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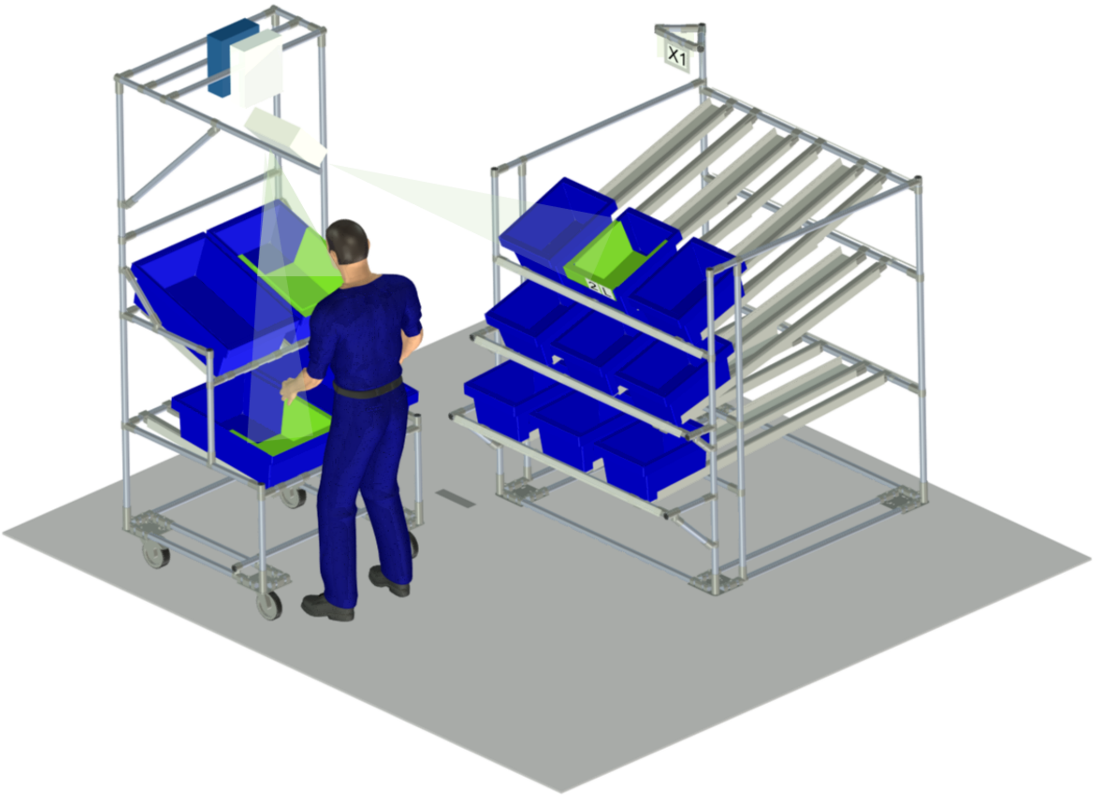

Interactive Augmented Reality with embedded smart-sensors as a means of conveying picking information in kit preparation

A comparative analysis of performance and cost against established picking information systems

Master of Science Thesis

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Cover: The Pick-by-beamer system.

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Abstract

A picking information system provides the picker with information on what to pick, what quantity should be picked and where to place what have been picked. Picking information systems are commonly deployed in kit preparation, i.e., the process of picking and sorting components into a kit that is delivered just-in-time to an assembly line. Picking information systems aim to minimize picking-error occurrences while maximizing the kit preparation pace. While technological development has catapulted parallel to lean concepts gaining prominence in the industry, means of conveying picking information in kit preparation have remained unchanged for decades. With fierce competition, companies are constantly evaluating ways to cut costs and increase their efficiency. The gap between technological development and current technology in kit preparation constitutes an opportunity of creating a picking information system superior to those most used today. The purpose of this thesis is to investigate the feasibility and competitiveness of Interactive AR with embedded smart-sensors in kit preparation (Pick-by-beamer). The system design of Pick-by-beamer is based on lean principles by conducting a Sequential Activity Methods Analysis (SAM) of three established picking information systems. An experiment was conducted to evaluate the kit preparation pace and picking errors for Pick-by-beamer and picking according to a paper list (Pick-by-paper) in single-kit and batch preparation. The experiment data was analyzed through a repeated measures ANOVA (rANOVA) with a Games-Howell post hoc test. An economic evaluation of the hourly cost was done for Pick-by-beamer, Pick-by-paper, Pick-by-light and Pick-by-voice. Lastly, a payback analysis was done for switching to Pick-by-beamer from Pick-by-paper in kit preparation. Pick-by-beamer was concluded to constitute a competitive solution for conveying picking information in kit preparation. The economic evaluation also suggested that Pick-by-beamer constitute a competitive alternative to established picking information systems.

Keywords: Picking information system, Augmented Reality, Kit preparation, Kitting, Pick-by-beamer, Pick-by-paper, Pick-by-light, Pick-by-voice

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Marvin Lagerberg Johannisson

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Joel Palage

Gothenburg, June 2020

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Acronyms

MTM Method time measurement. III, 9–11, 13, 14, 16, 30, 33, 35–37, 41, 42, 44–46, 48, 52, 53, 55, 80, 87, *Glossary:* MTM

NPV Net Present Value. 30, 35, 74

PMTS Predetermined Motion Time System. 10, 11, 16, *Glossary:* PMTS

ROI Return On Investment. 30, 35, 74

SAM Sequential Activity-and Methods. III, 9–11, 13, 14, 16, 30, 33, 35–37, 41, 42, 44–46, 48, 52, 53, 55, 80, 87, *Glossary:* SAM

Glossary

Batch preparation Batch preparation is when the kit preparation process involves preparation of more than one kit per picking sequence. Another term used to describe batch preparation is multi-kit preparation. In this study, batch preparation is limited to preparation of four kits per picking sequence. 4, 6, 7, 14, 17, 23, 26–30, 38–42, 44, 46–50, 52, 54, 57, 79–82, 87

Batching Policy The batching policy determines how many kits that are prepared during a picking sequence. Single-kit prepatation is a batching policy involving preparation of one kit per picking sequence while batch preparation refers to preparation of more than one kit per picking sequence. III, V, VI, XVII, 2, 11, 17, 23–26, 30

Central Limit Theorem The central limit theorem is a statistical theory. The theory states that given a sufficiently large sample size from a population with a finite level of variance, the mean of all samples from the same population will be approximately equal to the mean of the population. All the samples will follow an approximate normal distribution pattern, with all variances being approximately equal to the variance of the population when divided by each sample's size. 28

Module A module is a situation-specific movement performed by the picker. What module is performed by the picker is dependent on a number of variables that describe the situation where the movement is performed. III, XVII, 11

Module Category A module category contains all modules that are performed for the same purpose by the picker. An example is the module category Confirmation which contains all different confirmation modules. III, V, VI, 11

MTM Method Time Measurement originates from Scientific Management introduced by Frederick W. Taylor's book *Principles of scientific management* (Taylor, 1911). Several variants of Method Time Measurement exist with different precision levels. The choice of which method to use depends on the complexity and cycle time of the work task to be analyzed. 9

Picking assignment A picking assignment corresponds to one row in the picking sequence. A row in the picking sequence contains information on which storage location type to pick from, how many components to pick, which kit(s) the component(s) should be placed in, and for Pick-by-paper a hint of component size (large or small). XVII, 13, 14, 22, 23, 26, 27

Picking demand Picking demand is in this study referred to as the number of components that is demanded to be picked per hour.. 30, 32, 34, 57–59, 66, 69, 74, 88

Picking density Picking density is referred to as how many components are to be picked per meter of walking along the picking aisle. VI, 23, 27, 30

Picking sequence A picking sequence consist of one or more picking assignments. VI, 11, 12, 14, 17, 22, 23, 26, 27

PMTS Predetermined Motion Time System involves several different measurement techniques or systems, e.g Method Time Measurement. The main purpose of Predetermined Motion Time Systems are to quantify the time it takes to perform specific tasks in a given work environment. 10

SAM Sequential Activity-and Methods is a Predetermined Motion Time System that is based on the system Method-Time-Measurement-1. The method is used to design, document and establish norm times of work methods. The Nordic MTM association (Nordisk Produktivitet, 2020) describe SAM as a MTM-based system intended to unambiguously analyze manual working methods. 9

Single-kit preparation Single-kit preparation is when the kit preparation process involves preparation of one kit per picking sequence. 6, 17, 23, 26–29, 37–42, 44, 46, 48–50, 52, 55, 57, 80, 87

Storage section A storage section is a flow rack containing a specific number of storage locations. 19–21, 26

Storing density Storing density is referred to as the number of storage locations per meter of picking aisle.. 19, 23, 24, 26

1
Introduction

In this chapter, the background of the thesis is presented. First, a short background about the field of study and what motivated a study within the field. Second, the aim of the study and the scope which the study is carried out within is presented. A deeper theoretical ground is needed to specify the research questions, therefore those are presented in the subsequent chapter, Theory.

1.1 Background

Increased customer demand for customized products has forced manufacturers to carry an inventory of multiple variants of the same component, e.g. car headlights of different light technology, to offer assemble-to-order products that meet customer demand. Carrying inventory of multiple component variants is space consuming and limits the ability to efficiently use continuous supply, e.g. line stocking, as a materials feeding principle in mixed-model assembly (Brynzér and Johansson, 1995). As an alternative, preparation and delivery of an exact quantity of components in presorted assembly kits to the assembly line, i.e., kitting, has developed into a common material feeding principle in mixed-model assembly. Kitting has grown increasingly common since allocates non-value adding activities, i.e., walking and fetching components, away from the assembly station that is being supplied (Kilic and Durmusoglu, 2012). Kitting increases the the share of value adding activities performed by the assembly line worker at the assembly station and reduces the cycle time at the specific assembly station (Hanson and Medbo, 2016). Kitting also have the advantage of supporting small batch size assembly operations with high product variability (Brynzér and Johansson, 1995), a common situation, for example in the automotive industry today.

Kitting involves a process referred to as kit preparation which is the process of picking and sorting, i.e., preparing, components into a kit that is subsequently delivered to the assembly line (Bozer and McGinnis, 1992). High performance of the process is decisive to sustain high quality of the final product as faulty kit preparation could lead to assembly errors being made downstream in the production process Fager, Johansson, and Medbo, 2014. To prevent compromising product quality, it is important to deploy an adequate picking information system in the kit preparation process that supports the picker with guidance and instructions to pick the correct component and quantity and place it in the correct kit (Brynzér and Johansson, 1995). The picking information system also needs to enhance productivity for the kit preparation process to be aligned with the production rate (Brynzér and Johansson, 1995; Hanson and Brolin, 2013).

Picking information systems today use different means of conveying picking information with different pick-from and place-to confirmation methods (de Vries, de Koster, and Stam, 2016; Fager, 2019; Reif and Günthner, 2009). Companies practicing kit preparation deploy different picking information systems for essentially the same purpose and there is generally no consensus about which picking information system has the highest aggregated benefits supporting the picker in kit preparation (Fager, Hanson, Medbo, and Johansson, 2019; Hanson, Falkenström, and Miettinen, 2017). Studies have been carried out to investigate the performance of different picking information systems in kit preparation (Fager, 2019; Fager et al., 2019; Hanson et al., 2017), but the results vary depending on contextual factors, e.g. **batching policy** or what activity of the picking process is being studied.

As the pace of technological development has been accelerating in the last decades while current picking information systems have remained unchanged, a technological disparity is created between kit preparation practice and available technology. With declining costs as the technology progresses towards maturity, previously expensive technologies become available for use in new application areas. A low degree of acquisition and development of new means of conveying picking information in kit preparation motivates identification and test of new means of conveying picking information. New means of conveying picking information holds the potential of being superior to established picking information systems with an increased overall efficiency of the kit preparation process.

An interesting opportunity to disrupt the use of established picking information systems that has been around for decades is to investigate the use of Interactive Augmented Reality (IAR) for kit preparation. IAR utilizes beaming technology for information conveyance and validation. Picking information is projected through a projector that is connected to sensors that automatically detect movements and objects. The consultancy firm Virtual Manufacturing, which is supervising this study, has recently acquired an assembly guidance system called Human Interface Mate (HIM) that uses IAR technology. The system is currently used for guiding operators through an assembly assignment. To test and evaluate IAR in kit preparation, the HIM is used. For more information about the HIM unit, see Appendix A. Further on in this study, Pick-by-beamer will be used as the term describing a picking information system that uses projections together with sensors to convey picking information in kit preparation. In addition to testing efficiency and quality, it is of interest to test and conduct an economic evaluation of a Pick-by-beamer system against established picking information systems in kit preparation. An economic evaluation of established picking information systems has only been done before in the context of order picking (Battini, Calzavara, Persona, and Sgarbossa, 2015) and not in the context of kit preparation. The IAR innovation can expand the customer segment for Virtual Manufacturing and contribute to closing the technology disparity in kit preparation.

1.2 Aim

The aim of the project is to explore the feasibility, performance, and costs of Pick-by-beamer in kit preparation. The result intends to aid decision-makers regarding the choice of which picking information system to invest in for kit preparation.

1.3 Scope

This project includes studying the feasibility of deploying the Pick-by-beamer system where feasibility means the applicability of the Pick-by-beamer system in kit preparation in practice. The performance of Pick-by-beamer will be analyzed in terms of picking efficiency and picking error probability. The cost evaluation is limited to investment costs and operational costs not including service costs.

The project does not include a study of ergonomic factors of the Pick-by-beamer system. Order picking involves contextual factors in terms of order size and warehouse structure that is different compared to kit preparation. Despite having common processes, order picking is considered a different field of study and is not included in this study.

2
Theory

The theory chapter contains an in-depth description of the field of study which is narrowed down into two research questions presented at the end of the chapter. First, a description of kitting as a materials feeding principle and the challenges of kit preparation, a process within kitting, is presented. It is then described how picking information systems could be designed and used as a means to handle these challenges. The results of recent studies that have tested and evaluated the performance of various picking information systems in kit preparation are then presented. Emphasis is placed on the relative difference in performance between the systems and how this can differ between, picking one kit at the time called single kit preparation, and picking several kits simultaneously called **batch preparation**. Lastly, an explanation of why it is of interest to investigate the feasibility, performance, and costs of Pick-by-beamer in relation to other picking information systems is presented followed by the two research questions.

2.1 Kitting as a materials feeding principle

Increased customer demand for customized products has forced manufacturers to carry an inventory of multiple variants of the same component, e.g. car headlights of different light technology, to assemble and offer made to order products that meet customer demand. Carrying inventory of multiple component variants is space consuming and limits the ability to efficiently use continuous supply, e.g. line stocking, as a materials feeding principle in mixed-model assembly (Brynzér and Johansson, 1995). As an alternative, preparation and delivery of an exact quantity of components in presorted assembly kits to the assembly line, i.e., kitting, has developed into a common material feeding principle in mixed-model assembly. A kit is defined according to Bozer and McGinnis (1984) as:

> "a specific collection of components and/or sub-assemblies that together (i.e., in the same container) and combined with other kits (if any) support one or more assembly operations for a given product."

The reason for why kitting has grown increasingly common is because it supports small batch size assembly operations with high product variability (Brynzér and Johansson, 1995). With kitting as a material feeding principle, inventory is relocated from the assembly line to a separate storage location known as a kit preparation area (Bozer and McGinnis, 1992). A separation between the assembly line and inventory storage reduces occupied space and increases visibility at the assembly line (Bozer and McGinnis, 1992; Brynzér and Johansson, 1995). However, total space may increase as a new area for kit preparation would need to be allocated. The increased amount of space available at the assembly line allows for several performance improvements in the assembly operations. Brynzér and Johansson (1995) and Hanson and Medbo (2011) mention reduced travel time for the assembler as a performance improvement with reduced work cycle time at the station. The reduced work cycle of the assembler is achieved as the need of walking between storage locations to fetch components is eliminated since the components are, instead, delivered in a kit placed close to the assembly object. Another advantage of kitting is flexibility in terms of response to product changeovers (Hanson and Brolin, 2013). The same authors further argue that product changeovers could be carried out promptly as small quantities of inventory are presented at the assembly station, enabling responsive replacement.

2.1.1 Challenges related to kitting

Kitting involves a process referred to as kit preparation which is the process of picking and sorting, i.e., preparing, components into a kit (Bozer and McGinnis, 1992). The process of kit preparation could have a positive impact on the product quality level if the kit preparation results in components being positioned and delivered to resemble the assembly operation, functioning as a work instruction (Brynzér and Johansson, 1995). However, the opposite situation where product quality decreases could also occur as a cause of picking errors being made during the kit preparation. These picking errors cause complex disturbances at the assembly line (Brynzér and Johansson, 1995). An example of such a situation was mentioned by Bozer and McGinnis (1992), where the kit was delivered to the assembly line in an incomplete condition, either missing a component or containing a faulty or wrong component variant. In that situation it was common that other kits were used as spare kits, creating complex shortages that were hard to trace. Picking errors made in the kit preparation process increases the risk of poor product quality and requirement of additional handling to complement the kit with missing components (Fager et al., 2014).

Kit preparation not only faces challenges regarding quality but also man-hour productivity. In a paper by Hanson and Brolin (2013), it was stated that kitting as a material feeding principle could increase the total man-hours in comparison to continuous supply. To reduce the likelihood of increased man-hours it is important that the kitting system incorporates a kit preparation process that supports both efficiency and quality (Brynzér and Johansson, 1995; Hanson and Brolin, 2013).

2.1.2 Managing challenges in kit preparation

The greatest challenge of the kit preparation process is to prepare kits with minimal picking error occurrence at a high picking rate (Brynzér and Johansson, 1995; Hanson and Brolin, 2013). To reduce the likelihood of picking errors and increase the picking rate it is important to provide the picker with adequate support systems. Based on a literature review and workshop with industry experts, Hanson and Medbo (2016) concluded the picking information system used in kit preparation to be one of the most influential factors on man-hour productivity. Brynzér and Johansson (1995) describes how picking information systems affects the picking efficiency in kit preparation and emphasizes the importance a well designed picking information system in the kit preparation process to support the picker in managing the challenges related to kit preparation.

Several important design features of a picking information system were mentioned by the industry experts participating in the study by Hanson and Medbo (2016). It was concluded that the picking information system needed to be aligned with the overall design of the kit preparation process and convey information in a timely and user-friendly format. The thoughts expressed by the industry experts are in line with what is stated in the paper by Brynzér and Johansson (1995). In that paper, it is emphasized how the performance of a picking information system could vary depending on to what extent the design of information conveyance is aligned to the design of the kit preparation process. Picking errors could still occur during the kit preparation process if the picking information is conveyed in a less optimal format leading to misinterpretations.

2.1.3 Picking information systems performance in kit preparation

Three studies were found in the literature where the performance of different picking information systems was tested for kit preparation. Fager et al. (2019) studied how time-efficiency in the kit preparation process was affected by the choice of picking information system. In the study, Pick-by-paper, Pick-by-light, Pick-by-voice, and Pick-by-HUD (Head-Up Display) were tested for two different batching policies, **single-kit preparation** and batch preparation in a setting resembling a kit preparation area. The study found the results to vary depending on the batching policy, where pick-by-light and pick-by-HUD both had a higher picking rate and a lower amount of picking errors in single-kit preparation compared to batch preparation. The authors thought this was due to intuitive information conveyance and simple place-to confirmation, i.e. when confirming that components have been placed in a kit. The number of picking errors also varied depending on batching policy. In general, picking errors occurred more frequently in batch preparation. For Pick-by-light, picking an incorrect quantity or placing components in the wrong bin was the most commonly observed picking error. The authors thought these picking errors were caused by the picker confusing which light indicator corresponded to which kit, with components being placed in an adjacent bin.

Fager (2019) tested four different picking information systems; barcode scans using a ring scanner; pick-by-light; pick-by-voice; and RFID-scans (radio-frequency identification) with two RFID-reading wristbands. Fager (2019) showed the system's impact on efficiency i.e., the time needed to complete one picking tour, and quality which is the number of picking errors. The test was done in a laboratory environment that resembled a typical kit preparation area and focused mainly on the methods of confirmation used in the systems. The study found that pick-by-light and RFID scans with wristbands achieved the best results. The author concluded that systems that do not significantly interrupt the picking motions performed better. The biggest differences in time efficiency between the picking information systems were concluded to be in the pick-from task when components were picked from a storage location.

Pick-by-light and Pick-by-voice are both considered mature technologies, being used in industrial applications since 1970 and 1980 (AIOI Systems CO., 2018; Badwi, 2019). A study showing the potential of a new type of picking information system was done by Hanson et al. (2017). In that study, the potential of Augmented Reality (AR) glasses for conveying picking information in kit preparation (Pick-by-AR) was compared to Pick-by-paper. The study measured time-efficiency and picking accuracy in terms of the number of picking errors for single-kit and batch preparation. Pick-by-AR was found to be statistically significantly better for batch preparation. This was thought to be due to the ability of Pick-by-AR to present information in an intuitive way. For single kit preparation, there was no significant difference between the systems, however, this was concurrently argued to possibly change with continued development and adjustments of the AR application. The study concluded that it was possible to achieve a high picking accuracy using pick-by-AR as a means for conveying picking information.

2.2 Research questions and research gap

The three studies (Fager, 2019; Fager et al., 2019; Hanson et al., 2017) provide valuable information on current performance of different picking information systems in kit preparation. The studies have been carried out to answer what is the most time-efficient means of conveying picking information in kit preparation as different systems are currently used for the same purpose in the industry. The result of the three studies concludes that the time-efficiency of different picking information systems often varies with the batching policy and sometimes marginally, which could explain the lack of consensus in the industry. According to Hanson and Medbo (2016), a picking information system needs to be adapted to the conditions present in kit preparation to maintain high performance. As mentioned before, several of the established picking information systems have been around for decades. The pace of technological development in the last two decades suggests that new technology could be better adapted to the conditions present in kit preparation with a competitive advantage over established systems. Two studies previously mentioned (Fager et al. (2019); Hanson et al. (2017)) have tested two new types of picking information systems, Pick-by-AR and Pick-by-HUD, with high performing results. The studies support the notion that new technology can compete with established systems. It is therefore of interest to continuously investigate and test new technologies like Pick-by-beamer that could increase the efficiency of operations in assembly to order companies with kit preparation. The need to continue to investigate new types of means of picking information systems leads to the first research question:

1. *Can Pick-by-beamer be a feasible solution and compete in performance with Pick-by-paper, Pick-by-light and Pick-by-voice in kit preparation?*

Studies on performance of picking information systems contribute partly to reaching consensus in the industry, however, the choice of picking information system is rather complex and cannot be limited to time-efficiency (Brynzér and Johansson, 1995; Fager, 2019; Fager et al., 2019; Hanson and Medbo, 2016; Hanson et al., 2017). For companies to make an informed decision on which picking information system to use in kit preparation, several other factors need to be incorporated, e.g. costs, picking errors, flexibility, and ease of system maintenance. Fager (2019) expands this list to include ergonomics and compatibility with current technologies used and warehouse management systems. There is a need to understand these factors, however, no study was found in the literature studying the cost performance of different picking information systems when deployed in kit preparation. A study by Battini et al. (2015) evaluated the cost performance of different picking information systems for warehouse order-picking but the contextual differences between order-picking and kit preparation prevent the results from being generalized to kit preparation. A kit preparation area is different compared to a traditional order picking area as it has a higher number of picks per meter, i.e., picking density (Hanson and Medbo, 2016). The lower picking density means that travel time comprises a larger proportion of total picking time for order picking (Fager, 2019; Hanson et al., 2017). For traditional order-picking operations, traveling time constitutes about 50% of the total picking time while it only constitutes 15% to 25% of the total picking time in kit preparation (Brynzér and Johansson, 1995). The sensitivity to changes in picking density varies between picking information system and affects the performance (Fager et al., 2019). There is a need to compare the costs of different picking information systems to provide decision-makers with additional decision basis. The second research question of this report reads:

2. *Can pick-be-beamer compete economically with Pick-by-paper, Pick-by-light and Pick-by-voice in kit preparation?*

3 Methodology

In an earlier study by Fager et al. (2019), an experiment was carried out to determine the picking efficiency and error probabilities of Pick-by-paper, Pick-by-voice and Pick-by-light. However, it is difficult to compare results from experiments across studies as it is hard to reconstruct the exact same setup. Therefore, to accurately compare picking efficiency, a theoretical **Method-Time-Measurement (MTM) -Sequential Activity and Methods (SAM)** analysis was conducted for each of the systems. Initially, the analysis was done for Pick-by-paper, Pick-by-light and Pick-by-voice with support of the video recordings from Fager et al. (2019). The MTM-SAM analysis provided insights on how to design and adapt the Pick-by-beamer system to the kit preparation process. Thereby, a preliminary MTM-SAM analysis of the intended work process for the Pick-by-beamer system was conducted.

To obtain error probabilities and to verify the feasibility of using a Pick-by-beamer system for kit preparation, an experiment was conducted. The experimental design and setup were made as identical to Fager et al. (2019) as possible. Pick-by-paper was added in the experiment to verify that the experiments were of similar settings. Obtaining similar results for Pick-by-paper as Fager et al. (2019) indicated that the Pick-by-beamer was tested in a setup similar to Fager et al. (2019). Thereby, video recordings of the Pick-by-beamer system obtained from the experiment could be used to strengthen its preliminary MTM-SAM analysis. Further, by measuring the time consumption, the experiment provided an additional data set for the picking efficiency of Pick-by-beamer. Comparing those results to the results of the MTM-SAM strengthened the validity of the MTM-SAM. Further, a statistical analysis comparing the measured times from the experiment was conducted to get an additional credible comparison between Pick-by-paper and Pick-by-beamer.

Lastly, to guide investors of picking information systems in kit preparation an economic evaluation was done for Pick-by-beamer, Pick-by-paper, Pick-by-light and Pick-by-voice. The economic evaluation uses picking efficiency data from the MTM-SAM analysis together with error probabilities from both this study and the study by Fager et al. (2019). Additional data on the costs of hardware and software were gathered from industry actors and literature. The following method chapter cover in detail how each of the three sections, MTM-SAM analysis, experiment, and economic evaluation were conducted.

3.1 MTM-SAM analysis of picking information systems

In the book by Martin-Vega and Maynard (2004), it is argued that when assessing the cycle time of a process, no matter how accurately a time study is conducted, there will be uncertainty about how to measure the operators' level of effort. There will be a variance between measurements of different operators, or even, the same operator on different days. Differences between operators could be a consequence of some operators having a natural aptitude for working with a certain system. The variation between operators makes it difficult to credibly assess the efficiency of systems through regular time studies. It becomes even harder to compare systems tested in different environments using different test persons. Martin-Vega and Maynard (2004) explain that such validity problems can be avoided using **Predetermined Motion Time System (PMTS)** methods. Through predetermined times standards, appropriate times can be set for each element of a working process using time standards where each element can be combined into a complete process. Time standards are defined as "the time required by an average skilled operator, working at a normal pace, to perform a specified task using a prescribed method, allowing time for personal needs, fatigue, and delay" (Martin-Vega and Maynard, 2004, p.636). Further, Martin-Vega and Maynard (2004) explain that by using standard times, instead of measured times, the time assessment can with PMTSs be used in the planning phase of a project.

To avoid the limitations of time studies, a PMTS variant called MTM-SAM was used to analyze the efficiency of Pick-by-beamer, Pick-by-paper, Pick-by-light and Pick-by-voice. The three additional picking information systems were selected because they are considered established and mature technologies (AIOI Systems CO., 2018; Badwi, 2019; Battini et al., 2015). Video recordings of each system used in kit preparation were available from a previous study by Fager et al. (2019) which supported the MTM-SAM analysis. The outcome of the MTM-SAM analysis had two purposes: first, provide input on design parameters for the Pick-by-beamer system. Second, provide norm times for the time it takes to pick one component i.e., picking efficiency. The results on picking efficiency were used in the economic evaluation of Pick-by-beamer, Pick-by-paper, Pick-by-light and Pick-by-voice. MTM-SAM data was used instead of the experimental data because it is not affected by the variation existing between operators and setups.

MTM-SAM was chosen over other PMTS methods because it is well suited for the cycle times of the studied tasks where pickers walk approximately 15 m and pick 15 to 60 components. The tasks resulted in norm times of 5.7 to 36.8 minutes, and therefore, MTM-SAM provides sufficient accuracy and is time-efficient to use (Laring, Forsman, Kadefors, and Örtengren, 2002). IMD (2005) explain that a norm time above five minutes results in precision within ±5% of the theoretically exact norm time with 95% confidence. Nordisk Produktivitet (2020) further argue that MTM-SAM has a superior precision/time trade-off meaning that it can be faster than a MTM-3 but still give precision in between a MTM-3 and MTM-2 (lower number means increased precision but a more time-consuming analysis). The activities involved in a kit preparation process do not involve advanced high precision movements which further motivate the use of MTM-SAM in comparison to more detailed and exhaustive MTM-analysis methods. The MTM-SAM analysis was carried out using the lean production software AVIX.

3.1.1 Mapping and definition of kit preparation movements

Following the PMTS methodology outlined by Martin-Vega and Maynard (2004), the MTM-SAM analysis started with mapping and defining the involved activities in the kit preparation process. Video recordings of Pick-by-paper, Pick-by-light and Pick-by-voice from the study by Fager et al. (2019) were used to understand the involved activities of the kit preparation process for each system. A total of 300 video recordings of **picking sequence**s were available for the analysis, however, it was enough to study 60 of the videos to identify all the involved movements performed in a kit preparation process to conduct a MTM-SAM analysis. Two sequences from each person, using each picking information system, in each setting i.e., batch and single kit preparation were analyzed. That resulted in 60 ($2\times5\times3\times2$) sequences which was sufficient since it was only necessary to find a representative kit preparation work pattern for each picking information system and batching policy. As many of the identified movements were frequently reoccurring for the different picking information systems and picking sequences, modules were created. A **module** corresponds to a unique, situation specific, movement performed by the pickers. Occasionally, the module performed could vary despite the situation and task being the same. In that case, the most frequently performed module was selected. The situation of frequently reoccurring movements is known to reduce the required time to complete a MTM-SAM analysis (Ferreira, 2015) through the use of modules. A module library containing all modules were created. The module library allowed to efficiently build an extensive MTM-SAM analysis without needing to create new modules for every new analysis. The identified modules were grouped into five unique module categories (Table 3.1), where each **module category** consist of one or more modules. Movements that were unintentionally performed by the picker, and not necessary for the picking process were omitted from the analysis.

Table 3.1: Module category and number of modules in each category followed by a short description of each category.

Module Category	Modules	Description†
1. Search location	16	Searching for storage location Searching for kit location
2. Pick and place	15	One or multiple components picked/placed with one or two hands
3. Confirmation	6	After components have been picked After components have been placed
4. Push picking trolley	4	Grabbing picking trolley both hands Applying force to push picking trolley
5. Walk one step	1	Walking one step in any direction

†A detailed description of each module category and which module variables the modules in the category depend on is found in Appendix B.

3.1.2 Module variables

Continuously during the identification of movements from the 80 picking sequences, it was documented under what conditions the specific movement occurred. These conditions will further be referred to as module variables. Six module variables were observed to impact which module was performed by the picker. The six module variables is Picking information system, Storage location height, Component size, Placement location, Batching policy and Storing density. Table 3.2, presents a summary of the different module variables.

Table 3.2: Summary of module variables, number of levels for each module variable and description of the levels.

Module variable	Levels	Description of levels
Picking information system	4	Pick-by-beamer, Pick-by-paper Pick-by-light, Pick-by-voice
Storage location height	2	Middle shelf (10 to 45 cm from picker) High/low shelf (45 to 80 cm from picker)
Component size	2	Small Large
Placement location	8	A, B, C, D, E, F, G, H (Figure C.2)
Batching policy	2	Single-kit preparation Batch preparation
Storing density	2	High: 7.8 storage locations/m Low: 2.4 storage locations/m

Storage location height refers to the vertical positioning of the storage location. In this study, the facade has three levels, either the picker picks from the top, middle, or bottom shelf. In the MTM-SAM methodology, there are three available distance classes for a picking motion depending on how far the person needs to reach. The three distance classes are 0 to 10 cm, 10 to 45 cm and 45 to 80 cm, the 45 to 80 cm class includes a supporting step IMD, 2005. When standing in front of the storage location, the distance to the storage location varies slightly depending on the hands' position but do in general mainly depend on the storage location. Picks from the top and bottom shelves are initiated using the 45-80 cm class while middle shelf picks are initiated using the 10-45 cm class.

The module variable component size has two levels, small or large. The component size determines how many components the picker can hold in each hand. For the large-sized components, the picker is limited to only be able to hold one large-sized component per hand, while for small-sized components up to four can be held in each hand. The placement location module variable refers to which kit(s) the picker should place components in for the specific **picking assignment**. The placement location determines the placing action. A detailed description of the module variable placement location is found in Appendix C.

The state of the module variables can be determined based on the picking information system used and the information on the picking assignment. The picking assignment contains information on which storage location height to pick from, how many components to pick, the component size, and placement location, i.e., which kit(s) the component(s) should be placed in. The picking assignment also specifies the batching policy.

With knowledge of the six different module variables, an MTM-SAM analysis was created for all kinds of picking assignments for the four picking information systems based on the standardized module library. The analysis of each picking assignment was then combined into a complete picking sequence that consists of several picking assignments.

3.2 Design process of Pick-by-beamer

The design process of Pick-by-beamer constituted of an identification phase where the designs of Pick-by-paper, Pick-by-light and Pick-by-voice were studied. A conceptual design was then generated for Pick-by-beamer which in the second phase of the design process was evaluated through a preliminary MTM-SAM analysis. These two phases of the design process are described below. Structuring and documenting the design process aimed at increasing the likelihood of a suitable design that could compete with established picking information systems.

3.2.1 Identifying areas of improvement

In this first phase, the objectives was to identify areas of improvement for the Pick-by-beamer system and create a conceptual design of the system and the process of working with the system. To achieve a competitive design of the Pick-by-beamer system, improvement focused on achieving a high picking efficiency and picking accuracy.

The picking efficiency was mainly targeted by Identifying weaknesses in the kit preparation processes for Pick-by-paper, Pick-by-light and Pick-by-voice through an MTM-SAM analysis. The MTM-SAM analysis was visualized as flow model. In the flow model, modules were linked together into a sequence describing the working process of the picking assignment from start to finish. Flow models were created for Pick-by-paper, Pick-by-light and Pick-by-voice in single-kit preparation and batch preparation. The flow models for Pick-by-paper, Pick-by-light and Pick-by-voice are found in Appendix D. From the flow models, the value adding and non-value adding modules of the kit preparation process could easily be identified. By studying the flow models for the different systems a conceptual flow model was developed for Pick-by-beamer in single kit preparation (Figure 3.1) and batch preparation (Figure 3.2). During the development of the flow model for Pick-by-beamer, the picking efficiency was improved by minimizing the share of activities considered non-value adding in the kit preparation process. The flow model also allowed to recognize the wastes of a system based on the eight wastes of Lean (Bauch, 2004; Skhmot, 2017) to mitigate these. Waste was defined according to Womack and Womack (2003) as "any human activity that absorbs resources but creates no value". For a picking information system, Waiting and Motion where considered as relevant wastes to mitigate.

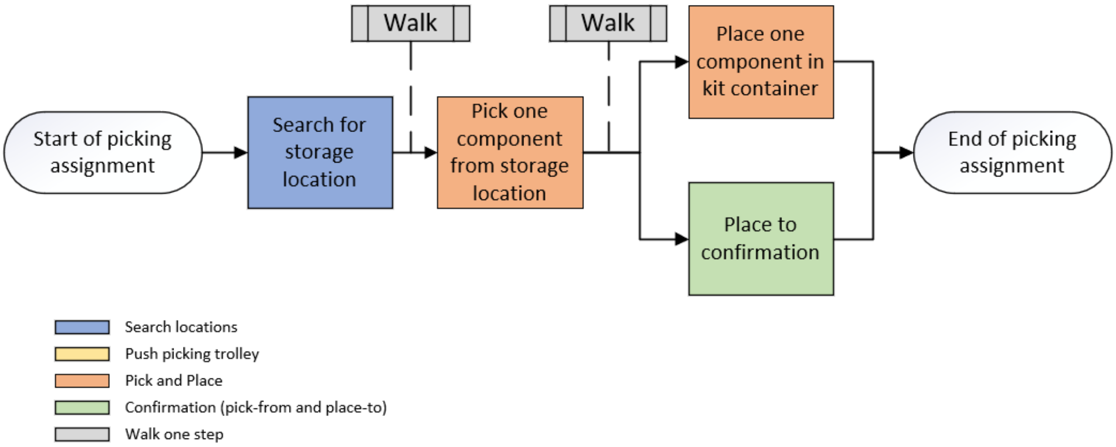


Figure 3.1: Flow model illustrating the order in which the module categories are performed for Pick-by-beamer in single-kit preparation. The flow model is color-coded according to the five module categories in Table 3.1.

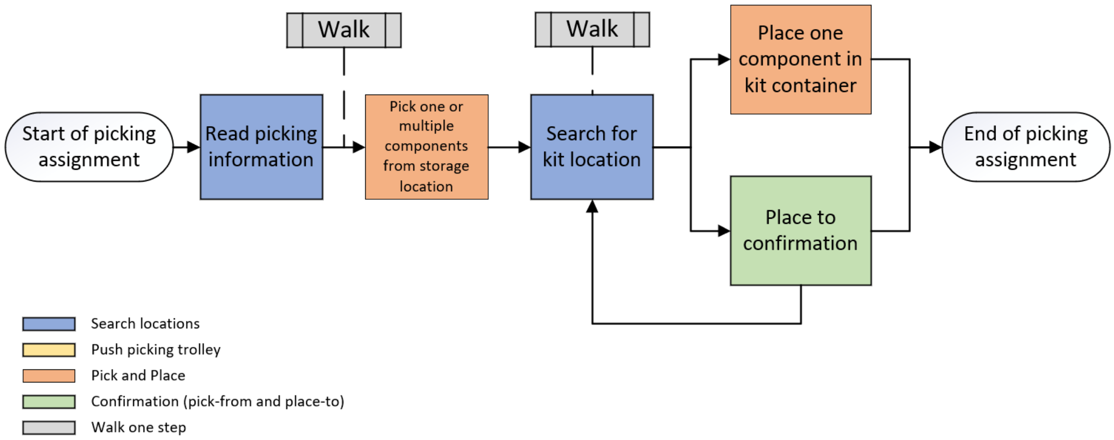


Figure 3.2: Flow model illustrating the order in which the module categories are performed for Pick-by-beamer in batch preparation. The flow model is color-coded according to the five module categories in Table 3.1.

The flow model helped in identifying areas of improvement and to further understand the process of kit preparation. The design suggestions related to the flow model was directly measurable in an MTM-SAM analysis. In the second phase described below, a preliminary MTM-SAM analysis was carried out for Pick-by-beamer to verify that these design suggestions developed from the flow models had a positive impact on picking efficiency for Pick-by-beamer.

Even though only the Pick and Place module category was considered value adding in the kit preparation process in terms of picking efficiency, other module categories could still have a supporting function to maintain a high picking accuracy. With the objective to achieve a high picking accuracy, some design suggestions that were not measurable in an MTM-SAM analysis was instead supported by literature and aimed at minimizing the probability of picking errors. Combining the approaches of an MTM-SAM and support from literature strengthened the validity of the design process and enabled to target both performance metrics in this study, picking efficiency and picking accuracy.

3.2.2 Preliminary MTM-SAM analysis of Pick-by-beamer

With a MTM-SAM analysis completed for the previously tested picking information systems, a preliminary MTM-SAM analysis was done for the conceptual design of Pick-by-beamer. As Pick-by-beamer only was in a conceptual state, no video recordings were available to study. However, as explained earlier, a MTM-SAM analysis can be done in the planning phase of a work process. Therefore, a MTM-SAM of the intended work design of the Pick-by-beamer was done prior to the experiments to assess its performance. The process was iterated by going back to the flow model, making adjustments or new suggestions and then implement suggestions into the MTM-SAM analysis. MTM methods provide an understanding of the process by identifying and structuring movements. Using that knowledge, it was possible to improve the design efficiency by removal of unnecessary activities and other work procedure improvements (Karim, Erns, and Amin, 2012).

As explained by Barnes (1980) and Martin-Vega and Maynard (2004), one of the advantages and application areas of using PMTS methods, of which MTM-SAM is a variant, is that they can be used efficiently before the process is up and running. With predetermined standard times, PMTS can objectively and accurately determine time consumption for activities in work cycles, in the planning phase of a project for work design. Ferreira (2015) argue that MTM-based methods can be used anywhere where the objective is to plan and find the effective execution of a human task. The MTM-SAM analysis helped to design the picking procedure in an effective way for the Pick-by-beamer system. The results from the preliminary MTM-SAM analysis enabled assessment of the efficiency of the Pick-by-beamer system before the experiment.

3.3 Experiment

To obtain error probabilities and to verify the feasibility of using a Pick-by-beamer system for kit preparation, an experiment was conducted. Further, the experiment provided video recordings of Pick-by-beamer and could thereby improve the MTM-SAM analysis. Lastly, it gave an additional data-set on the efficiency of Pick-by-beamer and Pick-by-paper which strengthened the validity of the MTM-SAM analysis.

The methodology for the experiment is presented in a chronological order according to the seven-step approach described in the paper by Montgomery (1991). The first three steps of the seven step approach treats the pre-design planning of an experiment. First, (i) the recognition and statement of the problem, then (ii) choice of factors and levels and third (iii) selection of response variables. For this pre-design planning phase, a systematic framework for the planning of an industrial experiment presented in an article by Coleman and Montgomery (1993) was used. The proposed framework by Coleman and Montgomery (1993) departed from the first three steps of the seven step approach by Montgomery (1991). A systematic planning approach increases the likelihood of an experiment being successful. Following the proposed methodology is especially appropriate for experiments with high complexity and with less experienced people conducting and designing the experiment. Between the third and fourth step of the seven step approach, a section describing the experiment setup is presented. The fourth step of the seven step approach of planning is (IV) the choice of experimental design, while the fifth and sixth step is about the (V) conduction of the experiment and subsequent (VI) data analysis. The seventh and last step, (VII) conclusions and recommendations, are presented in the results chapter.

3.3.1 Recognition and statement of the problem to be investigated

As no previous studies had been carried out investigating the performance of a picking information system using the same technology as Pick-by-beamer, the experiment intended should determine the feasibility and relative performance of the Pick-by-beamer system against Pick-by-paper for two different batching policies, single-kit preparation and batch preparation. The objective of the experiment was to separately measure the time consumption for Pick-by-beamer and Pick-by-paper to complete a picking tour when used for kit preparation.

3.3.2 Choice of factors and levels

The explanatory variable selected for the experiment was picking information system in a certain batching policy. This explanatory variable is called “configuration” and has four levels, (1) Pick-by-beamer in single-kit preparation, (2) Pick-by-paper in single-kit preparation, (3) Pick-by-beamer in batch preparation and (4) Pick-by-paper in batch preparation.

In terms of controllable factors, after each picking round, components in the bins were returned and corrected to resemble a typical placement in the bin. Each picking sequence also had a higher frequency of pick locations located at the middle shelf compared to the top and bottom shelf. This is a common positioning of components that are frequently picked in kit preparation.

3.3.3 Selection of the response variable

The response variables for the experiment were time consumption for a whole picking sequence and the total number of picking errors during a picking sequence. The reason for choosing time consumption as a response variable was because it supports the objective of measuring the difference in picking efficiency between Pick-by-beamer and Pick-by-paper. The number of picking errors made was selected as an additional response variable to monitor the correlation between time consumption and picking errors. It was important to conclude that a lower time consumption did not result in an increase in picking errors. The response variables were also in line with response variables selected in previous experiments by Fager et al. (2019) which is important for future comparison of results.

Picking errors where divided into three categories, e_1, e_2 and e_3 and are based on findings in previous research on kit preparation (Fager et al., 2014). Common to all the three error categories is that they are discovered after the picking tour is completed. A definition of the three picking errors and the required action to correct them are presented in table 3.3 below. The errors are assumed to be corrected by a water spider that is present at the assembly line. A water spider is an experienced operator stationed at the assembly line, supporting the operators working at the different assembly stations (Baudin, 2002). The water spider performs routine work related to picking and unpacking of components at the assembly line, enabling operators at the assembly stations to focus on the assembly task.

Table 3.3: Studied picking errors e_1, e_2 and e_3, their definition and what actions are required to correct them.

Error	Definition	Required action to correct error
e_1	Kit contains one too many components	1. Take component from kit 2. Walk to storage location 3. Place component in bin at storage location 4. Walk back to assembly station
e_2	Kit contains one too few components	1. Walk to storage location 2. Pick component from bin at storage location 3. Walk back to kit 4. Place component in kit
e_3	Kit contains wrong component	1. Take component from kit 2. Walk to storage location 3. Place component in bin at storage location 4. Walk to new storage location 5. Pick component from bin at storage location 6. Walk back to kit 7. Place component in kit

3.3.4 Experiment environment setup

The experimental setup was designed to resemble a typical kit preparation workspace for mixed-model assembly. The experiment environment was constructed to resemble a setup that had been used in previous studies (Fager, 2019; Fager et al., 2019; Hanson et al., 2017) to test the performance of different picking information systems. The details of the experiment setup are outlined in the sections below.

3.3.4.1 Kit preparation area

The experiment was carried out at a temporally built test environment at Virtual Manufacturing's main office in Gothenburg. It was built to resemble the kit preparation work space in previous studies (Fager, 2019; Fager et al., 2019; Hanson et al., 2017). For those studies, logistics engineers from the automotive industry had been consulted to achieve realistic conditions common to a kit preparation workspace. The engineers gave input on the work space layout, storage racks (height, tilt of bins, etc.), picking trolley and components which motivated the use of the same setup for this study. The components that were included in the experiment were selected based on size, shape and weight to match the characteristics of components common in the automotive industry.

The kit preparation area consisted of a straight picking aisle with **storage section** on the right side. Two types of storage sections were built to resemble two different storing densities, one section with high storing density (Figure 3.3) and one with low **storing density** (Figure 3.4). Storing density refers to the number of storage locations per meter. Different storing densities were used to simulate different types of kit preparation environments.

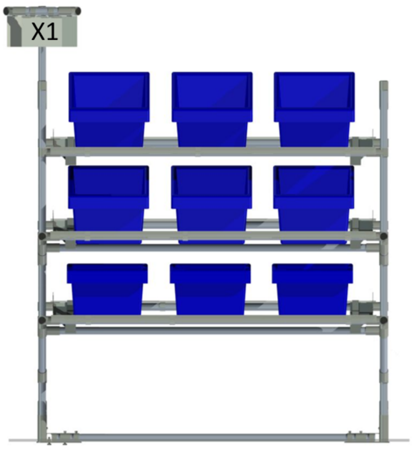


Figure 3.3: A storage section with high storing density.

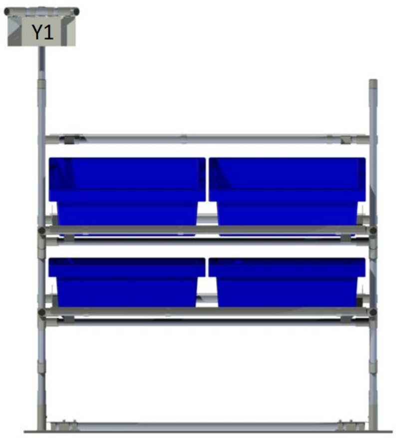


Figure 3.4: A storage section with low storing density.

The storage section with the higher storing density was 1150 mm wide and had three shelf levels with heights 550 mm, 930 mm and 1310 mm above floor level. Each shelf contained three storage locations with a unique location identity number. Each storage location was made up of a bin measuring 200 mm (width) × 300 mm (depth) × 200 mm (height), containing small components. Five storage sections of this type comprised the total high storage density side with a total width of 6.06 meters and 45 unique storage locations.

The storage section with the lower storing density was 1680 mm wide and had two shelf levels with heights 725 mm, 1105 mm above floor level. Each shelf contained two storage locations with a unique location identity number. Each storage location was made up of a bin measuring 800 mm × 600 mm x 200 mm, containing large components. Four storage sections of this type comprised the total low storage density side with a total length of 6.83 meters and 16 unique storage locations.

3.3.4.2 Picking trolley

A picking trolley was used for the kit preparation. The picking trolley had two shelf levels with each shelf having a capacity of two bins. Each bin measured 400 mm × 600 mm × 200 mm, representing one kit. For the Pick-by-beamer system to be installed on the picking trolley, an additional construction of pipe racking system components was built on top of the picking trolley. The Pick-by-beamer system was mounted on the construction on top of the picking trolley (figure 3.5).

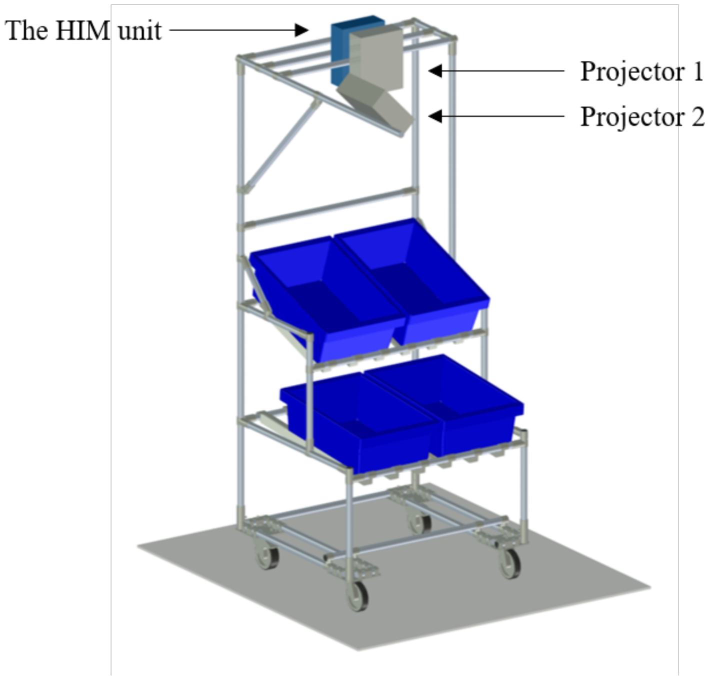


Figure 3.5: Pick-by-beamer system mounted on the picking trolley.

With the picking trolley standing in the picking aisle, the HIM unit and first projector (Projector 1) faced the four bins on the picking trolley while the second projector (Projector 2) faced the storage section. Projector 2 was mounted on a horizontal steel pipe extending in the reverse direction from the center of the picking trolley. The projection of Projector 2 covered one storage section (Figure 3.7).

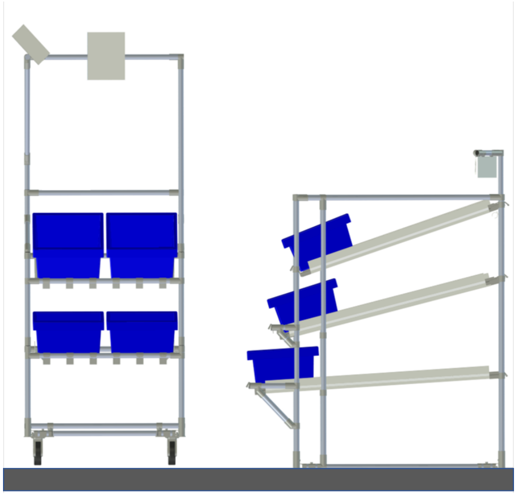


Figure 3.6: Pick-by-beamer mounted on picking trolley viewed from behind (left) and a storage section with high storing density (right).

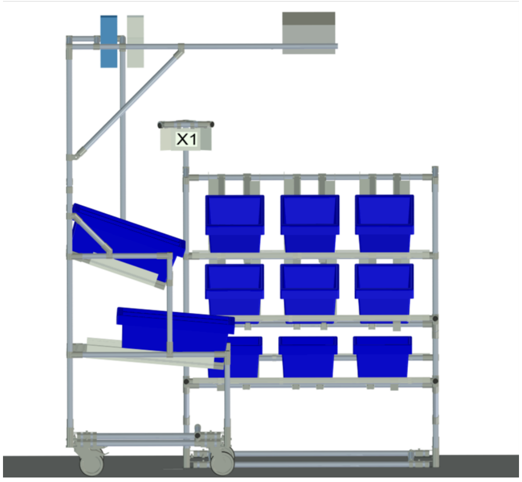


Figure 3.7: Pick-by-beamer mounted on picking trolley viewed from the side and a storage section with high storing density in the background.

Since Projector 2's projection had a limited reach, the perpendicular distance between the Projector 2 and the storage section needed to be long enough to get sufficient coverage of all the storage locations present at one storage section. Since the Pick-by-beamer system required access to a 230V power supply, the power cable was guided along the rail in the floor.

A black plastic board was mounted on the second shelf at the center of the picking trolley. The black plastic board enabled picking and placing instruction to be projected by Projector 1 onto it to provide the picker with additional support at a convenient location.

3.3.4.3 Storage section identification

Being mounted on the picking trolley, the HIM-unit needs a way to identify its position in order to know when and what to project on the storage section. Therefore, a unique reflective tape was attached to the floor at each storage section as an identification object. The HIM-unit was coded to interpret each unique reflective tape, with the IR-sensor, as a specific position and, thereby, know what to project on the storage section. The HIM-unit projects a green beam visualized in figure 3.8 to guide the operator to where the Pick-by-beamer needs to be positioned. Once the green beam is above the reflective tape, the next instructions will proceed.

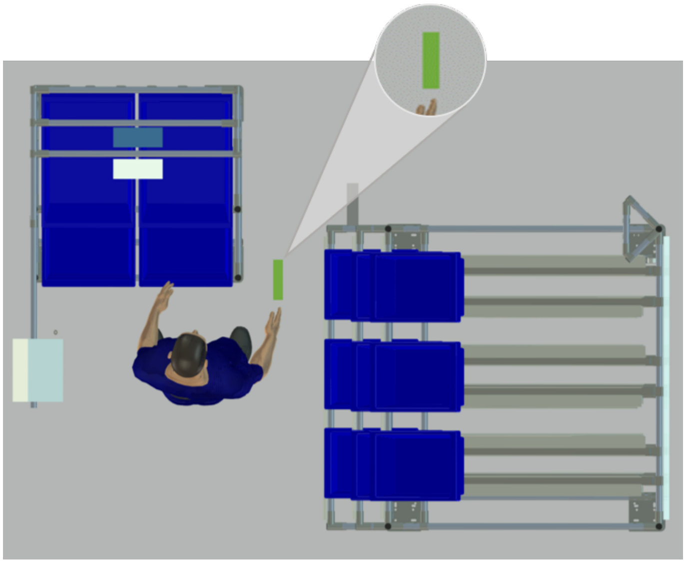


Figure 3.8: The Pick-by-beamer system and the green positioning beam seen from above. The trolley is positioned so the beam covers the reflective tape.

3.3.4.4 Documentation

The experiment was recorded through two video cameras: camera 1 and camera 2. Camera 1 was installed at the corner of the kit preparation area on a tripod two and a half meters above floor level to cover the whole kit preparation workspace. Camera 2 was mounted on the picking trolley, specifically set up to get a detailed view of the placement actions at the picking trolley. After the completion of each picking sequence, written documentation was filled in on the outcome of the response variables time consumption and picking errors. Any uncertainties were marked and checked on the recordings later.

3.3.4.5 Picking assignments

A picking assignment is defined as a task that requires the picker to read picking information, pick one or multiple components from one storage location with subsequent placement in one or multiple kits (one component per kit). A picking sequence consist of multiple picking assignments where one picking assignment corresponds to one line on the picking sequence. A line contains information on which storage location type to pick from, how many components to pick, a brief description of component and which kit(s) the component(s) should be placed in. Figure 3.9, illustrates the design of a typical line on a picking sequence.

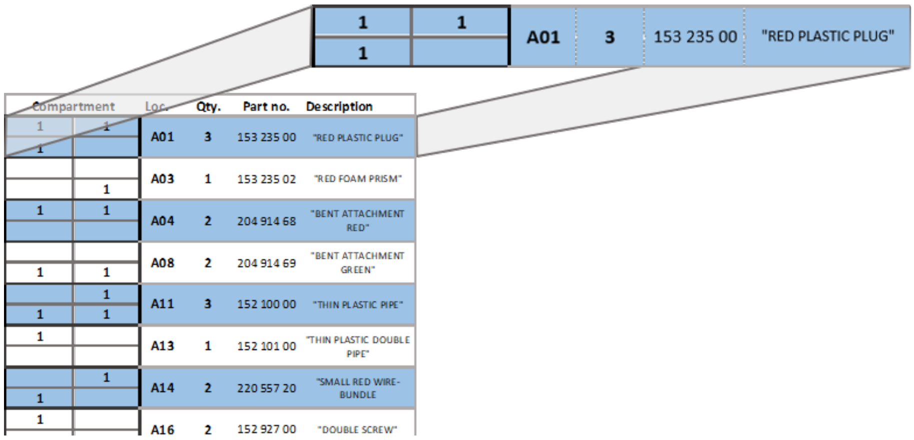


Figure 3.9: An example of a picking assignment, highlighted as a line on a picking list. The picking list contains several picking assignments where the total is equivalent to a picking sequence.

A picking sequence contains all the picking assignments that are required to be done for all kits to be considered completed after a picking tour. The picking assignments used in this study were originally developed by Fager (2019) (article published a few years after study was conducted) and have been used in several studies since (Fager, 2019; Fager et al., 2019; Hanson et al., 2017). The picking sequences are different depending on batching policies, i.e., the number of kits to be prepared. Either one (single-kit preparation) or four (batch preparation) kits were prepared during a picking tour. A batching policy of four kits was chosen to achieve the benefits of batch preparation regarding man-hour efficiency (Hanson, Medbo, and Johansson, 2015). batch preparation could however increase the risk of more picking errors being made. The preparation of multiple kits could increase the complexity of conveying information by the picking information system (Brynzér and Johansson, 1995). A total of twenty unique picking sequences were used in the experiment with ten for single-kit preparation and ten for batch preparation.

The number of picking assignments in a picking sequence differed between the single-kit preparation and batch preparation. For single kit preparation, a picking sequence consisted of 15 different picking assignments, ten for the high storing density side and five for the low storing density side. For each picking sequence in single-kit preparation, a total of ten components were picked from the high storing density side and a total of five components from the low storing density side. For the batch preparation, a picking sequence consisted of 27 different picking assignments, 18 for the high storing density side and nine for the low storing density side. For each picking sequence in batch preparation, a total of 40 components were picked from the high storing density side and a total of 20 components from the low storing density side. The kit size was 15 components per kit in both single-kit and batch preparation which is a reasonable size according to the literature (Fager et al., 2014; Hanson and Medbo, 2011).

In single-kit preparation, the **picking density** is 1.65 picks/meter for high storing density, and 0.73 picks/meter for low storing density. For batch preparation, the picking density is 6.67 picks/meter for high storing density and 2.92 picks/meter for low storing density.

3.3.5 Experimental design

The participants in the experiment were assigned a session where they conducted the preliminary training and later the experiment. A session was approximately six hours in length with time allocated for both training and the experiment. Only one session was scheduled each weekday to have the experiment scheduled roughly the same time of the day for each participant to avoid carry-over effects (Bramwell, Bittner, and Morrissey, 1992). Before the first session was scheduled, the experiment setup and procedure were tested. The reason for testing the experiment setup was to identify issues and make adjustments that would be difficult to foresee in the planning of the experimental design. The design of the experiment follows a counterbalanced repeated measures design where participants are randomly assigned a picking information system and batching policy to perform kit preparation. The participant then switches to the next picking information system and batching policy. The experimental design is presented in Figure 3.10 below.

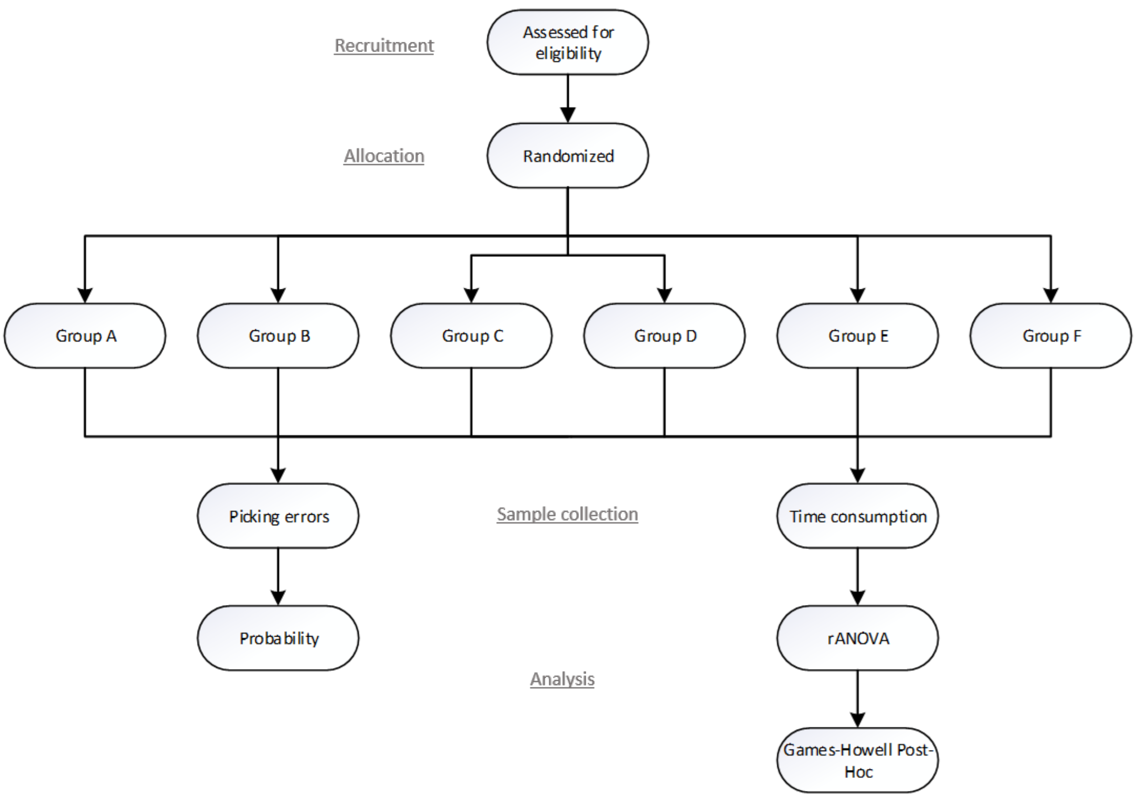


Figure 3.10: Overview of the experimental design

A counterbalanced repeated measures design is a within-subjects experimental design. Looking at Figure 3.10, the groups with the different letters from A to F corresponds to the treatment groups. One treatment group corresponds to a predetermined order in which the subject it exposed to the different treatments, in this study picking information system and batching policy. The order of treatments that each treatment group represent is presented in Appendix E A within-subjects design was selected as that kind of experimental design is an effective method to compare the impact of different interventions, in this case, two picking information systems and two batching policies. A within-subjects design is effective as it requires a smaller sample size to attain the same statistical power as a between-subjects design where one participant only tests one picking information system and batching policy Keren and Lewis, 2014. As the statistical analysis of a within-subjects design is only done within subjects and not between, the design is associated with a high statistical power (Keren and Lewis, 2014). According to the same authors, an advantage of the within-subjects experimental design is that the treatment effect is not confounded with individual differences, increasing the sensitivity to effects of a treatment.

3.3.5.1 Recruitment of participants

People recruited to participate in the experiment had to have no previous experience of kit preparation. Three males and three females of ages between 23-27 years old were recruited. The reason for recruiting pickers with no previous experience was to avoid introducing bias in the study from past experiences of kit preparation. It was also stated in the study by Fager (2019) to be common that new employees have no previous experience of kit preparation and picking information systems.

3.3.5.2 Preliminary training in kit preparation

The time for preliminary training was dedicated to learning the functions of the Pick-by-beamer system and allowed the participant to get familiar with kit preparation in general. The training was done prior to the experiment to reduce the learning-curve effects from the inexperienced pickers. The preliminary training also allowed participants to ask questions about the picking information systems and experiment in general. The training was finished when the time consumption had converged, indicating that the participant had learned the system. According to Coleman and Montgomery (1993), the length of the training should only constitute a smaller portion of the total experiment.

A nuisance factor is the variation in the learning curve that could exist between participants in the experiment. Another is at what time of the day the experiment is carried out which might affect the participant's performance. Nuisance factors cannot be eliminated but only mitigated. The variation in the learning curve between participants was mitigated by having the participants taking part in trial sessions where they tested Pick-by-beamer and Pick-by-paper for both batching policies. Variation in the participant's performance as a cause of the time of the day was mitigated by having the participants carrying out the experiment at the same hours during the day.

3.3.5.3 Experiment session

After the preliminary training was finished, the experiment was started. The participant was randomly assigned into one group that determined which of the four configuration levels that the participant started with. Randomization was done to more confidently conclude a causal relationship between the configuration (explanatory variable), and time consumption (response variables). The groups present in this study are presented in Figure E.1 in Appendix E. After being randomly assigned a group, the experiment started with the participant pushing the picking trolley forward in the picking aisle to the closest storage location on the high storing density side. The experiment always started on the high storing density side located on the right side of the picking aisle. When the participant was at the storage location, components were picked from the storage location and placed in the kit on the picking trolley according to the specific picking assignment. For the single-kit preparation, only one kit was present on the picking trolley in the top right corner. For batch preparation, four bins were placed on the picking trolley.

When the picking assignment was completed, the participant pushed the picking trolley once again to the next storage location to carry out the next picking assignment. When all picking assignments were completed and the participant had reached the end of the picking aisle on the high storing density side, timekeeping was stopped. The picking trolley was reversed to the start of the picking aisle and the participant continued the picking sequence with the remaining picking assignments on the low storing density side. A total of ten picking sequences according to this route was done for each picking information system and batching policy. Commonly, the picking routes follow the same pattern in small kit preparation areas (Hanson et al., 2015), having only one picker performing the kit preparation (Hanson et al., 2017). A detailed explanation of the experiment procedure specifically for Pick-by-beamer and Pick-by-paper follows below.

For Pick-by-beamer, the participants confirmed the start of the picking sequence by hovering over a virtual button projected on the black plastic board on the picking trolley. Once the virtual button had been triggered, the timekeeping started. The participants received information on which storage section to go to through a pre-recorded voice that was played up by the Pick-by-beamer system. The voice provided the participants with instructions on which storage section to go to, e.g. "Go to section, X1". Supplementary information about which storage section to go to was also projected on the black plastic board on the picking trolley. The pickers pushed the picking trolley to the communicated storage section and parked it at a marked location right at the end of the section. Upon parking at the specified location, the reflective tape on the floor was recognized by the Pick-by-beamer system through its infra red-sensor. When the unique reflective tape pattern of the storage section was recognized and confirmed, Projector 2 facing the specific section projected light onto the storage location to pick from. The number of components to be picked from the storage location was also projected onto the storage location. At the picking trolley, Projector 1 facing the kits projected a constant green light on the kit where the components should be placed. As components are placed in the kit, the depth sensor identified the hand movement at the kit and the projector shuts down the light. The placement of the component was not required to follow a specific orientation. When the detection unit of the Pick-by-beamer system had recognized and confirmed the correct placement, the next picking assignment was initiated through corresponding projections. When all picking assignments had been completed at the storage section, the participant was told by the system's pre-recorded voice to go to the next section and the kit preparation process continued. Supplementary instructions on information on the specific picking assignment was projected on the black plastic board to provide additional support to the participant if needed.

For Pick-by-paper, the participant was provided with an A4-sized paper list containing all different picking assignments involved in the picking sequence as separate lines on the paper list. The timekeeping started when the participant started reading at the top line of the paper list containing the first picking assignment. The participant then pushed the picking trolley to the storage location of the picking assignment and picked the requested components. The requested components were then placed in the kits according to the picking assignment and a check mark was placed at the specific line on the paper list to confirm the completion of the picking assignment. The participant then read on the next line of the paper list and the kit preparation process continued.

3.3.6 Data analysis

After the completion of the experiment sessions, a statistical analysis was carried out on the data obtained from the experiments. The data was structured into four different levels, (i) Pick-by-beamer in single-kit preparation, (ii) Pick-by-paper in single-kit preparation, (iii) Pick-by-beamer in batch preparation and (iiii) Pick-by-paper in batch preparation. As six participants took part of the study and carried out ten picking sequences for each of the four groups, the sample size for each level was 60. In the first step of the univariate statistical analysis, a Repeated measures one-way ANOVA (rANOVA) was done. A rANOVA is a method for statistical analysis where the mean value of the selected response variable is investigated for different levels. The purpose of the rANOVA was to determine if there was a statistically significant difference in mean time consumption between the levels. After the rANOVA, a Games-Howell post hoc test was done on the rANOVA result to further analyze the between-groups difference in time-consumption. The rANOVA and Games-Howell post hoc test were repeated for high picking density and low picking density separately for all the groups. A detailed description of the two analysis methods is found in the subsequent sections below.

3.3.6.1 Repeated measures one-way ANOVA

A rANOVA was carried out to determine if the difference in mean time consumption for each picking information system was statistically significant. rANOVA was chosen because it enables a comparison of the means of the response variable for one explanatory variable with three or more levels. The rANOVA is used for analyzing data where the same subjects, i.e., participants in the experiment, are measured on the same response variable under different conditions. As this study follows a counterbalanced repeated measures experimental design where participants were measured on separate occasions for different configuration levels, the samples cannot be assumed to be independent. The repeated measures were done to analyze the impact of different combinations of picking information system and batching policies on time consumption.

As rANOVA is a parametric statistical test, meaning that certain assumptions are made about the population distribution, these assumptions needed to be validated before doing the analysis. The measured data from the experiment needed to meet the five assumptions of rANOVA. The numbered list below contains the five different assumptions of rANOVA (Bramwell et al., 1992) followed by short comments on the ability of the experiment data to meet the assumptions. Assumptions one and two are related to the methodology of the experiment while the other three are related to the distribution of experiment data. A crossed box as a sub-bullet means that the assumption has been met while an empty box means that the assumption could not be met.

1. The response variable should be measured on a continuous interval

    ☒ Time consumption measured in seconds

2. Explanatory variable has more than two related categorical levels

    ☒ Four levels of the explanatory variables are used in the experiment. The four levels are (i) Pick-by-beamer in single-kit preparation, (ii) Pick-by-paper in single-kit preparation, (iii) Pick-by-beamer in batch preparation and (iiii) Pick-by-paper in batch preparation. Groups are related as data for each participant is present at each level.

3. No significant outliers in response variable data

    ☒ A boxplot was generated for the data where no significant outliers were detected.

4. Distribution of time consumption data for each level should be approximately normally distributed (rANOVA is quite robust to violations of this assumption).

    ☒ According to **Central Limit Theorem**, the distribution of a random sample can be considered to follow a normal distribution if the size of the sample is greater than 30. Each level consist of 60 data points which are well above 30.

5. Assumption of sphericity: The variance of the difference in time consumption between the levels must be equal.

    ☐ The assumption of sphericity was evaluated using Mauchly's test. The test came out significant to a $\alpha = 0.05$ significance level, meaning that the assumption of sphericity was violated. It is relatively common that the assumption of sphericity is violated as data rarely follows strict sphericity when more than two levels of the explanatory variable exist (Bramwell et al., 1992; O'Brien and Kaiser, 1985). Below follows the procedure for managing a violation of the sphericity assumption.

A rANOVA is sensitive to violation of the assumption of sphericity, requiring corrective action to be taken (Morrissey, Bittner, and Ghahramani, 1990). Violating the assumption of sphericity could result in a too liberal rANOVA, changing the actual level of significance of the F-statistic, the test statistic of the rANOVA, and increasing the likelihood of a false positive, or type I error, i.e., the analysis provides a statistically significant result rejecting the null hypothesis when the result is non-significant and alternative hypothesis should be rejected. To reduce the likelihood of having the test becoming too liberal due to the violated assumption, a sphericity correction method should be applied to the analysis. Which method is chosen depends on how much the data deviates from the sphericity assumption. The deviation from sphericity ϵ is measured on a scale from 0 to 1 where 1 is perfect sphericity. Mauchly's test gave $\epsilon = 0.6$, indicating that the Greenhouse-Geisser correction to be used ($\epsilon < 0.75$) (Girden, 1992). The Greenhouse-Geisser correction method is a conservative correction method that adjusts the degrees of freedom to the maximum amount which in turn yields a high p-value of the rANOVA (Bramwell et al., 1992). In general, conservative statistical procedures tend to be more desirable than liberal ones (Quintana and Maxwell, 1994).

3.3.6.2 Games-Howell post hoc test

After the repeated measures one-way ANOVA was done, a Games-Howell post hoc test was done to further analyze the statistically significant result from the ANOVA. The post hoc test was carried out to explore differences between multiple groups means, in comparison to the repeated measures one-way ANOVA which only tested if there was an overall difference between the levels. The Games-Howell is a pairwise comparison test and was chosen as a post hoc test since it is appropriate to use for sample sizes larger than 50 and since it can be used when the assumption of sphericity is violated.

3.3.7 Expanding results to previous studies

Since the experiment carried out in this study was limited to comparing the performance of Pick-by-beamer and Pick-by-paper in single-kit preparation and batch preparation, it was of interest to expand the results to include other picking information systems. Prior to this study, it was known that Fager et al. (2019) had carried an experiment testing the performance of three conventional picking information systems; Pick-by-paper, Pick-by-light and Pick-by-voice in kit preparation. With video-recordings available from that experiment together with discussions with the experiment owners, a similar experiment setup was recreated for this study. However, despite sharing the same methodological approach for the experiment with the aim of achieving a high degree of similarity in experiment setup, combining the data across the two studies would not be possible. The rANOVA statistical analysis of a within-subjects experimental design, which the experiment in Fager et al. (2019) and this study followed, had an assumption that each subject needs to be present for all different levels or treatments, i.e., picking information systems. Since the subjects differ between the studies, this assumption could not be met and a statistical analysis of the combined data could not be made. Therefore it was not not possible to combine the experiment data and conduct a merged statistical analysis.

To overcome the methodological limitations and conduct a comparison of productivity between not only Pick-by-beamer against Pick-by-paper but also and Pick-by-light and Pick-by-voice, a MTM-SAM analysis was carried out. However, for the MTM-SAM analysis to achieve a high degree of accuracy, the video-recordings from the different studies still needed to be used to support the analysis. Since video-recordings from two different studies needed to be used, it was imperative to verify the consistency between the video-recordings to avoid introducing bias into the MTM-SAM analysis. The consistency of the video recordings were verified by comparing the average time consumption for Pick-by-paper in single-kit preparation and batch preparation between this study and the study by Fager et al. (2019). With a high degree of consistency in average time consumption between the studies, it was possible to more confidently conclude that the experiment setup between the studies was close to identical. A similar experiment setup motivated using video-recordings from both studies to create a conclusive MTM-SAM analysis of the four picking information systems which data could be used for the economic evaluation in the next section below. The MTM-SAM analysis would then accomplish expanding the comparison of Pick-by-beamer beyond Pick-by-paper.

3.4 Economic evaluation

The economic evaluation is divided into three parts, first, an analysis with the aim of finding an hourly cost depending on demand for the different systems if one were to open a new factory. Second, an analysis finding the payback period depending on demand if a factory is using Pick-by-paper today and invests in a Pick-by-beamer system. Third, an analysis including the time value of money finding the key figures, **Net Present Value (NPV)** and **Return On Investment (ROI)** depending on demand. The studied picking demand range will be limited to between 500 and 10 000 picked components per hour. This has been confirmed by industry experts as a range that encompasses the most common settings used in the mixed-model assembly. For example, the picking demand in the automotive industry could be roughly 5 000 components per hour. This number was derived based on an example from the automotive industry. The example included the assumption of having five out of 100 assembly stations supplied through kitting and a takt time of one minute. This sets the demand for each station to be 60 kits per hour which for five stations equals 300 kits. Having a kit size of 15 components sets the total picking demand for all five stations to 4 500 components per hour.

The comparisons are based on four main types of data; first, both fixed investment costs and investment costs depending on demand obtained from various industry actors and academic sources; second, efficiency measured in theoretical time to pick one component depending on picking density and batching policy based on the MTM-SAM analysis; third, error probabilities obtained from the experiments in this study and from earlier experiments done by Fager et al. (2019); fourth, the cost of a picker set at EUR 1 992 per month adjusted for payroll taxes and overhead costs accumulating to 50% of the salary. The cost of a pickier can vary depending on the company and the country, in this study, the cost is based on a low wage factory worker in Sweden.

3.4.1 Hourly cost of a picking information system

In the paper by Brynzér and Johansson (1995) it was explained that historically, the focus of picking information system studies have been related to the efficiency of the system rather than the picking accuracy. However, the same authors stated the picking accuracy to be of highest importance to minimize the likelihood of causing issues both internally for the production and externally for unsatisfied customers. In the paper, picking accuracy was argued to be highly influenced by the picking system used in the kit preparation process. This perspective was supported by Grosse, Glock, Jaber, and Neumann (2015) who in one of their propositions stressed the importance of adding more objectives when analyzing the performance of picking processes. The authors argued that travel time minimization is a too narrow objective and that the impact of picking error reduction needs to be researched further and taken into consideration when designing an order picking process. Therefore, it became vital to take picking accuracy into account when conducting an economic evaluation of a picking information system. Grosse et al. (2015) argued for further studies on a trade-of, in particular, if the cost of investment in a picking information system, e.g. Pick-by-beamer, can be paid off not by the increased efficiency but by the reduced costs as a result of lowered picking errors.

With the aim of including additional factors in the analysis as requested by academia, this study incorporated the hourly cost of a picking information system when used in kit preparation. The hourly cost of a picking information system in this paper was to a great extent based on the hourly cost function for paperless picking technologies in order picking presented by Battini et al. (2015). The difference between the hourly cost function in Battini et al. (2015) and the one presented below is related to the cost of demand and the cost of picking errors. In the cost of demand, a term for the cost of consumables related to the use of a specific picking information system is added. In kit preparation, the picking error is often discovered at the assembly station that ordered the kit which changes the picking error formula significantly.

The time horizon used to calculate the hourly cost of the different investments included in the formula is set to five years with the picker working 1 760 hours per year, equivalent to eight hours a day, 220 days a year (resulting in 32 days vacation excluding public holidays in Sweden). The salvage value after the five years is assumed to be EUR 0. The analysis was also tested with a two year horizon, lowering it to two years changed the values in the result slightly but did not affect the main conclusions of the study. It did not have a big impact since the investments portion on the total hourly cost is small even with a two year horizon. As the Pick-by-beamer system is in a conceptual state, no data on the average lifetime of a system in use is available. After a discussion with industry professionals at Virtual Manufacturing, five years was decided to be a fair assumption for all of the systems. two years was reasoned to be too pessimistic and few factories invest in a system intending to only use it for two years. As mentioned in the scope, no service costs are included, such as repairing broken lights using the Pick-by-light system. Below follows a step by step derivation of the cost formula used for the economic evaluation of the picking information systems in kit preparation. After each equation, a definition of involved parameters and corresponding units is presented.

Total cost of a picking information system per hour $C_{h,tot}$

The following formula includes investments and operational costs related to using a picking information system.

$$C_{h,tot} = C_{h,SL} + C_{h,D} + C_{h,E} + C_{h,F} \tag{3.1}$$

where:

$C_{h,SL}$ = Cost (€/hour) depending on number of storage locations
$C_{h,D}$ = Cost (€/hour) depending on demand
$C_{h,E}$ = Cost (€/hour) depending on picking errors made
$C_{h,F}$ = Fixed investment costs (€/hour)

Below follows a derivation of the formulas for the four hourly cost terms that comprises the total hourly cost $C_{h,tot}$ in equation 3.1.

Cost of storage locations per hour $C_{h,SL}$

Includes costs such as, lights, labels, cables, I/O boxes and gateway.

$$C_{h,SL} = \frac{n_{SL} \cdot c_{SL}}{h} \tag{3.2}$$

where:

n_{SL} = Number of storage locations in the kit preparation area
c_{SL} = Cost (€) of one storage location
h = Time horizon in hours for economic evaluation

Cost of demand per hour $C_{h,D}$

Includes investment costs in additional devices needed for systems were each picker needs a personal system, and cost of picker including taxes and overhead costs, and system specific consumable material that depends on picking demand.

$$C_{h,D} = \left(c_{h,P} + \frac{c_I}{h}\right) \cdot \underbrace{\left\lceil \frac{n_D}{\dot{p}} \right\rceil}_{\substack{\text{Number} \\ \text{of pickers}}} + c_c \cdot n_D \tag{3.3}$$

where:

$c_{h,P}$ = Cost (€) of one picker per hour
c_I = Cost (€) of device/equipment for one picker
n_D = Demand of picked components per hour
$\dot{p}$ = Picking rate of one picker (components/hour) depending on system
c_c = Cost of system specific consumable material per picked component

Cost of picking errors made per hour $C_{h,E}$

Includes the time it takes to correct picking errors multiplied with the hourly cost of the employee that corrects the picking errors. This cost, do as seen depend on demand as well, but it is presented in this separate section as it is a complex part which needs to be emphasized. The formula includes the three picking errors types (i=1,2,3), presented as response variables in table 3.3.

$$C_{h,E} = c_E \cdot n_D \tag{3.4}$$

where:

$$c_E = c_{h,P} \cdot \Big(p_{e_1} t_{e_1} + p_{e_2} t_{e_2} + p_{e_3} t_{e_3}\Big) \tag{3.5}$$

where:

$p_{e,i}$ = Probability of picking error type i occurring with $i = 1, 2, 3$
t_{e_i} = Time to correct picking error type i with $i = 1, 2, 3$

The time to correct a picking error t_{e_i} depends on several factors, such as MTM-SAM times and distances. For picking error type one and two, the water spider only searches for a storage location once. Further, it is assumed that the water spider walks on average half the aisle length back and forth resulting in one full aisle. The formula for the time to correct picking error one and two is:

$$t_{e_1} = t_{e_2} = \underbrace{t_{pick} + t_{place} + t_s}_{t_{net}} + \underbrace{t_w \cdot \Big(L_{pa} + 2\bar{D}\Big)}_{t_{trav}} \tag{3.6}$$

For picking error type three, the water spider searches for two storage locations, one to retrieve and one to put back. Further, it is assumed that the water spider walks on average half the aisle length back and forth plus an additional walk to get the new component resulting in one and a half full aisle. The formula for the time to correct picking error three is:

$$t_{e_3} = 2 \cdot (\underbrace{t_{pick} + t_{place} + t_s}_{t_{net}}) + \underbrace{t_w \cdot \Big(1.5 \cdot L_{pa} + 2\bar{D}\Big)}_{t_{trav}} \tag{3.7}$$

where:

t_{pick} = Time to pick one component
t_{place} = Time to place one component
t_s = Time to search for a storage location
t_w = Time to walk one meter
L_{pa} = Length of picking aisle end to end
$\bar{D}$ = Distance between kit preparation area and assembly station where the error is detected

Fixed investment costs per hour $C_{h,F}$

The fixed cost does not depend on the picking demand. It is a cost for software and servers that could be required for the operations of a picking information system. The fixed cost per hour is calculated according to the formula below:

$$C_{h,F} = \frac{c_F}{h} \tag{3.8}$$

where:

c_F = Fixed investment cost for specific system

3.4.2 Payback period T_{pb}

A common way for managers to determine whether to go through with an investment is to evaluate the payback period, a shorter payback period makes the investment more attractive. Therefore, the payback period for different settings depending on the picking demand was calculated. The formula for the payback period when switching from one picking information system (system 1) to another (system 2) is presented in equation 3.9. This study only analyzes the situation where a factory is using Pick-by-paper today and switches to Pick-by-beamer.

Payback period T_{pb} in months:

$$T_{pb} = \frac{C_{inv}}{C_{h,op_1} - C_{h,op_2}} \cdot \underbrace{\frac{1}{\frac{h_{w,year}}{12}}}_{\substack{\text{Conversion} \\ \text{to months}}} \tag{3.9}$$

where:

C_{inv} = Initial investment cost in system 2
$C_{h,op,i}$ = Operational cost per hour for system i with $i = 1, 2$
$h_{w,year}$ = Total working hours over a year

Operational cost per hour for picking information system i is calculated as:

$$C_{h,op,i} = c_{h,P} \cdot \underbrace{\left\lceil \frac{n_D}{\dot{p}} \right\rceil}_{\substack{\text{Number} \\ \text{of pickers}}} + c_c \cdot n_D + C_{h,E,i} \tag{3.10}$$

For Pick-by-paper (system 1), operational cost is equal to:

$$C_{h,op,1} = c_{h,P} \cdot \frac{n_D}{\dot{p}_1} + \underbrace{\frac{n_D}{n_{cp}}}_{\substack{\text{No. of} \\ \text{papers}}} \cdot c_{pl} + C_{h,E,1} \tag{3.11}$$

where:

n_{cp} = Number of components on one picking list (paper)
c_{pl} = Cost (€) of one piece of A4 paper

For Pick-by-beamer (system 2), operational cost is equal to:

$$C_{h,op,2} = c_{h,P} \cdot \frac{n_D}{\dot{p}_2} + C_{h,E,2} \tag{3.12}$$

Last, below follows the equation describing the investment cost of a Pick-by-beamer system:

$$C_{inv,2} = c_{D,2} \cdot \underbrace{\left(\frac{n_D}{\dot{p}_2}\right)}_{\substack{\text{Number} \\ \text{of pickers}}} + C_{h,F,2} \tag{3.13}$$

c_D = Cost of tools and equipment per picker

3.4.3 Net present value and return on investment

Payback period is one common metric used to aid investment decision, however, complementary metrics are essential. Payback period does not include the time value of money nor does it give any number on what the monetary savings become (Kagan, 2020). Therefore, it is complemented with both a graph of NPV and one with ROI. Thus, the time value of money, the monetary savings, and the savings in relation to the investment size are included in the economic evaluation.

The net present value is based on the same operational savings used in the payback analysis, $C_{h,op_1} - C_{h,op_2}$. The savings are calculated yearly and discounted with a discount rate of 10%. It assumes the same time horizon as the hourly cost function, five years, which means that the operational savings are constant each year for five years, then the systems break and have EUR 0 salvage value. The return on investment is calculated using the net present values in relation to the investment for the specific demand.

3.5 Limitations

There are some limitations to the method which should be considered when interpreting the results. These limitations are:

- The MTM-SAM analysis works great for body movements, however, in some cases, it is limited in its ability to include cognitive parts. For example, the time it takes to interpret different forms of visual information instructions. This is an important part of the comparison between the systems as each of the systems have different ways of conveying information. Failing to accurately include those differences may affect the results on the efficiency of the systems.

- The times to corrects the different errors used when calculating the cost of an error have a cycle that is too short to obtain a precision within ±5% of the theoretically exact norm time with 95% confidence when using a MTM-SAM analysis. The error correction times may, therefore, have a slightly worse precision. However, they were analyzed using the same methodology as the rest of the MTM-SAM analysis which resulted in credible results of the picking times for each system.

- The experiment setup for the experiment of Pick-by-beamer is done to resemble the conditions of earlier experiments (Fager, 2019; Fager et al., 2019; Hanson et al., 2017) carried out with other picking information systems. However, some parameters e.g. having the same participants are hard to recreate which affects the ability to fairly compare the results from the experiments. In the end, this has no major impact as the MTM-SAM times were used for the further analysis and the experiments were partly supportive in terms of providing video recordings for the MTM-SAM analysis.

- In the experiments in this study and in the previous study by Fager et al. (2019), more than one component from the same storage location is never placed in the same kit. Allowing for several components to be placed in the same kit could change the results of the studies. For some systems, it would change the way a component would have to be confirmed. For Pick-by-beamer, to reduce the effect on the error probabilities when two identical components are placed in the same kit, a clear visualization of the number two can be beamed directly on the kit. If further quality assurance is needed, two separate placements are a solution. The Pick-by-beamer would then only confirm if the hand or object has been detected in the kit twice with a set delay in between. This would assure the quality but reduce the efficiency.

4 Results

The result chapter is presented in the same logical order that was presented in the method chapter. First, the result of the MTM-SAM analysis for Pick-by-paper, Pick-by-light and Pick-by-voice is presented. Then, the insights from the MTM-SAM combined with literature related to the design of the Pick-by-beamer system is explained.

The second part of the result chapter presents the time consumption and the number of picking errors for Pick-by-beamer and Pick-by-paper that were measured in the experiment. The time consumption for Pick-by-paper is then compared to the time consumption measured in the study by Fager et al. (2019) to verify consistency in the experimental design. Then, a statistical pairwise comparison of time consumption between Pick-by-beamer and Pick-by-paper across batching policies is presented. Lastly, picking error occurrences and probabilities are presented.

The third part of the result section presents the final MTM-SAM analysis of the Pick-by-beamer system after adjusting it with support from the video-recordings obtained from the experiment.

The fourth part of the result section presents the complete result and comparison of the picking efficiency from the MTM-SAM for each of the systems. This is the picking efficiency times with the highest comparability and the once used in the subsequent economic evaluation.

In the fifth section, the economical evaluation of Pick-by-beamer, Pick-by-paper, Pick-by-light and Pick-by-voice are presented in three parts. First, the hourly cost that each picking information system carries. Second, the payback period when switching from Pick-by-paper to Pick-by-beamer. Third, a visualization of the additional metrics, net present value and return on investment.

4.1 MTM-SAM analysis of Pick-by-paper, Pick-by-light and Pick-by-voice

The result of the MTM-SAM analysis is structured into the five module categories *(1) Search location*, *(2) Pick and Place*, *(3) Confirmation (pick-from/place-to)*, *(5) Push picking trolley*, *(5) Walk one step* presented in Table 3.1. Theoretical percentage for each module category, and an example of time consumption when picking a total of 60 components is illustrated in Figure 4.1, 4.2 and 4.3 for Pick-by-paper, Pick-by-light and Pick-by-voice respectively. As one picking sequence in single-kit preparation only involves picking of 15 components, the time consumption for single-kit preparation is adjusted to 60 components to facilitate comparison between batching policies. The time consumption includes both high and low picking density.

The systems are analyzed independently, however, some conditions that affect the result are general for all the systems. To understand but not repeat those for each section, they are explained below and hold for Pick-by-paper, Pick-by-light and Pick-by-voice.

Search locations: In single-kit preparation, picking 60 components requires searching for a total of 60 storage locations. In batch preparation, multiple components are sometimes picked from the same storage location and therefore the picker only searches for a total of 27 storage locations to pick 60 components.

Walk: The lower picking density present in single-kit preparation requires the picker to walk a longer distance between the picking assignments, making the total time spent on walking longer for single-kit preparation compared to batch preparation. However, the more efficient workflow with fewer interruptions in single-kit preparation allows the picker to take diagonal steps where the supporting step included in the picking movement also makes the picker move forward. This explains why the time spent on walking in single-kit preparation is not four times longer despite the distance walked being four times as long. The diagonal walking is a result of a lower picking density.

Pick and Place: Simultaneous picking and placing (only Pick-by-paper and Pick-by-light) of more than one component in batch preparation reduce the time spent on this activity for batch preparation.

4.1.1 MTM-SAM analysis of Pick-by-paper

Figure 4.1 presents the values of the different module categories for Pick-by-paper. The result for batch preparation is illustrated to the left and the result for single-kit preparation is found to the right.

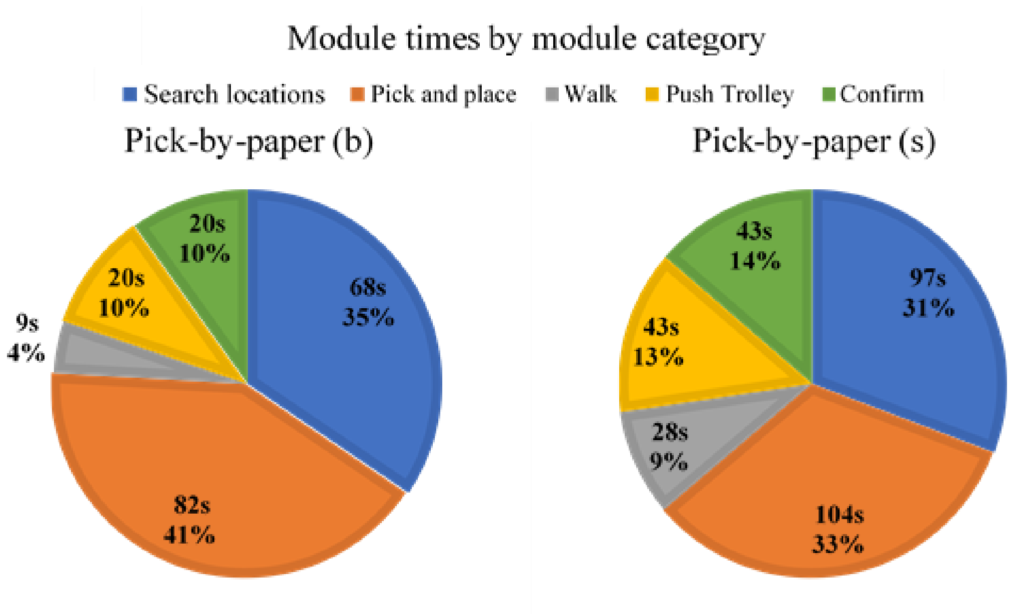


Figure 4.1: Theoretical percentage for each module category for Pick-by-paper, and an example of time consumption when picking a total of 60 components. Left: Batch preparation (b). Right: single-kit preparation (s).

Comments on time consumption for each module category:

Search location: The search location module category involves interpreting how many components to pick from a storage location. More information needs to be processed for the picking assignment in batch preparation compared to single-kit preparation. As only one component is picked from each storage location in single-kit preparation, the picker does not need to read the quantity to be picked on the picking assignment. Further, identifying the correct kit to place components in on the picking trolley is less time-consuming in single kit-preparation. As single-kit preparation involves only one kit to place components in, searching for the correct place location is assumed to not have any time consumption. Despite having less time consumption for each searched location, the additional amount of location searches in single-kit preparation have a greater impact on total time consumption for the module category.

Confirmation (pick-from/place-to): Pick-by-paper does not have a separation between the pick-from and place-to confirmation. The completion of a picking assignment is confirmed with a confirmation mark with a pen on the Pick-by-paper list. Since the confirmation is made after the placement of a component in a kit, the confirmation module category for Pick-by-paper can be seen as a consolidated place-to confirmation. A consolidated place-to confirmation confirm several placements with one action, in the case of Pick-by-paper with a check mark on the Pick-by-paper list. The consolidated place-to confirmation means that fewer check marks are done per picked component in batch preparation, resulting in less time spent on this module category.

Push picking trolley: For both single-kit and batch preparation, the confirmation of a picking assignment is followed by the picker pushing the picking trolley to the next storage location depicted by the next picking assignment. There is one exception when this does not happen and that is when the picker can reach the next storage location without needing to push the trolley. Not needing to push the picking trolley generally occurs one to two times in batch preparation when the next storage location is located on the shelf above or below the previously visited storage location.

4.1.2 MTM-SAM analysis of Pick-by-light

Figure 4.2 presents the values of the different module categories for Pick-by-light. The result for batch preparation is illustrated to the left and the result for single-kit preparation is found to the right.

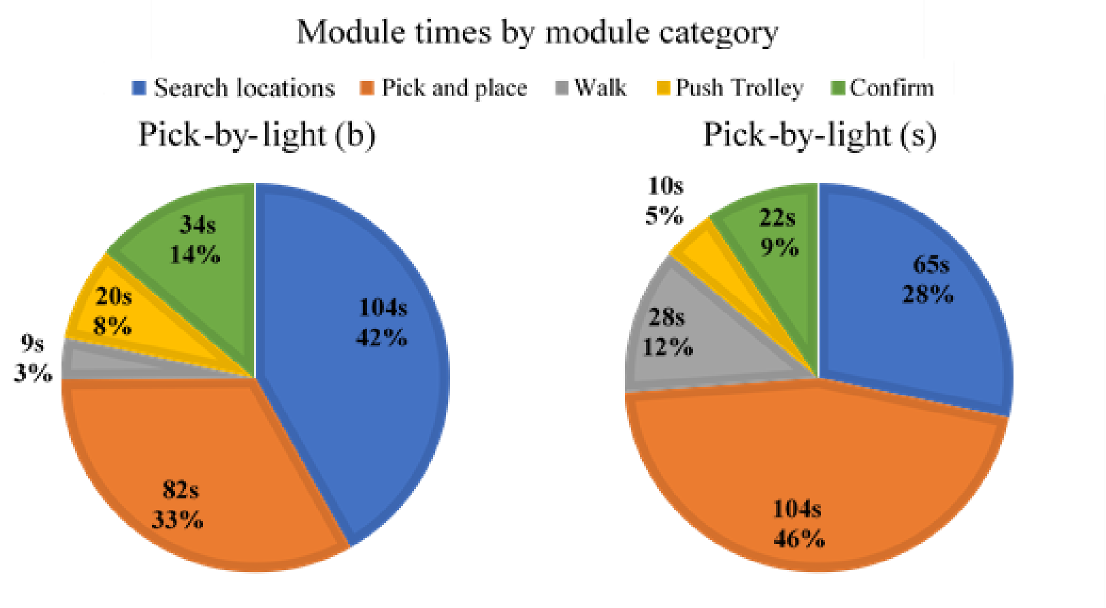


Figure 4.2: Theoretical percentage for each module category for Pick-by-light, and an example of time consumption when picking a total of 60 components. Left: Batch preparation (b). Right: single- kit preparation (s).

Comments on time consumption for each module category:

Search location: For Pick-by-light, search location means identifying a flashing light indicator located above the storage location to pick from. The identification of the light indicator on the storage location has a lower time consumption for single-kit preparation as the picker does not have to search for the location on the picking trolley or identify the amount top pick which for Pick-by-light is very time-consuming activities. As for Pick-by-paper and Pick-by-voice in single-kit preparation, searching for the correct kit to place components does not have any time consumption as only one bin is present with the light indicator removed. Despite more storage locations being identified per picked component for single-kit preparation, the difference in time consumption between the search location modules have a higher impact on total time consumption.

Confirm: The pick-from confirmation is performed for both batching policies with one confirmation per storage location irrespective of the number of picked components. As only one kit is available on the picking trolley to place components in, the place-to confirmation becomes redundant and is not performed. No place-to confirmation reduces time consumption for confirmation, making it lower for single-kit preparation compared to batch preparation.

Push picking trolley: As only one component is picked per picking assignment in single-kit preparation, the picker could keep having one hand on the picking trolley while performing picking, pick-from confirmation and placing with the other hand. With the picker being able to keep one hand on the center of the picking trolley, the need for repetitively performing the module of grabbing and pushing the picking trolley is eliminated. Instead, the picker could continuously push the picking trolley forward while simultaneously performing modules from the other four module categories. The ability to perform two modules simultaneously gives the same MTM-SAM analysis result as if one of the modules was eliminated.

4.1.3 MTM-SAM analysis of Pick-by-voice

Figure 4.3 presents the values of the different module categories for Pick-by-voice. The result for batch preparation is illustrated to the left and the result for single-kit preparation is found to the right.

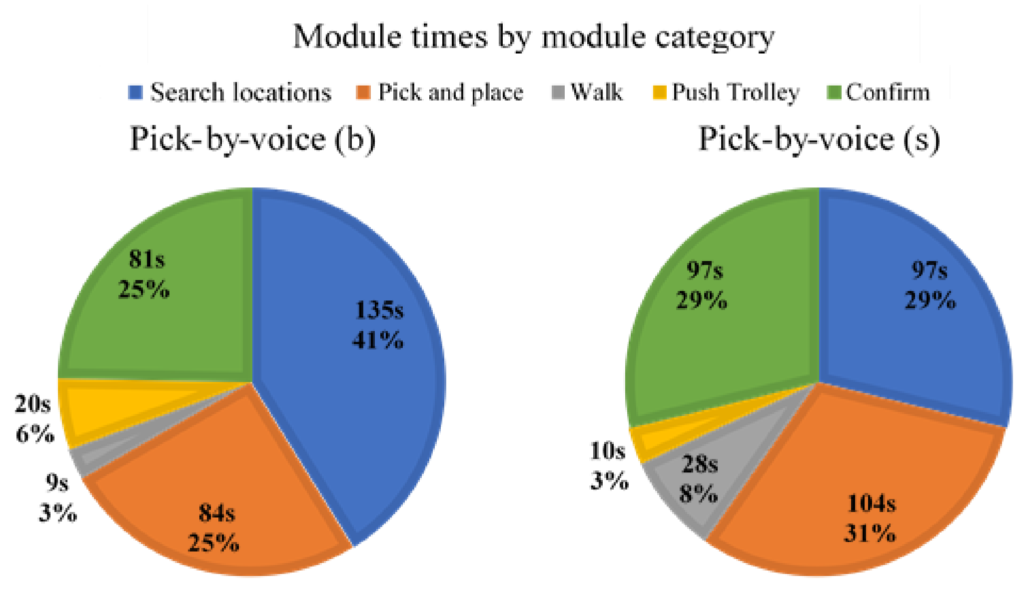


Figure 4.3: Theoretical percentage for each module category for Pick-by-voice, and an example of time consumption when picking a total of 60 components. Left: Batch preparation (b). Right: single- kit preparation (s).

<u>Comments on time consumption for each module category:</u>

Search locations: Searching location with the Pick-by-voice system includes listening to audio information and searching for the storage location and kit location that matches the audio information. The module for searching for a storage location is the same for both batching policies. However, as for Pick-by-paper and Pick-by-voice, searching for a kit location on the picking trolley does not have any time consumption, explaining the higher time consumption for batch preparation. The lower picking density in single-kit preparation is beneficial for the Pick-by-voice system as less time is spent on waiting on the audio information.

Pick and Place: The activity of pick and place is slightly higher for Pick-by-voice in batch preparation. The reason for this is that the picker cannot place components in multiple kits simultaneously. The Pick-by-voice system requires the picker to confirm the placement before information on the next placement is given. As placements need to be done subsequently after each other, the pick and place activity has a higher time consumption than for the other picking information systems. However, the time consumption of picking and place is still slightly lower for batch preparation as multiple components still can be picked simultaneously in batch preparation compared to single-kit preparation.

Confirm: As previously explained for the pick and place module category, the confirmation module needs to be performed by the picker after each placement in a kit irrespective of batching policy. However, as the Pick-by-voice system permits consolidated pick-from confirmation, fewer pick-from confirmations are made for batch preparation (27) compared to single-kit preparation (60).

Push picking trolley: The pattern of how often the picking trolley is pushed is the same for Pick-by-voice as for Pick-by-light. The picker has one hand placed on the picking trolley while performing picking and placing with the other and confirm picking and placing by speaking in the headset simultaneously.

4.1.4 The Pick-by-beamer system design

The work design and user experience of the Pick-by-beamer system are based on the MTM-SAM analysis of Pick-by-paper, Pick-by-light and Pick-by voice together with literature findings. The design of the Pick-by-beamer aims to harness the advantageous features of the established picking information systems that were identified in the MTM-SAM analysis presented in the sections above. The design process of the Pick-by-beamer system also aims at identifying and reducing non-value adding activities of the kit preparation process. Out of the five module categories Search location, Pick and Place, Confirmation (pick-from/place-to), Push picking trolley, and Walk one step only Pick and Place was considered as value adding. The design of the Pick-by-beamer system hence aimed at reducing the time spent on the remaining non-value adding module categories.

From the video recordings of kit preparation with Pick-by-paper, Pick-by-light and Pick-by-voice, it was observed that each picking assignment was followed by the picker grabbing and pushing the picking trolley. To minimize time spent on handling the picking trolley, the Pick-by-beamer system was instead designed to operate at one storage section of the picking aisle at a time. This meant that the picker could visit multiple storage locations within that storage section before being required to push the picking trolley to the next section.

To reduce the number of steps required between storage locations and the picking trolley, the recognition zone was placed at a central position of the section (Figure 4.4). To prepare the picker for when to push the picking trolley and minimize waiting, the letter “L”, indicating the Last pick, was projected on the storage location (Figure 4.5). A pre-recorded voice then informed the picker which storage section to go to, e.g. “Go to section X1”, where the section name can be seen as a sign on the storage section (Figure 4.5). The Pick-by-beamer system forces the picker to push the trolley to the end of the section and park it within the recognition zone. Storage-section-specific picking information will only be conveyed when the Pick-by-beamer system has detected and recognized the unique reflective tape pattern, seen as the bottom magnifying circle in Figure 4.5. The method of forcing the picker to follow a predefined working procedure is known as using a forcing function which is a powerful design mechanism (Norman, 2013). The forcing function prevents an assignment to proceed to the next step if an incorrect action is carried out.

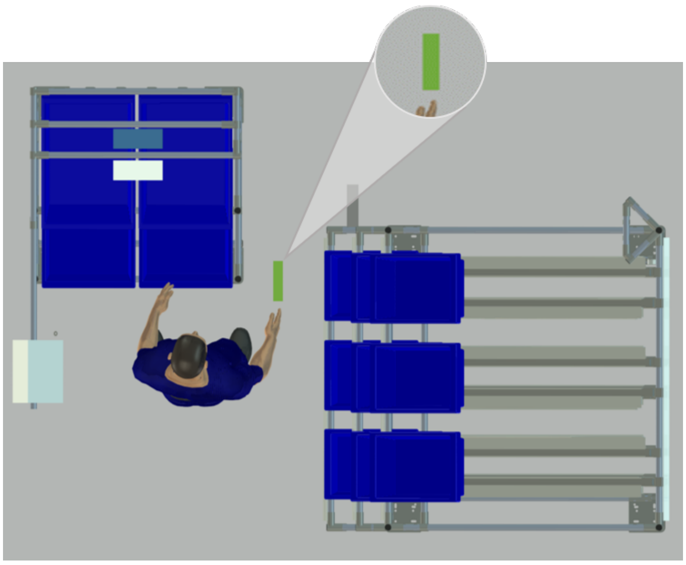


Figure 4.4: The Pick-by-beamer system and a high storing density section seen from above. The green recognition zone is magnified, the green stripe is a projection from the projector on the picking trolley to help guide the picker to position the trolley correctly relative to the reflective tape.

One key function that the Pick-by-beamer system enables is to integrate the confirmation activity into the value adding activity of pick and place. In comparison to Pick-by-light, the physical button at the location is replaced with a virtual 3D-cube right above the location, detecting the movements of the hand of the picker. The virtual recognition allows for the picker to perform the two activities simultaneously which eliminates the time for the non-value adding activity confirm. As the Pick-by-beamer does not have a separate activity of confirmation, the picker was made aware of a confirmation taking place through a short sound. Careful consideration was taken before using sound as a signifier as the sound could create annoyance. The use of sound should be used for informing the user about the source and confirmation of an important and invisible action that has been executed. Not using sound could give negative effects caused by missing feedback (Norman, 2013).

As described above, the system is equipped with a depth sensor that confirm placements, however, this sensor also detects placements in wrong kit. When the picker places a component in the wrong kit, the system alerts the picker by projecting red light onto the kit and a issuing a warning sound, indicating that an error has been made. Making errors more detectable is argued to be an efficient way of preventing errors and providing feedback to the picker to take corrective actions (Norman, 2013).

In terms of searching for locations, for Pick-by-paper, the picker needs to compare given information with the information displayed at the storage locations. For Pick-by-light, the picker only needs to search for the light indicator at the storage location with no need of comparing this information to an initial source of information. The use of light indicator for storage location identification had an advantage according to the MTM-SAM analysis when comparing the Search location module category for single-kit preparation. As mentioned before, no time was spent on searching for the kit location on the picking trolley in single-kit preparation. Why Pick-by-light did not have the lowest time consumption for search locations for batch preparation is due to the information conveyance with only small displays and light indicators. The small displays and light indicators on the picking trolley delayed the picker as the information to be interpreted was of a small font size. The Pick-by-beamer system overcomes the disadvantage of the small indicator light used in Pick-by-light by eliminating the physical indicator. The indicator was instead replaced with a beaming light projected from the projector unit that would cover approximately the entire storage location. Projecting light directly onto the storage location would make the storage location more prominent compared to having a physical light indicator place adjacent to the storage location.

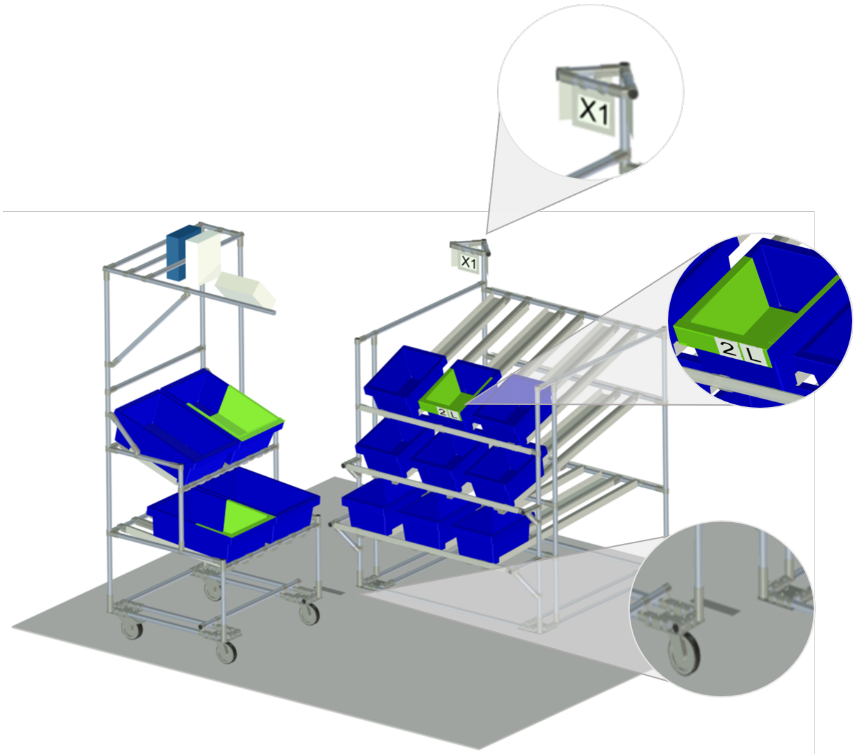


Figure 4.5: Picking information conveyance with Pick-by-beamer with the picking trolley to the left and storage section (high storing density) to the right.

The quantity to be picked was also projected on the storage location (Figure 4.5). Presenting information this way lets the user focus on both interpretation and usage of the information which reduces dependency on memory (Norman, 2013). The advantage of this could not be evaluated through the preliminary MTM-SAM analysis, however, a judgemental assessment thought this would have a positive impact in picking error reduction. Picking errors are thought to be reduced since the picker does not have to rely on memory when picking and placing components. The picking information on what quantity to pick is conveyed on two separate occasions during a picking assignment. The first occasion is on the storage location where the picker reads the quantity to be picked while having the hand in the bin at the storage location. The second occasion is when the picker returns to the picking trolley, then the number of kits lightened up corresponds to the quantity projected on the storage location. If the picker returns to the picking trolley with the incorrect quantity, the projections on the picking trolley are conveying picking information on quantity (Figure 4.5). This two-stage information conveyance allows for the picker to recognize a picking error before it is being made.

By changing the appearance of the storage location by highlighting it, the storage location becomes more prominent and visible which increases the focus of that storage location for the picker. Highlighting and placing a bright indicating light directly onto the storage location makes the location more distinguishable from other locations which according to Norman (2013) is referred to as natural mapping. Natural mapping reduces the need of the picker to require any additional guiding support which in turn reduces the load on human memory significantly. A less appropriate mapping, e.g. light indicator placed close to the storage location, which does not display the relationship as clear carries a higher risk of leading to picking errors (Fager et al., 2014; Norman, 2013). Highlighting the storage location and making it more prominent could reduce the likelihood of a slip error, where the picker misunderstands the conveyed information and performs an incorrect action, in this case picking components from the wrong storage location. This was thought by Fager et al. (2019) to be the reason for several picking errors for Pick-by-light where the picker picked from a vertically adjacent storage location as a consequence of misinterpreting the light indicator placement.

4.2 Experiment

In this section, the results from the experiment are presented, first the average time it takes for Pick-by-beamer and Pick-by-paper to pick one component. Then, the times are compared to the results from Fager et al. (2019) to validate the similarity of the studies. Then, a pairwise comparison between Pick-by-paper and Pick-by-beamer with corresponding statistical significance is presented. The pairwise comparison can credibly determine when there is a difference between the performance of Pick-by-paper and Pick-by-beamer. However, to be able to generalize the results and compare with Pick-by-voice and Pick-by-light, the MTM-SAM values for each system are used. In the last part of the section, the number of picking errors and their probabilities are presented.

4.2.1 Average time to pick one component

The average times to pick one component measured in the experiment is visualized in Figure 4.6 for high picking density and in Figure 4.7 for low picking density. The values of the response variable time consumption $\bar{t}$ vary greatly depending on the batching policy. Below follows two charts illustrating the time consumption for Pick-by-paper and Pick-by-beamer in single-kit preparation and batch preparation. Figure 4.6 presents the results for high picking density and Figure 4.7 for low picking density.

For high picking density (Figure 4.6), Pick-by-beamer in batch preparation was found to be the fastest with 2.59 seconds per picked component. Pick-by-beamer is approximately twice as fast in batch preparation compared to single-kit preparation. The whisker on the top of the bars illustrates the 95% confidence interval. The narrower confidence interval for Pick-by-paper (b) and Pick-by-beamer (b) indicates that the time to pick one component was more consistent for batch preparation.

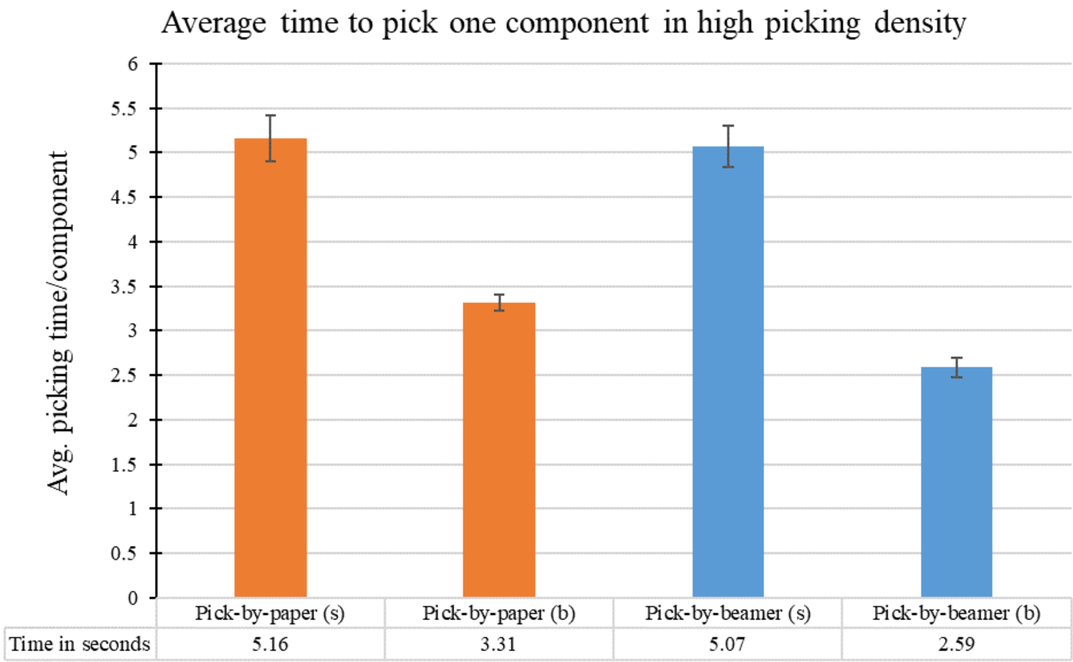


Figure 4.6: Average picking time consumption for Pick-by-paper and Pick-by-beamer in single-kit preparation (s) and batch preparation (b) when tested in high picking density. The whiskers on top of the bars shows 1.96 times the standard error equivalent to the 95% confidence interval.

Looking at Figure 4.7, it can be seen that Pick-by-beamer in batch preparation and low picking density has the lowest time consumption of 3.36 seconds per picked component. In general, all systems experience an increase in time consumption per picked component for low picking density compared to high picking density. The performance of Pick-by-beamer is more sensitive to changes in picking density with a 30% increase in time consumption between high picking density and low picking density which can be compared to 14% for Pick-by-paper.

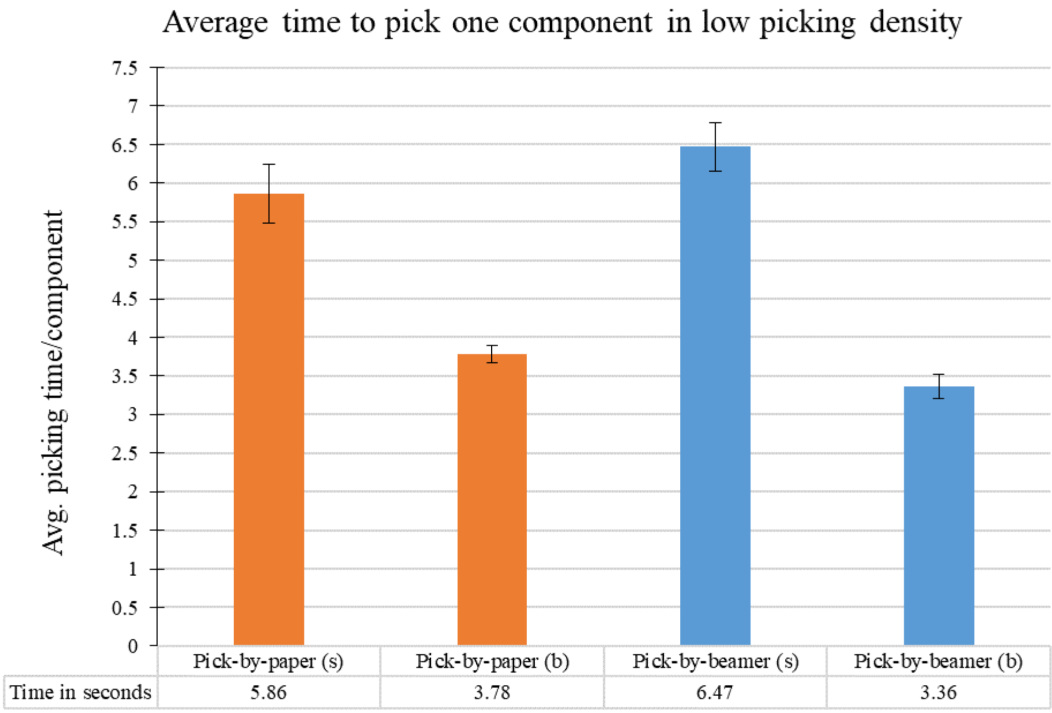


Figure 4.7: Average picking time for Pick-by-paper and Pick-by-beamer in single-kit preparation (s) and batch preparation (b) when tested in low picking density. Top whisker shows 1.96 times the standard error, giving a 95% confidence interval.

4.2.2 Results in relation to the previous study

To validate that the experimental design of this study is consistent with the experimental setup in the study by Fager et al. (2019), a comparison of time consumption is made for Pick-by-paper. As Pick-by-paper was tested in both studies, the average time consumption should be close to identical between the studies to conclude a close to identical experiment setup. Consistency in the experiment setup is crucial for a coherent MTM-SAM analysis of all picking information systems. The MTM-SAM analysis uses the video recordings as support to determine involved movements of the kit preparation process. Differences in the experimental setup could affect the movements performed by the picker which in turn would affect the result of the MTM-SAM analysis that could violate its validity. It is therefore important to compare the results of Pick-by-paper between the studies as an indication of how well the experiment was replicated. The comparison is illustrated in Figure 4.8 for both single-kit preparation and batch preparation in high picking density and low picking density.

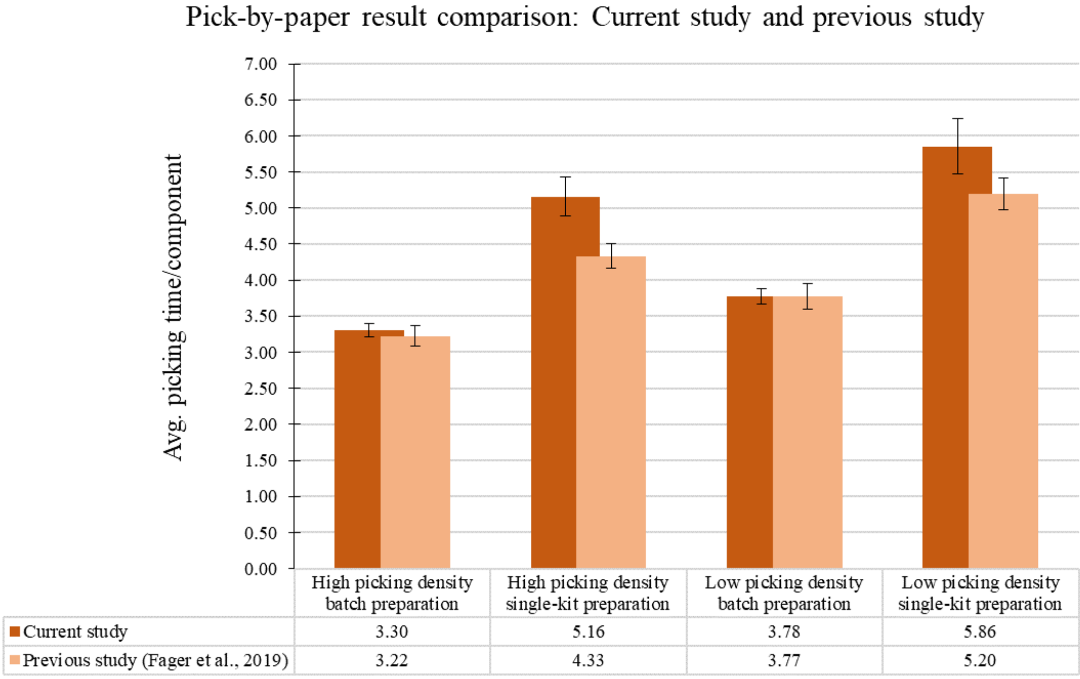


Figure 4.8: Comparison between the time consumption results measured in the current study and previous study for Pick-by-paper. Top whisker shows 1.96 times the standard error ($\sigma_{\bar{x}}$), giving a 95% confidence interval.

Looking at Figure 4.8, it can be seen that the time consumption is very accurate for both high and low picking density in batch preparation. For single-kit preparation, the previous study by Fager et al. (2019) achieves a significantly lower average time consumption for single-kit preparation in both high and low picking density. Four independent two-sample t-tests were done to test for difference in mean. The t-tests for batch preparation was found to be non-significant, concluding that the average time consumption is equal between the studies (null hypothesis cannot be rejected to a 5% error level). The t-tests for single-kit preparation was found to be significant, concluding that the average time consumption is different between the studies (null hypothesis is rejected to a 5% error level).

The lower average time consumption for Pick-by-paper in single-kit preparation measured in the study by Fager et al. (2019) indicates that there is a small difference in population or experiment setup that affects single-kit preparation. The consequence is that the video-recordings from the experiment by Fager et al. (2019) show a single-kit preparation process that has a slightly faster working pattern.

4.2.3 Pairwise comparisons across batching policies

An overview of the results from the rANOVA with Games-Howell Post-Hoc test is presented in Table 4.1. The pairwise comparisons between the systems are presented by setting, i.e., high picking density, medium picking density and low picking density. The medium picking density is a combination where one third of the picking sequence is low picking density and the remaining two thirds are high picking density. However, further on in the report, the results will only consider high and low picking density separately as the results for the medium picking density could only be generalized to kit preparation with that specific composition of low and high picking density. By isolating results to kit preparation in high and low picking density separately, it can be determined if the performance of a picking information system depends on the picking density and to what extent.

Looking at the results from the statistical analysis in Table 4.1, it can be seen that the pairwise comparisons between single-kit preparation for Pick-by-beamer (s) and Pick-by-paper (s) are non-significant for all three settings. This means that for a 95% confidence level, the null hypothesis cannot be rejected. Being unable to reject the null hypothesis means that there is no statistically significant difference in mean time consumption between the systems for single-kit preparation.

For high picking density, the fastest system was Pick-by-beamer in batch preparation. The greatest difference in mean was between Pick-by-paper (s) and Pick-by-beamer (b). For that comparison, there was a statistically significant difference where Pick-by-beamer (b) was 2.57 seconds faster per picked component. The smallest statistically significant difference was between Pick-by-paper (b) and Pick-by-beamer (b) where the latter was found to be 0.72 seconds faster per picked component. For high picking density, Pick-by-paper was only found to be statistically significantly better (1.80 s per picked component) than Pick-by-beamer when comparing Pick-by-paper in batch preparation with Pick-by-beamer in single-kit preparation.

For the low picking density setting, the fastest system was Pick-by-beamer (b) which was in line with the high picking density result. The greatest difference was between Pick-by-beamer (s) and Pick-by-beamer (b). Pick-by-beamer was 3.11 seconds faster per picked component in batch preparation compared to single-kit preparation. Pick-by-paper (b) was 2.70 seconds faster per picked component in comparison to Pick-by-beamer (s), which was also the only comparison where Pick-by-paper was faster than Pick-by-beamer.

Table 4.1: Results from the repeated measures one-way ANOVA analysis with Games-Howell post hoc test. Interpretation: A negative mean difference indicates that system 1 has a lower time consumption than system 2.

Setting	**System** 1		**System 2**		**Mean diff.**	**95% CI**	**p-value**
high picking density	Pick-by-paper	(s)	Pick-by-beamer	(b)	2.570	[2.195 , 2.945]	***
			Pick-by-beamer	(s)	(0.095)	[-0.359 , 0.549]	.948
			Pick-by-paper	(b)	1.850	[1.484 , 2.216]	***
	Pick-by-paper	(b)	Pick-by-beamer	(b)	0.720	[0.535 , 0.905]	***
			Pick-by-beamer	(s)	-1.755	[-2.076 , -1.434]	***
	Pick-by-beamer	(s)	Pick-by-beamer	(b)	2.475	[2.143 , 2.807]	***
Medium picking density	Pick-by-paper	(s)	Pick-by-beamer	(b)	2.525	[2.179 , 2.871]	***
			Pick-by-beamer	(s)	(-0.259)	[-0.688 , 0.170]	.401
			Pick-by-paper	(b)	1.956	[1.628 , 2.284]	***
	Pick-by-paper	(b)	Pick-by-beamer	(b)	0.569	[0.382 , 0.757]	***
			Pick-by-beamer	(s)	-2.215	[-2.532 , -1.898]	***
	Pick-by-beamer	(s)	Pick-by-beamer	(b)	2.784	[2.448 , 3.120]	***
Low picking density	Pick-by-paper	(s)	Pick-by-beamer	(b)	2.499	[1.961 , 3.037]	***
			Pick-by-beamer	(s)	(-0.613)	[-1.250 , 0.023]	.063
			Pick-by-paper	(b)	2.081	[1.563 , 2.599]	***
	Pick-by-paper	(b)	Pick-by-beamer	(b)	0.418	[0.172 , 0.665]	***
			Pick-by-beamer	(s)	-2.694	[-3.122 , -2.266]	***
	Pick-by-beamer	(s)	Pick-by-beamer	(b)	3.113	[2.660 , 3.565]	***

Note: Significance code: < 0.05 ‘***’

4.2.4 Picking error occurrences and probabilities

Occurrence of picking errors is measured to ensure that a low time consumption associated with a picking information is not achieved at the expense of more picking errors being made. Picking errors are also measured to calculate the probability of a picking error occurring. The picking error probability is incorporated in the economic evaluation in the next section. Below follows a presentation of the occurrence of the different picking errors e_1, e_2 and e_3 presented earlier in Table 3.3. No picking errors were recorded for Pick-by-beamer and Pick-by-paper in single-kit preparation and neither for Pick-by-beamer in batch preparation. Hence, only data for Pick-by-paper in batch preparation is presented in the Table 4.2 below. The picking errors probabilities recorded in the experiment should be treated with caution as picking errors are rare events that needs to be tracked over a longer period to be representative. No statistical analysis is done for the mean picking error occurrence as the sample size of number of picked components is too small to achieve significant statistical power for comparing means between systems.

Table 4.2: Picking error data for Pick-by-paper in high and low picking density.

Picking information system	e_1	e_2	e_3
Pick-by-paper (b) - High picking density			
Recorded picking errors†	11	10	1
P(Picking error)	0.0046	0.0042	0.00042
Pick-by-paper (b) - Low picking density			
Recorded picking errors‡	6	6	2
P(Picking error)	0.0050	0.0050	0.0017

† Data based on a total of 2400 picked components.
‡ Data based on a total of 1200 picked components.

The relatively high number of picking errors measured for Pick-by-paper (b) over a small sample size, can serve as an indication that Pick-by-beamer (s/b) and Pick-by-paper (s) would have had fewer picking errors when studied over a longer period. The data in the Table indicate that picking error e_3, is occurring at a lower rate than e_1 and e_2. The lower occurrence of e_3 is an indication that a picking error is more likely to be caused by the picker either picking one component too many from the storage location or that the component is placed in the wrong kit.

4.3 MTM-SAM analysis of Pick-by-beamer

The video recordings from the experiment provided visual support to finalize the preliminary MTM-SAM analysis of Pick-by-beamer that was done during the design phase. The results are presented as time consumption by module category single-kit preparation (s) and batch preparation (b) in Figure 4.9 below.

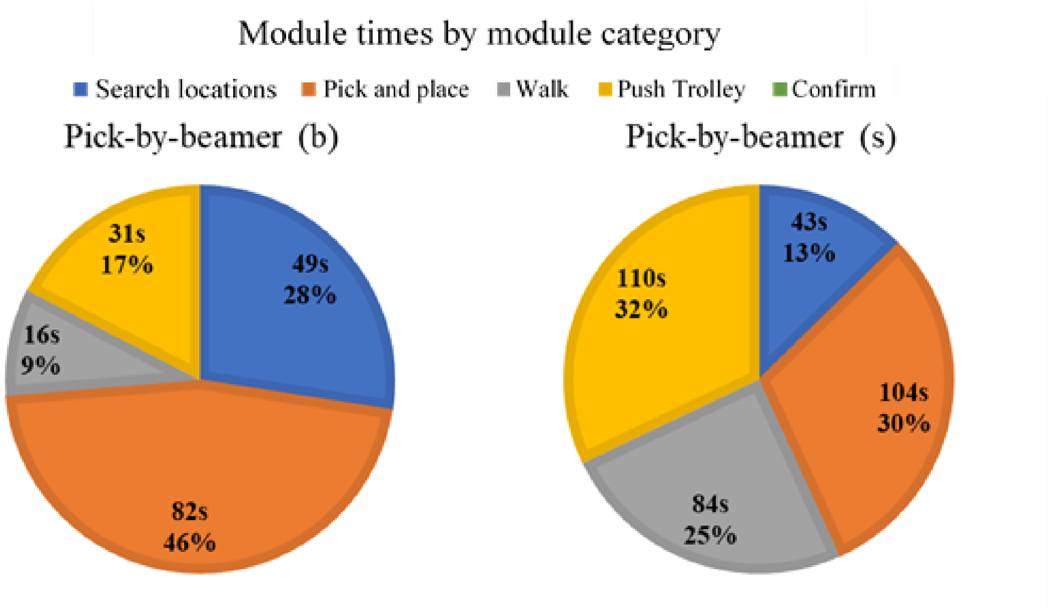


Figure 4.9: Theoretical percentage for each module category for Pick-by-beamer, and an example of time consumption when picking a total of 60 components. Left: batch preparation (b). Right: single- kit preparation (s).

Looking at Figure 4.9, it can be seen that no time is spent on confirmation as Pick-by-beamer does not require an additional module to be performed separately. The greatest reduction in time consumption is achieved for the search locations module category due to the intuitive guidance to storage location and kit location. An increased time consumption is observed for the Walk and Push picking trolley module category despite an effort to reduce the time consumed by these categories. However, a system requirement of the Pick-by-beamer system required these activities to be performed at certain fixed occasions which complicated reducing them. The system requirement was related to the identification process of the storage sections reflective tape pattern for the system to recognize the storage section.

4.4 Results from MTM-SAM of all systems

In this section the time consumption extracted from the MTM-SAM analysis is presented for Pick-by-beamer, Pick-by-paper, Pick-by-light and Pick-by-voice. The values on time consumption are presented in the number of seconds it takes to pick one component when conducted in a picking tour with a specific picking density. The data is presented separately for high picking density (Figure 4.3) and low picking density (Figure 4.4).

Table 4.3: Time consumption per picked component in batch preparation and single-kit preparation for each picking information system for high picking density.

	Pick-by-			
Batching policy	**Beamer**	**Paper**	**Light**	**Voice**
Batch preparation (b)	2.81	3.15	3.95	5.52
Single- kit preparation (s)	5.08	5.09	3.56	5.92

Table 4.4: Time consumption per picked one component in batch preparation and single-kit preparation for each picking information system for low picking density.

	Pick-by-			
Batching policy	**Beamer**	**Paper**	**Light**	**Voice**
Batch preparation (b)	3.19	3.45	4.35	5.24
Single- kit preparation (s)	6.86	5.75	4.27	4.93

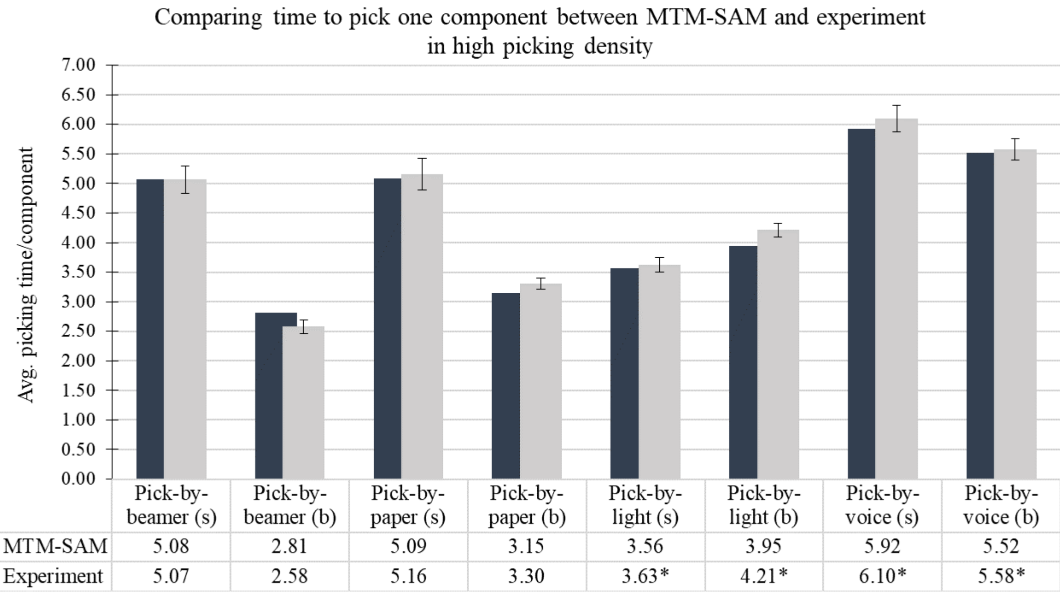
As seen, Pick-by-beamer is the fastest picking information system for both high and low picking density. Relating this to the previously presented distributions between the module categories for each system, it is clear that there are two main reasons for Pick-by-beamer's superior performance. First, less time is spent searching for locations to pick from and place to. The intuitive conveyance of information with the Pick-by-beamer allows for much faster identification of storage locations and kits. Second, the non-value adding confirm movements are not needed as the Pick-by-beamer system detects the confirmation automatically with the sensors. However, the system is limited in its mobility and needs to be pushed in a certain way. The process is optimized as well as possible for Pick-by-beamer, but still, more time is spent on walking and pushing the trolley compared to the other systems. Lastly, the module category pick and place is indifferent or marginally better for Pick-by-beamer.

In the end, the two module categories where the Pick-by-beamer system performs better outweighs the two were it performs worse. Therefore, Pick-by-beamer becomes the fastest picking information system for both picking density settings.

Another insight is that most picking information systems perform better in batch preparation due to the reduced time per component spent on walking, picking, placing, and confirming. However, for Pick-by-light this is not true, mainly because it loses more time than the others searching for the kit position on the trolley and interpreting the number of components to pick, which are activities only present in batch preparation. That is a result of the smaller displays used with Pick-by-light.

4.4.1 MTM-SAM results validation

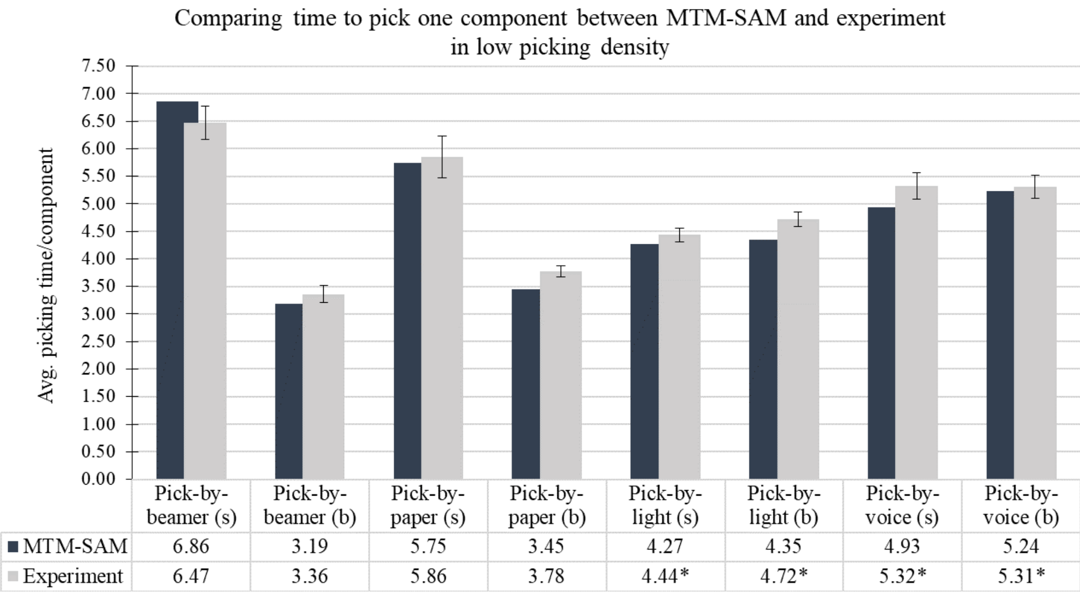
In general, when comparing the theoretical norm times to the measured time consumption from the experiments the results are similar to a high degree and correlates well. A trend could be observed where the MTM-SAM analysis gives slightly lower values than the measured time consumption from the experiments (Figure 4.10 for high picking density and Figure 4.11 for low picking density). The MTM-SAM analysis correlates slightly better with the experiment for high picking density compared to low picking density. A larger variation in time consumption can also be observed for the measured data in single-kit preparation.



*Time obtained from previous study (Fager, Hanson, Medbo, and Johansson, 2019).

Figure 4.10: Theoretical time consumption per picked component with the average values measured during the experiment for high picking density.

In Figure 4.10, it can be seen that Pick-by-beamer is the only system where the MTM-SAM analysis gives higher values, meaning that the theoretical norm times are higher than the time consumption measured in the experiment. This can be due to Pick-by-beamers' intuitive way of displaying information, such fine cognitive differences can be hard to fully appropriate in a MTM-SAM analysis.



	Pick-by-beamer (s)	Pick-by-beamer (b)	Pick-by-paper (s)	Pick-by-paper (b)	Pick-by-light (s)	Pick-by-light (b)	Pick-by-voice (s)	Pick-by-voice (b)
MTM-SAM	6.86	3.19	5.75	3.45	4.27	4.35	4.93	5.24
Experiment	6.47	3.36	5.86	3.78	4.44*	4.72*	5.32*	5.31*

*Time obtained from previous study (Fager, Hanson, Medbo, and Johansson, 2019).

Figure 4.11: Theoretical time consumption per picked component with the average values measured during the experiment for low picking density.

The difference between the theoretical and measured time consumption seen in Figure 4.11 is greater for low picking density. The theoretical time consumption is generally lower than the measured time consumption. Pick-by-beamer (s) is, once again the only case where the theoretical time consumption is higher than the measured. This is, as for high density, assumed to be because of the cognitive parts.

4.5 Results from economic evaluation

This section presents the result of the economic evaluation. First, the hourly cost depending on demand is presented along with a sensitivity analysis visualizing the optimal system for different scenarios. Secondly, the payback period achieved for different settings if Pick-by-paper is used and one invests in Pick-by-beamer is shown. Last, the result of the additional investment metrics, net present value and return on investment are visualized. The assumptions and prerequisites are explained in the text, for a detailed overview of all data used in the analysis, e.g. system or setting specific data, see Appendix F.

4.5.1 Hourly cost depending on picking demand

The hourly cost is divided into four different settings varying with two values of picking density and kit size. Two values are used on both variables since it is then possible to see a trend and use the graphs even if the evaluated factory have values higher or lower than these. The kit size, meaning the amount of component that is included in a picked kit, is set to 15 and 50. The two density settings have individual variations depending on the batching policy used. Picking density is calculated as the number of picked components divided by the length of the facade. The high picking density case corresponds to a value of 1.7 picks/meter for single-kit preparation and 6.6 picks/meter for batch preparation using four kits. The low picking density case corresponds to 0.7 picks/meter for single-kit preparation and 2.9 picks/meter for batch preparation using four kits.

The figures in this chapter are visualized for each of the four settings individually. Therefore, Figure 4.12, 4.14, 4.16 and 4.18 all visualize the cost per hour for each system depending on picking demand. All four assumes that the travel distances ($\bar{D}$) between where a picking error is detected and where it needs to be corrected are 25 m. Figure 4.13, 4.15, 4.17 and 4.19 visualize which system has the lowest hourly cost, i.e. the lowest curve in Figure 4.12, 4.14, 4.16 and 4.18. It is displayed for three different travel distances ($\bar{D}$), 0 m, 25 m and 50 m. All eight graphs assume that the investment horizon is five years, working 1 760 hours per year, and the salvage value is 0. The figures use data from the best batching policy for each system in each setting, that means that Pick-by-beamer and Pick-by-paper use batch preparation for every graph, Pick-by-light uses single preparation, and Pick-by-voice uses batch preparation for the high picking density graphs and single preparation for the low picking density graphs.

A specific picking density and kit size naturally corresponds to a specific length of the picking aisle. The length of the picking aisle affects the number of storage locations and thereby the investment costs for the different systems. However, practical usage of these graphs would usually be done the other way, i.e. the picking aisle length and kit size is known and fixed in the factory and those would correspond to a certain picking density. Knowing those three values, one can use the graphs in the following result sections to get an understanding of the hourly cost of investing in and using the systems. The figures can be used for several kit preparation areas simultaneously or even a whole factory, as long as the factory have agile teams were the pickers can help each other out if one kit preparation area temporarily needs extra pickers.

4.5.1.1 High picking density and a kit size of 15 components

Figure 4.12 is applicable for a setting where you have a high picking density, a kit size of 15 components and a travel distance ($\bar{D}$) from the kit preparation area to the assembly station of 25 m. The bar below the graph displays the color of the picking information system with the lowest hourly cost for that specific demand range. The graphs' y-values are calculated with Formula 3.1 shown in method section Economic evaluation, 3.4.1. The steps seen in the graph are a result of needing an additional picker. An additional picker heavily increases the hourly cost. The height of the steps depends on the hourly cost for a picker and the investment cost per picker for the specific system. The frequency of the steps depends on the efficiency of the systems. As seen, Pick-by-beamer has the fewest/longest steps since it is the most efficient system. At the highest studies picking demand of 10 000 components per hour, Pick-by-beamer needs eight pickers; Pick-by-light and Pick-by-paper need nine; and Pick-by-voice needs 16. Pick-by-paper also has an underlying gradient which depends on the hourly cost for picking errors. This only affects Pick-by-paper since Pick-by-paper is the only system with picking errors for this setting. Lastly, each curve has a vertical offset that depends on costs from the initial investment, both fixed costs related to software and servers, and costs depending on the number of storage locations at the factory.

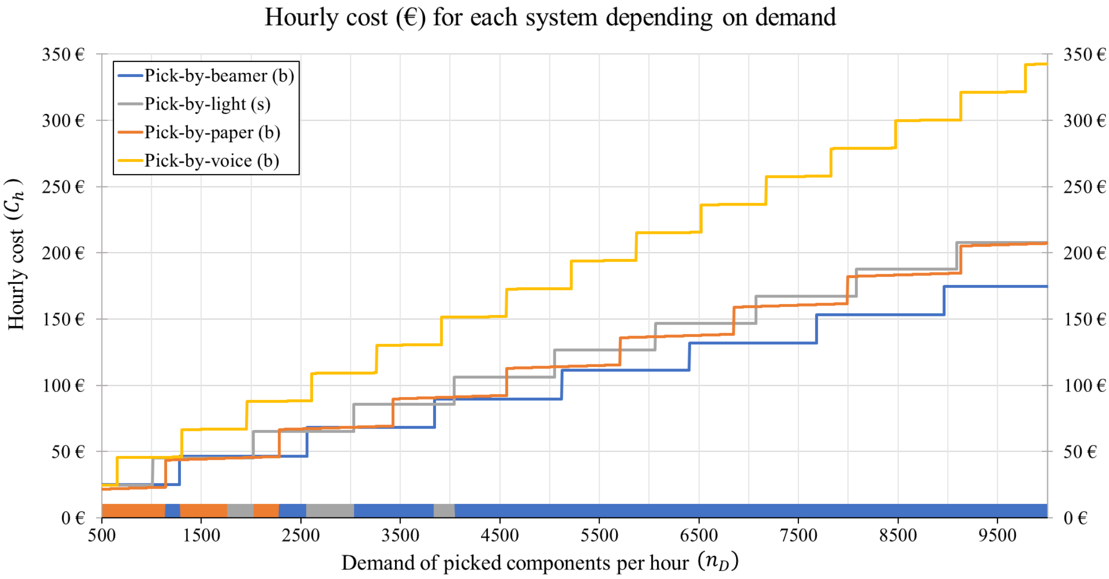


Figure 4.12: Graph shows hourly cost for the different systems assuming an investment horizon of five years and a distance ($\bar{D}$) of 25 m. High density picking and a kit size of 15 components.

As seen in the graph, Pick-by-paper is cheapest for lower demand, Pick-by-light takes some ground in the low-mid demand range and Pick-by-beamer takes over as the demand goes up. This is a result of the better performance and relatively small investments needed to achieve this. Pick-by-paper, Pick-by-light and Pick-by-beamer have fairly similar hourly cost but Pick-by-beamer slowly increases the marginal as the demand goes up. Pick-by-voice is far more expensive, mainly due to the lower efficiency but also because the investment cost as a result of additional pickers needed is a lot higher than for Pick-by-paper and Pick-by-light. However, not as high as for Pick-by-beamer.

The investment costs of Pick-by-light is linearly dependent on the number of unique articles. The number of unique articles is fixed for each setting and does not depend on the picking demand, the investment costs of Pick-by-light is therefore not affected by adding an additional picker in the same environment. The total investment costs for Pick-by-light is, in this setting, always smaller than that of Pick-by-beamer. If the kit size would increase to 50 which is presented in the next section (4.5.1.2), the amount of storage locations increases and, thereby, the investment of Pick-by-light becomes higher than that of Pick-by-beamer for a picking demand below 2 561.

However, in this setting, if a longer investment horizon than five years is used, Pick-by-beamer would, as it has the highest investment costs, take the lead earlier and have a bigger marginal. Further, looking at the demand for higher values than 10 000 picks per hour would as the trend shows, also increase the margin.

In the previous figure (Figure 4.12) it is assumed that the distance ($\bar{D}$) between the assembly station and the kit preparation area is 25 m. However, this distance ($\bar{D}$) may differ in factories. Therefore, Figure 4.13 shows a sensitivity analysis of which system is the cheapest, i.e. the lowest graph in the previous figure, for three different distances ($\bar{D}$). As seen, the 25 m case is the same as the bar under the previous figure, 4.12.

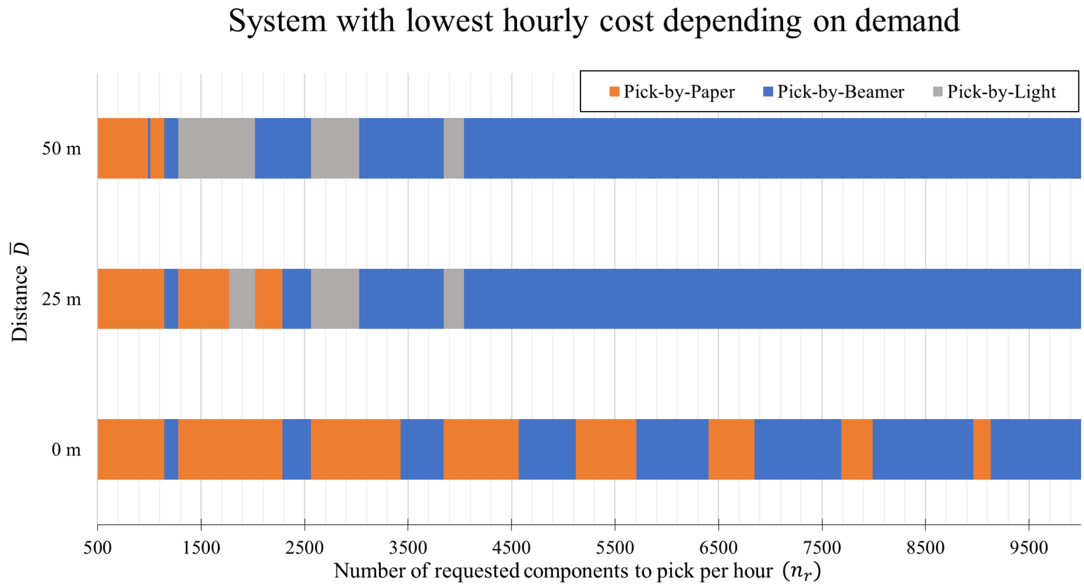


Figure 4.13: The bars represent the horizontal bar, i.e. the cheapest system, from the previous figure (Figure 4.12) for three different distances ($\bar{D}$) to correct a picking error. A distance ($\bar{D}$) of zero means that the picking errors are assumed to be detected right after the picking tour is completed. Applicable for high picking density and a kit size of 15 components.

In general, Pick-by-paper is the best solution for low demand ranges since the investment costs are low, and Pick-by-beamer is the best solution as demand goes up. A trend seen is that Pick-by-beamer and Pick-by-light benefit from longer distances ($\bar{D}$) since they have the lowest picking error probabilities. Light can overtake some lower demand-ranges since it has relatively low investment costs and is more efficient than Pick-by-paper. However, Pick-by-beamer is dominant at higher ranges. At the 0 m case, Pick-by-paper stays competitive at some high picking demand ranges. However, the 0 m case means that the distance ($\bar{D}$) between where the kit is prepared and the assembly line where the picking error is detected is 0 m. Therefore, only the length of the picking aisle would have to be walked to correct the error. This is a very rare theoretical scenario, most factories will have a longer distance ($\bar{D}$). Having a distance ($\bar{D}$) of 0 m is possible if there is a control station right next to the kit preparation area, however, that would be a huge time-waste. Interpreting this figure, one should keep in mind that it only visualizes which option is the best, it does not show the marginal between the best and second-best system. At some demand ranges, the difference is a lot smaller than at others.

4.5.1.2 High picking density and a kit size of 50 components

Figure 4.14 builds upon the same formula and is interpreted the same way as Figure 4.12, however, the settings are changed. The result is applicable for a kit preparation setting with high picking density, a kit size of 50 components and a travel distance ($\bar{D}$) of 25 m. The setting is the same as for Figure 4.12 but with a different kit size.

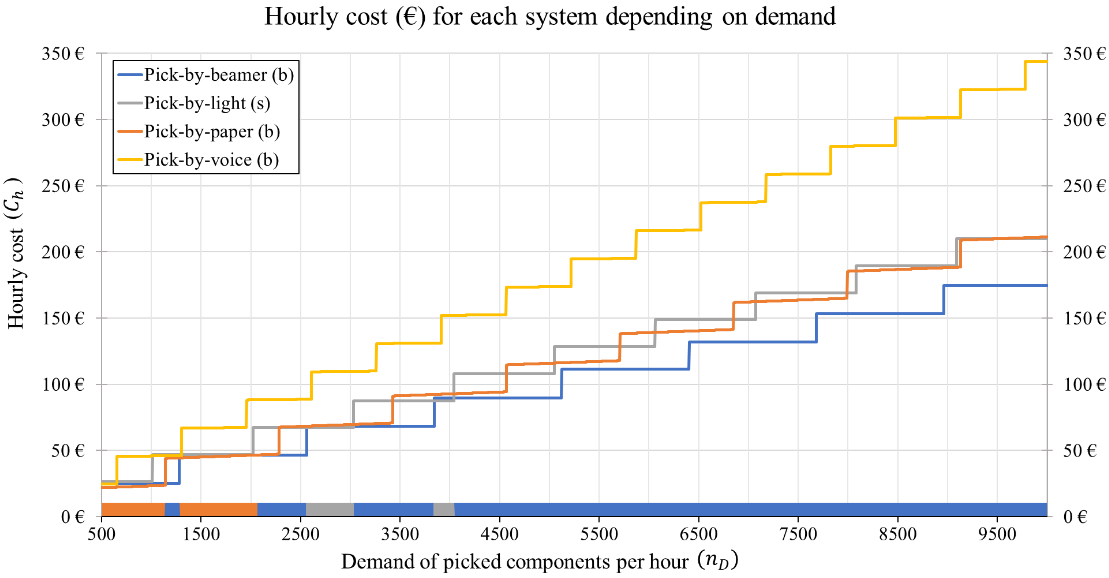


Figure 4.14: Hourly cost for the different systems assuming an investment horizon of five years and a distance ($\bar{D}$) of 25 m. High density picking and a kit size of 50 components.

Factories with a kit size of 50 components and a picking density at the same level, high picking density, will have an aisle more than three times longer than that of a factory having a kit size of 15 components. As the size of the boxes on the facade is fixed for high and low picking density, a longer aisle results in more storage locations. Therefore, a kit size of 50 components impacts the initial investment costs needed for the different systems. This makes Pick-by-light worse as Pick-by-light has the by far highest investment cost per storage location. Another effect of increasing the kit size and thereby the length of the aisle is the cost of picking errors. Since you need to walk more to correct picking errors, they become more costly. Therefore, for higher kit sizes, Pick-by-paper becomes slightly worse. However, comparing with Figure 4.12, the total change in hourly cost for the graphs is minimal. This is a result of that the investment due to more storage locations is small in comparison to other costs when spread over five years. Further, the longer aisle results in a longer picking error correction time, however, the aisle still only correspond to a small portion of the total picking error correction time.

Looking at Figure 4.14, Pick-by-beamer is the best pick for most of the demand range. Further, Pick-by-beamer becomes dominant slightly earlier for this setting and the marginal towards Pick-by-paper and Pick-by-light increases.

Figure 4.15 shows the sensitivity analysis, interpreted in the same way as Figure 4.13, but for the new setting with a kit size of 50 components. As explained, in Figure 4.14, the new setting is beneficial for Pick-by-beamer and worst for Pick-by-light. This sensitivity analysis confirms that this is valid for all distances ($\bar{D}$). Pick-by-beamer becomes dominant earlier for all distances ($\bar{D}$) and Pick-by-light loses some demand range to Pick-by-paper in the 25 and 50 m cases. In general, as for Figure 4.13, Pick-by-beamer becomes dominant for higher demand and, Pick-by-beamer and Pick-by-light benefit from a longer distance ($\bar{D}$).

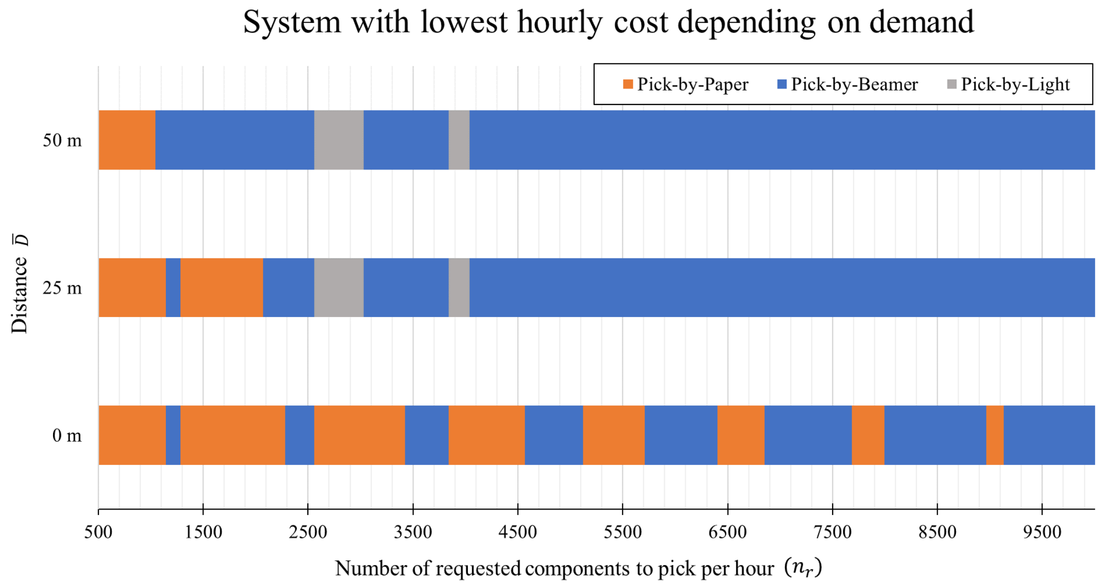


Figure 4.15: The bars represent the horizontal bar i.e. the cheapest system, from the previous figure (Figure 4.14) for three different distances ($\bar{D}$) to correct a picking error. A distance ($\bar{D}$) of zero means that the picking errors are assumed to be detected right after the picking tour is completed. Applicable for high picking density and a kit size of 50 components.

4.5.1.3 Low picking density and a kit size of 15 components

Figure 4.16 builds upon the same formula and is interpreted the same way as Figure 4.12, however, the settings are changed. The result is applicable for a kit preparation setting with low picking density, a kit size of 15 components and a travel distance ($\bar{D}$) of 25 m. The setting is the same as for Figure 4.12 but with a different picking density.

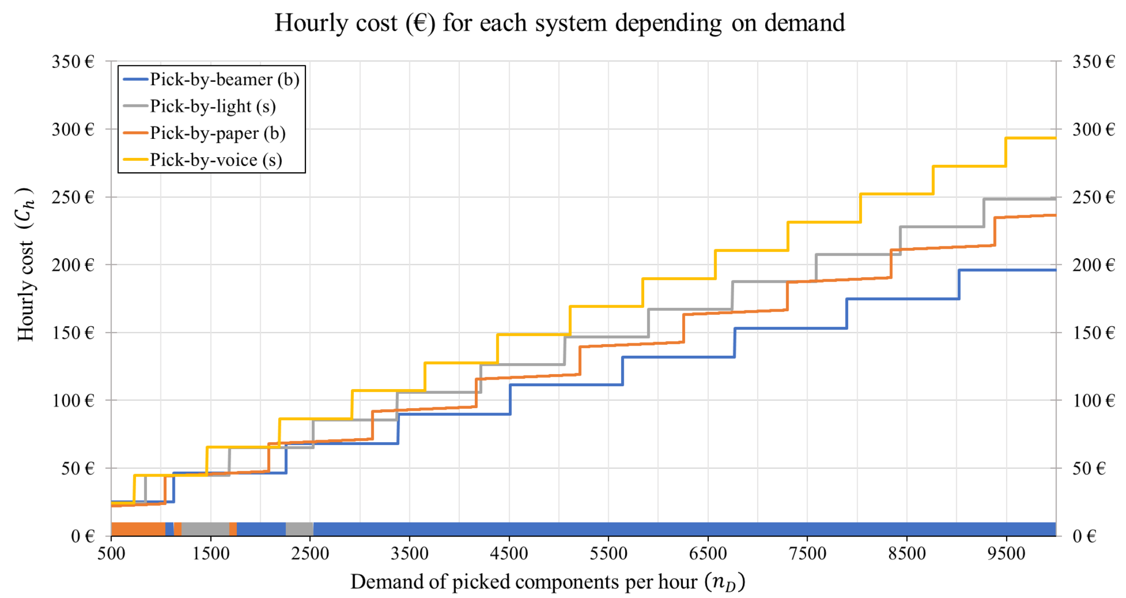


Figure 4.16: Hourly cost for the different systems assuming an investment horizon of five years and a distance ($\bar{D}$) of 25 m. Applicable for low picking density picking and a kit size of 15 components.

Factories having the same kit size but a lower picking density will also have a longer picking aisle. Comparing the picking aisle to Figure 4.14, with a high picking density and a kit size of 50 components, the aisle will in Figure 4.16 be slightly shorter. That is because the high kit size case increases the kit size with 330% while the high picking density case only increases the picking density with 227%. Therefore, this setting will have a picking aisle somewhere in between the two previous ones and, thereby, affect investment costs and picking error costs correspondingly. Further, the picking error probabilities increase for Pick-by-paper at the lower density section which further increases the picking error costs. Another effect of a different picking density is related to the efficiency of the systems. By lowering the picking density, the efficiency of all the systems but Pick-by-voice decreases. The biggest decrease is seen for the Pick-by-light system and the smallest is seen for Pick-by-paper (apart from Pick-by-voice). As a result, this lower density setting can slightly benefit Pick-by-paper.

Looking at Figure 4.16, Pick-by-beamer is the best pick for most of the demand range. Pick-by-beamer becomes dominant even more quickly than in Figure 4.12 showing that compared to Pick-by-paper the relative effect from the aisle and picking error probability was bigger than that of the changed efficiency. However, Pick-by-light becomes slightly worse compared to Pick-by-paper as its increased investments and lower efficiency had a bigger impact than the increased picking error correction costs of Pick-by-paper. Further, for the low picking density case, Pick-by-voice is a lot closer to the efficiency of the others which can be seen to have an impact in Figure 4.16.

Figure 4.17 is a sensitivity analysis interpreted in the same way as Figure 4.13 but for the new setting with a low picking density. As with Figure 4.16, the new setting is slightly beneficial for Pick-by-beamer and Pick-by-paper. This sensitivity analysis shows that it is beneficial for Pick-by-beamer in the 50 m and 25 m cases, while beneficial for Pick-by-paper in the 0 m case as the picking error correction costs have a smaller impact there. In general, as for Figure 4.13, Pick-by-beamer becomes dominant for higher demand and, Pick-by-beamer and Pick-by-light benefit from a longer distance ($\bar{D}$).

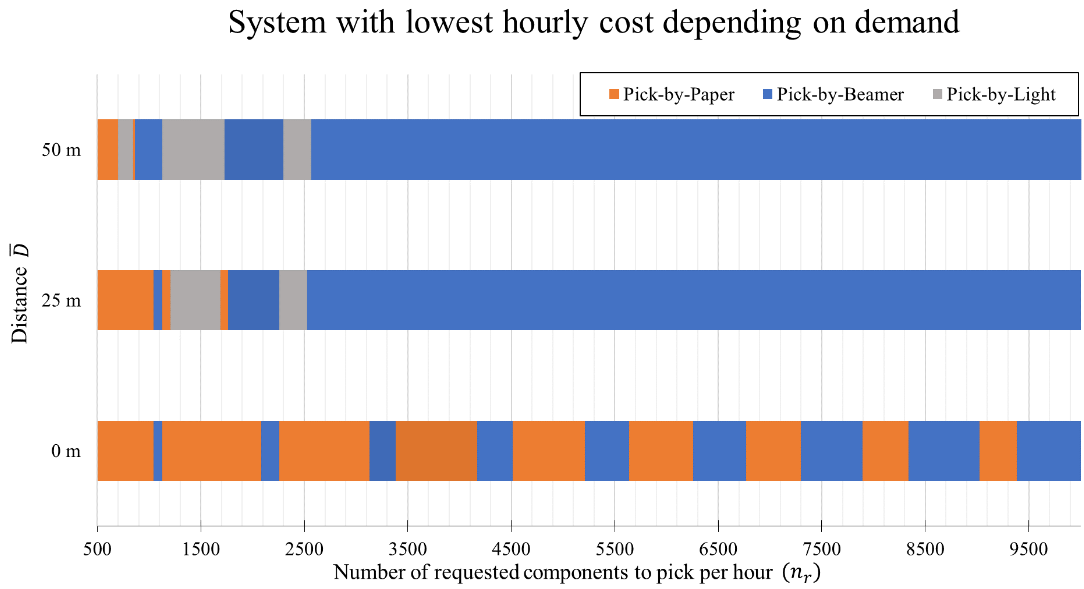


Figure 4.17: The bars represent the horizontal bar i.e. the cheapest system, from the previous figure (Figure 4.16) for three different distances ($\bar{D}$) to correct a picking error. A distance ($\bar{D}$) of zero means that the picking errors are assumed to be detected right after the picking tour is completed. Low picking density and a kit size of 15 components.

4.5.1.4 Low picking density and a kit size of 50 components

Figure 4.18 builds upon the same formula and is interpreted the same way as Figure 4.16, however, the settings are changed. The result is applicable for a kit preparation setting with low picking density, a kit size of 50 components and a travel distance ($\bar{D}$) from the kit preparation area to the assembly station of 25 m. The setting is now completely different from the first case (Figure 4.12).

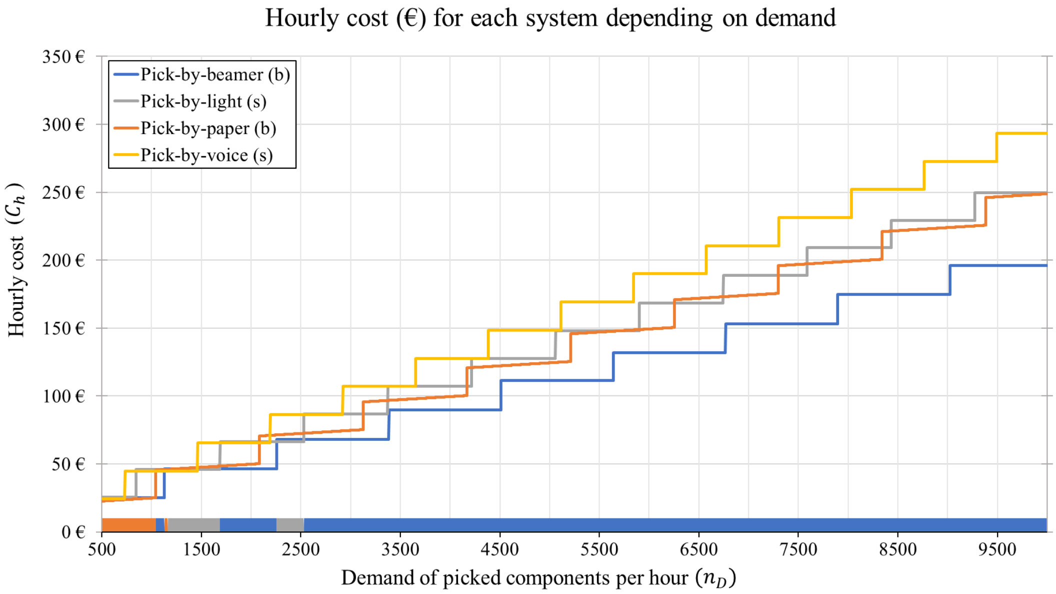


Figure 4.18: Hourly cost for the different systems assuming an investment horizon of five years and a distance ($\bar{D}$) of 25 m. Applicable for low picking density picking and a kit size of 50 components.

As explained in the previous settings, Pick-by-beamer benefits, compared to the others, from both the lower density and the higher kit size. As seen in the graph, Pick-by-beamer quickly becomes dominant with a higher margin than earlier settings. Being a low picking density setting, Pick-by-light is once again almost competitive.

Figure 4.19 is a sensitivity analysis interpreted in the same way as Figure 4.13, but for the new setting with a low picking density and a kit size of 50. As explained, in Figure 4.18, the new setting is significantly beneficial for Pick-by-beamer. This sensitivity analysis confirms that this is valid for all distances ($\bar{D}$). Compared to Figure 4.13, Pick-by-beamer becomes dominant earlier for all distances ($\bar{D}$). In general, as for Figure 4.13, Pick-by-beamer becomes dominant for higher demand and, Pick-by-beamer and Pick-by-light benefit from a longer distance ($\bar{D}$).

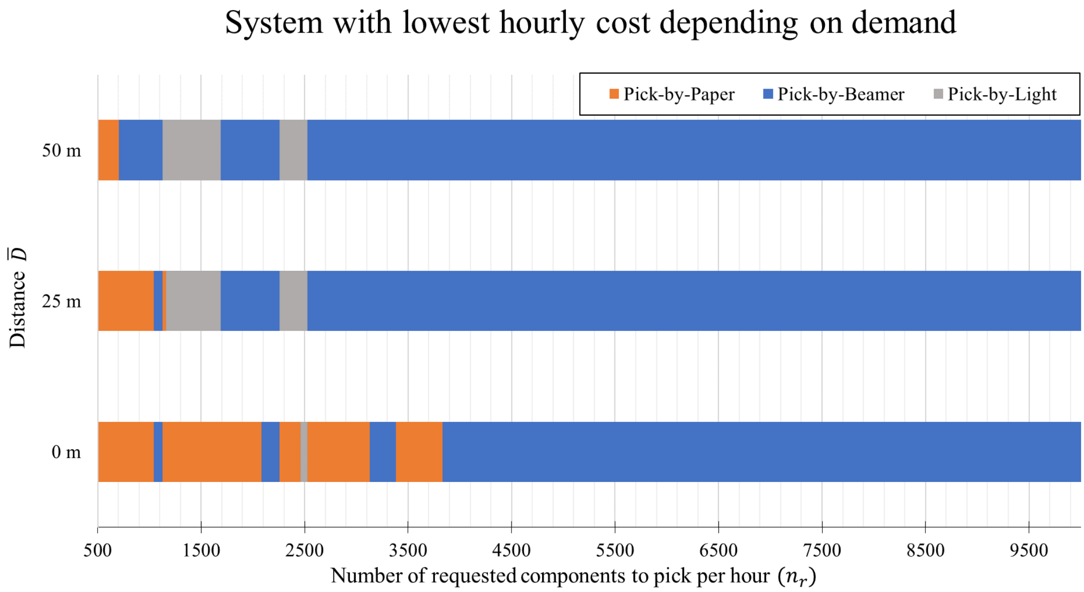


Figure 4.19: The bars represent the horizontal bar i.e. the cheapest system, from the previous figure (Figure 4.18) for three different distances ($\bar{D}$) to correct a picking error. A distance ($\bar{D}$) of zero means that the picking errors are assumed to be detected right after the picking tour is completed. Low picking density and a kit size of 50 components.

4.5.2 Payback period

The previous figures have shown which system is the best for different settings if the investment horizon is five years. However, an interesting key performance indicator for managers is the payback period, i.e. when will break-even be achieved. The following figures show a scenario where Pick-by-paper is used today and the factory invests in Pick-by-beamer. This is calculated using Formula 3.9 seen in method chapter 3.4.2. As seen, the operational savings are weighted towards the needed investment. The payback analysis is divided into two settings, high picking density and low picking density. Both are using a kit size of 15 components and shows the payback period for three different distances ($\bar{D}$). a kit size of 50 components are excluded for the payback analysis as it is not as common as a kit size of 15 components and the results between them vary very little.

4.5.2.1 Payback period for high picking density

Figure 4.20 shows the payback period for the high picking density setting, the x-axis once again is the picking demand, while the y-axis shows the payback period in months. The bars below the graph show the number of pickers needed for each of the systems depending on the picking demand. The general trend in the graphs is that the payback period decreases as demand increases, this is expected as previous figures show that Pick-by-beamer benefits from higher demand due to the lower picking error probabilities and better efficiency. Further, the 0 m case results in much higher payback periods, especially when an equal amount of pickers are needed. However, as mentioned earlier, this is a very rare case.

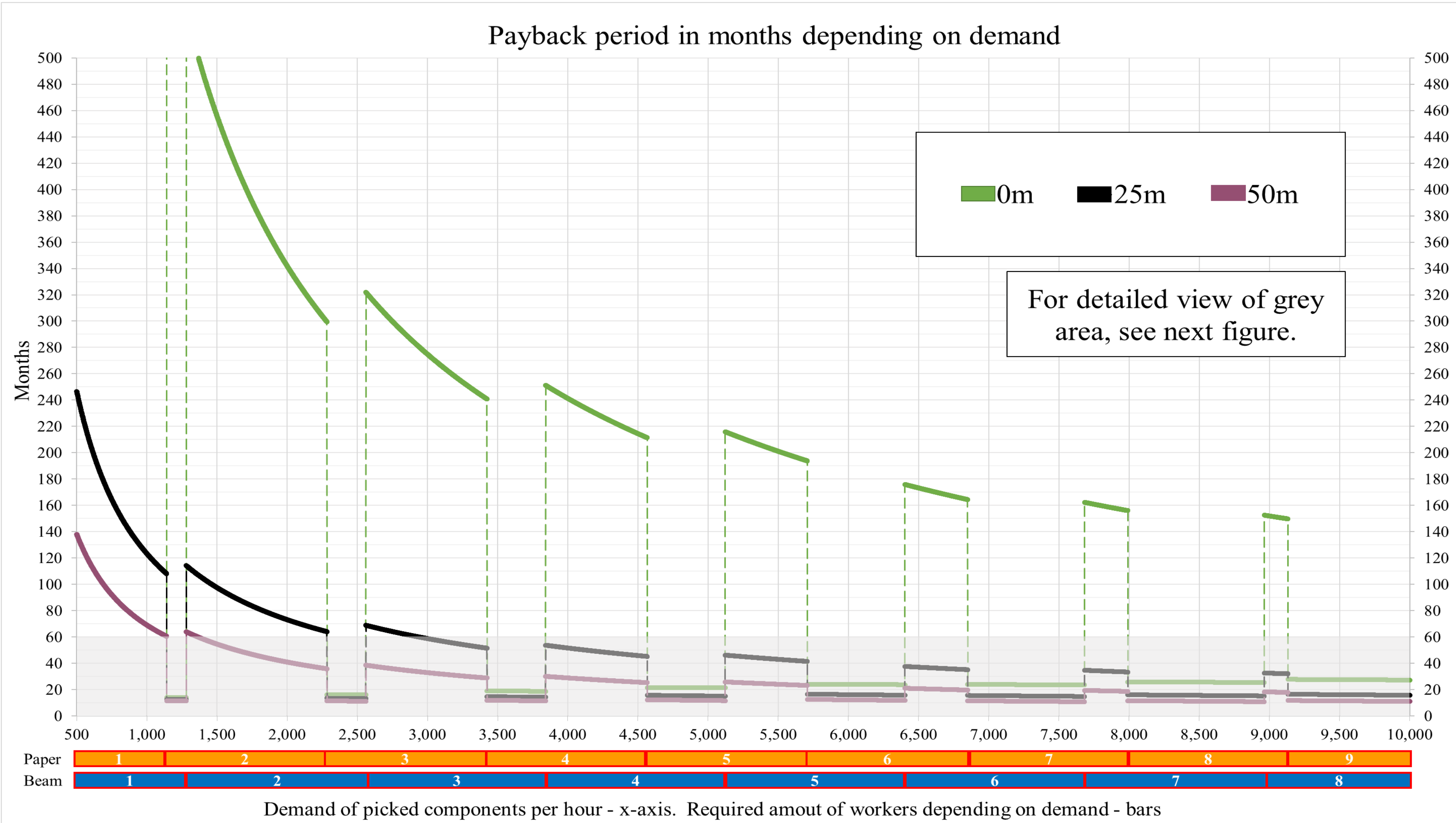


Figure 4.20: Payback period in months if Pick-by-paper is used today and one invests in Pick-by-beamer. Applicable for high picking density and a kit size of 15 components. The bottom part is visualized in the next figure as well and is therefore highlighted grey.

A distinct feature of the graphs is the jump discontinuities. These are a result of having different picking efficiency, the systems need an additional picker, and for Pick-by-beamer, an additional system, at different demand levels. When Pick-by-beamer needs an additional picker the payback period jumps up and when Pick-by-paper needs an additional picker the payback period jumps down. The ranges where the graphs have jumped down will further be referred to as “low values”. The impact of having a different amount of pickers is big since labor costs are a significant portion of the operational costs. For a demand higher than 10 275 components per hour, Pick-by-paper will never be able to achieve the same number of needed pickers and the payback period will constantly be low alternating between one and two additional pickers until it starts alternating between two and three, etc. Comparing to previous figures, e.g. hourly cost Figure 4.12, the jump discontinuities occur at the same demand levels.

Previous graphs on hourly costs show that Pick-by-paper is the best solution in some lower demand ranges, this means that it is the best solution with an investment horizon of five years and EUR 0 salvage value, however, Pick-by-beamer has the lowest operational costs at lower demand as well. Therefore, break-even is still reached at some point. Further, the investments for Pick-by-paper are very low and therefore, when Pick-by-paper is less costly than Pick-by-beamer in Figure 4.13, the payback period is above five years, and when Pick-by-beamer is less costly, the payback period is below five years. That analysis is confirmed by the results presented in Figure 4.20.

Further, the graphs have a negative gradient as a result of the lower picking error probability using Pick-by-beamer. Visually, it seems that this only affects the higher values of demand. However, the cost savings related to picking errors increase linearly as demand increases. The impact of picking errors on the lower values in the graph is lower since the operational savings are already very high for those values. Changing the operational savings from EUR 5 to EUR 6 per hour will have a bigger effect on payback period than changing it from EUR 50 to EUR 51.

As the lower part of Figure 4.20 has significant differences which are hard to interpret from the figure, Figure 4.21 shows a magnified view of this grey area. Most parts of the graphs are still visible apart from the high values for the less frequently used 0 m case. The 50 m case is seen to achieve around two months faster break-even than the 25 m case for the lower values and around five months faster for the higher values.

An interesting pattern is that the lower values for each setting are fairly constant as demand goes up or even increases for the 0 m case. This is because the cost of correcting picking errors for Pick-by-paper is increasing at a similar speed as the cost of investing in additional systems for Pick-by-beamer. All the low values use one more picker for Pick-by-paper, however, the Pick-by-beamer will need an additional system each time an additional picker is needed. Another pattern is that, looking at the low values it is seen that between, one and two, or five and six, pickers for Pick-by-beamer, the payback period drops slightly more, this is a result of the pricing model for Pick-by-beamer where the unitary price drops when more than two or five systems are bought. To conclude, a higher demand is still beneficial for Pick-by-beamer, as seen, the ranges where the lower values are achieved are increasing as picking demand goes up. Further, if it is increased to more than 10 000, a new low level would be achieved where it differs with two pickers.

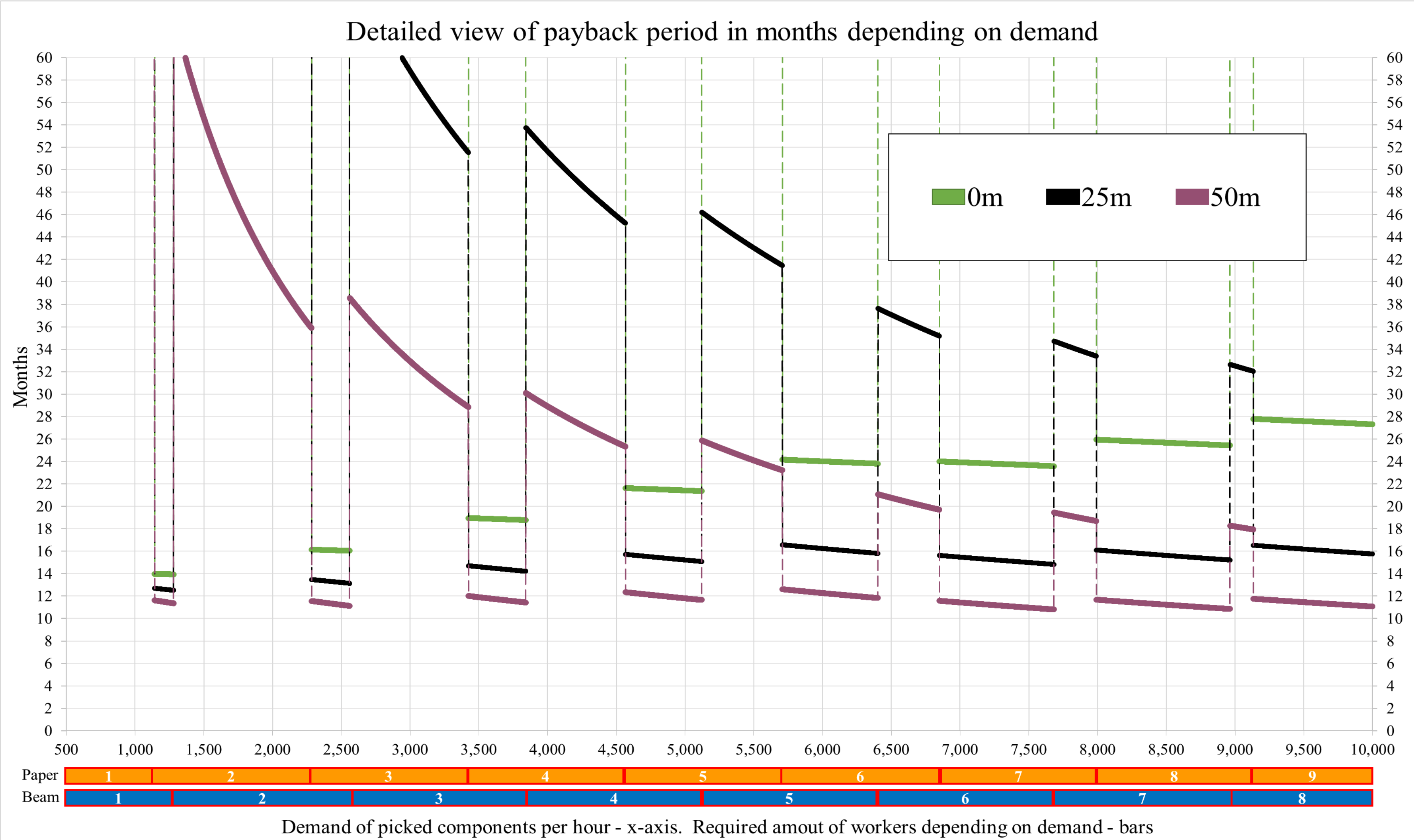


Figure 4.21: Detailed view of the grey area in Figure 4.20.

4.5.2.2 Payback period for low picking density

Figure 4.22 shows the payback period for the low picking density setting. It is based on the same formula and interpreted in the same way as Figure 4.20. Comparing them, the low picking density graphs have shorter payback periods, this is due to the higher costs for a picking error when the aisle is longer combined with the higher probability of a picking error occurring for Pick-by-paper due to the low picking density setting. However, the difference in efficiency between the two systems is slightly smaller for low picking density picking making the demand ranges giving low values thinner. Ultimately, the demand at which only the lower values will be achieved since Pick-by-beamer will have at least one less picker is moved from 10 275 to 13 552 components per hour, corresponding to 13 and 14 pickers.

As the lower part of Figure 4.22 has significant differences which are hard to identify, Figure 4.23 shows a detailed view of the same graph. Most parts of the graphs are still visible apart from the high values for the less frequently used 0 m case. The 50 m case is seen to around one month faster break-even than the 25 m case for the lower values and around four months for the higher values.

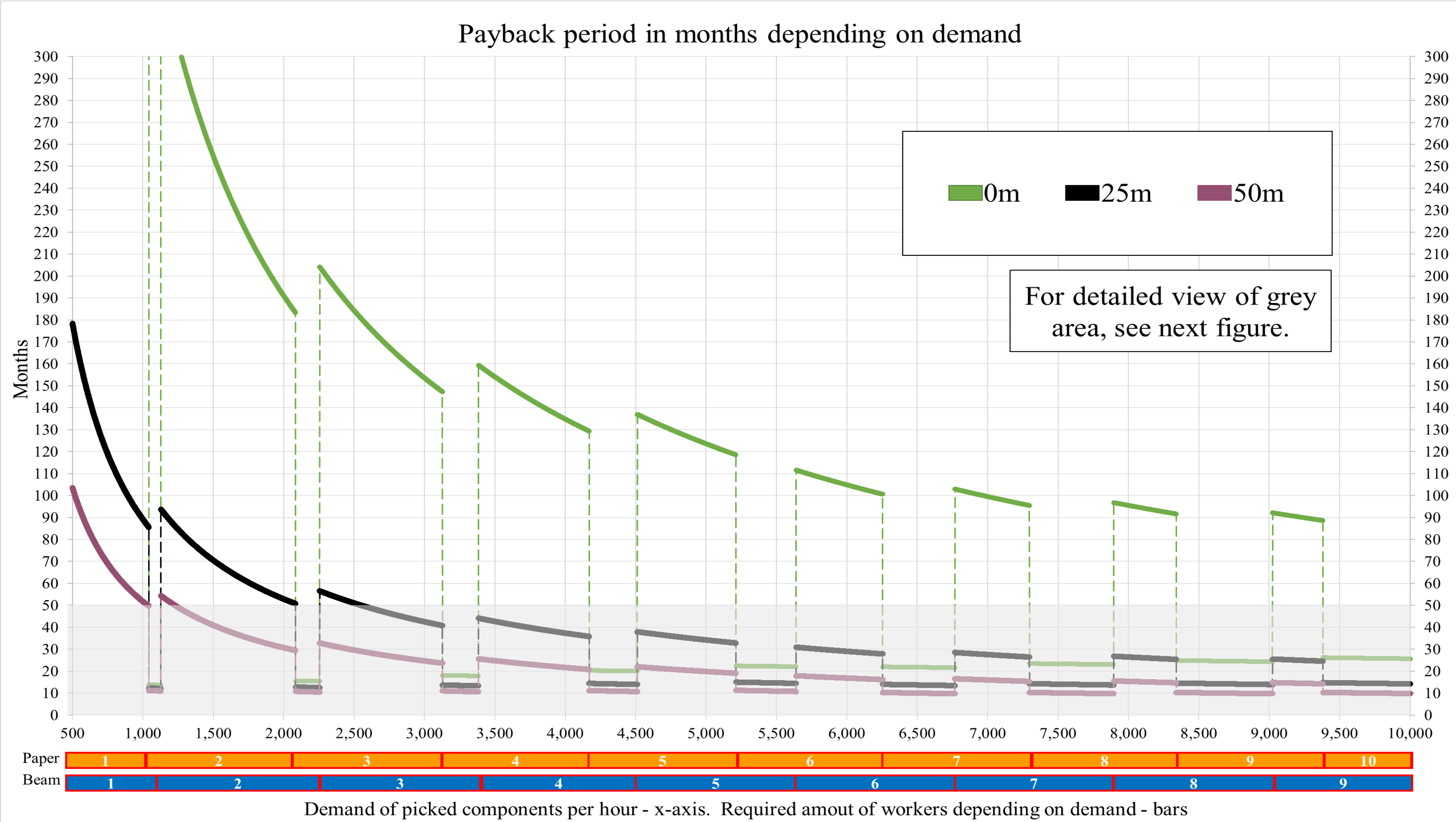


Figure 4.22: Payback period in months if Pick-by-paper is used today and one invests in Pick-by-beamer. Applicable for low picking density and a kit size of 15 components. The bottom part is visualized in the next figure as well and is therefore highlighted grey.

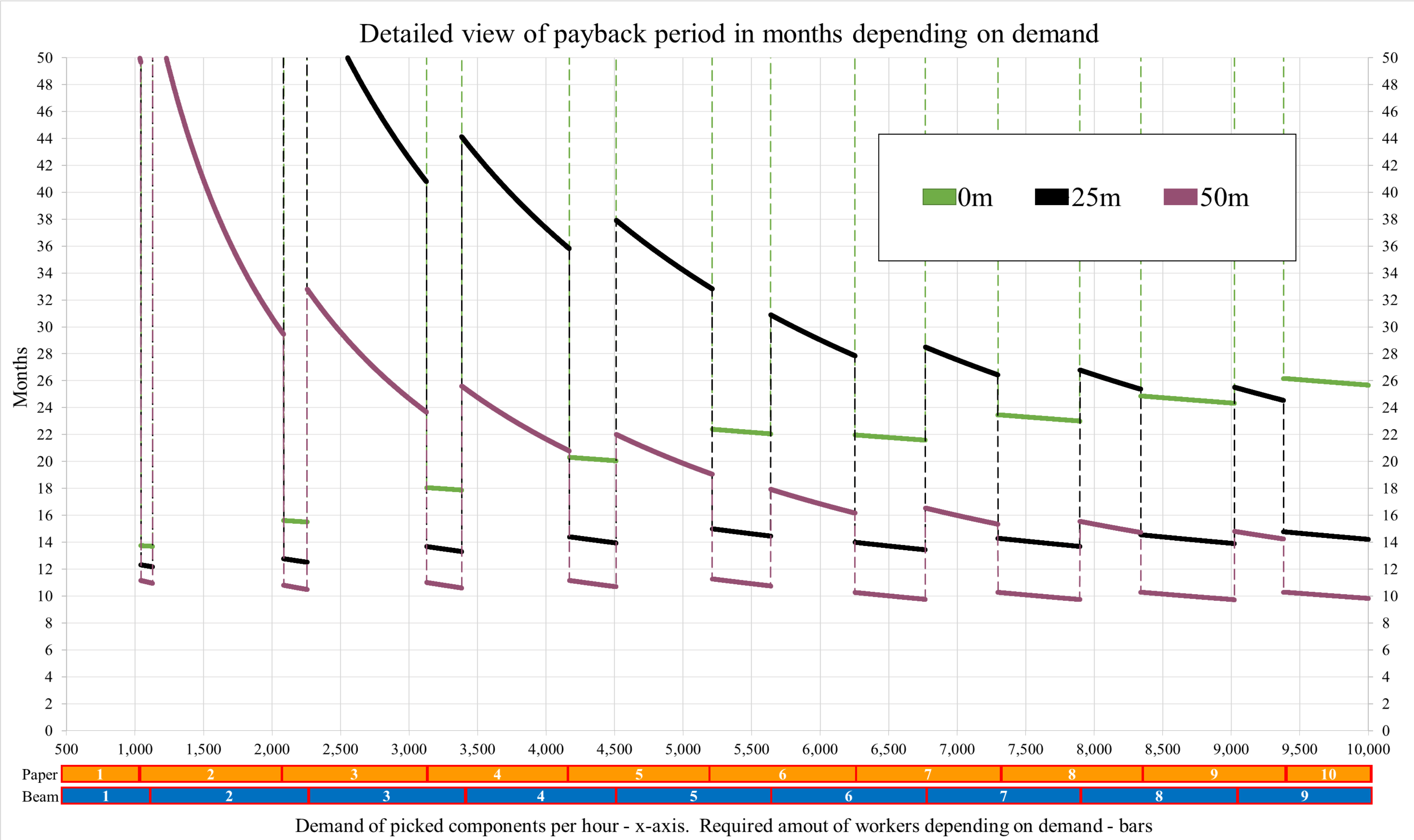


Figure 4.23: Detailed view of grey area in Figure 4.22

4.5.3 Net present value and return on investment

Figure 4.24, 4.25, 4.26, 4.27, show NPV and ROI for high and low picking density. As for payback, the figures showing settings with a kit size of 50 components are excluded. The NPV is based on the same operational savings used in the payback analysis, $C_{h,op_1} - C_{h,op_2}$. The savings are calculated yearly and discounted with a discount rate of 10%. It assumes the same time horizon as the hourly cost function, five years, which means that the operational savings are constant each year for five years, then the system breaks and has EUR 0 salvage value. The ROI is calculated using the NPV in relation to the investment at the specific demand.

Comparing the following figures to the payback graphs, a similar pattern is seen. However, it is inverted. As high NPV and ROI values are positive for the investment, while a low payback period is positive, the following figures' jump discontinuities are jumping the opposite direction. When Pick-by-beamer needs an additional picker, the graphs jump down and when Pick-by-paper needs an additional picker, they jump up. As a result, the high values are now the range where Pick-by-paper needs one more picker than Pick-by-beamer.

Looking at the first figure, 4.24, it is seen that the value of the investment is increasing steadily as picking demand goes up. Both, amount of pickers, and the picking error correction costs can heavily affect the value of the investment, at some ranges and distances ($\bar{D}$), over EUR 150 000 is saved. The 0 m case is once again behaving differently, the values are decreasing since the investment of an additional Pick-by-beamer is more expansive than what is saved in picking error correction costs. However, the NPV graph can disclose that a pattern seen in the payback period graph is not valid for the NPV. The "good" low values in the payback period figure seem the be fairly constant as the picking demand goes up, however, the respective "good" high values of the investment is actually increasing as the picking demand goes up.

The next figure (Figure 4.25) is affected in a similar way as the low picking density for the payback period was. It gives higher NPV as the setting is disadvantageous for Pick-by-paper due to the increased picking error correction cost. However, the "good" high values are thinner as the difference in efficiency is lower.

Figure 4.26 and 4.27 visualize the ROI. The ROI shows for the majority of the higher demand ranges steady high values. The high values in the graph (excluding 0 m case) is fairly constant as demand goes up, this is because the percentage increase of the NPV and the investment costs are similar.

In general, the investment can give very high NPV and ROI. This is logical as the cost of additional pickers and wasted time spent correcting picking errors is, for a five year period, a lot higher than the investment cost of the Pick-by-beamer.

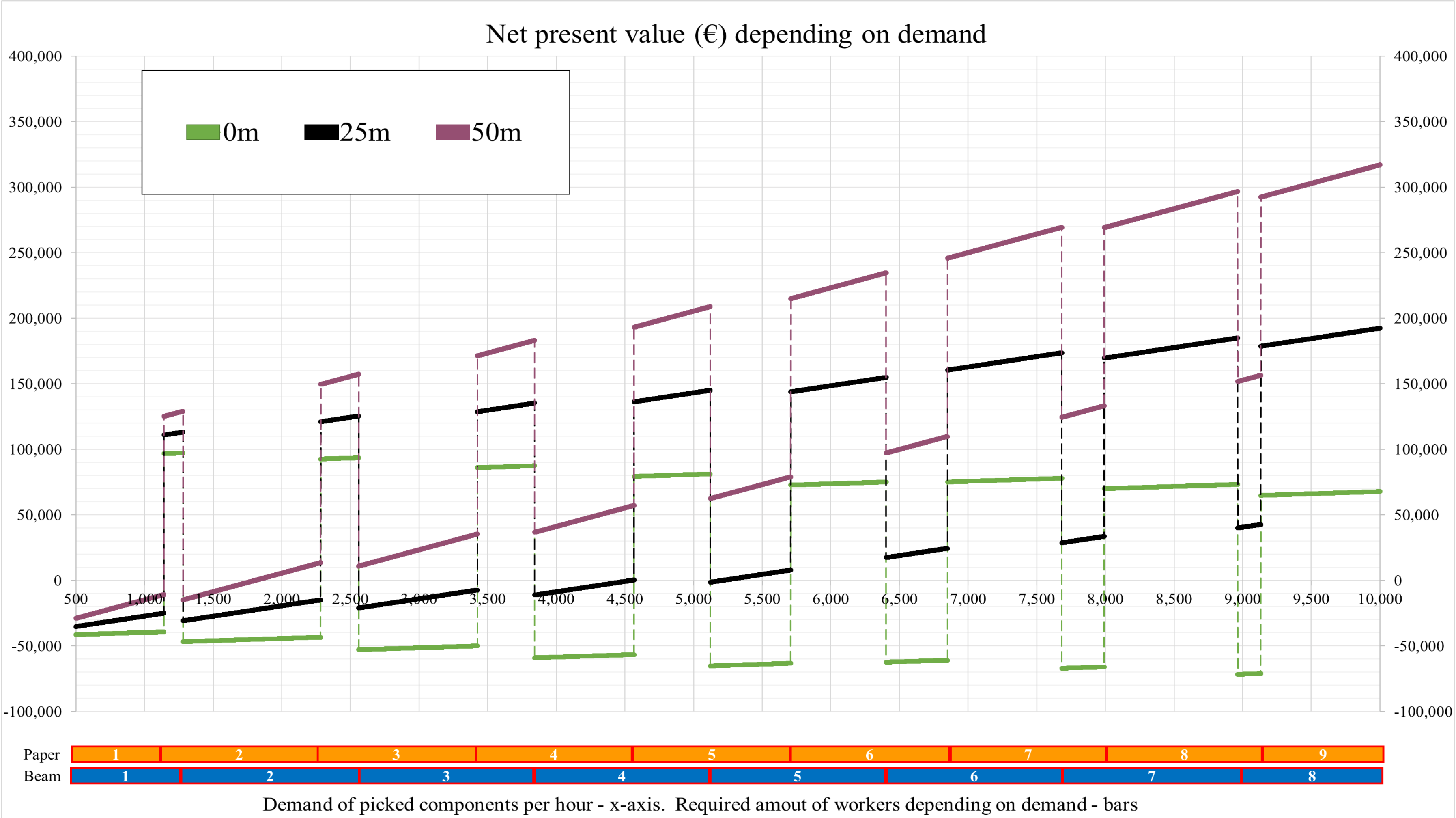


Figure 4.24: Graph shows net present value (€) of investment if Pick-by-paper is used today and one invests in Pick-by-beamer. Applicable for high picking density and kit size of 15 components.

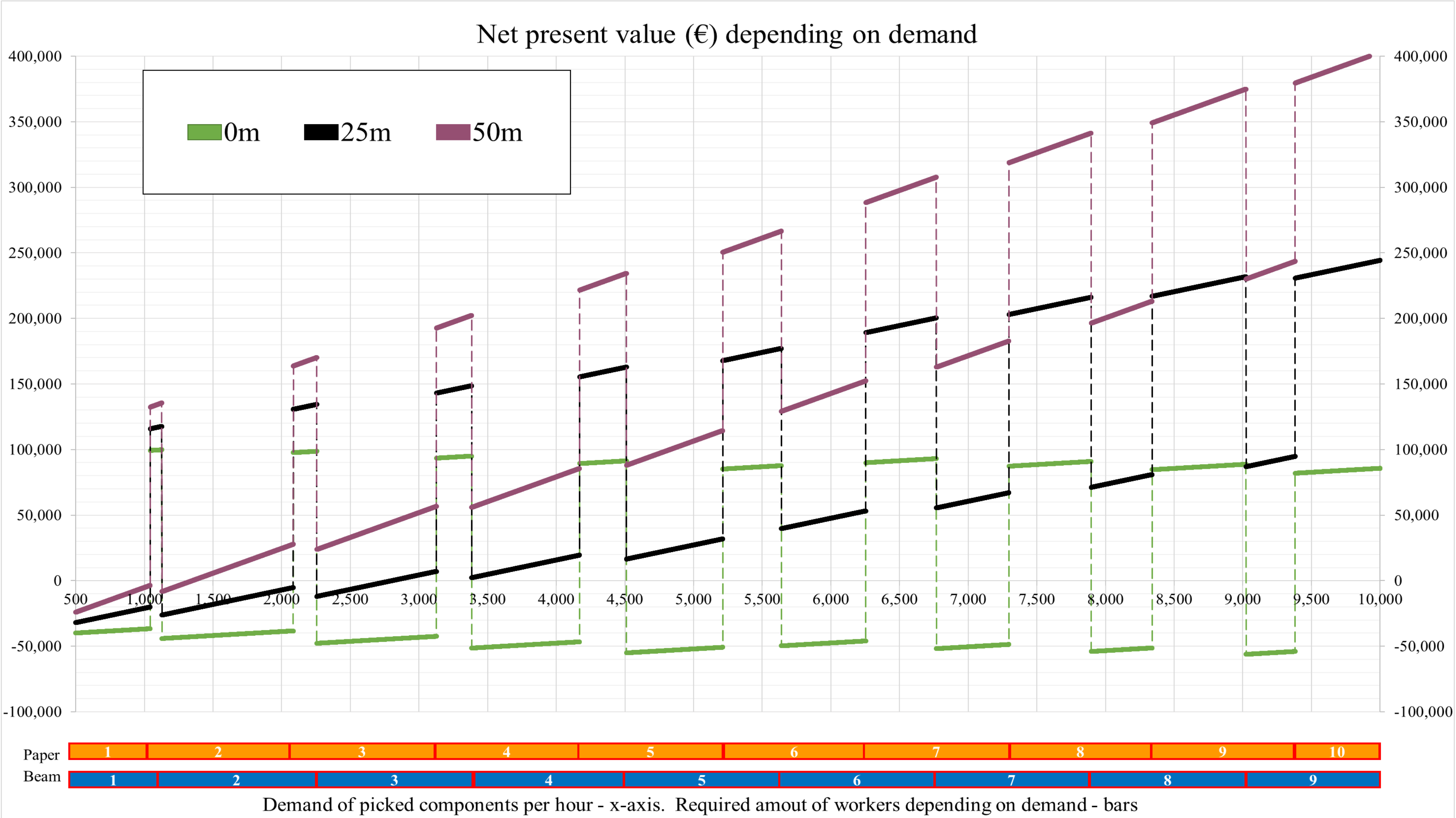


Figure 4.25: Graph shows net present value(€) of investment if Pick-by-paper is used today and one invests in Pick-by-beamer. Applicable for low picking density and a kit size of 15 components.

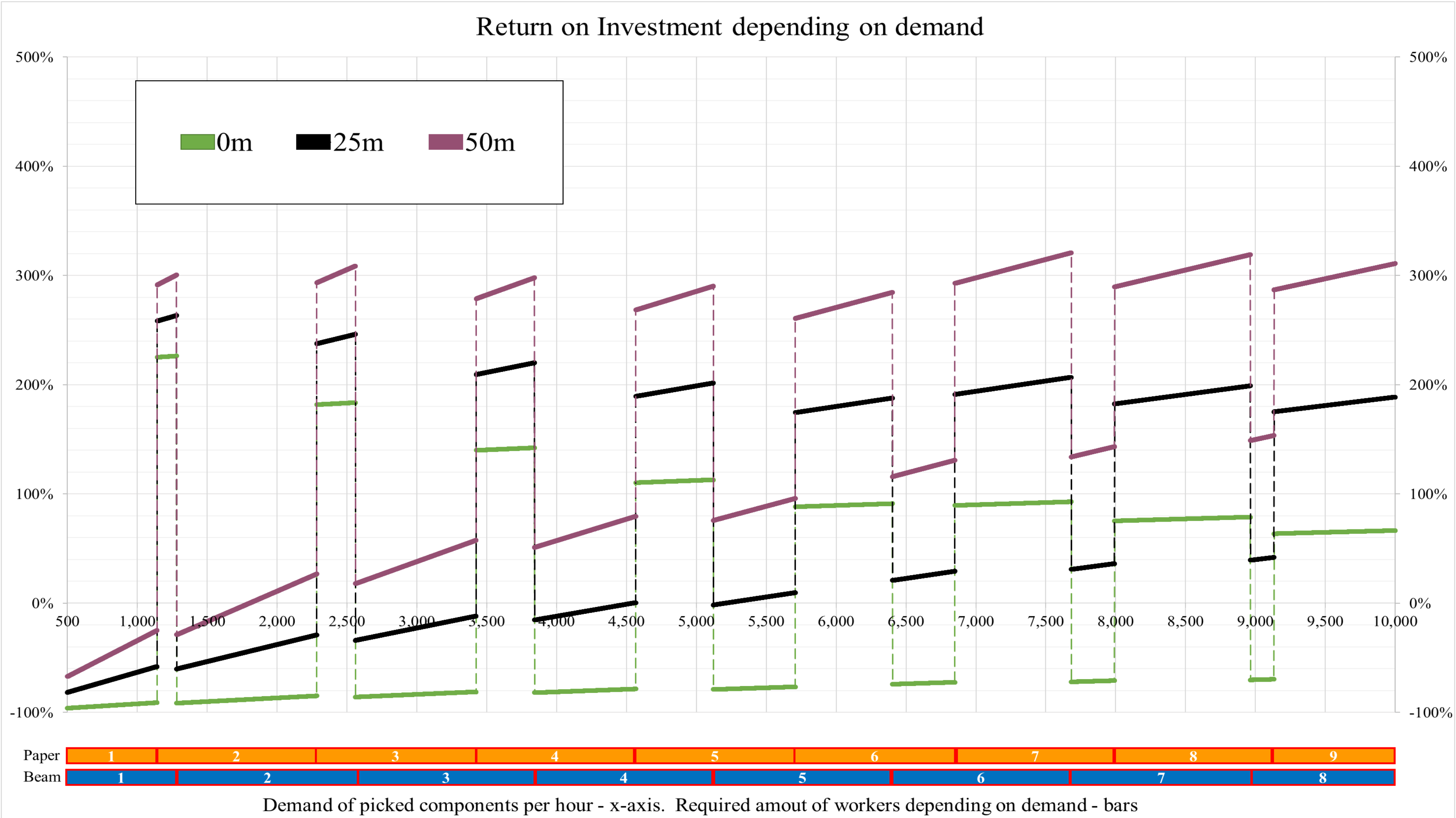


Figure 4.26: Graph shows return on investment if Pick-by-paper is used today and one invests in Pick-by-beamer. Applicable for high picking density and a kit size of 15 components.

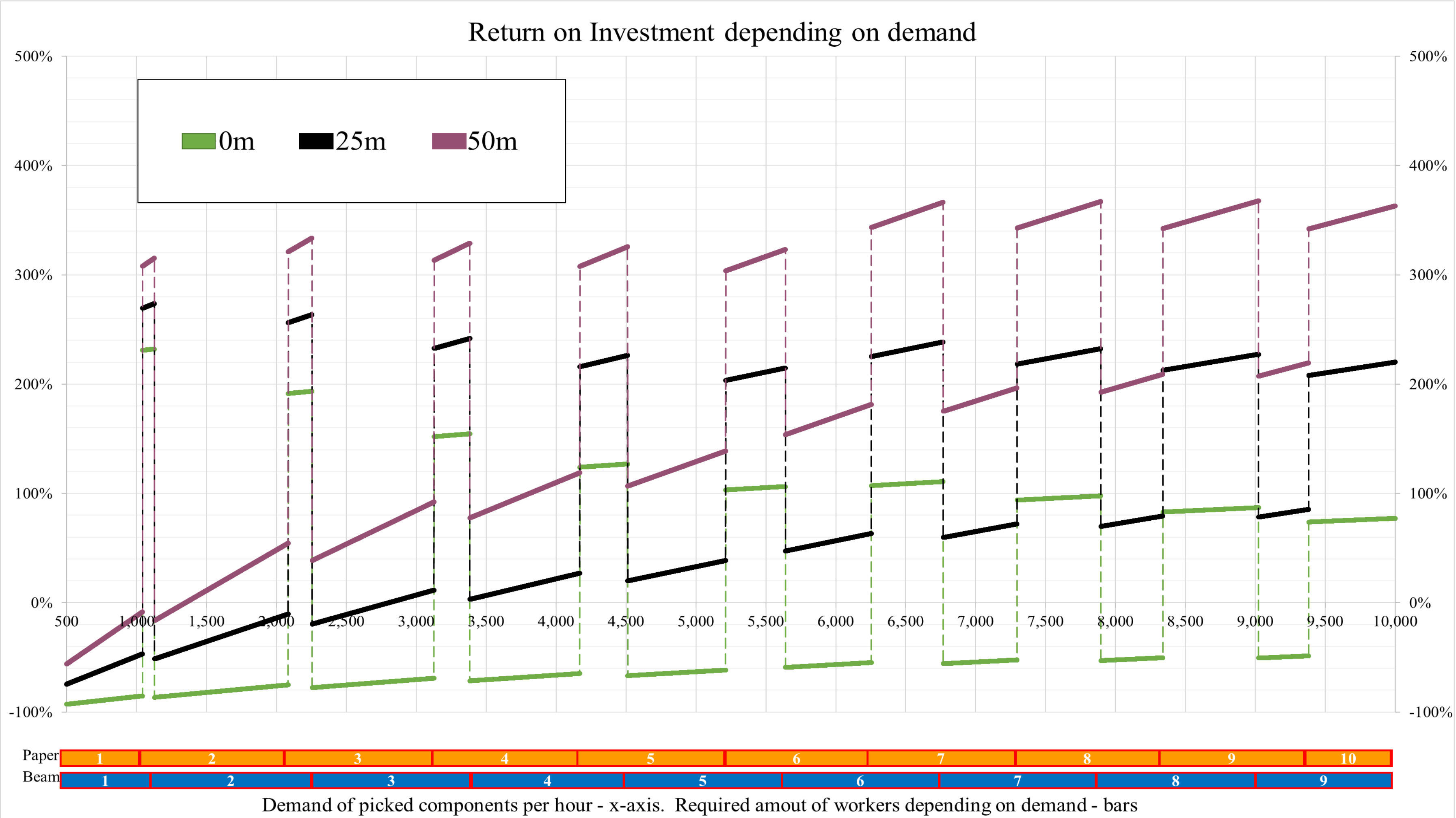


Figure 4.27: Graph shows return on investment if Pick-by-paper is used today and one invests in Pick-by-beamer. Applicable for low picking density and a kit size of 15 components.

5
Discussion

The discussion chapter is divided into two sections. The first section discusses the performance of the Pick-by-beamer system and how this performance could be explained through system-specific functions. The second section, economic evaluation, elaborates on the application areas and interpretations of the different graphs that were presented in the economic evaluation result section.

5.1 The performance of Pick-by-beamer

For a new type picking information system to constitute a competitive option in kit preparation, it has to offer advantages that established systems lack. As no previous studies had been done testing a picking information system using the same technology as Pick-by-beamer in kit preparation, it was important to determine the performance of the system. As mentioned previously in the report, the performance measure includes picking efficiency and picking accuracy. The subsections below discusses the results on performance on these two metrics for Pick-by-beamer that were presented in the previous result chapter.

5.1.1 Picking efficiency of Pick-by-beamer

As many different picking information systems are used for kit preparation today, it was of interest to investigate the relative picking efficiency of Pick-by-beamer to these systems. The picking efficiency of Pick-by-beamer was measured from two sources, an experiment and an MTM-SAM analysis. From the experiment, the performance of Pick-by-beamer was observed to be dependent on batching policy with significantly higher picking efficiency in batch preparation. Looking at the relative performance in single-kit preparation, the picking efficiency of Pick-by-beamer was approximately equal to the picking efficiency of Pick-by-paper. The statistical analysis confirmed that there was no significant difference in picking efficiency in single-kit preparation between the systems. For the other batching policy, batch preparation, Pick-by-beamer had a very competitive picking efficiency. The picking efficiency of Pick-by-beamer was observed to be higher than for Pick-by-paper and statistically significant. The lower competitiveness of Pick-by-beamer was thought to be caused by the limitations of the system described in section 4.1.4. As no permanent equipment e.g. light indicators are installed at the storage locations, the Pick-by-beamer system required the picking trolley to remain parked at a designated spot during a picking assignment for it to project light onto the storage locations. This requirement limited the pickers' mobility when using the system and required extra precision when parking the picking trolley. Therefore, the ability to reduce the time consumption of non-value adding activities Walk one step and Push picking trolley was limited and, thereby, more time was spent on these two module categories for Pick-by-beamer compared to other picking information systems. However, if enough picking assignments are to be done between each parking of the picking trolley, the time spent on parking the picking trolley with precision had less impact on the total time consumption. This was the case of batch preparation with Pick-by-beamer.

However, as the experiment only enabled a comparison of Pick-by-beamer against Pick-by-paper, an MTM-SAM analysis was carried out to expand the comparison to include Pick-by-light and Pick-by-voice. It was confirmed from the MTM-SAM analysis that Pick-by-beamer in batch preparation did not only have a higher picking efficiency than Pick-by-paper but also higher than Pick-by-light and Pick-by-voice. One of the key strengths of the Pick-by-beamer system in terms of picking efficiency is the touch-less confirmation. The touch-less confirmation of a placement in kit allowed the picker to place a component in a kit while the system simultaneously confirmed the placement through its depth sensor. As the confirmation was done simultaneously as the placement of a component, the time spent on the non-value adding activity of confirming a placement was eliminated, resulting in an increase in picking efficiency. A similar strength was found for Pick-by-light in single-kit preparation in a study by Fager et al. (2019) where the placement of components in the kit did not require an additional activity. In that study, Pick-by-light in single-kit preparation was found to have superior picking efficiency in kit preparation. The study concluded that the selection of appropriate confirmation activity procedures had a significant efficiency potential for a picking information system in kit preparation (Fager, 2019).

An overall observation from the MTM-SAM analysis was that a majority of the studied picking information systems had a higher picking efficiency in batch preparation apart from Pick-by-light which had a higher picking efficiency in single-kit preparation. This result is in line with the results of Fager et al. (2019). The higher picking efficiency in batch preparation is thought to be due to the reduced time per component spent on walking, picking, placing, and confirming. However, for Pick-by-light in single-kit preparation, an explanation to the high picking efficiency is thought to be the less time spent on searching for the kit on the trolley and not having to interpret the amount of components to pick on a small display together with no confirmation of a placement.

It became evident from the MTM-SAM analysis of Pick-by-paper, Pick-by-light and Pick-by-voice that the design of a picking information system had a significant impact on the picking efficiency efficiency of the kit preparation process. A structured design process of the new Pick-by-beamer system was therefore imperative to design a system that was promoting a high picking efficiency. However, despite the structured and multi-faceted design process carried out in this study, the design of the Pick-by-beamer is remaining at an exploratory stage where further design enhancements can improve the performance of the system. Therefore it is possible that the picking efficiency of Pick-by-beamer is limited by the design process rather than the system itself. It is likely that the Pick-by-beamer system developed in this study could achieve an even higher picking efficiency if the system had been tested and optimized over a longer period.

When comparing the picking efficiency measured from the experiment and MTM-SAM analysis, it was observed that the picking efficiency was also very consistent between the two sources. The high degree of consistency of the picking efficiency is is an indication that the modules developed for the MTM-SAM analysis had an adequate level of detail to describe the kit preparation process of different picking information systems.

Since the MTM-SAM analysis used video-recordings from two different experiments conducted at different occasions by different people, it was also important to mitigate the risk of introducing biases into the MTM-SAM analysis from different working movements caused by differences in experiment setup. Despite different subjects, i.e., participants, in the experiments in the two studies, this was thought to have little impact on the performed movements during the kit preparation process. As movements from different participants in the experiments were analyzed and translated into most commonly performed movements, the most significant impact on movements performed by the participants was thought to be differences in the experiment setup. If the experiment setup could be concluded to be similar and the recruitment of participants followed the same criteria, the movements performed by the participants in the experiment was assumed to be the same as if they would have been done by one group of participants.

Apart from examining video-recordings of the experiment setup and consulting the experiment owners, the similarity of the experiment setup was verified by comparing the average time consumption for Pick-by-paper. Pick-by-paper was tested in both this experiment and the experiment by Fager et al., 2019 and hence allowed to verify consistency in time consumption between the studies. In Single-kit preparation, the average time consumption was lower in the experiment Fager et al. (2019). However it was thought that this would not impact the validity of the MTM-SAM analysis since both Pick-by-beamer and Pick-by-paper showed a considerably lower average time consumption in batch preparation compared to single-kit preparation. The lower average time consumption in single-kit preparation is indicating that the video-recordings for single-kit preparation from the study by Fager et al. (2019) shows a slightly faster working pattern. This could in turn make the MTM-SAM analysis liberal to Pick-by-light and Pick-by-voice in single-kit preparation and conservative to Pick-by-beamer in single-kit preparation. With video-recordings showing a slightly slower working pattern in this study, it is possible that Pick-by-beamer could achieve an, on average, higher time consumption single-kit preparation in the MTM-SAM analysis. However, even if Pick-by-beamer would have been tested in the slightly faster single-kit preparation environment in the study by Fager et al. (2019), it is unlikely that Pick-by-beamer would have achieved a lower average time consumption in single-kit preparation compared batch preparation. As Pick-by-beamer in batch preparation has an average time consumption that is between 2.5 (high picking density) and 3.1 (low picking density) seconds faster per picked component, it is very likely that the system would still have a lower time consumption in batch preparation where the studies have, as validated, similar settings.

5.1.2 Picking accuracy of Pick-by-beamer

The other performance metric, picking accuracy was also measured for Pick-by-beamer and Pick-by-paper in the experiment. The picking accuracy served as a variable that was monitored to assess if a high picking efficiency was achieved at the expense of more picking errors being made. A second indication on the competitiveness of the Pick-by-beamer system was provided by its high picking accuracy. Out of 3 600 picked components in batch preparation, Pick-by-beamer had zero picking errors which can be compared to 36 of Pick-by-paper. A theory to the potentially high picking accuracy of Pick-by-beamer stems from three design aspects. The beaming light projected from the projector unit is covering approximately the entire storage location that a component is to be picked from. Projecting light directly onto the storage location is making the storage location more prominent compared to having a physical light indicator place adjacent to the storage location. By highlighting a storage location, the location is more distinguishable from other locations which according to Norman (2013) could reduce the likelihood of an error being made. Also, the two-stage information conveyance is thought to be effective in preventing picking errors as it reminds the picker on what quantity to pick multiple times during a picking assignment. The third and last function of the Pick-by-beamer system that prevents placement errors is the detection of a wrong placements described in section 4.1.4.

With over 90% of the picking errors being in error category e_1 and e_2 for Pick-by-paper, there is an indication that a picking error is more likely to be caused by the picker either picking one component too many from the storage location or that the component is placed in the wrong kit. Based on this information, it could be argued that a picking information system more efficiently can prevent picking errors errors if intuitive information conveyed at the picking trolley. However, as the sample size in this study was too small to conduct a statistical analysis of the picking errors, these results should be treated treated cautiously. To be able to conclude the true picking error probability of a picking information system, the system needs to be studied over a longer period as picking error have a rare occurrence.

It cannot be emphasized enough that the picking error results presented should merely be used as an indication. It is not appropriate to believe that picking errors never occur with Pick-by-beamer in neither of the batching policies tested in this study. Even though the results indicate that the probability of picking errors may be lower for Pick-by-beamer compared to Pick-by-paper in batch preparation, a larger sample size would provide a more accurate, non-zero, estimate of the picking error probability.

5.2 Economic evaluation of Pick-by-beamer

Using the figures presented in the result chapter, managers can get an understanding of the costs related to each of the picking information systems. The hourly cost graph can guide a manager who is constructing a new kit preparation area and wants to know which of the four systems will be the least costly to invest in and use. Further, managers who are using Pick-by-paper today and want to reduce their operating costs can use the payback, NPV and ROI to evaluate the investment opportunity of a Pick-by-beamer system.

As graphs for several settings are presented, the graphs indicate the trends that occur if the kit size or picking density is changed. Therefore, managers constructing or using a picking setting not included in the visualized settings can still get an understanding of the costs connected to their specific setting. Figure 5.1 summarizes the relative difference of how the systems are affected if a variable were to increase. The table shows in order what system has the highest percentage increase in cost if a specific variable were to increase. A remark is that Pick-by-beamer gain more efficiency than Pick-by-paper from increasing the picking density. That is expected as a large portion of the picking time using Pick-by-beamer is spent putting the trolley into position. However, Pick-by-paper still has a lower increase in cost when density increases since the error probabilities for Pick-by-paper used in this study are lowering when the picking density increases. That trend of fewer errors as picking density increases for Pick-by-paper is hard to explain and can be a result of the small sample size for errors. Deducting that trend, the Pick-by-beamer would benefit more from increasing the picking density than Pick-by-paper. In general, changing the kit size or picking density does not bring in any major changes in the result, however, they do function as a sensitivity analysis. Therefore, the cost results and general trends identified related to picking demand and distance ($\bar{D}$) present throughout all the settings become increasingly robust since it is tested in four different settings.

PBP = Pick-by-paper
PBB = Pick-by-beamer
PBL = Pick-by-light
PBV = Pick-by-voice

Picking information system with highest and lowest percentual increase in hourly cost

Increasing variable	Highest			Lowest
Picking demand	PBV	PBP	PBL	PBB
Kit size	PBP	PBL	PBV	PBB‡
Distance ($\bar{D}$) to correct picking error	PBP	PBV	PBB/PBL‡	
Picking density	PBV	PBB†	PBP†	PBL†

† The hourly cost decreases.
‡ The hourly cost does not change.

Table 5.1: Effect on the hourly cost for each system when the value of a variable is increased.

To better understand and interpret the results, three factors and their effect should be emphasized and elaborated. Those are a set of assumptions and simplifications. The first factor is the simplification that the only way picking errors are accounted for in the cost formula is by adding an error correction time and multiplying that with the cost of a picker. In practice, the cost of an error can have much larger consequences than the time it takes to correct the specific mistake. In a worst-case scenario, it can stop the production line or deliver faulty products to end customers. As argued by Brynzér and Johansson (1995), picking accuracy is of highest importance causing issues both internally for the production and externally for unsatisfied customers. Consideration such consequences in the investment decision strengthens the incentives to proceed with Pick-by-light or Pick-by-beamer as that lowers the error probability.

The second factor is the investment horizon of five years, and zero salvage value, used in the hourly cost, the NPV, and the ROI graphs. If a company uses a longer investment horizon, which is reasonable considering that the system could be used for longer, or adds a salvage value, the results would change slightly. Investment heavy systems would obtain a slightly lower hourly cost. For most settings and demands, Pick-by-beamer is the most investment heavy system, followed by Pick-by-light for low demands and Pick-by-voice for high demands while Pick-by-paper has by a large margin the lowest investment costs. It would also increase the NPV and ROI of investing in a Pick-by-beamer

The third factor is the jump discontinuities and the steps seen in the graphs, those are based on a simplification of reality. These are a result of not including the potential value that may be created when pickers are at a lower workload. Right after the graphs jump up, the average workload at the kit preparation area will decrease. This decrease in workload can in several ways be beneficial for the company, those are not accounted for in the model. Examples of this are; the pickers may use the time to create value or bring revenue elsewhere in the company; the lower workload creates a safety margin in case of disturbance or disruption of the working process, the pickers could have flexible teams helping at other stations; lastly, the lower workload may affect things such as company culture or even the health of pickers. Accounting for value created by decreasing the workload, the sharp edges i.e., the steps, of the hourly cost graphs, seen in Figure (4.12), would be removed. Thereby, the jump discontinuities would also change and instead have a sharp incline or decline. However, this would affect all systems and, therefore, it would not significantly change the result. However, as a result of the offset in the steps due to the different efficiency between systems, seen in Figure (4.12), the workload varies differently between systems depending on the picking demand. Thereby, at some demand ranges, one system will have a very high workload while the other has a very low. Consequently, some extremes would be mitigated and some would be amplified. Those are identified by "smoothening" the corners and jumps of graphs and in the result chapter. Managers should consider this factor when choosing a picking information system, pushing the top limit efficiency of a system may not be the best strategy as it has external effects.

There are four additional limitations helpful to understand to make full use of the economic evaluation. First, as discussed earlier, the design of the Pick-by-beamer solution is as opposed to the competing solutions, still at an exploratory stage. Therefore the performance of the Pick-by-beamer may be hindered by the process design rather than the concept itself. Secondly, related to the payback, NPV and ROI figures, for a few low demand ranges in certain settings seen in the hourly cost graphs, e.g. (Figure 4.12), Pick-by-light performs slightly better and would, therefore, achieve better results on the investment metrics than Pick-by-beamer. Third, the data set for errors were small and could slightly alter the financial analysis. Forth, the investment costs used did not include service costs for the picking information systems in use. For example, the buttons do with time need a replacement for Pick-by-light.

To conclude, the graphs in the result chapter gives a solid indication of the investment value of different systems. However, as a consequence of the discussed factors and other limitation's within the study, the investment decision should be complemented with additional situation-specific analysis. Three general trends are persistent through all the settings and can be deducted as true regardless of the specific scenario. Those are:

1. Pick-by-beamer is a superior option for the majority of scenarios and demand ranges
2. Pick-by-beamer becomes increasingly competitive as the demand increases
3. Pick-by-beamer and Pick-by-light become increasingly competitive as the distance ($\bar{D}$) between the assembly line and the kit preparation area increases.

5.3 Sustainability aspects of Pick-by-beamer

In terms of social sustainability, subjects in the experiment thought that the Pick-by-beamer system was providing picking information in a very intuitive way that relieved the participant from relying on memory. Being less dependent on memory during the kit preparation process is an advantage from a picking error prevention perspective as this avoids memory lapses (Norman, 2013). However, reducing the cognitive load makes the kit preparation process less stimulating for the picker. Despite providing great picking error prevention capabilities, consideration must also be taken to the psychological health of the person using the system. One way to minimize the likelihood of deteriorating the psychological health of the picker due to monotonous work tasks is having scheduled rotation between different work tasks (Bauch, 2004).

Another aspect of sustainability is economic sustainability, it is either defined as; economic development that does not have a negative impact on ecological or social sustainability; or as, simply economic growth in terms of increased capital resources of Tehnology, 2018. This study has developed a system that can potentially increase the value created with a picking information system using less economical resources. Further, implementing it does not have any major effect on other aspects of sustainability.

5.4 Future studies

Future studies should focus on contributing to the knowledge of the competitiveness of Pick-by-beamer. Research is needed regarding the implementation and business opportunities for Pick-by-beamer. Also future research should be aimed at continuing investigating other aspects relevant in the choice of a picking information system in kit preparation.

In terms of implementation of Pick-by-beamer, future studies should include development of an automatic communication between the Pick-by-beamer software and an ERP-system. This would simplify the process of implementing the Pick-by-beamer system in the already existing ecosystem of a factory. Further, additional testing in a factory environment over a longer time-period needs to be studied. By doing this, one can obtain data on service costs, accurate error probabilities and the average lifetime for the Pick-by-beamer system which should be incorporated in the analysis. Also, in terms of disrupting the current use of picking information systems in kit preparation, additional business analysis is essential to understand the dominance of established competitors producing picking information systems, the barriers to entry, the value chains, logistics, etc.

As emphasized in the literature (Fager et al., 2019; Fager, 2019; Hanson et al., 2017), the choice of picking information system in kit preparation depend on many variables. This study has outlined two, a comparative analysis of the performance and cost of different Picking information systems with focus on Pick-by-beamer. Future research should focus on other aspects to aid decision makers in their choice of picking information system. These aspects include flexibility, ergonomics and a comprehensive analysis of picking errors for different systems.

6 Conclusion

In this chapter, the two research questions stated in section 2.2 in Chapter 2 are answered.

1. *Can Pick-by-beamer be a feasible solution and compete in performance with Pick-by-paper, Pick-by-light and Pick-by-voice in kit preparation?*

This study has shown that Pick-by-beamer can be a feasible solution as a picking information system in kit preparation. The design of the system is based on an MTM-SAM analysis of Pick-by-paper, Pick-by-light and Pick-by-voice with support from the literature. The first indication of the competitiveness of Pick-by-beamer was observed from the preliminary MTM-SAM analysis of the system where the design of the system was verified in terms of picking efficiency. The indication of the competitiveness of Pick-by-beamer was in turn verified through both through the experiment and MTM-SAM analysis. The statistical analysis of the experiment data verified that Pick-by-beamer is a competitive picking information system when used in batch preparation. Pick-by-beamer in batch preparation is superior to Pick-by-paper in both in single-kit preparation and batch preparation. The MTM-SAM analysis made it possible to broaden the comparison to include Pick-by-light and Pick-by-voice. Also in the MTM-SAM analysis, Pick-by-beamer in batch preparation is concluded to be a competitive picking information system with the highest theoretical efficiency of all other picking information systems in both single-kit preparation and batch preparation. The competitiveness of Pick-by-beamer is achieved through its ability to convey intuitive picking information through projections together with simultaneous place-to confirmation through its embedded smart sensors. It is concluded both from the statistical analysis and MTM-SAM analysis that these features of Pick-by-beamer can be less advantageous depending on the batching policy of the kit preparation process. It is concluded that Pick-by-beamer is less advantageous and does not constitute a competitive solution when used in single-kit preparation. In terms of picking error occurrences, Pick-by-beamer produced very promising results in the experiment. No picking errors were recorded for neither single-kit preparation nor batch preparation out of 4 500 picked components which can be compared to 36 of Pick-by-paper. As no statistical analysis could be done on the picking errors due to the insufficient sample size, the results on picking error occurrences for Pick-by-paper and Pick-by-beamer should only be interpreted as an indication of picking accuracy.

2. *Can pick-by-beamer compete economically with Pick-by-paper, Pick-by-light and Pick-by-voice in kit preparation?*

This study shows that Pick-by-beamer can compete economically with Pick-by-paper, Pick-by-light and Pick-by-voice in kit preparation. Accounting for the needed investments and for the operational costs of the picking information systems, Pick-by-beamer is the least costly option to invest in for a majority of the settings (varying with kit size, picking density and distance ($\bar{D}$)) and picking demand ranges. Further, if the factory is already up and running and Pick-by-paper is currently used, investing in Pick-by-beamer is a lucrative choice for a majority of the settings and picking demand ranges. However, for some situations, Pick-by-beamer is not economically justified, the situation in which the Pick-by-beamer becomes lucrative is in general decided by two factors: first, the number of pickers needed, and second, the cost of correcting errors for Pick-by-paper. If the picking demand combined with the system-specific picking efficiency results in a situation where Pick-by-beamer needs at least one fewer picker, the system becomes lucrative. Further, if the cost of correcting errors is high, either because of the specific setting combined with a high picking demand, or because of external effects not included in this study such as interruption of the production, the Pick-by-beamer system becomes lucrative. If both the needed amount of pickers are lower for the Pick-by-beamer system, and the cost of errors in the specific factory is high, the system becomes a superb investment achieving an ROI of up to 300% equivalent to an NPV of around EUR 300 000 for eight invested units operated for five years.

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A

The Human-Interface-Mate

The Human-Interface-Mate (HIM) is a system used for conveying information and task confirmation. The current application area is in operator guidance for complex assembly tasks of high variability where it is hard for the operator to remember each step (Arkite NV, 2020b). The system provides real-time visual instructions with images and text through a projector with the ability to detect and warn if the instructions are not followed correctly (Arkite NV, 2020b). HIM has proven to be especially useful for tasks where quality mistakes are costly and where there is a high employee turnover.

The HIM unit (Figure (A.1) consists of an infra red sensor and a depth sensor connected to an internal computer, running a Windows 10 operating system. The HIM unit is in turn connected to one up to three projectors conveying picking information. The quality of operations increases as the sensors can validate if the picking and assembly is executed correctly and thereby, human errors are mitigated. The hardware of the HIM unit and projectors are integrated through a software (Schildt, 2018). The physical components are not invented by Arkite NV, hence, the innovation lies within the software rather than the physical components.

Figure A.1: The Human-Interface-Mate by ARKITE Nv.

The HIM software is has a user friendly interface that makes it possible for anyone to create operator guidance instructions without prior programming knowledge. Further Arkite NV (2020a) state that it is possible to integrate the HIM with the customer's ecosystem, such as smart tooling, MES and ERP.

In 2019, Arkite NV (2019) revealed that they had raised EUR 1.5 million to grow internationally. They explain that they intend to use the money to answer to the coming customer needs in the new markets, further they are investing in system integrators to expand their sales network. Therefore, they state that investors believe that the expansion can make HIM an important industry 4.0 player. They saw ARKITEs' potential in the tough industry 4.0 market as the HIM is already used by leading customers in the manufacturing industry today (Arkite NV, 2019). Today, HIM is used at around a hundred facilities across Europe including several industry-leading actors such as Volvo Cars, Atlas Copco and CNH (Arkite NV, 2020b).

B

Modules in MTM-SAM analysis

The following appendix shows the different modules used in the MTM-SAM analysis. In total, the modules were used 2872 times, each time with a factor of 1 to 40. The factor depends on the amount of time the modules were used in the specific sequence for the specific system. In the tables below, the factor is set to 1 for all modules apart from the searching modules. At the searching modules, the factor represents the number of times the module was needed in one sequence for the specific system. Below follows a description of the five different module categories in table 3.1, how each of them were derived and which of the five variables in table 3.2 that the module category depends on. The variables that the module category depends on determine which module in that category is performed by the picker in a specific situation.

B.1 Module category 1: Search location

The Search location module category involves searching for storage locations to pick component(s) from and kit to place component in. The choice of module in the module category is dependent on the variables Picking information system, storage density and batching policy. Below follows three tables for Pick-by-paper, Pick-by-light and Pick-by-voice, illustrating the choice of module depending on the levels of each variable. A dash sign in a table indicate that no module was performed for that activity, e. g in single-kit preparation where the activity of searching for the kit on the picking trolley is assumed with such low level of simplicity for that module to be ignored.

Table B.1: The different modules for Pick-by-paper (PBP in the table) for the search locations activity.

Variable	Search storage location				Search kit location			
Picking information system	PBP							
Storing density	High		Low		High		Low	
Batching policy	(s)	(b)	(s)	(b)	(s)	(b)	(s)	(b)
	S2	S2	S6	S6	-	S3	-	S3

Table B.2: The different modules for Pick-by-light (PBL in the table) for the search locations activity.

Variable	Search storage location				Search kit location			
Picking information system	PBL							
Storing density	High		Low		High		Low	
Batching policy	(s)	(b)	(s)	(b)	(s)	(b)	(s)	(b)
	S1	S1	S1	S1	-	S1	-	S1

Table B.3: The different modules for Pick-by-voice (PBV in the table) for the search locations activity.

Variable	Search storage location				Search kit location			
Picking information system	PBV							
Storing density	High		Low		High		Low	
Batching policy	(s)	(b)	(s)	(b)	(s)	(b)	(s)	(b)
	S4	S4	S6	S6	-	S5	-	S5

B.2 Module category 2: Pick and place

The first module category, *Pick and place* in table 3.1 depend on four variables. The four variables are: Picking information system used, storage location height, component size and placement location where the last three depends on the picking assignment. Figure B.1 presents the result for how the different modules for *Pick and place* was determined based on the levels of the four variables Picking information system used, storage location height, component size and placement location where the last three depend on the picking assignment. A description of each module that belongs under the pick and place module category can be found in Figure B.4 and B.5.

Variable	Pick				Place			
Picking information system	PBL, PBP, PBV				PBL, PBP		PBV	
Storage location height	High/low shelf		Medium shelf		Not applicable		Not applicable	
Component size	Large	Small	Large	Small	Large	Small	Large	Small
Compartment ID								
A	GO1	GO1	GO2	GO2	PO1	PO1	PO1	PO1
B	GO1	GO1	GO2	GO2	PO1	PO1	PO1	PO1
C	GT1	GO3	GT2	GO4	PT1	PO2	PO2	PO2
D	GT1	GO3	GT2	GO4	PT1	PO2	PO2	PO2
E	GO1 + GT1	GO5	GO2 + GT2	GO6	PO1 + PT1	PO3	PO2 + PO1	PO3
F	GT1	GO3	GT2	GO4	PO2	PO2	PO2	PO2
G	GT1 + GO1	GO5	GT2 + GO2	GO6	PT1 + PO1	PO3	PO2 + PO1	PO3
H	2 x GT1	GO7	2 x GT2	GO8	2 x PT1	PO4	2 x PO2	PO4

Figure B.1: Module sequence for pick and place depending on the four variables: Picking information system, Storage location height, Component size and Placement location.

B.3 Module category 3: Confirmation (pick-from/place-to)

The module category confirmation includes pick-from confirmations and place-to confirmations. A pick-from confirmation refers to a confirmation that takes place after picking one or multiple component(s) from a storage location. A place-to confirmation refers to a confirmation that takes place after placing a component in a kit. The confirmation module category is dependent on four variables; Picking information system, Component size, Placement location and Batching policy.

Activity category	Place-to confirmation	
Picking information system	PBL	
Component size	Large	Small
Compartment ID		
A	C3	C3
B	C1	C1
C	C2	2 x C3
D	C2	2 x C1
E	C1 + C2	C1 + 2 x C3
F	2 x C1	C1 + C3
G	C2 + C3	2 x C1 + C3
H	2 x C2	2 x C1 + 2 x C3

Figure B.2: Place-to modules for Pick-by-light.

Activity category	Place-to confirmation		Pick-from confirmation		
Picking information system	PBP	PBV	PBP	PBL	PBV
	C5	C6	-	C4	C6

Figure B.3: Pick-from modules for Pick-by-paper, Pick-by-light and Pick-by-voice and and place-to modules for Pick-by-paper and Pick-by-voice.

B.4 Module category 4: Push picking trolley

The number of picking trolley pushes occurring was dependent on which picking information system and batching policy was used. The video recordings with pickers using the different systems, obtained from Fager et al. (2019), were used as a support for determining the number of picking trolley pushes for each system and batching policy. Based on the video-recordings, a model describing the number of times the picking trolley was pushed was developed for each picking information system and batching policy. According to the model, the picking trolley is grabbed and pushed if the next storage location is not vertically aligned with the storage location most recently picked from. If the next storage location is not vertically aligned with the most recent storage location, the picker is required to move forward where the picking trolley needs to be grabbed and pushed. This relationship was observed to hold for Pick-by-paper, Pick-by-light and Pick-by-voice in batch preparation. For single-kit preparation, the model is different and the final amount of picking trolley pushes also vary between the studied picking information systems. The model varies between batching policies because a smoother workflow is achieved in single-kit preparation where it was common that the picker had one hand grabbing the picking trolley and pushing while picking with the other hand. Meaning that the picking trolley was only grabbed once at the beginning of the picking sequence. This relationship holds for Pick-by-light and Pick-by-voice. For Pick-by-paper, the activity of marking the paper list with a checkmark with a pen prevented the picker from having the same workflow as Pick-by-light and Pick-by-voice, requiring the picker to let go of the picking trolley and write a checkmark after placing the component in the kit. The push trolley activity for Pick-by-paper in single-kit preparation follows the same relationship as was described for batch preparation.

B.5 Module category 5: Walk one step

The module category *Walk one step* was dependent on batching policy. The number of steps taken during a picking sequence was determined based on the video recordings. From the video recordings, the number of steps taken during a picking sequence excluding the supporting steps taken during a pick and place was counted for single-kit preparation and batch preparation. Those were excluded since the specific activities codes used for pick and place in the SAM analysis do by default include a supporting step. As the picking sequences was the same for each picking information system, the number of steps taken by the picker was assumed to be the average counted number of steps for all picking systems. The number of steps taken was different depending on batching policy and picking density.

AviX SAM		**Analysis Report**		Document	TEKX08 - Pick
Owner	Marvin Johannisson and Joel Palage	Date	5/25/20	Drawing	
Task	Pick	Performed	Marvin Johannisson and Joel Palage	Sheet	1

		GET					**PUT**							**USE**					**PUT BACK**								**Factors**		
Method Description		Step	**GS**			Add. for Handful	Step	Weight > 5kg	**PD**			Add. for Precision	Apply Force	No. of strokes/grip	No. of places	Time of stroke/grip	Product	Apply Force	Step	Weight > 5kg	**PD**			Add. for Precision	Apply Force	Bend and Raise			
		S	**80**	**45**	**10**	**-H**	**S**	**AW**	**80**	**45**	**10**	**-P**	**AF**	**f**	**n**	**t**		**AF**	**S**	**AW**	**80**	**45**	**10**	**-P**	**AF**	**B**			
Row No.		3	5	4	2	6	3	2	5	4	2	3	3	f	n	t	=	3	3	2	5	4	2	3	3	12	F	f	S:a F
1	**GO1**. *Pick one component from low or high shelf*	3	5	4	2	6	3	2	5	4	2	3	3					3	3	2	5	4	2	3	3	12			
			1																								5	1	**5**
2	**GO2**. *Pick one component from middle shelf*	3	5	4	2	6	3	2	5	4	2	3	3					3	3	2	5	4	2	3	3	12			
				1																							4	1	**4**
3	**GO3**. *Pick two components with one hand from low*	3	5	4	2	6	3	2	5	4	2	3	3					3	3	2	5	4	2	3	3	12			
	or high shelf		1		1																						7	1	**7**
4	**GO4**. *Pick two components with one hand from*	3	5	4	2	6	3	2	5	4	2	3	3					3	3	2	5	4	2	3	3	12			
	middle shelf			1	1																						6	1	**6**
5	**GO5**. *Pick three components with one hand from*	3	5	4	2	6	3	2	5	4	2	3	3					3	3	2	5	4	2	3	3	12			
	high or low shelf		1		2																						9	1	**9**
6	**GO6**. *Pick three components with one hand from*	3	5	4	2	6	3	2	5	4	2	3	3					3	3	2	5	4	2	3	3	12			
	middle shelf			1	2																						8	1	**8**
7	**GO7**. *Pick four components with one hand from high*	3	5	4	2	6	3	2	5	4	2	3	3					3	3	2	5	4	2	3	3	12			
	or low shelf		1		3																						11	1	**11**
8	**GO8**. *Pick four components with one hand from*	3	5	4	2	6	3	2	5	4	2	3	3					3	3	2	5	4	2	3	3	12			
	middle shelf			1	3																						10	1	**10**
9	**GT1**. *Pick two components, one in each hand*	3	5	4	2	6	3	2	5	4	2	3	3					3	3	2	5	4	2	3	3	12			
	simultaneously from low or high shelf		1		1																						7	1	**7**
10	**GT2**. *Pick two components, one in each hand*	3	5	4	2	6	3	2	5	4	2	3	3					3	3	2	5	4	2	3	3	12			
	simultaneously from middle shelf			1	1																						6	1	**6**

Figure B.4: The different modules of Pick used to describe the kit preparation process in the MTM-SAM analysis.

AviX SAM		**Analysis Report**		Document	TEKX08 - Place
Owner	Marvin Johannisson and Joel Palage	Date	5/25/20	Drawing	
Task	Place	Performed	Marvin Johannisson and Joel Palage	Sheet	2

Method Description		**GET**					**PUT**							**USE**					**PUT BACK**								**Factors**		
		Step	GS			Add. for Handful	Step	Weight > 5kg	PD			Add. for Precision	Apply Force	No. of strokes/grip	No. of places	Time of stroke/grip	Product	Apply Force	Step	Weight > 5kg	PD			Add. for Precision	Apply Force	Bend and Raise			
		S	80	45	10	-H	S	AW	80	45	10	-P	AF	f	n	t		AF	S	AW	80	45	10	-P	AF	B			
Row No.		3	5	4	2	6	3	2	5	4	2	3	3	f	n	t	=	3	3	2	5	4	2	3	3	12	F	f	S:a F
1	**PO1**. *Place one component*	3	5	4	2	6	3	2	5	4	2	3	3					3	3	2	5	4	2	3	3	12			
									1																		5	1	**5**
2	**PO2**. *Place three components, two simultaneously*	3	5	4	2	6	3	2	5	4	2	3	3					3	3	2	5	4	2	3	3	12			
	and one consecutively after								1	1																	9	1	**9**
3	**PO3**. *Place three components consecutively*	3	5	4	2	6	3	2	5	4	2	3	3					3	3	2	5	4	2	3	3	12			
									1	2																	13	1	**13**
4	**PO4**. *Place four components consecutively*	3	5	4	2	6	3	2	5	4	2	3	3					3	3	2	5	4	2	3	3	12			
									1	3																	17	1	**17**
5	**PT1**. *Place two components simultaneously*	3	5	4	2	6	3	2	5	4	2	3	3					3	3	2	5	4	2	3	3	12			
									1		1																7	1	**7**

Figure B.5: The different modules of Place used to describe the kit preparation process in the MTM-SAM analysis.

AviX SAM		Analysis Report																						Document		TEKX08 - C			
Owner	Marvin Johannisson and Joel Palage							Date		5/25/20														Drawing					
Task	Confirmation (pick-from/place-to)							Performed		Marvin Johannisson and Joel Palage														Sheet		1			
Method Description		GET					PUT							USE					PUT BACK								Factors		
		Step	GS			Add. for Handful	Step	Weight > 5kg	PD			Add. for Precision	Apply Force	No. of strokes/grip	No. of places	Time of stroke/grip	Product	Apply Force	Step	Weight > 5kg	PD			Add. for Precision	Apply Force	Bend and Raise			
		S	80	45	10	-H	S	AW	80	45	10	-P	AF	f	n	t		AF	S	AW	80	45	10	-P	AF	B			
Row No.		3	5	4	2	6	3	2	5	4	2	3	3	f	n	t	=	3	3	2	5	4	2	3	3	12	F	f	S:a F
1	**C1.** *Light - Press one button on picking trolley*	3	5	4	2	6	3	2	5	4	2	3	3				PA	3	3	2	5	4	2	3	3	12			
				1												2											4	1	**4**
2	**C2.** *Light - Press two buttons simultaneously on*	3	5	4	2	6	3	2	5	4	2	3	3				PA	3	3	2	5	4	2	3	3	12			
	picking trolley			1	1											2											4	1	**4**
3	**C3.** *Light - Press one button on picking trolley,*	3	5	4	2	6	3	2	5	4	2	3	3				PA	3	3	2	5	4	2	3	3	12			
	simultaneously placing a component				1											2											0	1	**0**
4	**C4.** *Light - Press one button on storage location*	3	5	4	2	6	3	2	5	4	2	3	3				PA	3	3	2	5	4	2	3	3	12			
					1											2											2	1	**2**
5	**C5.** *Paper - Mark with pen on paperlist for*	3	5	4	2	6	3	2	5	4	2	3	3				NB	3	3	2	5	4	2	3	3	12			
	pick-by-paper									1				1		3											4	1	**4**

Figure B.6: The different modules of Confirmation (pick-from/place-to) used to describe the kit preparation process in the MTM-SAM analysis.

AviX SAM		Analysis Report		Document	TEKX08 - C
Owner	Marvin Johannisson and Joel Palage	Date	5/25/20	Drawing	
Task	Push picking trolley	Performed	Marvin Johannisson and Joel Palage	Sheet	1

Method Description		GET					PUT							USE					PUT BACK								Factors		
		Step	GS			Add. for Handful	Step	Weight > 5kg	PD			Add. for Precision	Apply Force	No. of strokes/grip	No. of places	Time of stroke/grip	Product	Apply Force	Step	Weight > 5kg	PD			Add. for Precision	Apply Force	Bend and Raise			
		S	80	45	10	-H	S	AW	80	45	10	-P	AF	f	n	t		AF	S	AW	80	45	10	-P	AF	B			
Row No.		3	5	4	2	6	3	2	5	4	2	3	3	f	n	t	=	3	3	2	5	4	2	3	3	12	F	f	S:a F
1	**TP1.** *Voice & Light - Single - Get trolley and*	3	5	4	2	6	3	2	5	4	2	3	3					3	3	2	5	4	2	3	3	12			
	apply force to walk long			1									1														7	1	**7**
2	**TP2.** *Paper - Single - Get trolley after marking*	3	5	4	2	6	3	2	5	4	2	3	3					3	3	2	5	4	2	3	3	12			
	paperlist, applying force to walk long				1								1														5	1	**5**
3	**TP3.** *Beamer - Single & Batch - Get trolley and apply*	3	5	4	2	6	3	2	5	4	2	3	3				RB	3	3	2	5	4	2	3	3	12			
	force to walk long, put in position using light indication			1							1	1	1	1	1	7	7										19	1	**19**
4	**TP4.** *All but beamer - Batch - Get trolley and*	3	5	4	2	6	3	2	5	4	2	3	3					3	3	2	5	4	2	3	3	12			
	push ligthly short			1																							4	1	**4**

Figure B.7: The different modules of Push picking trolley used to describe the kit preparation process in the MTM-SAM analysis.

AviX SAM		Analysis Report		Document	TEKX08 - W
Owner	Marvin Johannisson and Joel Palage	Date	5/25/20	Drawing	
Task	Walk one step	Performed		Sheet	1

Method Description		GET					PUT							USE					PUT BACK								Factors		
		Step	GS			Add. for Handful	Step	Weight > 5kg	PD			Add. for Precision	Apply Force	No. of strokes/grip	No. of places	Time of stroke/grip	Product	Apply Force	Step	Weight > 5kg	PD			Add. for Precision	Apply Force	Bend and Raise			
		S	80	45	10	-H	S	AW	80	45	10	-P	AF	f	n	t		AF	S	AW	80	45	10	-P	AF	B			
Row No.		3	5	4	2	6	3	2	5	4	2	3	3	f	n	t	=	3	3	2	5	4	2	3	3	12	F	f	S:a F
1	**W.** *Walk one step*	3	5	4	2	6	3	2	5	4	2	3	3					3	3	2	5	4	2	3	3	12			
		1																									3	1	**3**

Figure B.8: The module of Walk one step used to describe the kit preparation process in the MTM-SAM analysis.

AviX SAM		Analysis Report		Document	TEKX08 - SH
Owner	Marvin Johannisson and Joel Palage	Date	5/25/20	Drawing	
Task	Search storage location, one sequence - High density - Batch preparation	Performed	Marvin Johannisson and Joel Palage	Sheet	1

Method Description		GET					PUT							USE					PUT BACK								Factors		
		Step	GS			Add. for Handful	Step	Weight > 5kg	PD			Add. for Precision	Apply Force	No. of strokes/grip	No. of places	Time of stroke/grip	Product	Apply Force	Step	Weight > 5kg	PD			Add. for Precision	Apply Force	Bend and Raise			
		S	80	45	10	-H	S	AW	80	45	10	-P	AF	f	n	t		AF	S	AW	80	45	10	-P	AF	B			
Row No.		3	5	4	2	6	3	2	5	4	2	3	3	f	n	t	=	3	3	2	5	4	2	3	3	12	F	f	S:a F
1	**S1:** *Beamer - Batch - Identify storage location*																RA												
	Big blinking beam easy to identify, guess right on second try													1	2	2	4										4	18	72
2	*Identify amount on storage location*																RA												
														1	1	2	2										2	18	36
	Sum																												**108**
1	**S2:** *Paper - Batch - Identify storage location.*																RB												
	Compare paperlist with a storage location, miss first try													1	1	7	7										7	18	126
2	*Guess right location with second search*																RA												
														1	1	2	2										2	18	36
3	*Identify amount on paper*																RA												
														1	1	2	2										2	18	36
	Sum																												**198**
1	**S3:** *Light - Batch - Identify storage location*																RD												
	Small light harder to identify, guess right on second try													1	2	3	6										6	18	108
2	*Identify amount on display*																RA												
														1	1	2	2										2	18	36
	Sum																												**144**
1	**S4:** *Voice - Batch - Identify and confirm storage*																MT												
	location and hear number. Based on time study													1	1	25	25										25	18	450
	Sum																												**450**

Figure B.9: The different modules of Search storage location for high picking density and batch preparation used to describe the kit preparation process in the MTM-SAM analysis.

AviX SAM	Analysis Report			Document	TEKX08 - SH
Owner	Marvin Johannisson and Joel Palage	Date	5/25/20	Drawing	
Task	Search storage location, one sequence - High density- Single Preparation	Performed	Marvin Johannisson and Joel Palage	Sheet	2

		GET					PUT							USE					PUT BACK									Factors		
	Method Description	Step	GS			Add. for Handful	Step	Weight > 5kg	PD			Add. for Precision	Apply Force	No. of strokes/grip	No. of places	Time of stroke/grip	Product	Apply Force	Step	Weight > 5kg	PD			Add. for Precision	Apply Force	Bend and Raise			
		S	80	45	10	-H	S	AW	80	45	10	-P	AF	f	n	t		AF	S	AW	80	45	10	-P	AF	B			
Row No.		3	5	4	2	6	3	2	5	4	2	3	3	f	n	t	=	3	3	2	5	4	2	3	3	12	F	f	S:a F
1	**S5:** *Beamer - Single - Identify storage location*																RA												
	Big blinking beam easy to identify, guess right on second try													1	2	2	4										4	10	40
	Sum																												**40**
1	**S6:** *Paper - Single - Identify storage location*																RB												
	Compare paperlist with a storage location, miss first try													1	1	7	7										7	10	70
2	*Guess right location with second search*																RA												
														1	1	2	2										2	10	20
	Sum																												**90**
1	**S7:** *Light - Single - Identify storage location*																RD												
	Small light harder to identify, guess right on second try													1	2	3	6										6	10	60
	Sum																												**60**
1	**S8:** *Voice - Single - Identify and confirm storage*																MT												
	location - Based on time study													1	1	19	19.44										19.4	10	194
	Sum																												**194**

Figure B.10: The different modules of Search storage location for high picking density and single-kit preparation used to describe the kit preparation process in the MTM-SAM analysis.

AviX SAM		**Analysis Report**		Document	TEKX08 - SL
Owner	Marvin Johannisson and Joel Palage	Date	5/25/20	Drawing	
Task	Search storage location, one sequence - Low density - Batch preparation	Performed	Marvin Johannisson and Joel Palage	Sheet	3

Method Description		**GET**					**PUT**							**USE**					**PUT BACK**								**Factors**		
		Step	GS			Add. for Handful	Step	Weight > 5kg	PD			Add. for Precision	Apply Force	No. of strokes/grip	No. of places	Time of stroke/grip	Product	Apply Force	Step	Weight > 5kg	PD			Add. for Precision	Apply Force	Bend and Raise			
		S	**80**	**45**	**10**	**-H**	**S**	**AW**	**80**	**45**	**10**	**-P**	**AF**	**f**	**n**	**t**		**AF**	**S**	**AW**	**80**	**45**	**10**	**-P**	**AF**	**B**			
Row No.		3	5	4	2	6	3	2	5	4	2	3	3	f	n	t	=	3	3	2	5	4	2	3	3	12	F	f	S:a F
1	**S9:** *Beamer - Batch - Identify storage location*																RA												
	Big blinking beam easy to identify, guess right on second try													1	2	2	4										4	9	36
2	*Identify amount on storage location*																RA												
														1	1	2	2										2	9	18
	Sum																												**54**
1	**S10:** *Paper - Batch - Identify storage location*																RB												
	Compare paperlist with a storage location, miss first try													1	1	7	7										7	9	63
2	*Guess right location with second search*																RA												
														1	1	2	2										2	9	18
3	*Identify amount on paper*																RA												
														1	1	2	2										2	9	18
	Sum																												**99**
1	**S11:** *Light - Batch - Identify storage location*																RD												
	Small light harder to identify, guess right on second try													1	2	3	6										6	9	54
2	*Identify amount on display*																RA												
														1	1	2	2										2	9	18
	Sum																												**72**
1	**S12:** *Voice - Batch - Identify and confirm storage*																MT												
	location and hear number. Based on time study													1	1	17	16.67										16.7	9	150
	Sum																												**150**

Figure B.11: The different modules of Search storage location for low picking density and batch preparation used to describe the kit preparation process in the MTM-SAM analysis.

AviX SAM		Analysis Report		Document	TEKX08 - SL
Owner	Marvin Johannisson and Joel Palage	Date	5/25/20	Drawing	
Task	Search storage location, one sequence - Low density - Single preparation	Performed	Marvin Johannisson and Joel Palage	Sheet	4

Method Description		GET					PUT							USE					PUT BACK								Factors		
		Step	GS	GS	GS	Add. for Handful	Step	Weight > 5kg	PD	PD	PD	Add. for Precision	Apply Force	No. of strokes/grip	No. of places	Time of stroke/grip	Product	Apply Force	Step	Weight > 5kg	PD	PD	PD	Add. for Precision	Apply Force	Bend and Raise			
		S	80	45	10	-H	S	AW	80	45	10	-P	AF	f	n	t		AF	S	AW	80	45	10	-P	AF	B			
Row No.		3	5	4	2	6	3	2	5	4	2	3	3	f	n	t	=	3	3	2	5	4	2	3	3	12	F	f	S:a F
1	**S13:** *Beamer - Single - Identify storage location*																RA												
	Big blinking beam easy to identify, guess right on second try													1	2	2	4										4	5	20
	Sum																												**20**
1	**S14:** *Paper - Single - Identify storage location*																RB												
	Compare paperlist with a storage location, miss first try													1	1	7	7										7	5	35
2	*Guess right location with second search*																RA												
														1	1	2	2										2	5	10
	Sum																												**45**
1	**S15:** *Light - Single - Identify storage location*																RD												
	Small light harder to identify, guess right on second try													1	2	3	6										6	5	30
	Sum																												**30**
1	**S16:** *Voice - Single - Identify and confirm storage*																MT												
	location Based on time study													1	1	10	10										10	5	50
	Sum																												**50**

Figure B.12: The different modules of Search storage location for low picking density and single-kit preparation used to describe the kit preparation process in the MTM-SAM analysis.

Table B.4: Description of the different standardized SAM-codes that were used for modules related to identification seen in SAM report in Figure B.7, B.11 and B.12.

ID	Description
RA	Read a term. One term is one word irrespective of its length or a group with a maximum of three figures and/or signs.
RB	To compare terms and includes to read one term in one place and then read the same term in another place in order to check that both terms are identical.
RD	RD to control and includes to recognise an easy recognisable quality on on object.

C

Placement locations

C.1 Placement locations

Placement locations refers to which kit(s) a component should be placed in after it has been picked from a storage location during a picking assignment. In theory, a total of sixteen distinct placement locations can exist (see equation (C.1)) for a picking assignment.

$$2^{(n\times m)} = 2^{(2\times 2)} = 16 \tag{C.1}$$

with:

n = Square matrix dimensions (number of kits)
m = Unique figures in matrix, i.e., 0 and 1 (Either no component (0) or one component (1) could be placed in a kit)

An overview of the 16 possible placement locations could be found in Figure C.1. Three placement locations were not included in the randomized sequences as these were not included in the originally developed picking sequences by Fager et al. (2019).

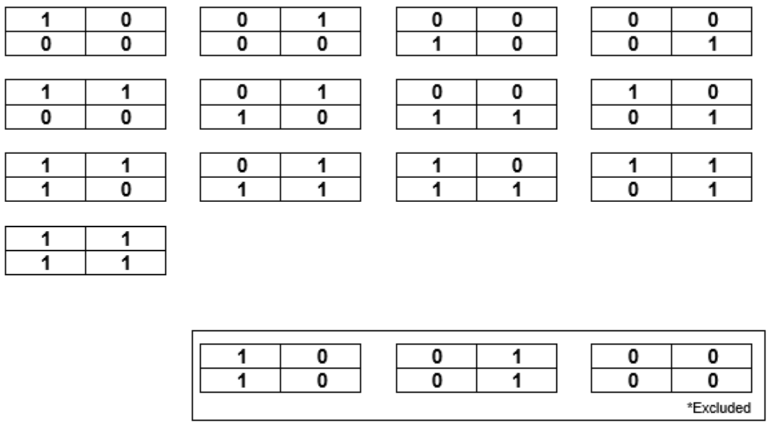

Figure C.1: The sixteen distinct compartment combinations with the three that were omitted from the study.

Some placement locations shared a common layout resulting in the same module being performed by the picker. Placement locations with the same type of layout were grouped and assigned a letter from A to H for identification purposes (Figure C.2. Placement location A corresponds to single-kit preparation with one kit in the top right corner on the picking trolley. The pick and place module is not dependent on batching policy since this is already covered by placement location A.

ID	Compartment combination	
A	$\begin{array}{\|c\|c\|}\hline 1 & 0 \\ \hline 0 & 0 \\ \hline\end{array}$	$\begin{array}{\|c\|c\|}\hline 0 & 1 \\ \hline 0 & 0 \\ \hline\end{array}$
B	$\begin{array}{\|c\|c\|}\hline 0 & 0 \\ \hline 1 & 0 \\ \hline\end{array}$	$\begin{array}{\|c\|c\|}\hline 0 & 0 \\ \hline 0 & 1 \\ \hline\end{array}$
C	$\begin{array}{\|c\|c\|}\hline 1 & 1 \\ \hline 0 & 0 \\ \hline\end{array}$	
D	$\begin{array}{\|c\|c\|}\hline 0 & 0 \\ \hline 1 & 1 \\ \hline\end{array}$	
E	$\begin{array}{\|c\|c\|}\hline 1 & 1 \\ \hline 1 & 0 \\ \hline\end{array}$	$\begin{array}{\|c\|c\|}\hline 1 & 1 \\ \hline 0 & 1 \\ \hline\end{array}$
F	$\begin{array}{\|c\|c\|}\hline 1 & 0 \\ \hline 0 & 1 \\ \hline\end{array}$	$\begin{array}{\|c\|c\|}\hline 0 & 1 \\ \hline 1 & 0 \\ \hline\end{array}$
G	$\begin{array}{\|c\|c\|}\hline 0 & 1 \\ \hline 1 & 1 \\ \hline\end{array}$	$\begin{array}{\|c\|c\|}\hline 1 & 0 \\ \hline 1 & 1 \\ \hline\end{array}$
H	$\begin{array}{\|c\|c\|}\hline 1 & 1 \\ \hline 1 & 1 \\ \hline\end{array}$	

Figure C.2: Grouping of placement locations and their corresponding letter.

D

Flow models of a picking assignment

D.1 Pick-by-paper in single-kit preparation

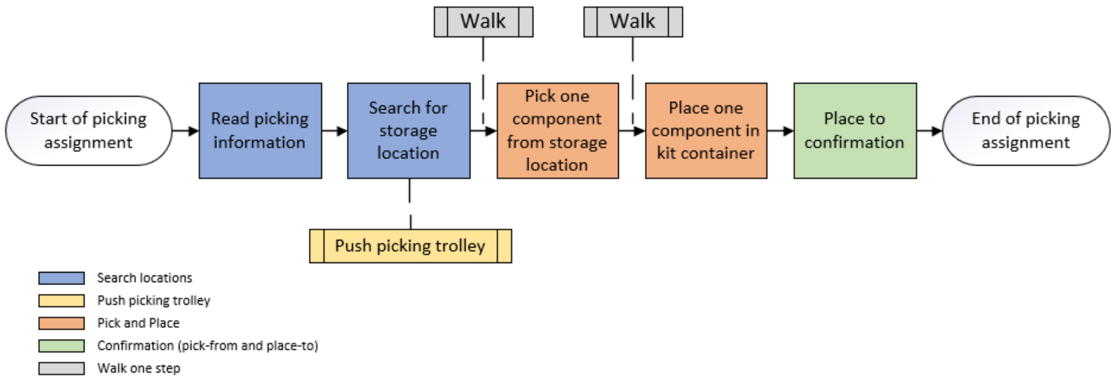

Figure D.1: Flow model illustrating the order in which the module categories are performed for Pick-by-paper in single-kit preparation.

D.2 Pick-by-paper in batch preparation

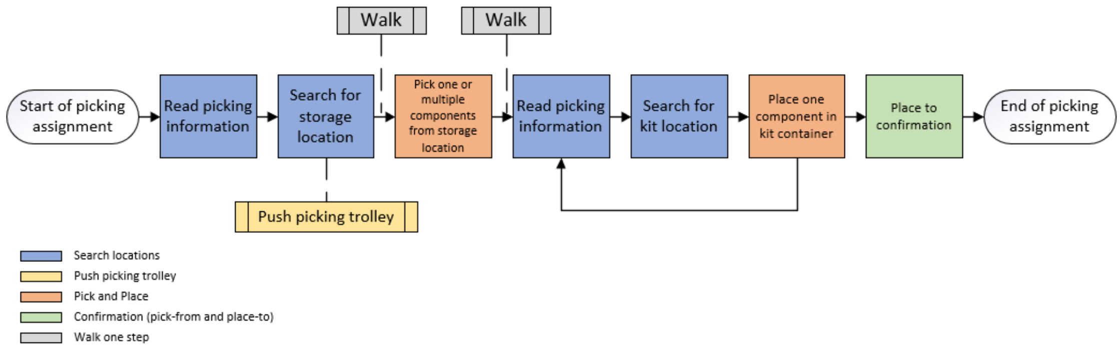

Figure D.2: Flow model illustrating the order in which the module categories are performed for Pick-by-paper in batch preparation.

D.3 Pick-by-light in single-kit preparation

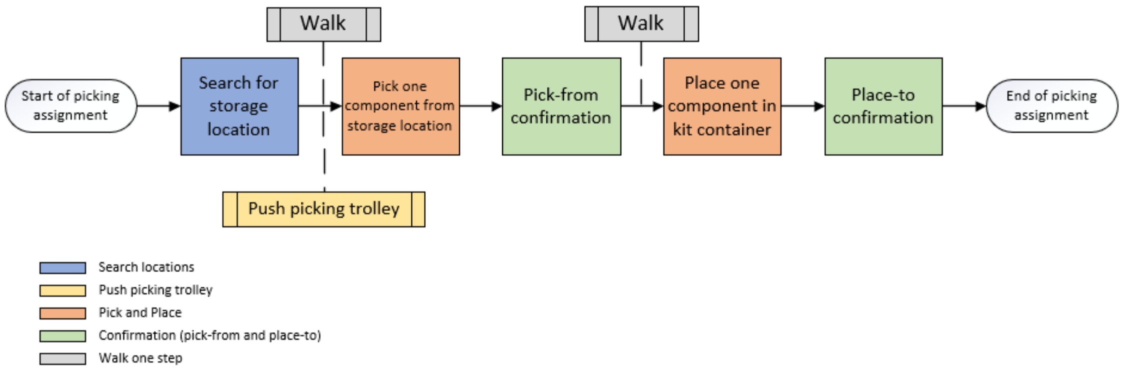

Figure D.3: Flow model illustrating the order in which the module categories are performed for Pick-by-light in single-kit preparation.

D.4 Pick-by-light in batch preparation

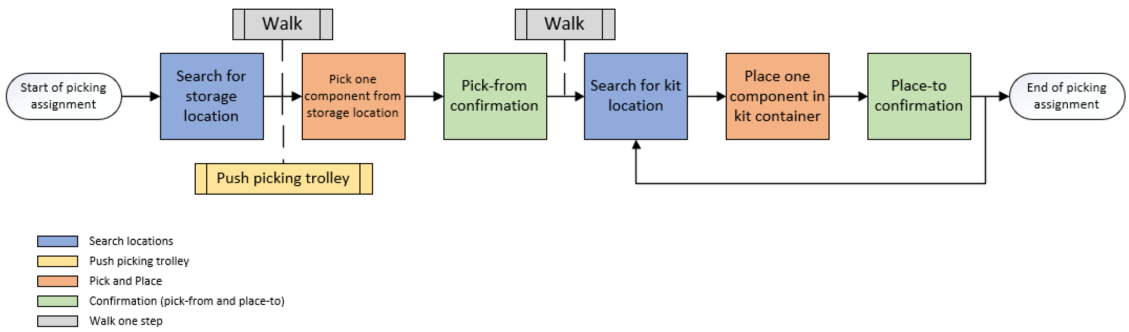

Figure D.4: Flow model illustrating the order in which the module categories are performed for Pick-by-light in batch preparation.

D.5 Pick-by-voice in single-kit preparation

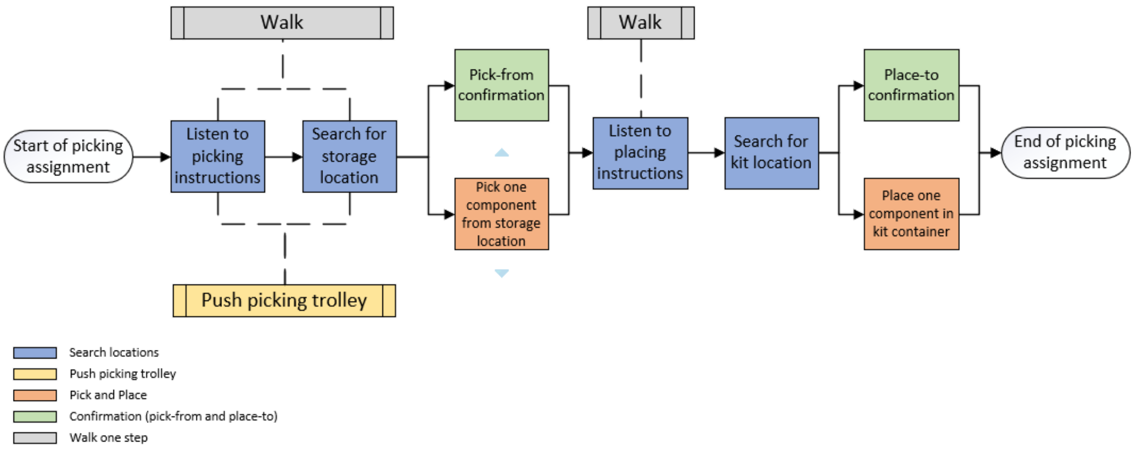

Figure D.5: Flow model illustrating the order in which the module categories are performed for Pick-by-voice in single-kit preparation.

D.6 Pick-by-voice in batch preparation

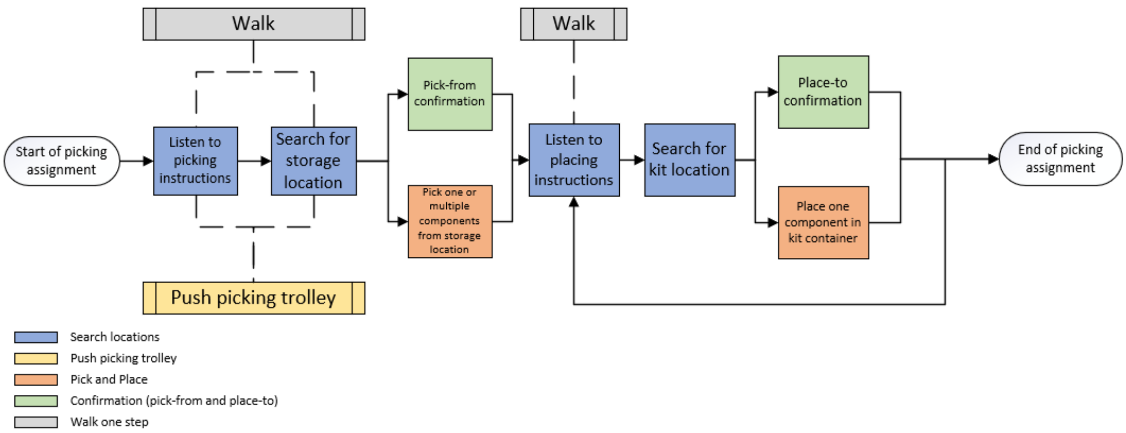

Figure D.6: Flow model illustrating the order in which the module categories are performed for Pick-by-voice in batch preparation.

E

Experiment parameters

E.1 Treatment groups

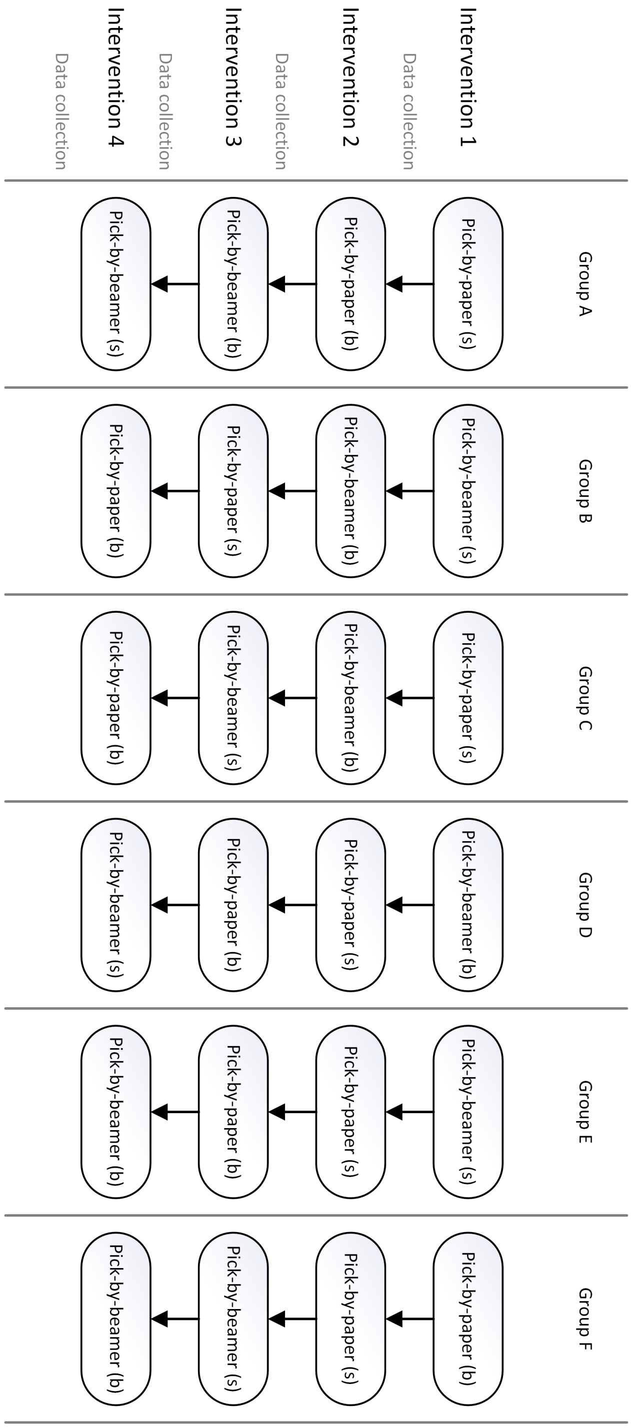

Figure E.1: Groups that each participant in the experiment were randomly assigned to. The six groups determined the order for which picking information system and batching policy that the participant would be exposed to in the experiment.

F

Data for economic evaluation

F.1 Data on investment cost

Data on investment cost used in the economic evaluation is presented in Table F.1 below. All costs are expressed in Euro (€). Further explanation to the different costs and their origin is presented below Table F.1.

		Pick-by-		
Cost type	**Beamer**	**Paper**	**Light**	**Voice**
Picker devices cost	13 000†	0.0074	0	3 000
	10 500‡			
	9 000§			
Fixed costs	30 000	0	30 000	30 000
Cost per storage location	0	1.10	100	1.10

† Buying one device.
‡ Buying between two and five devices.
§ Buying six or more devices.

Table F.1: Summary of investment costs (€) for each picking information system.

F.1.1 Cost of picker devices

The picker device costs are related to the cost of hardware and software that is unique to the picking information system that is dependent on the number of pickers. Without the picker device, the picker is not able to perform kit preparation. The cost of a picker device for Pick-by-beamer is based on the costs of a the Human-Interface-Mate from Arkite according to their current price list as of 2020. Picker devices cost includes both the cost of hardware (HIM unit and two projectors) and software license. Three different price levels are shown for Pick-by-beamer in Table F.1. What determines the price per device is how many devices that are bought at a single occasion. One device corresponds to the highest level of EUR 13 000 per unit, while buying between two and five devices correspond to EUR 10 500 per unit. If six or more units are bought, the price is EUR 9 000 per device.

The cost for Pick-by-paper is the cost of paper, for that cost, it is assumed that each one picker needs one piece of paper size A4 to pick 60 components (the A4 paper is limited to being able to contain picking information of no more than 60 components). This assumption makes it possible to estimate how many A4 papers a picker needs when the picking demand is at a certain level. The price of one piece of paper is based on purchasing 2 500 A4 papers in a box at a price of EUR 20 and is presented in cost per piece of A4 paper in Table F.1.

The picker device cost for Pick-by-light is zero. In single-kit preparation for Pick-by-light, there is no picker device installed on the picking trolley (lights, cables, etc.) in comparison to batch preparation.

The cost for picker devices Pick-by-voice is EUR 3 000 which includes the headset that the picker wears when picking. This cost is the same as was used by Battini et al. (2015).

F.1.2 Fixed costs

The fixed costs in table F.1 include server and software costs that are not dependent on the number of pickers. The fixed costs are EUR 30 000 for Pick-by-beamer, Pick-by-light and Pick-by-voice while being zero for Pick-by-paper. The fixed cost of Pick-by-paper is assumed to be zero as the Picking information system is not connected in real-time to any warehouse management system or other servers.

F.1.3 Cost per storage location

For Pick-by-light, the cost per storage location is based on information from a Swedish supplier of Pick-by-light systems. In their price estimate, the cost per storage location was EUR 100. The price included rail, light indicator, cables, I/O-box and gateway. The cost per storage location for Pick-by-paper and Pick-by-voice include storage location labels. The price data is based on the study by Battini et al. (2015).

F.2 Data on employee cost

The cost of an employee performing kit preparation is the total aggregated cost for the employer related to having one person employed. The cost is based on a monthly salary of EUR 1 992 with the employee working 1 760 hours per year, equivalent to eight-hour a day 220 days a year (resulting in 32 days vacation excluding public holidays in Sweden). The payroll is adjusted for payroll tax and other cost objects accumulated to a total value of 50% of the salary which is common in Sweden. The aggregated cost for the employer to have one person employed is 20.38 € per hour where the salary for the employee is EUR 13.50 per hour of that amount.

F.3 Data on time consumption

Data on time consumption for different modules performed by the water spider when correcting a picking error is presented in Table F.3 and F.2 for low and high picking density respectively. The time consumption is assumed to be the same for all picking information systems as it is assumed that the water spider corrects the picking error without using any picking information system. The different times are assumed to be the same as for Pick-by-paper as this is the system that most closely resembles manual picking without support. It is assumed that the time to search location is done by manually searching for the storage location similarly as done for Pick-by-paper in a regular picking sequence.

Table F.2: Data for each specific time type involved in the economic evaluation, for high picking density.

Time type	Time (s)
Time to search	2.10
Time to pick	1.80
Time to push picking trolley	2.50
Time to walk one meter	0.00031

Table F.3: Data for each specific time type involved in the economic evaluation, for low picking density.

Time type	Time (s)
Time to search location	1.70
Time to pick and place	1.80
Time to push picking trolley	2.50
Time to walk one meter	0.00031

F.4 Data on walking distances

In this section, the walking distances that were used in the economic evaluation are presented.

F.4.1 Length of picking aisle

The length of the picking aisle refers to the length from one end of the picking aisle to the other end (one way). The length of the picking aisle and the number of components included in a kit, i.e., the kit size, determines the picking density. As two cases of picking density were tested in this study, low and high picking density, this parameter is considered to be fixed which means that both the length of the picking aisle or the kit size needed to change proportionally to maintain the same picking density. This is the reason why different kit sizes correspond to a different length of the picking aisle in Table F.4

Table F.4: Length of the picking aisle in the kit preparation area.

	High picking density	**Low picking density**
Kit size of 15 components	9.05 meter	20.52 meter
Kit size of 50 components	30.30 meter	68.40 meter

It was considered interesting to vary the length of the picking aisle as this impact how long distance the water spider needs to walk when correcting a picking error. The length of the picking aisle was multiplied with the Time type *Time to walk one meter* in table F.3 and F.2 to get the total time to walk that distance.

F.4.2 Distance ($\bar{D}$) to correct picking error

The distance between the kit preparation area and assembly station is equivalent to the distance between the location where the picking error was discovered (assembly station) and the storage location in the kit preparation area that needed to be visited to correct the picking error. As with the length of the picking aisle, the distance between the kit preparation area and assembly station was multiplied with the Time type *Time to walk one meter* in table F.3 and F.2 to get the total time to walk that distance. Three different distances were part of the economic evaluation, 50 meter, 25 meter and 0 meter. The 0 meter case means that the picking error was discovered right after the picking sequence was completed.

F.5 Data on productivity

Below follows the theoretical time to pick one component that was the result of the MTM-SAM analysis. Time to pick one component is the average time based on 10 picking sequences. Time to pick one component includes picking of one component, place one component in kit, search storage and kit location, push picking trolley, walk and confirmation (pick-from/place-to). Data on productivity for each picking information system for high picking density is presented in Table F.5. Data on productivity for each picking information system for low picking density is presented in Table F.6.

Table F.5: Data on productivity used in the economic evaluation, for high picking density.

		Pick-by-		
Time type	**Beamer**	**Paper**	**Light**	**Voice**
Time to pick one component	2.81	3.15	3.56	5.52
Picking rate (picks/hour)	1280	1142	1010	652

Table F.6: Data on productivity used in the economic evaluation, for low picking density.

		Pick-by-		
Time type	**Beamer**	**Paper**	**Light**	**Voice**
Time to pick one component	3.19	3.45	4.27	4.93
Picking rate (picks/hour)	1128	1042	843	730

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