work station design and order picking system design, showing good potential for generalisation to materials preparation. The outcome of phase 2 was a set of frameworks describing how the materials preparation design influences the materials preparation performance, serving as refined propositions and the basis for hypotheses for continued research efforts in phase 3.

All case studies performed within the project followed the same general procedure. First, a literature study was performed from which a framework was synthesised, acting as refined propositions for the research question addressed. Second, cases were selected based on the derived framework, looking to establish replication logic between cases. The case selection was supported by the knowledge gained about the current practice of materials preparation processes during the study visits performed in phase 1. Third, a framework for data collection was developed that then was applied to the cases. The manner in which the data collection frameworks worked differed between the cases, depending on the specific question being studied, as did the data types collected. All case studies did however focus on the expertise provided by managers of and workers in the materials preparation processes studied, which was studied by means of interviews and focus groups. Following data collection, the fourth stage involved data analysis, where also any missing or ambiguous data was supplemented by returning to case process. Finally, the fifth step involved drawing conclusions from the analysis outcome, writing and publishing scientific papers and presenting the results in different forums.

4.3.3. Phase 3 - Experiments

In *phase 3*, experiments were used to isolate more specific relations between certain design variables and performance objectives, which were identified as particularly important during phase 2. Two experiments were set up to address time efficiency, targeting research questions 4 and 5. The first experiment focused the relation between order batching and time-efficiency, seeking to determine if order batching of several orders is advantageous over a single order policy in regard to time-efficiency in kit preparation—as claimed, but not shown, in previous research. The second experiment focused on the relation between the picking information system and the time efficiency during the picking tour, also considering the batching policy and travel time between pick location, seeking to establish how the picking information system impact time efficiency in kit preparation. For addressing research question 6, a third experiment was set up, studying the effect on ergonomics and time efficiency of materials exposure in form of picking height, as well tilt and size of packaging picked from.

A guiding principle for the experiments was to simulate real-life high performing materials preparation processes as they occur in industry. To this end, two of the experiments were possible to perform at the sites of the project companies, using the same equipment as is used in regular production. The third experiment was performed in a laboratory setting, in order to fully be able to control the settings for the experiment. In addition to the project parties, the experiments involved parties external to the project, for example suppliers of picking information systems and materials handling equipment, as well as students from Chalmers' bachelor- and masters programmes. The inclusion of project external parties in the experiments contributed to improved dissemination of the experiment results, in addition direct marketing of the project towards both industry and academia.

Although treating different questions, the experiments followed the same general procedure. First, a literature study was performed for establishing the theoretical framework and to derive hypotheses, based on propositions developed in the earlier phases of the project. The first step was supplemented by discussions with the project companies in order to account for all relevant factors when designing the experiment plan. Second, the experimental plans were developed, which specified what the test setting should look like and who was going to perform the picking. The second step also involved procurement and installation of the hardware and software required for performing the experiments. Third, data collection was performed, which for all experiments were performed during a short continuous time period, in order to reduce the impact factors which could not be controlled. Fourth, the data was analysed and the conclusions were formulated.

4.3.4. Phase 4 – Conclusions and dissemination

In *phase 4,* the final phase of the project, the knowledge developed during the project was compiled in a handbook that first will become available to all project parties and then also for Swedish industry and academia in general. Building on the third experiment in the project, phase 4 also involved the development of a demonstrator for picking information systems. The demonstrator utilised the kit preparation workspace designed for the third experiment, where picking information systems, supplied by the parties involved in the experiment, are kept on display for industry and academia to use for their own testing. Phase 4 also involved the conclusion of the collaborations between project parties, which had led to several substantial reconstructions of existing materials preparation designs—informed by the project results.

5. Objective

In the project application (Dnr: 2013-05626), the project was planned in 5 work packages. The five work packages and their contents, methods and deliverables are restated in Table 2—exactly as they appeared in the application. Comments to how the plan in table 5.1 was followed are presented in the subsequent subsections.

Table 5.1. Description of work packages. Milestones are indicated M1-M5.

Work Package 1	**Project management and coordination**
WP leader	Lennart Lundgren
Participants	WP leaders and company representatives
Content and method	See “Project management” paragraph
Deliverables	Formal organisation and administration of the project
Work Package 2	**Current practice of materials preparation processes**
WP leader	Henrik Brynzér
Participants	Patrik Fager and company representatives
Content and method	• Theoretical frame of reference (literature review). o Descriptions and definitions of materials preparation processes and related concepts o Approaches for assessment of sustainability variables cost- and time-efficiency, quality, flexibility and ergonomics • Empirical frame of reference (literature review, study visits, case studies). o Understanding different designs of materials preparation processes - Materials exposure, layout, picking procedure, equipment, upstream and downstream processes etc. o Kitting processes at Volvo Car Corporation o Framework for mapping materials preparation processes o Testing and verification of sustainability assessment approaches • Case studies mapping current practice of materials preparation processes as used in industry at the project companies. o Visits to each of the project companies o Descriptive framework of designs used in industry today
Deliverables	• Categorisation of materials preparation processes in present materials supply systems. (M1) • Current use of picking support systems in the automotive industry. • Methodologies for assessing quality outcome of materials preparation processes. (M2) • Model for operationalization of flexibility in materials preparation processes. (M2)
Work Package 3	**Choice of materials preparation process design**
WP leader	Lars Medbo
Participants	Patrik Fager, Lars Medbo and company representatives

Content and method	• Case studies to understand how materials preparation process context and designs, e.g. materials exposure, layout, picking procedures and picking support systems, affects the sustainability variables cost- and time-efficiency, quality, flexibility and ergonomics. • Experiments at participating companies and in Chalmers production systems laboratory where different designs, in terms of materials exposure, picking procedure and picking support systems, are compared on the basis of established sustainability measures. • Development and testing of methods and equipment. • Pilots in production environments at participating companies.
Deliverables	• Model describing how different factors in a materials supply system impact the choice of materials preparation process design. (M3) • Handbook with guidelines how to choose and design materials preparation processes (including picking support systems) in different types of materials supply systems. (M5) • Demonstrators of materials preparation processes.
Work Package 4	**Materials preparation process localisation**
WP leader	Carl Wänström
Participants	Patrik Fager and company representatives

Content and method	• Case studies of materials supply systems at participating companies.
	  ○ Knowledge of requirements for re-configuring an existing design
	  ○ Knowledge of requirements for re-locating a materials preparation process
	  ○ Knowledge of how the localisation of the materials preparation process impacts sustainability aspects, primarily quality cost efficiency and CO2, of the materials supply system
	• Mapping of materials supply systems.
	• Pilot studies of process relocation at participating companies.

Deliverables	• A model for understanding how sustainability aspects of the material supply system depends on the localisation of the materials preparation processes and is affected by configuration and relocation of the materials preparation process. (M4)
Work Package 5	**Dissemination**
WP leader	Lars Medbo
Participants	All project participants
Content and method	See "Exploitation and dissemination" paragraph
Deliverables	Dissemination through workshops, demonstrations, conferences, publications, networks etc.

5.1 WP 1 - Project management and coordination

The project leader, Lennart Lundgren, has fulfilled the role as project leader throughout the project. For the work package leaders, one change was made during the project, where Robin Hanson replaced Carl Wänström as leader for work package 4. The change of work package leader led to changes in the contents of work package 4, see section 5.4 for more details. Overall, the project management and coordination has worked in line with the intention in the project application that was submitted on December 13, 2013.

5.2 WP 2 - Current practice of materials preparation processes

The contents of work package 2 were addressed as planned. The deliverables were achieved according to plan, where Milestone 1 was achieved during phase 1 of the project and Milestone 2 was achieved during phase 2 (see Chapter 4.3 for descriptions of the four phases of the project).

5.3 WP 3 - Choice of materials preparation process design

The contents of work package 3 were addressed as planned. The deliverables were achieved according to plan, during phases 2, 3 and 4 of the project. Milestone 3 was achieved during phase 3 of the project, while Milestone 5 was achieved during phase 4.

5.4 WP 4 - Materials preparation process localisation

Due to the change of work package leader for work package 4, the focus of this work package was shifted from a focus on localisation to a focus on picking ergonomics, which was dealt with over multiple studies. The effect of localisation on performance and knowledge of requirements for re-locating and re-configuring existing materials preparation processes was dealt with on a practical level, involving ongoing projects at the participating companies. Hence, Milestone 4 was changed from a model for understanding how sustainability aspects of the material supply system depends on the localisation of the materials preparation processes and is affected by configuration and relocation of the materials preparation process, to a model for how the materials exposure at the preparation area should be designed for optimal ergonomics and time efficiency. Milestone 4 was achieved during phase 3 of the project.

5.5 WP 5 - Dissemination

The contents of work package 3 were addressed as planned. The deliverables were achieved according to plan and were addressed continuously throughout each of the four phases of the project.

6. Results and deliverables

This project and the research studies which it includes has been based on a core idea for how to develop knowledge that is both of theoretically relevant as well as relevant for industry. This idea can be acknowledged by reviewing the research purpose and the research questions, where each research question adheres to the same logic, targeting to answer the question of how a particular design influences performance. The research purpose, on the other hand, is formulated in reverse in terms of the direction of influence between the design and the performance. That is, the purpose aims to treat the problem of which design can be used to reach a desired performance. The conclusions from the individual studies can thus be regarded as the improved understanding on how the design influences the performance objective. On a project level as opposed to the individual study level, the knowledge is re-framed into the format in which it will be used in industry, e.g. for providing answers to questions like: "if I want my materials preparation to perform well in regards to quality, how should I then design my process"? The knowledge from the individual studies then give guidance in how the desired performance influences the materials preparation design.

6.1. Response to research question 1

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

The findings, and the resulting framework, developed in the multiple case study "Flexibility of kit preparation processes in production systems", contributes to research by building on general models of flexibility from manufacturing, e.g. Correa (1992) and Slack (2005) and applying them to the specific context of materials preparation. Previous findings on flexibility in this context, for example Brynzér and Johansson (1995) and Hanson et al. (2011), do not result from research specifically aimed at this relation, but provide some scattered observations and propositions. A somewhat surprising finding was that the modern technologies, e.g. pick-to-light systems, may delimit flexibility by introducing requirements on changes both in the information data bases and in the physical system. This confirms the statement by Park (2012, pp. 9-10), stating that "Proper automation has several advantages. […] But it usually requires a substantial investment. Furthermore, it is inflexible, i.e., it is more difficult to reconfigure the system to adapt to new business environments".

6.2. Response to research question 2

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

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

6.3. Response to research question 3

Research question 3 of the project focuses on the relation between materials preparation design and time efficiency. This was been addressed in a multiple case study, where each case was constituted by a kit preparation station in the automotive industry. The companies in the project provided access to a large set of cases in different settings. In total, 15 cases were included in the study, including representation from eight different assembly plants in five countries in Europe, Asia and South America, all of which were operating according to a mixed-model assembly approach. Based on the multiple case study, and utilising the expertise of a set of experienced practitioners, aspects of critical importance to the man-hour efficiency of materials preparation systems were identified, including aspects of both the design and the context of the systems. Among the most important aspects was the picking density, defined as the number of components picked per cycle, divided by the number of square metres available to the picker. Other aspects of great importance were found to be the picking information system and the batch size used in the picking.

6.4. Response to research question 4

The order batching and its relation to the time efficiency of the kit preparation relate to research question 4 of the project and were studied in a separate study, based on two experiments conducted at the Volvo Construction Equipment plan in Eskilstuna. In each of the experiments, the time spent on kit preparation was recorded both for batch preparation and for preparation of one kit at a time. Based on a quantitative analysis of the data, it was found that batch preparation can offer significant benefits in terms of time efficiency. In both experiments, the picking time was significantly shorter for the batch preparation than for the preparation of one kit at a time. However, as indicated in a subsequent experiment study, named “Time efficiency of picking information systems”, the potential benefits of batch preparation are closely linked to if and how the picker performs confirmations during picking, i.e. if and how the picker confirms each picking and each placement activity. As indicated in the same study, these confirmations can in turn impact the quality of the resulting kits. The study indicates that a single order policy with a simple picking information system may be worthy of consideration as an alternative to order batching by support of an advanced picking information system.

6.5. Response to research question 5

The answer to research question 5 improves the understanding of the extent to which the picking information system influences the time efficiency of materials preparation, by presenting a comparison made in a laboratory experiment of the time efficiency achieved from using four different picking information systems in kit preparation, for two different batching policies. The results make clear that the picking information system influence both the pickers’ search time for parts and the picking confirmation function. The inclusion of the recently developed pick-by-vision type of system, and the use of RFID bracelet confirmation in the comparison is considered a contribution to both practice and theory. For example, in their concluding remarks after comparing four picking information systems in an order picking context, Guo et al. (2015) ask the question “how will including pick-confirming sensors or a button push affect accuracy and speed relative to the pick-by-HUD method?”. An educated response to this question can be formulated based on the results from the experiment “Time efficiency of picking information systems”, which exemplifies the theoretical contribution of the response to research question 5. In relation to the objectives of the research program, the response to research question 5 entails knowledge the effects of new types of technology, which contribute to the development of cost efficient and competitive production systems.

The result of the experiment “Time efficiency of picking information systems” also reveals that the multi-kit order batching policy presents a different set of requirements on the picking information system than does a single order policy, where the quality assurance of the placement operation, in terms of a placement confirmation, to a great extent determine the time efficiency of a particular information system design. In this regard, the answer expands previous knowledge on the time efficiency of order batching in materials preparation (Hanson et al., 2015) by explaining how the efficiency potentials from batching may be realised with consideration taken to the picking information system design. This is another important contribution to the program objective of developing cost efficient and competitive production systems.

6.6. Response to research question 6

Picking from tilted and horizontally placed containers was studied in two different experiments at project companies and one lab study at Padua University, each study addressing research question 6. Overall, the results indicate that in terms of picking time, picking from a tilted container is beneficial in comparison to picking from a horizontal one, and that picking from a smaller container is beneficial in comparison to picking from a larger one. However, there are large variations in picking time between different sections of a pallet and between different heights of boxes.

By studying the picking of components with different characteristics in industrial setting, quantitative evidence was provided of how picking time and physical workload vary in picking from large containers. Components located at a short horizontal distance from the picker, and at the top instead of the bottom of the pallet, are associated with shorter picking times as well as less physical workload. Picking from horizontal pallets was compared with pallets tilted 45° towards the picker and found that the tilted ones allowed significantly shorter picking times on average and smaller variations. The effects that the tilting of the pallets had on the physical workload differed depending on from which section of the containers picking was performed. The greatest values of physical workload were observed for the tilted pallets, presumably due to differences in how the pickers performed picking from a tilted instead of a horizontal pallet.

6.7. Work conducted in the form of thesis projects

During the course of the Design of Materials Preparation Processes project, several master’s and bachelor’s thesis projects have been conducted by students at Chalmers University of Technology. Researchers from Chalmers University of Technology, participating in the project, have supervised these thesis projects and made sure that they have contributed to the objectives of the overall project. In the thesis projects, it has been possible to address several narrow but relevant and important questions that relate to the focus of the Design of Materials Preparation Processes project. Some of the student projects were initiated by project companies, which sought solutions to practical problems in the area of materials preparation. Other thesis projects were initiated by researchers and then had more of a research-oriented focus, aiming to achieve results with a higher degree of generalisability. One of the master thesis projects was found to have sufficient potential to develop into a research paper, which is now in the final stage of review by the International Journal of Production Research.

6.8. Work conducted within and between project companies

In parallel with the research studies in the project, the project companies have performed their own local projects, both individually and in collaboration with other project parties, addressing problems related to the company specific setting. One example is from Volvo Car Corporation, where a longstanding internal project has been to optimise floor space use of materials preparation, which have resulted in principally new layout solutions for materials preparation work spaces. Another example is Scania, who have established their own picking laboratory for testing an evaluation of picking information systems—inspired by the experiment setups developed in the current project—that serve as basis for company internal discussions regarding decisions related to the materials preparation performed within the company. Further, one of Scania's sites have changed standard for which picking information systems to use in materials preparation, upgrading from stickers with pick information to pick-by-voice, which led to additional insights captured by the project. Scania have also created general company guidelines for how to design their materials preparation processes, building on own experiences and studies, as well results from the current project. Volvo AB have in some of their factories introduced Automatic Guided Vehicles (AGVs) for moving the picking package during materials preparation, as well as for transporting the prepared materials to assembly, generating new insights regarding how automation can improve the otherwise manual materials preparation work. Several of the project companies have made additional improvements in their own systems, often influenced by the discussions and findings in the current project, where a few examples are:

- Mapping and improvement of existing material flows that include materials preparation
- Re-localisation of existing materials preparation processes for improved warehousing operations
- Implementation of solutions for automated materials handling, including AGVs for transport and AS/RS-solutions for inventory management
- Design of materials supply system, using guidelines developed in the current project, upon a factory changeover
- Evaluation of options for handling increasing amounts of variants with floor space restrictions
- Development of IT-system for integration of picking information with the production planning system

In summary, the company internal projects have worked synergistically with the aim of current project, building on insights generated by the current project as well as generating new insights for the current project. In this way, the company internal projects have served a very valuable role in providing knowledge of the practical considerations of the questions treated in the research project, thereby improving the relevance of the project for industry.

6.9. Addressing the research purpose

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

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

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

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

7. Dissemination and publications

7.1 Dissemination

Due to that the project execution has been based on case studies and experiments performed collaboratively with practitioners and researchers, the results have been automatically implemented in the companies' activities. Several case studies have also been linked to various development projects in the companies which resulted in an expectation of change which thus facilitated the implementation of the project results. Through project meetings have results from different studies been discussed within the project team. Further, the project has utilised its web-portal to continuously disseminate results within the project group.

Continuously during the project, a number of workshops focusing on various problem areas have been organized. During the workshops, project results have been presented and discussed with participants from across the automotive industry, organisations involved with order picking, research institutes and universities. In addition, the project results have been presented at industry conferences and trade exhibitions. Interest in the project's area of concern has been and is still great. Two reasons are surely that many companies are experiencing uncertainty regarding how to handle the increasing number of product variants and that many technologies that can support materials handling processes are emerging. Existing guidelines and standards does not often lead to improvements and need to continuously be reviewed and updated in order to remain useful. Furthermore, the differences in how materials supply systems have been designed in Sweden compared to many other countries is large, a trend accentuated in recent years. These differences also affect the interest of the industry to embrace project results.

In education, the project results continuously conveyed knowledge to the students at Chalmers who take courses given by the Division of Supply & Operations Management. This applies mainly to the courses "Lean Production" and “Production Logistics” at International Masters Programme Production engineering and the course "Production flow management" at International Masters Programme Supply Chain Management as well as courses in "Lean production" for professionals in the Chalmers Professional Education. Through courses directed towards professionals, the project results are widely disseminated to both large, small and medium-sized enterprises. Through linkage and cooperation with Produktionslyftet, seven to eight courses, each with 25 participants is conducted per year around the country.

Results and experiences from the project have, in addition to occasions internal to the project and at the university as described above, been communicated at:

- EurOMA conference, Title*:* “Kit preparation using batching – quantitative results from two experiments”, Palermo, June 20-25, 2014.

- Conference ”Swedish Production Symposium” (SPS), Title: ”Quality problems in materials kit preparation”, Gothenburg, September 18, 2014.
- EurOMA conference, presentation at conference and participation in PhD student workshop where project results were discussed, Title: Flexibility of materials preparation processes in production system”, Neuchâtel, June 26 – July 2, 2015.
- FKG’s conference ”Stora leverantörsdagen”, Title: ”Materialfasaderna ska stödja montörerna – så här påverkas logistiken”, Gothenburg, October 14, 2015.
- Industry conference ”Scania Technology Day”, Title: ”Current trends within Logistics - in Swedish automotive industry and according to researchers”, Södertälje, November 4, 2015.
- Seminar at Innovatum in Trollhättan, Title: ”Current trends within Logistics - in Swedish automotive industry and according to researchers”, November 25, 2015.
- Conference ”Monteringsforums årliga monteringskonferens”, Title: ”Plocka fort är stort, plocka rätt är större – stöd finns för att plocka fort och rätt”, Presenters: Robin Hanson and Patrik Fager, Stockholm, March 16, 2016.
- Industry conference ”Volvo Car RFID-day”, Title: ”Reserchers view on logistics innovations in RFID information systems”, Gothenburg, April 12, 2016.
- CIRP Conference on Assembly Technologies and Systems (CATS), Title: “Aspects influencing man-hour efficiency of kit preparation for mixed-model assembly”, Gothenburg, May 16-17, 2016.
- EurOMA conference, Title: “Performance effects of using external warehouses in materials supply to assembly”, Trondheim, June 17 – 22, 2016.
- IFC Conference on Manufacturing Modelling, Management and Control (MIM), Title: “Manual Picking from Large Containers – Time Efficiency and Physical Workload”, Troyes, June 28-30, 2016.
- PLAN’s forsknings- och tillämpningskonferens, Växjö, October 19-20, 2016.
- Conference ”Logistik & transportmässan”, Title: ”Plocka fort är stort, plocka rätt är större – ett materialhanteringsexperiment”, Presenter: Patrik Fager, Gothenburg, November 8, 2016.
- Industry workshop ”Pick-by-AR and Pick-by-MR”, where representatives from more than 10 different companies tested and discussed two different technologies for pick-by-vision systems at the demonstrator lab developed in the project, Schenker Logistics, Landvetter, February 14, 2017.
- Conference ”Monteringsforums årliga monteringskonferens”, Title: ”Rätt, snabb och flexibel materialpreparering – en handbok med riktlinjer för utformning av effektiv materialpreparering”, Presenter: Patrik Fager, Stockholm, March 15, 2017.

- Conference ”IFAC World Congress”, Title: ”Picking from pallet and picking from boxes: a time and ergonomic study”, Toulouse, July 9-14, 2017.

In October 2016, the project “Automation of Kitting, Transport, and Assembly” (AKTA) was initiated, with the support of the Vinnova programme “Produktion2030” (dnr. 2016-03322). The AKTA project has an interface to the Design of Materials Preparation Processes project, as they both consider the materials handling processes associated with preparing materials for assembly. The two projects share some participants and it is therefore natural for the AKTA project to consider and take advantage of the findings from the Design of Materials Preparation Processes project. Another project, the “Emerging Digital technologies and their Applicability as Picking Support in materials handling” (EDAPS), was initiated in February 1st 2017 (dnr. 2016-05477), directly builds on the findings in the current project. The aim of EDAPS is to derive propositions for how digital technologies, which are under rapid development, can be used in materials preparation for improving the performance beyond what is possible today.

The aim for dissemination of the project results beyond the project’s life-span is summarised in Table 7.1.

Table 7.1. The aim for dissemination of the project results beyond the life-span of the project.

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	**X**	Presentations at scientific conferences and publications in scientific journals as input to theses projects.
Be passed on to other advanced technological development projects	**X**	Results from the current project will be used as input for propositions in continued research.
Be passed on to product development projects		
Introduced on the market	**X**	The handbook with design guidelines that was developed is feely available for industry. Demonstrator of picking information systems to be used by industry. Results are included in master’s courses and in professional education courses, as well as presented at industry conferences etc.
Used in investigations / regulatory / licensing / political decisions	**X**	The results from the project has potential for being used in evaluative frameworks and protocols for materials handling processes.

7.2 Publications

The project have resulted in a number of publications, in form journal articels, conference articles, and thesis works (Bachelor's and Master's), presented below in alphabetical order.

Andersson, C. and Kype, B. (2014), *BRA Metodik - Balanserad ruttanpassning för mjölkrundetåg i JIT-organiserade monteringsavsnitt*, Bachelor's thesis. Chalmers University of Technology.

Assaf, M. and Jukic, P. (2015), *Utilizing Lean Six Sigma to Improve Material Handling Operations in the Production of Heavy-Duty Engines at Volvo Powertrain - A Six Sigma Black Belt Project*. Master's thesis. Chalmers University of Technology.

Bark, D. and Järvitalo, M. (2014). *Development of a framework for designing a Material Supply System - A case study at Volvo CE in Hallsberg*. Master's thesis. Chalmers University of Technology.

Bulun, D. and Konstantinidis, K. (2017), *Location of kit preparation – A case study within the automotive industry*, Master's thesis. Chalmers University of Technology.

Bäckstedt, K., Nordström, P. and Persson, M. (2015), *Improving construction supply chains using load carriers - Effects of implementing a load carrier for reinforcement bars to construction sites*. Master's thesis. Chalmers University of Technology.

Calzavara, M., Hanson, R., Sgarbossa, F., Medbo, L. and Johansson, M.I. (2017). "Picking from pallet and picking from boxes: a time and ergonomic study", in: *Proceedings of 20th IFAC World Congress*, July 9-14, Toulouse, France.

Dahlén, H. and Spång, S. (2016), *Packaging usage for spare parts Distribution - A case study of packaging products at a spare parts distribution center in Maastricht*, Bachelor's thesis. Chalmers University of Technology.

Döllinger, A. and Larsson, T. (2016), *Selection of Automated Order Picking Systems - Automated Storage and Retrieval Systems within Contract Logistics*, Master's thesis. Chalmers University of Technology.

Fager, P., Johansson, M. I. and Medbo, L. (2014). "Quality problems and quality costs in materials kit preparation", in: *Proceedings of 6th International Annual Swedish Production Symposium SPS14*, September 16-18, Göteborg. (Google scholar times cited: 2)

Fager, P., Hanson, R. and Johansson, M. I. (2015), "Flexibility of materials preparation processes in production systems", in: *Proceedings of the 22nd international Annual EurOMA conference*, June 26 – July 1, Neuchâtel.

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

Fager P., Hanson R., Medbo L., and Johansson M. I. (2016) "Time efficiency of information systems in materials kit preparation", working paper submitted to the journal of *Industrial Management and Data Systems*.

Fager, P. (2016). "On the link between materials preparation design and performance", *Licentiate thesis,* Chalmers university of technology, Gothenburg.

Hanson, R. and Medbo, L. (2014). "Kit preparation using batching – quantitative results from two experiments", in: *Proceedings of 21st International Annual EurOMA Conference: Operations Management in an Innovation Economy*, June 20-25, Palermo. (Google scholar times cited: 1)

Hanson, R., Medbo, L. and Johansson, M.I. (2015). "Order batching and time efficiency in kit preparation", *Assembly Automation*, Vol. 35, No. 1, pp. 143-148. (Google scholar times cited: 1)

Hanson, R. and Medbo, L. (2016). "Aspects influencing man-hour efficiency of kit preparation for mixed-model assembly", in: *Proceedings of 6th CIRP Conference on Assembly Technologies and Systems (CATS)*, May 16-17, Göteborg, Elsevier, Vol. 44, pp. 353 – 358.

Hanson, R., Johansson, M.I. and Medbo, L. (2016). " Manual picking from flat and tilted pallet containers", paper submitted to the *Journal of Manufacturing Technology Management.*

Hanson, R., Medbo, L. and Johansson, M.I. (2016). "Performance effects of using external warehouses in materials supply to assembly", in: *Proceedings of 23rd International Annual EurOMA Conference: Interactions*, June 17-22, Trondheim.

Hanson, R., Medbo, L., Jukic, P. and Assaf, M. (2016). "Manual Picking from Large Containers – Time Efficiency and Physical Workload", in: Proceedings of 8th IFC Conference on Manufacturing Modelling, Management and Control (MIM), June 28-30, Troyes, France.

Hanson, R., Medbo, L., Jukic, P. and Assaf, M. (2017). "Time efficiency and physical workload in manual picking from large containers", paper under review in the *International Journal of Production Research*.

Hanson, R., Medbo, L., Berlin, C. and Hansson, J. (2017). "Manual Picking from Flat and Tilted Pallet Containers – a Study of Physical Ergonomics and Picking Time", paper submitted to the *International Journal of Industrial Ergonomics*.

Hanson, R. and Medbo, L. (2017) "Man-hour efficiency of manual kit preparation in the materials supply to mass-customised assembly", working paper submitted to the *International Journal of Production Economics.*

Karlsson, A. and Svanström, M. (2016), *Parts feeding of low-volume parts to assembly lines in the automotive industry*. Master's thesis. Chalmers University of Technology.

Rajaguru. R.K. and Mathew, B.C. (2017), *The control of material flow between external warehouses and assembly plants in the material supply to automotive industry*. Master's thesis. Chalmers University of Technology.

Skoog, L. and Bäckström, R. (2017), *Samhalls returemballage: En fallstudie av ojämn arbetsbelastning*, Bachelor's thesis. Chalmers University of Technology.

8. Conclusions and future research

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

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

Six research questions were formulated in order to align the research with the research purpose, and the research studies were accordingly designed to address the research questions. Three studies were designed as multiple case studies, focusing how and why various design options influence performance. Three studies were designed as experimental studies, more narrowly focusing the influence on performance from using different types of picking information systems, from different batching policies and from different materials presentation.

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

Flexibility performance was studied in a similar way. The result of this study includes knowledge of the individual links between flexibility performance and the set of design variables identified in the project, and contributes to research by building on general models of flexibility from manufacturing, applying them to the specific context of materials preparation. An important observation is modern technologies in its current form and practice, e.g. pick-to-light systems, may delimit flexibility by introducing requirements on changes both in the information data bases and in the physical system. As for the quality area, the more comprehensive results on causes to quality problems in the materials preparation context, further traced back to the design variables, contributes to previous research.

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

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

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

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

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

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

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

9. Participating parties and contact persons

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