An investigation of cognitive aspects affecting human performance in manual assembly

by

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ABSTRACT

Modern manufacturing systems seem to be shifting from mass production to mass customisation, which means that systems must be able to manage changes in customer demands and requirements, new technology as well as environmental demands. This in turn leads to an increase in product variants that need to be assembled. To handle this issue, well designed and presented information is vital for assembly workers to perform effective and accurate assembly tasks. In this thesis the main focus has been to find factors that affect human performance in manual assembly. A literature review was made on the subject of manufacturing and usability as well as basic cognitive abilities used to utilise information, such as memory. This investigation identified applicable factors for assessing human cognitive performance within the research field of manufacturing. The thesis further investigates how some of these factors are handled in manual assembly, using case studies as well as observational studies. The results show that how material and information are presented to the assembler needs to be considered in order to have a positive effect on the assembly operation. In addition, a full factorial experimental study was conducted to investigate different ways of presenting material and information at the workstation while using mixed assembly mode with product variants. The material presentation factor involved the use of a material rack compared to using an unstructured kit as well as a structured kit and the information presentation factor involved using a text and number instruction compared to a photograph instruction. The results showed that using a kit is favourable compared to the traditional material rack, especially when using a structured kit combined with photographic instruction. Furthermore, the use of unstructured kits can lead to better productivity and reduced perceived workload, compared to a material rack. Although they are perhaps not as good as using a structured kit, they most likely bring a lower cost, such as man-hour consumption and space requirements. However, the number of components in an unstructured kit needs to be considered in order to keep it on a manageable level. As a conclusion, several scenarios were developed in order to understand how different assembly settings can be used in order to improve human performance at the assembly workstation.

KEYWORDS: manual assembly, manufacturing, usability, cognitive workload, information presentation, material presentation, product variants, kitting.

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CONTENTS

1 INTRODUCTION

Within the automotive industry, increasing customer demands and requirements, environmental laws and new technology have resulted in a high variant flora of products, and further increases in variety can be expected in the future. The higher level of product variation leads to an increasing workload for the assembler who has to search for, fetch and assemble all the component variants. This puts high demands on the information that is given to the assembler to fulfil the assembly task. However, the information systems used in today's assembly are lacking in usability in many ways (Thorvald et al., 2010). When faced with poorly constructed and poorly presented information, the assembler's workload increases due to the fact that they must concentrate on mental sorting and searching for the appropriate information (Watts-Perotti & Woods, 1999). These external stressors influence the quality of information received by the receptors and the perception of the motor or vocal response. For example, time stress may decrease the amount of information that can be perceived and hence result in a degraded performance. Some of the stressors may also affect the efficiency of processing information (Wickens & Hollands, 2000). Wickens and Hollands (2000) and Bäckstrand et al. (2005) also state that there are connections between stress and error, which further strengthen the aspect that presenting information at the right time, with the right content, in the right layout, in a perceivable way will ease the cognitive workload for the assembler (Wilson, 1997, D'Souza & Greenstein, 2003). Knowledge of human performance can help to support the design of more stress-tolerant assembly environment and provide the appropriate information rather than all information to the assembler.

1.1 Introducing the problem

Due to the increase in product variants, which are causing an increased information flow and a huge information overload (Bäckstrand, 2009), the cognitive aspects as well as usability aspects from the field of human-computer-interaction (HCI) were valuable and needed in this research. It is for example important to understand how to perceive and to best present information, so that the assembler is able to perform a correct task based on the given information. In the automotive industry well designed and presented information is thus vital for the assembly personnel to perform effective and accurate assembly operations. The main research focus is therefore to improve the work situation for the assembler by investigating usability and cognitive aspects that affect human performance in a mixed mode assembly (meaning that the assembly line contains both standard products as well as product variants at the same time and is henceforth the kind of manual assembly system that will be considered by this thesis).

Traditionally cognition has been described as mental activities that take place inside the human brain, where the cognitive abilities enable the human being to experience the world and act in it. Perception, decision-making, problem solving, memory processes etcetera are all cognitive activities that human beings are engaged in every day. Although human cognition is comprehensive, there are limitations, such as when exposed to stimuli the cognitive system experiences what is commonly referred to as a cognitive or a mental load. Thus, cognitive load refers to the mental load that performing a specific task imposes on the human's cognitive system. People are always experiencing different levels of cognitive load, which also changes depending on the situation, the tasks and the tasks demands on the individual. Related to assembly, a worker performing an assembly task is also constantly exposed to situations with varying cognitive demands. In the context of manual assembly, this can be experienced through the amount of information, time pressure, interruptions, rapid decisions, high variant flora of components and physical layout of workstations. However, each of these factors can be handled with relative ease so long as there is no time pressure, but when combining these with the triggering factor of time pressure, a mental load will be created. Hence, poor information design, which is an issue in many manual assembly environments, is usually not a problem unless the information needs to be processed in a hurry. Besides understanding how cognitive aspects affect human performance, it is relevant to look into the area of usability, in order to understand how to deal with how information could be presented. Usability can be broadly defined as the capacity of a system to allow users to carry out their tasks safely, effectively, efficiently, and enjoyably (Preece et al., 2002). Bligård (2012) further states that usability concerns the emerging property of the object in relation to the user, the goal of the task and the context. Related to manual assembly, it is important to design the information system and thus how information is presented to the assembler, so that the worker can easily understand what the goal of the assembly task is and how to reach it in a given situation.

This thesis is to a large extent concerned with a cognitive, but also a usability approach, when evaluating the work situation of assemblers and performance outcomes (i.e. productivity and quality). Productivity and quality are referred to in this thesis as time spent on assembly tasks and assembly errors respectively.

1.2 Aims and objectives

The *aim* of this research is to:

> *identify factors that affect human cognitive performance in manual assembly and investigate this through observations and experiments in order to increase knowledge within this field.*

The research objectives are to:

- Identify and explore applicable factors for assessing human cognitive performance within the research field of manufacturing.
- Investigate how current manual assembly information systems present information to the assembler at the workstation.
- Identify suitable factors affecting the cognitive aspects of human performance in manual assembly, for deeper study and investigation.
- Investigate how the combination of factors affects the cognitive aspects of human performance in manual assembly.

1.3 Industrial and academic collaboration

When the research related to this thesis commenced in 2010, it was largely inspired by the running research project FACECAR (Flexible Assembly for Considerable Environmental improvements of CAR's), which ran between 2009 and 2011. The main focus of the FACECAR project was to conceptualise the transition of a flexible assembly line in short term (2012) and long-term (2020) being able to combine existing and future technology in the same production system. Noted collaboration within the research were: Volvo Cars, Volvo Group (Trucks, Powertrain and Technology), Saab Automobile, Scania, Electrolux and Chalmers University of Technology. The research was carried out whilst employed as a PhD student (doktorand) at the School of Engineering Science at University of Skövde, Sweden and registered as a PhD student at the department of Mechanical, Electrical and Manufacturing Engineering at Loughborough University, UK.

1.4 Organisation of thesis

This thesis identifies appropriate factors for assessing human cognitive performance that are used in the research field of manufacturing, through a literature review presented in Chapter 2. These factors are then further investigated in several exploration studies performed in a manual assembly context (Chapter 3). The findings from both literature and the studies in manual assembly gave valuable input towards creating the hypotheses (section 5.1) and set-up of the empirical experiment (Chapter 5). Chapter 6 provides the results of the experiment, but since this experiment involves a lot of data and therefore also a lot of results (including many graphs and tables) Chapter 7 provides the key findings of the experimental results. Finally Chapter 8 summarises the thesis and discusses the validation of the thesis and its separate parts as well as discusses its contribution and finally proposes future research directions.

2 LITERATURE REVIEW

Modern manufacturing systems are shifting from mass production to mass customisation, which means that the systems must be able to manage changes in customer demands and requirements, new technology and environmental demands. Of course this is easier said than done, especially if a low cost approach is added (Hu et al., 2011). In order to stay competitive and uphold sustainability, manufacturers have begun to design production systems that are more flexible and efficient. For example, the Swedish vehicle industry accommodates a large range of different vehicle models in one production line, so called mixed mode assembly, ultimately causing a high variant flora of products which have to be assembled. Although automation is increasing in production systems of vehicle manufacturers, manual assembly is still a vital part of the assembly system and thus requires consideration. Mixed mode assembly systems consist of both so called volume products (products that occur frequently) and variants (products that have some special components, hence customisation) being assembled simultaneously. Complicating issues with this kind of system is that the assembler needs be prepared for both types of product configurations. But as the likelihood of a volume product will occur more often compared to a variant product, there is a high risk that the assembler will end up in a previous assembly pattern, using an automated behaviour (Reason, 1990, Wickens & Hollands, 2000), and assemble a volume product, when it should have been a variant. From a human factors perspective, this way of arranging assembly work puts considerable strain on the assembler. The assembler might not only be mentally unprepared for some variants at different random times, but may also have to search and fetch components or assembly instructions that, at worst, are rarely used further increasing the search and the need for information. To handle this issue well designed and presented information is vital for the assembly workers to perform effective and accurate assembly tasks (Shalin et al., 1996, Wilson, 1997, Wilson, 2000, D'Souza & Greenstein, 2003, Thorvald et al., 2008), and this is at the core of this thesis.

Initially, this chapter presents a broad background of manufacturing areas, including logistics and complexity (section 2.1). Section 2.2 attempts to provide perspectives of manufacturing and manual assembly, which will form the basis of a framework of factors and a model that affects the human cognitive performance in manual assembly. This also includes a more detailed exploration of factors that have been developed and to some extent can be connected to usability. As a complement to the current models used in manual assembly, section 2.3 provides the founding usability and design principles (although usually assessed in HCI as well as within product design). Finally, section 2.4 summarises this chapter in a discussion that attempts to find common areas of these models and principles that can be linked together to form categories that theoretically affect the assembler at the workstation.

2.1 Manufacturing and assembly systems

Various investigations have shown that increases in product variants increases the complexity in manufacturing (Calinescu, 2002, ElMaraghy & Urbanic, 2003, Hu et al., 2008, Gullander et al., 2011, Hu et al., 2011, ElMaraghy et al., 2012, Mattsson et al., 2014b). In addition, increased product variants has a negative effect on overall performance, i.e. quality and productivity (MacDuffie et al., 1996, Fisher & Ittner, 1999) as well as human factors aspects in manual assembly (Shalin et al., 1996, Bäckstrand, 2009, Thorvald, 2011, Säfsten et al., 2014, Lim & Hoffmann, 2015).

Complexity within manufacturing is commonly described to emerge from an uncertain and constantly changing environment due to increasing mass-customisation and demand, product design and new technology. ElMaraghy et al. (2005) elaborates on manufacturing complexity:

> *It has been established that the real or perceived complexity of engineered products, their design and their manufacture is related to the amount of information to be processed. It arises due to increased product complexity and the uncertainty created by product variety and market fluctuations and their effects which propagate throughout their life cycle. Increased variety generates more information and provides opportunities for unexpected or unknown behaviour of products, processes or systems. It increases the data, knowledge and effort needed for operating and managing the resulting consequences, anticipating them, designing or guarding against their effects or recovering from and rectifying their consequences. Manufacturing systems have evolved over time and new mechanisms*

> *and methods have been developed to cope with and manage the effects of increased product variety on process planning and production planning as well as the evolution of manufacturing paradigms.*

When considering factors that affect complexity in manual assembly, they can arguably be related to usability aspects in manufacturing, for instance, factors related technology use, communication, workplace design, etc. Over the years a number of researchers have investigated and explored the broader perspective of complexity in engineering design and/or manufacturing with regards to human factors (Calinescu, 2002, ElMaraghy et al., 2012, Falck et al., 2012, Gullander et al., 2012, Mattsson, 2013). However, there is still much to do in this field and this thesis mainly discusses the aspects related to usability and cognition (further elaborated in section 2.3).

Other aspects of manufacturing include for instance the field of production logistics which is relevant when looking at the handling and flow of material. From a human factors perspective, the flow of material is highly connected to the assembler´s situation (i.e. at the workstation). As mentioned previously, due to increased product variants, assemblers are often faced with a larger number of components at the workstation which need to be handled. Several investigations have explored and developed methods to improve both quality and productivity in production systems, such as studying the material supply process (Hanson, 2012) as well as the presenting of material (Limère, 2011). One of the most interesting areas within material supply systems is the principle of kitting (further investigated in section 3.1). The kitting method was primarily introduced as a logistic tool, to solve the problem of material racks that expanded alongside of the assembly line. The use of kitting means that pre-sorted kits of components are delivered to the workstation either by so called traveling kits or stationary kits (Bozer & McGinnis, 1992). Compared to continuous supply, which traditionally has been the predominant way of presenting material to the assembler at the workstation, while kitting entails a number of components being stored at the assembly station where they are to be assembled. When using continuous supply (sometimes also referred to as "line stocking") in mixed mode assembly, the assembler at each workstation needs to identify the right components to assemble on each assembly object. This further means that, compared to kitting, continuous supply often is associated with a direct flow of materials within the assembly plant, and not first being gathered into kits. Within the literature, kitting has been stated to be associated with a number of effects, both benefits and drawbacks (Sellers & Nof, 1989, Ding & Puvitharan, 1990, Johansson, 1991, Christmansson et al., 2002, Medbo, 2003, Hanson & Medbo, 2012). However, the effects are mostly regarding quality, productivity (Finnsgård et al., 2008, Wänström & Medbo, 2008), man hour consumption, space requirements near the final assembly line (Bukchin & Meller,

2005) and flexibility issues (Sellers & Nof, 1986, Bozer & McGinnis, 1992). A kit can also be regarded as a carrier of information that complements, supports or even replaces conventional assembly instructions. Medbo (2003) argues that, correctly structured, a kit can support assembly by functioning as a work instruction. If the parts are placed in the kit in a manner that reflects the assembly operations, kitting can facilitate learning and, consequently, reduce learning times and improve product quality (Johansson, 1991). The benefit, from an ergonomics perspective, is that the assembler only has to focus on the assembly process, i.e. *how* to assemble, and does not need to be concerned with *what* parts to assemble, which ultimately can result in high support of product quality (Bäckstrand, 2009). Further, several researchers have associated kitting with ergonomic aspects (Christmansson et al., 2002), for instance stating that the configuration of a kit supports the assembly work (Medbo, 2003). As this insight seems to be in line with the subject matter of this research, the matter of kitting supporting assemblers will be further investigated in the exploration studies (section 3.1).

One way to handle complexity in manufacturing is to use automation. However, nowadays automated production and shop floor workplaces in manufacturing not only includes mechanical tasks such as welding and screwing. Automation also includes cognitive automated tools such as a pick-by-light systems, where a picking operator or assembler is guided by a light which indicates which components to pick (further described in section 3.2.2). It is suggested that an increased level of automation could accordingly improve the assemblers' performance and workload, while maintaining the physical automation (Fasth & Stahre, 2010). It is further emphasised that a well formed cognitive automation strategy is important when considering the increasing product variants in manual assembly (Fasth-Berglund & Stahre, 2013, Mattsson et al., 2014a). The area of level of automation, and in particular cognitive automation, is therefore another research field within the manufacturing area which is of concern to this research.

2.2 Usability approaches in manual assembly

One of the main objectives with this research has been to explore factors that affect human cognitive performance in manual assembly, and so it was of interest to look deeper into the above mentioned manufacturing areas and to investigate models and the factors involved that have been used when assessing different aspects of manufacturing.

In order to handle complexity in manufacturing as well as to support assemblers Mattsson et al. (2012, 2013) developed an assessment method to assess the complexity level of a workstation. In this method, Mattsson and her colleagues used elements or factors that had been derived from several other methods used within complexity research. The following factors or elements were considered:

- **Product variants**; means the number of product variants that can be found on the station.
- **Work content**; regards the work tasks except for the final assembly, such as if the assembler knows what to do when arriving to the workstation.
- **Layout**; means the layout of the workstation (involving material handling, material rack and ergonomics issues connected to this).
- **Tools** and **Support tools**; refers to the types of tools used by the workstation and how these tools help the assemblers in their work.
- **Work instructions**; refers to the instructions used every day and if they help the assembler in their work.

Medbo (2003) further developed a so-called basic design principle for parallel flow, long cycle time assembly work derived from the work of Engström et al. (1996). This principle states that the material kit should function as an assembly instruction which then enables the assemblers to monitor their work, and thus provide support. However, there must be correspondence (congruence) between:

- **Operator's way of working**; refers to the operator's own view and ideas about how to perform the assembly work.
- **Materials display**; means the material kits configuration, i.e. the organisation of components.
- **Description of the assembly work**; entails for example the stipulated work pattern, i.e. the predefined division of labour in the form of so-called work modules comprised of clusters of work operations.

Helander and Furtado (1992) states that engineers have taken for granted the adaptability of the human operator and ignored opportunities for ergonomics improvements which could increase productivity as well as operator comfort. The authors further state that (1992, p. 181)

> *it is important to recognize that even in manual assembly where behaviour may be automatic, information processing take place, and depending on the design of the product and the layout of the workstation, there are great opportunities to simplify manufacturing.*

In light of this they propose guidelines that may be used when designing for manual assembly. Four different guidelines were explored when considering redesign of products (both applicable in automated and manual assembly): (i) what to do and what to avoid in product design, (ii) Boothroyd's method for redesigning products, (iii) use of predetermined time systems to diagnose product design and (iv) human factors design principles applied to product design. Of these four principles, the latter was considered the most relevant to this research, and is also known as design for assembleability. All of the principles not only apply to components but to any items that are touched during the assembly process, including components, controls and hand tools. The principles are:

- **Design for ease of manipulation and tactile feedback**; refers to the use of physical stop barriers which are often designed along with auditory feedback, such as a snap that makes a damped sound. Altogether, this indicates that a task action has occurred.

- **Design for visibility and visual feedback**; occurs at the same time as motions such as reach, move and position etcetera. All features should be fully visible and provide visible feedback, as hidden features may complicate the assembly task.

- **Design for spatial compatibility**; means the spatial layout of the workstation, such as layout of the material rack and bins. The layout of the components could then either correspond to the assembly process or be arranged so that their placement mimics the product construction. Typical items that belong together in the performance of the assembly task should be brought and placed together, including hand tools and controls.

- **Design to enhance the formation of a mental model**; discusses the differences between designer's and user's mental models. The authors emphasises the importance of enhanced functionality features that communicate the mental model. Further, conceptual compatibility is also related to mental models. The enhancement of conceptual compatibility is done by using incorporated various codes, such as using colour coding (Bäckstrand et al., 2008) of components that belong to a certain subassembly task.

Regarding mental models, Wilson and Rutherford (1989) combined several earlier definitions of mental models and stated that

> *mental model is a representation formed by a user of a system and/or task, based on previous experience as well as current observation, which provides most (if not all) of their subsequent system understanding and consequently dictates the level of task performance.*

- **Design for transfer of training**; refers to when an assembler has learnt to perform a similar task in a specific way. But when modifying the product design, workstation layout and utilisation of relationships of compatibility, the assembler might get confused and dissatisfied. Therefore, it is better to analyse the type of skills the assembler has established and utilise the same set of skills for the new product.

- **Design for job satisfaction**; has to do with the responsibilities that the designers of manufacturing processes, facilities or products have, such as opportunities to cooperate or to communicate with others, performance feedback, control over own pace, use of judgement and decision making, and opportunities to learn new things and develop.

Thorvald has, through several investigations (Thorvald et al., 2012, Thorvald, 2013, Thorvald et al., 2014), suggested ways to improve how information is presented to the assembler at the workstation. The following factors could be drawn from his research in manual assembly contexts:

- **Sequenced, batched information**; involves how presentation of information can be minimised without reducing the information content, by using alternate information syntax and alternate layouts. The author showed through an investigation that presenting sequenced, batched information compared to sequenced information is better, due to there being less information on the screen (the computer screen which shows information instructions to assemblers) provides the assembler with a better overview of what to assemble. It was further suggested that the assemblers might even use pattern recognition to aid in the identification of components to assemble.

- **Information presented as symbols**; suggests the fact that symbols carry semantic memory within themselves as opposed to using component numbers in manual assembly as component identification. The author suggested that a symbol is most likely to be established in the long-term memory as well as the assembler having a personal meaning or association with the content of the symbol. Therefore symbolic representations are believed to result in better recognition, recall and matching of the same symbol, when searching for the same symbol in a material rack.

- **Spatial range of information**; encompasses to the area where a piece of information can be reached. By using a mobile information source (compared to a stationary computer) in a manual assembly context, the quality, i.e. number of assembly errors, was improved. This was suggested to be because the subjects were more prone to use the information source if it was more accessible to them, including both physical effort and time wasted to gather this information. While using a stationary computer, as in this case, the physical (fetching) and mental (relay on memory) effort potentially might increase.

Bäckstrand stated that many manufacturing companies often provide the assembler with too much information which is poorly designed, which causes information overload and ultimately results in an increased mental workload (Bäckstrand, 2009). Related to this Bäckstrand conducted various investigations and the following factors were established from his research within manual assembly contexts:

- **Information triggers**; means the use of triggers in the information content which will change the attention mode from passive attention to active attention of the user. In a study performed by Bäckstrand et al. (2010) colour coding was used as a trigger which had a positive effect on assembly errors as well as the information seeking behaviour. It was also believed that the simplified information system (colour coding product variants) made it easier to interpret the information, especially as assemblers could prepare physically and mentally for the approaching product, as they could see the colour code of the product at a distance down the assembly line.

- **Active information seeking behaviour**; encompasses the use of triggers in the information content which will catch the attention of the user. Bäckstrand et al. (2005) proposed that it does not matter how much information assemblers are clouded with if an active information seeking behaviour is not triggered. Instead, while in a passive attention mode, the assembler is unable to be subjected to information overload. A widely known definition of active attention is that active attention is to actively gather or process information, whereas passive attention is to passively await a situation (James, 1890/1950) which fits quite well, according to the abovementioned study. Himma (2007) further explains that information overload arises as human attention is strictly limited as it needs full focus and humans have only so much attention resource available. Accordingly, since the cognitive resource is scarce and is being stretched in ways that exceed its limits, the problem of information overload occurs.

  Information seeking, which is traditionally considered from a systems perspective, views information users as passive and situation-independent retrievers of objective information (Dervin & Nilan, 1986, Byström et al., 1995). Belkin et al. (1982) instead state that information needs and information-seeking processes depend on worker's tasks. Further, Ingwersen and Järvelin (2005) and Ingwersen (1996) point out that effective information retrieval must be based on an understanding of a worker's tasks and problems. When confronted with an assembly task, as in this case, the assembler perceives information needs that reflect the assembler's interpretation of the information requirements, such as prior knowledge, and ability to memorise it. It is also important to point out that personal factors as for example attitude, motivation or current mood also affect information seeking and perception (Kuhlthau, 1991).

The abovementioned research in this section has investigated factors within manufacturing, that to some or a high extent affect human cognitive performance as well as human factors in manual assembly. However, much research has been inconclusive and unable to establish robust links between usability and cognitive aspects of human performance and the contextual factors identified in the literature that are beneficial to manual assembly. Further, much research has also used mathematical models in order to help understanding and to explain certain human factors issues in a manufacturing context (ElMaraghy & Urbanic, 2004, ElMaraghy et al., 2005, Limère, 2011). Although these models probably explain the issues to a certain degree, perhaps a more flexible approach or assessment is needed as human factors and cognitive workload is ever-changing, and so are the issues that they affect.

Figure 2.1 visualises the wide field of manufacturing and relevant factors that have been used within manufacturing research. As the factors considered consist of different levels of detail, where some have a more general implication than others, it was necessary to re-write some factors in a more unified language, where their previous definition helped to gather the factors in a more comprehensible manner. There were however some factors that were considered to not really relate as much to others (*Tools and support tools* and *Transfer of training*) and were therefore unchanged. Furthermore, from the investigation it was evident that the factor *Product variants* was considered to affect not only the overall production performance but also complexity. Therefore this factor was kept unchanged, in order to be able to match this factor correctly to other factors found in literature (section 2.2 - 2.3).

The factors usage or assessment within the manufacturing field could be considered as a little loose and there is some difficulty in knowing what they really assess or measure, as well as what type of area that is considered. Consequently some of the factors were aggregated into "main factors" (illustrated as dashed boxes to the right, in Figure 2.1), as this makes them more understandable and positions them in a broader concept.

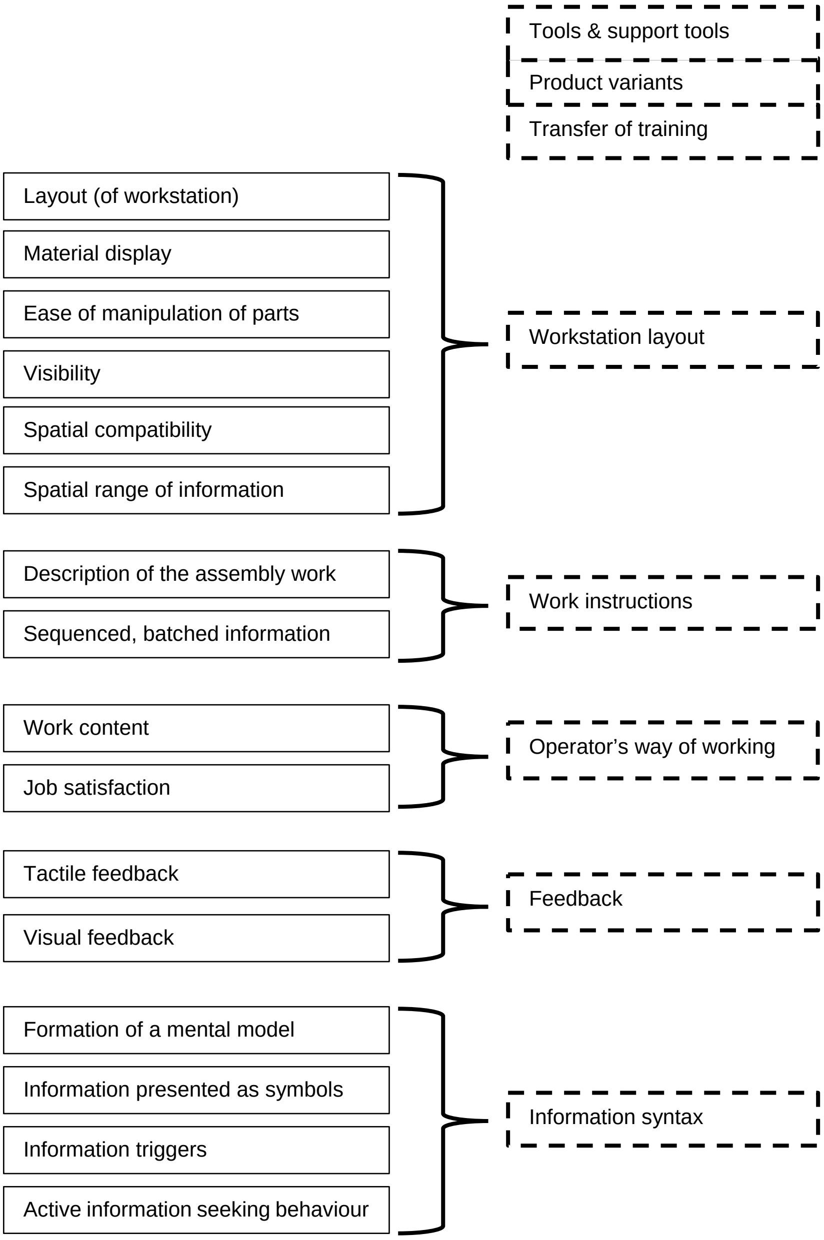


Figure 2.1 Relevant factors from the manufacturing research field. Main representation of categories to the right

The aforementioned factors approached in the context of manual assembly can be considered as a basis for further research (section 2.3). However, it was decided to further explore factors based on a models or methods which have been used to assess aspects of manufacturing. The chosen models were derived from the complexity research area (section 2.2.1) as well as the studies of usability and design principles (section 2.3) in order to provide a deeper understanding of the ability of the chosen factors to relate to usability aspects within manufacturing.

2.2.1 Complexity model

One highly cited model concerning complexity in manufacturing is the Complexity model, developed by ElMaraghy and Urbanic (2003, 2004, ElMaraghy et al., 2012). According to this model there are three types of complexity that need to be considered in a manufacturing context: product complexity, process complexity and operational complexity. The most relevant model for this research is the *Operational complexity model* (ElMaraghy & Urbanic, 2004), as this model claims to include complexity at an operational level and therefore also affects the systems usability as well as being relevant to product quality and process output (Figure 2.2). ElMaraghy and Urbanic further state that there are three core elements of complexity which are interrelated with the complexity areas in the model: *absolute quantity of information, diversity of information* and *information content (effort).*

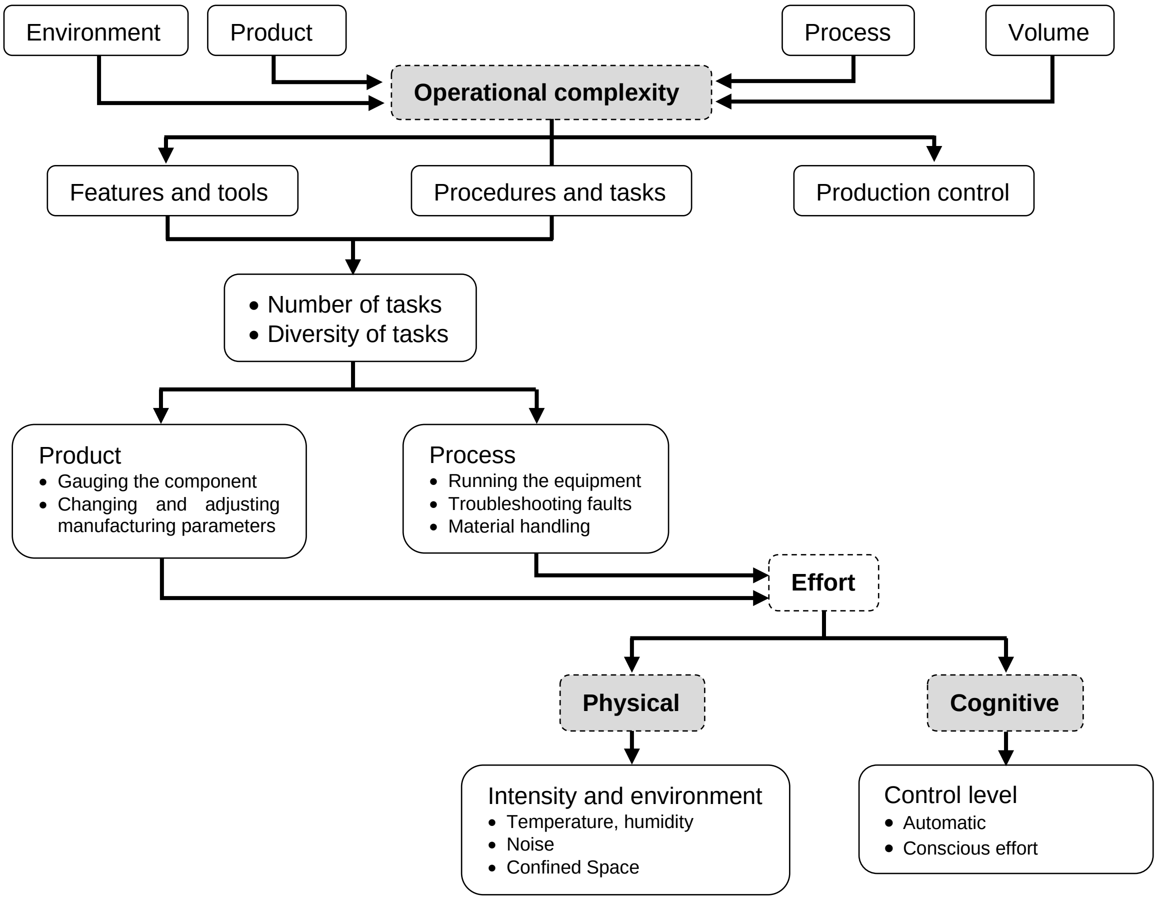


Figure 2.2. The manufacturing complexity model (modified from ElMaraghy & Urbanic, 2004)

Product complexity is referred to as the function of material (components), design and special specifications for each component within the product. Process complexity is referred to as the function of the product, the volume requirements and the work environment. Here, the work environment dictates process decisions such as type of equipment, fixtures, tooling, and gauges etcetera. Further, operational complexity is referred to as the function of product process and production logistics, involving scheduling, equipment set-ups, monitoring, fetching and maintenance tasks of the process. Moreover, the information and skills required to perform the tasks in the operational model are either product related (quality related) or process related (involving machine operation and efficiency).

The product related tasks directly relate to metrics in-process requirements or final product requirements: *gauging, changing tools and adjusting manufacturing parameters* (quality adjustments). In the complexity model, complexity of products increases with: i) number and diversity of features to be manufactured, assembled and tested; and ii) number, type and effort of manufacturing tasks.

Process related tasks directly relate to the manufacturing process, involving; *process related set-ups, pre-assembly, running the equipment, proper equipment safety lockout, process fault analysis, material handling.*

Further, the two main physical aspects of the abovementioned product and process related tasks are the work environment and labour which mainly consist of:

- **Temperature, humidity**
- **Noise**
- **Cleanliness**
- **Envelope**
- **Strength**
- **Dexterity**
- **Confined space**

The cognitive aspect of effort focuses mainly on the control level of:

- **Procedures**
- **In-process relationships**
- **Performance issues (troubleshooting quality and reliability concerns)**

Although vague and ambiguous (due to the task dependency in this model), these factors were suggested by ElMaraghy and Urbanic and were used as input to a larger framework of factors that had an impact on the human factors aspects in manufacturing (section 2.4).

2.2.2 Complexity dimension

Another aspect of complexity in manufacturing is provided by Calinescu (2002, p. 82) who defines manufacturing complexity as:

> *A systemic characteristic that integrates several key dimensions of the manufacturing environment: structural aspects (size, variety and concurrency of both products and resources), decision-making (objectives, information and control), dynamic aspects (variability and uncertainty) and goals (cost and value).*

This definition suggests that the overall manufacturing complexity is the result of the interactions and cause-effect relationships between all of these dimensions, which is defined according to Calinescu as:

- **Size**; refers to the number of resources, information channels or products of each type, either structural or operational.

- **Variety**; represents a static concept that integrates the number of different classes of entities (machines, tools, products and communication channels) and, within each class, the various types of entities it contains.

- **Concurrency**; exists in two forms, resource concurrency refers to one product requiring more than one resource at a given manufacturing stage. Task concurrency refers to more than one product being produced within the system at the same time, as in a mixed assembly mode.

- **Objectives**; represent any formal or informal targets established for a system, for instance the types of products, the time and quantity required at a given stage, or a certain level of performance. Although the quality and thoroughness of a given objective are assumed, it is often the case that a subjective or based-on-limited-information objective provides an inaccurate representation of the problems.

- **Information**; is about the formal and informal data, knowledge and expertise transmitted and utilised through the system. Information is featured as mainly accuracy, relevance, timeliness, comprehensiveness, accessibility, format and dynamics.

- **Variability**; refers to measurable variations between the expected and actual behaviour of the entities in the system, such as variable processing times or variable level of product quality.

- **Uncertainty**; represents a dynamic concept which refers to aspects that are difficult to predict such as breakdowns, absenteeism and poor quality of material or information. These characteristics make the schedules difficult to achieve and the manufacturing system difficult to predict. But by using spare resources and buffers and by an increase in the monitoring and decision-making frequency, potential effects of the uncertainty can be counteracted.

- **Control**; encompasses any action, such as decision-making and decision implementation as well as planning and scheduling, needed for bringing the actual system behaviour closer to the expected behaviour.

- **Cost**; means any costs incurred in the manufacturing system. Every time an action is taken a cost is generated, actions such as decision-making, information gathering or operating a machine. While most of the production costs are generally considered and relatively transparent, the information processing costs are often ignored.

- **Value**; refers to the value added to the final product by any activity. Manufacturing processes directly add value to products, whereas information processing indirectly adds value to products. Potential value only becomes achieved value when a product is sold. Calinescu means that traditional approaches of defining the added value consider mainly that production adds value, while information processing represents overhead costs.

According to Calinescu these dimensions are observable and measurable and are also related to information, which can therefore be used in order to improve system understanding, performance and control. Therefore these dimensions or factors were interesting to have as input to the framework of factors, see section 2.4.

2.2.3 CLAM

Recently, a useful framework and method of considering cognitive aspects that can be connected to manual assembly, has been suggested and this has resulted in an assessment method called CLAM, Cognitive Load Assessment for Manufacturing method (Lindblom & Thorvald, 2014, Thorvald & Lindblom, 2014). CLAM was developed for identifying and reducing the possible cognitive load among assembly personnel in a manufacturing context. It was argued that pro-actively identifying relevant issues at the assembly workstations can lead, for instance, to saved time and resources on the shop floor. Through the development of the framework of factors that might affect high cognitive load, workstation developers are guided as well as educated on how to design in order to reduce cognitive load and on aspects that are argued to have effects on the cognitive workload of the operator. Additionally, and more importantly, this framework also presents a connection between cognitive load and manual assembly environments, which very few researchers have done in such a concrete way.

The factors that are argued to impact cognitive load in manual assembly are shown in Table 2.1.

Table 2.1. Cognitive load factors from CLAM (www.clam.se)

CLAM factors	Description
Saturation	The amount of work that is planned on a workstation, related to the particular balance of the assembly task.
Variant flora	A product or process variation from the most common type of product (volume). Mostly an issue in mixed mode assembly flow. Strongly connection to cognitive workload.
Level of difficulty	A subjective estimation about the required physical and cognitive effort to perform a task. Heavily tied to required time of necessary training and skills needed to perform task independently.
Production awareness	Refers to how much focused /active attention that must be applied to the task and the level of “production awareness” that the worker has to muster.
Difficulty of tool use	Refers to both the amount of tool use required but also the estimated complexity of the tool use. Including all tool use, even special or non-standard tools.
Number of tools	The number of tools used during a normal assembly task, including special and non-standard.
Mapping of workstation	Refers to how well the workstation design maps with the assembly sequence. Tools and parts that are used together should be placed together and in the correct order.
Parts identification	The identification syntax used at the workstation, such as components numbers and material racks or kitting.
Quality of instruction	Refers to on a general level how visible and readable the instructions are used to gather information about the work.
Information cost	Refers to how much physical and cognitive effort is required to utilize the information.
Poka-yoke	Using poka-yoke solutions or constrains to reduce assembly errors. Including designing the task and/or product in order to prevent assembly errors.

As seen in Table 2.1, there are several factors related to usability, intended to be assessed in a manual assembly context. It is therefore suggested that these factors should serve as valuable input to the framework of factors (section 2.3) as they relate both to usability and cognitive workload in a manual assembly context.

Although the factors considered within the manufacturing research area provided valuable and useful understanding of the manufacturing and assembly work environment, it was necessary to further explore the research field of usability. Through the investigation of commonly used models and factors within this field, it was possible to get a deeper understanding and insight into how these usability factors could be applied to a manual assembly work environment. As the usability research area is very wide, only a few widely used principles and models were selected, mainly from the human-computer-interaction (HCI) field as well as the product design field (section 2.3).

2.3 Usability approaches in HCI and product design

How many of us have bought gadgets that we did not understand how to use or misunderstood the instructions? Utilizing a user centred design perspective, this is simply unacceptable as the product or system should be developed with the end-user (in particularly) in mind. If we think of the assembly environment and especially manual assembly workstations, the same requirements needs to apply here as well, where further investigation of usability is one way of improving the work instructions as well as the work situation. Usability has been investigated for a long time, although primarily within the research field of HCI, but also within product design, some of which will be discussed in this section. The International Standards Organisation defines usability as "*the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use*" (ISO, 1998).

Effectiveness refers to the accuracy and completeness of which a user achieves a specified goal. Efficiency refers to the resources that are needed in order to achieve the specified goal accurately. Satisfaction refers to comfort and acceptability of use (Helander, 2006). Over time, many researchers have used and modified this definition (Grudin, 1992, Nielsen, 1993, Bevan, 1995, Jordan, 1998, Norman, 2002, Abras et al., 2004), some which are described in this section.

2.3.1 Usability goals

According to Preece et al. (2002) usability means to ensure that interactive products and systems are easy to learn, easy and effective to use, and enjoyable from a user's perspective. They further break down usability into several goals as well as establishing key questions which were of assistance when exploring usability factors that could be applied in a manual assembly context.

> **Effective to use** (effectiveness); refers to how good a system is at doing what it is supposed to do, on a general level.
>
> > *Question:* Is the system capable of allowing users to learn well, carry out their work efficiently, access the information they need et cetera?

As this goal is quite broad, it therefore relates to several aspects involving the interactions at the assembly workstation, such as how intuitive the assembler's work environment is and how perceivable the provided information is to the assembler.

> **Efficient to use** (efficiency); means the way a system supports the user in carrying out the intended task.
>
> > *Question:* Once users have learned how to use a system to carry out the intended task, can the user then sustain a high level of productivity?

In any company, productivity, as well as quality, are among the top prioritised production outcomes and therefore always relevant. This goal could relate to issues such as that the information provided to the assembler at the workstation needs to be appropriate for the intended task as well as being easy to access. In addition, when presenting information about the task, the content should be suitable for assemblers with different levels of experience to be able to sustain productivity (time spent on assembly task).

> **Safe to use** (safety); relates to the protection of the user from dangerous conditions and undesirable situations. In contrast to the previous ergonomics aspect, this goal relates to external conditions where people work.
>
> > *Questions:* Does the system prevent users from making serious errors and, if they do make an error, does it permit them to recover easily?

According to Preece et al. (2002) this goal refers to helping users in certain situations to avoid accidently carrying out undesirable actions as well as the perceived fear of the consequences of making errors and how this affects their behaviour. Related to manual assembly environment, this seems in line with the poka-yoke methodology which means to develop systems and products that ensures that mistakes cannot be made (Shingo & Dillon, 1989). In manual assembly this could mean that the assembly task and/or the product is developed so that an assembly error cannot occur. The manual assembly environment should also stimulate the confidence of the user and provide support if they, contrary to expectations, make assembly errors.

> **Have good utility** (utility); refers to the extent to which the system provides the right kind of functionality so that users can do what they need or want to do.
>
> > *Question:* Does the system provide an appropriate set of functions that enable users to carry out all intended tasks in the preferred way?

In the manual assembly environment this could relate to the support systems that are provided to the assembler, which then should be in proportion to the tasks (hence, not too much just good enough to not lead to too much information) to be able to assimilate and exploit the intended support function. In addition, the assembly environment (with everything that entails) should also allow the user some flexibility when performing the assembly task (Preece et al., 2002):

> **Easy to learn** (learnability); means how easy a system is to learn to use.
>
> > *Question:* How easy is it and how long does it take: i) to get started using a system to perform core task, and ii) to learn the range of operations to perform a wider set of tasks?

When relating this goal to a manual assembly environment the most apparent issues concern both how the material (i.e. components) are presented to the assembler, especially the component variants, as well as how the instructions are designed to best support the assembler. As mentioned earlier, investigations in manual assembly have shown that assemblers are faced with too much information rather than the right or appropriate information (Bäckstrand et al., 2005, Thorvald et al., 2008).

> **Easy to remember how to use** (memorability); refers to how easy a system is to remember how to use, once the user have learned the system.

Question: What kind of interface support has been provided to help users remember how to carry out tasks, especially for systems and operations that are used infrequently?

Infrequently used operations in a manual assembly context refer to product or component variants. Therefore, when relating this goal to the manual assembly environment, it is necessary to consider how component variants are handled and presented at the assembly workstations as well as how to best support assemblers when a product variant appears on the assembly line.

2.3.2 Design principles

It is also relevant to investigate the concept of usability in the related field of product design and thus explore *design principles*. Several design principles have been widely promoted, where the most common concerns how to determine what users should see and do when performing a task using an interactive product or system. The book *The design of everyday things* (2002), written by Donald Norman, is well-known and established within this research field and therefore this thesis will use the design principles described in his famous book, as a foundation when investigating the connections of these principles to a manual assembly context. The most common design principles elaborated by Norman are:

Visibility; means the visibility of functions. Good visibility means that the user is reminded of what and how to perform the next action. Norman states "*in general, the relationships among user's intentions, required actions, and the results are sensible, non-arbitrary, and meaningful*" (2002, p. 22). In contrast, inadequate visibility results in complex interfaces for essentially simple things, such as too many controls for a few possible actions. When relating this to the assembly workstations, this principle could indicate that the information and the material presented to the assembler needs to be structured in a way so that the assembler quickly can move on to the next task, instead of having to search for components or what to assemble.

Mapping; related to visibility, mapping refers to the relationship between controls and the things controlled, such as using a labelled button to perform some function. In contrast, when using a badly designed product interface, the mapping is often arbitrary meaning that the relationships between the actions the user must perform and the intended results lack reasoning. It is therefore vital that the control is clear and used consistently as well as positioned logically in order to map to the real-world objects. When related to a manual assembly workstation this could for instance mean that the components themselves are displayed and positioned in a way that maps the order of the assembly operation, which also can be related to so called natural mapping (Norman, 2002). Natural mapping does not require any labels, diagrams or instructions instead it carries all the information that is required and thus reduces the need for the user to keep that information in memory, more particularly in the working memory.

In 1968 Atkinson and Shiffrin came up with a model that is still valid today, involving human *memory* consisting of three major components; long-term memory, short-term memory (working memory) and sensory memory. Atkinson and Shiffrin (1968) describe sensory memory as the initial stage of information processing. As sensory memory is limited and most of the information held in sensory memory fades away quickly, only selective attention can make certain aspects of the information held in sensory memory to enter the short-term memory. The short-term memory is a memory store which only holds a limited amount of information temporarily before the information is transferred into the more permanent storage of long-term memory or simply forgotten (Atkinson & Shiffrin, 1968). Short-term memory is often referred to as working memory (Baddeley, 2002), and deals with all conscious activities by storing and actively manipulating information (Sweller et al., 1998) in order to support cognitive functions such as problem solving, information seeking and decision making. Miller (1956) describes this limited capacity of the working memory as "the magical number seven, plus or minus two". This indicates that the majority of people only can hold five to nine units or chunks (7 ± 2) at the same time in short-term memory, often it is less. As these units are divided into groups, they are recognised as a single gestalt (unified whole) and therefore releasing additional storage. For instance phone numbers being divided into chunks is not a coincidence as this meets the Miller estimate of memory capacity. In contrast, long-term memory is considered to have an unlimited storage capacity and it functions as a permanent record of all learned material (Kirschner, 2002). Furthermore, Sweller et al. (1998) claim that humans are seldom conscious of long-term memory since its content and functioning is filtered through working memory.

Feedback; means the requirement that the user should be given confirmation that an action has been performed successfully (or unsuccessfully). By sending back information about what action was performed and accomplished, the user can continue to do tasks. The content of the feedback can consist of several different modes of information such as tactile, audio, verbal, visual, and sometimes a combination of some of these. It is however important to think through what type of feedback is appropriate for the intended action. At the assembly

> workstation feedback for the assemblers is essential in order to know if the right component was picked and assembled correctly. It is therefore necessary to provide feedback as soon as possible in a distinct way to the assembler since assembly errors might otherwise be discovered further down the assembly line which enormously increases the cost to correct the assembly error.

This means that it is easier to perceive a signal rather than having to perform an action or even worse, read some text. At some workstations feedback of picking the right component is provided by scanning a code attached to the assembly object. This can be argued to be a bit too late as the assembler has already picked and assembled the component, and moreover the assembler had to perform an action in several steps in order to get the feedback. But at the same time it is still done at the assembly workstation and not further down the assembly line.

> **Constraints**; refers to determining ways of restricting user interaction that might lead to incorrect actions which can take place at a given moment. By using constraints it is possible to instead reduce the amount that must be learned to a reasonable quantity. As previously described with the usability goal, this can also be related to poka-yoke methodology where, for instance, assembly instructions and the display of components should be designed in a way which prevents the user from selecting an action that might result in an assembly error. Moreover, Norman (2002) categorises constraints as physical, logical and cultural. Physical constraints are about the way physical objects are restricted by the physical form of, for instance, shape and size in order to be placed correctly or moved in the right way, and also relate to the poka-yoke methodology. Logical constraints refer to people's common-sense and reasoning behind actions and their consequences when interacting with the world. Related to manual assembly, it is important to make actions and the effects obvious, enabling assemblers and operators to understand and follow a logical order of what further actions are needed and available. Cultural and semantic constraints refers to the conventions that people have learnt thought experience of social situations and meanings of the world, e.g. red for warning, turning screws clockwise to tighten and counter-clockwise to loosen. Since the majority of the conventions merely represent an abstract idea of things that we have learnt, accordingly it is only through learning and experience we are able to accept these conventions.

C**onsistency**; relates to the design of products and systems that follow rules in which similar operations and similar elements achieves similar tasks. This means that when one has learnt one system, this readily transfers to other systems as a pattern knowledge, which makes the interaction of similar products or systems easy to learn and use. Consistency helps users recognise and apply previously experienced patterns. However, when designing a system or product it can be difficult to decide whether to design consistently to how people use things in the outside world (external consistency) or in the existing system (internal consistency). Consequently inconsistency can confuse users as the system or product does not always work out as expected. As assemblers often rotate to different workstations it would benefit the assembler greatly if components and instructions were presented in a consistent way at each workstation, such as the placement of often used components. Then the assemblers would immediately know where to find components and information instead of having to search every time.

Affordance; Gibson coined the term affordance as special property of the environment in relation to an organism (1966), using his perception theory as an approach. It was in the late '80s when Norman in his book *The design of everyday things* (2002), although first edition was called The psychology of everyday things, popularised the concept of affordance in the context of product design. Here Norman defined affordance as the perceived and actual properties of things, primarily those fundamental properties that determine just how the thing could possibly be used (Norman, 2002). Norman argues further that affordances result from users' mental interpretation of things and themselves, which are based on their previous knowledge and experience. Although he later clarified that he meant that affordance refers to when using a product design approach as visual attributes of an object (e.g. clues) that allows users to know how to use it. Meaning that visual cues are used in order to make products interact in the way the user is intended to use it, such as clickable or touchable.

Strongly related to the field of affordance is the research field of product *semantics*, which can be described as the study of the symbolic qualities of man-made forms in the cognitive and social contexts of their use (Krippendorff & Butter, 1984, Krippendorff, 1989). They further described the concern for these symbolic qualities in design as a paradigm shift from 'design for function' to 'design for meaning'. This approach then presumed that a product carries information and communication that enables reconstruction of intended meanings. Consequently, designers used the well-established design elements of shape, colour and texture to represent the intended message as form. However, You and Chen (2007) argue the difference between affordance and semantics, being "*affordance is about action but not communication*", and further elaborates that "*the core of affordance concept in design lies not in communicating the design intention for designers, but providing the requisite structure to await the emergence of functional affordances for target users*".

However, as the application of the research in this thesis lies within the context of manual assembly it can be argued that this subject should be approached on an even higher level of user-centred design by exploring the field of *semiotics*. This since in the manual assembly environment there are several plausible factors which affect the assembler, both related to object but also information, causing a complex situation. It is further possible that not only visual objects (relating to affordance) affect the assemblers. Thus, exploring the field of semiotics can aid in the understanding and interpretation of physical objects as well as information technology, which possibly affect the assembler at the workstation.

The theory of semiotics not only relates to product design and gestalt principles but it also embraces semantics, as well as the other traditional branches of linguistics: syntax and pragmatics as seen in Figure 2.3 (Morris, 1938/1970, Monö, 1997, Chandler, 2007).

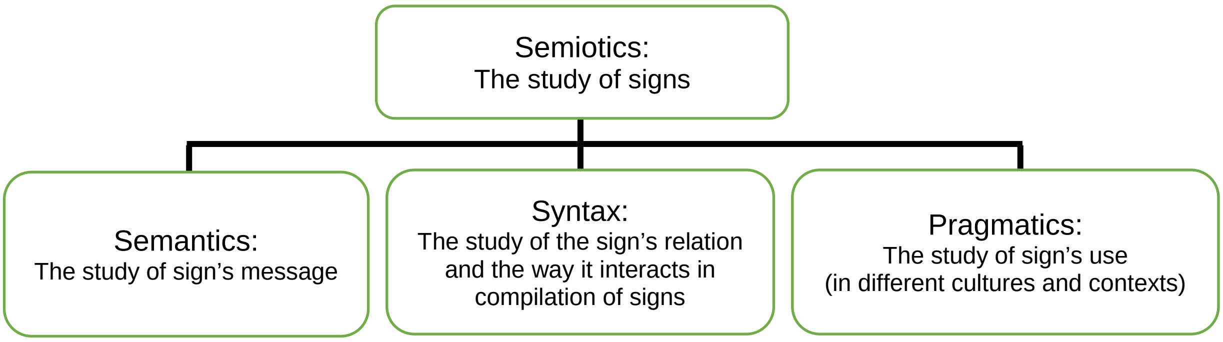


Figure 2.3. The definition of semiotics according to Monö (1997)

The theory of signs as well as semiotics seems to appear throughout history with varying definitions. In contemporary semiotics the primary definitions are derived from the philosopher Charles Sanders Peirce (1839 – 1914) and the linguist Ferdinand de Saussure (1857 – 1913). The modern interpretation of semiotics is to study how 'meanings' are made and not to focus on the classification of sign systems or communications but also the construction and maintenance of reality (Chandler, 2007). Eco (1976) used the broad description of semiotics in studies of signs in everyday speech. Monö (1997) further elaborated on Eco stating that semiotics is the study of signs that we interpret through all our senses such as words, images, sounds odours, flavours, gestures or objects, everything which appears as something else but have no meaning unless we invest them with meaning (Figure 2.4).

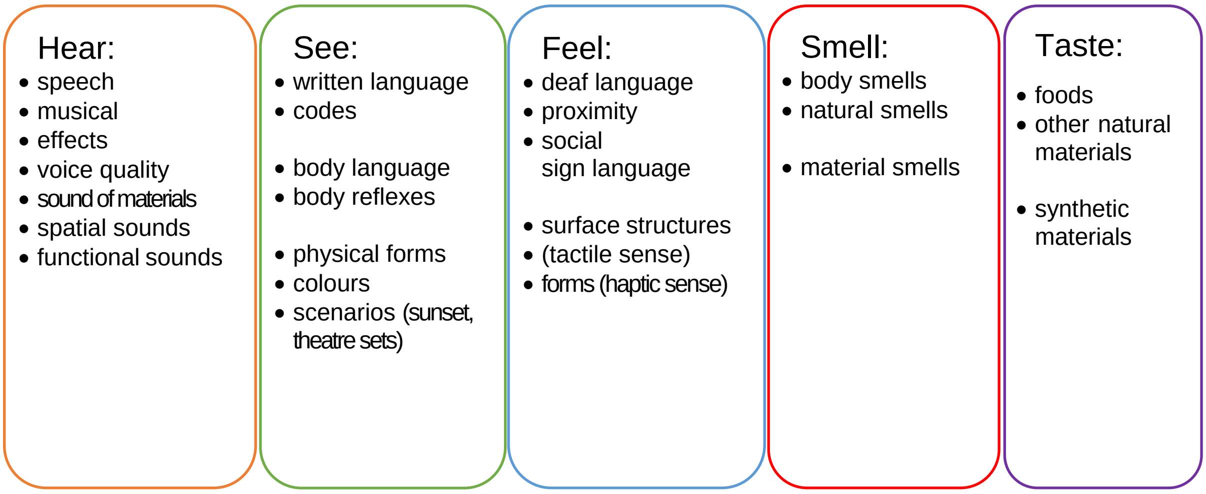


Figure 2.4. Overview of the study areas of semiotics and examples of types of signs in different areas (adapted from Monö 1997)

As we interpret things as signs rather unconsciously by relating them to familiar systems and society, it is this meaningful use of signs which is at the heart of the concerns of semiotics. When we for instance subjectively see, feel and hear a sign, this then makes it easier for users to orient in the system, simpler to use the product or system and more efficient. By exploring the characteristics of semiotics it can help users to understand that information or meaning is not 'contained' in the world or in books, computers, media or products. Nor is it passively 'transmitted' to users – instead users actively create it according to a complex interplay of codes or conventions (as aforementioned when discussing Norman's constraints) of which we are normally unaware (Chandler, 2007). By using all senses, it is possible to enhance the interpretation and understanding of information or objects, especially when using for instance haptic or tactile information. This can therefore also be argued to enhance the communication and guidance at the manual assembly workstations. Perhaps by using a rougher surface on certain objects to more easily distinguish them from others or perhaps by sorting components by shape or size in the material rack.

The study of semiotics obviously leads into the research field of *perception*, which refers to the recognition and interpretation of stimuli registered by our senses. This implies that perception is mainly concerned with observation and gathering of information about the environment. There are mainly two approaches applied to explain the perception phenomenon:

- bottom-up approach, the processing is passive and driven by sensory inputs (Gibson, 1986, Kornmeier et al., 2009).
- top-down approach, the processing is active and is driven by the perceiver's knowledge, beliefs and goals (Gregory, 1990, Kornmeier et al., 2009).

Both approaches stress the importance of mental representations (stored mental concepts) in order to interpret the stimuli and identify objects or signs.

Although we are constantly presented with lots of diverse and ever-changing information, we are still able to attain a stable representation of our visual society. It is therefore suggested that our perception is highly organised. To help us organise all aspects of perception, theories from *gestalt* psychology suggest that visual objects interact with each other and that, by doing so, are producing a whole that is different from the sum of its parts (Rookes & Willson, 2000). As aforementioned, different material structures, shapes and colours can constitute different signs, and furthermore, according to Gestalt psychology, these signs are not introduced to the whole as separate factors, but instead we experience how these factors work together and influence each other. The Gestaltists even proposed a set of perceptual principles or laws, describing the way we group together elements to form a perceptual whole further influencing the understanding of the environment (Rock & Palmer, 1990). The law which encompassed all their other principles of grouping is called *the principal of Prägnanz* or the *law of good form* (Koffka, 1935, Rookes & Willson, 2000). This principle refers to the fact that humans tend to perceive the simplest and most stable figure of all possible more complex alternatives.

Other gestalt principles of grouping are included in Table 2.2.

Table 2.2. Some gestalt principles of grouping (Rookes & Willson, 2000)

Law	**Definition**	**Example**
Proximity	Elements that are physically close, tend to be perceived as a unit.	Written text on page forms rows, rather than columns since the letters are closer to the ones on the side compared to the ones above and underneath. Also, controls can be grouped according to functions, making it easier for the user to get an overview.
Similarity	Similar elements tend to be grouped together.	As in the previous example, a control with similar functions usually has grouped controls, allowing the user faster and more accurate actions. Relating to an assembly workstation, components that are placed together according to shape, function etcetera therefore serve the assembler best.
Good continuation	Elements aligned in either straight or smoothly curved lines tend to be seen as a unit.	This principle advises us on how to effectively perceive ways to indicate relatedness and is especially useful for allowing us to understand meaning as indicated by different sorts of visual structures.
Closure	When a figure has a gap, the mind still tends to perceive it as complete, closed figure or pattern.	A circle on the whiteboard will still seem like a circle even though it is not totally unified.
Common fate	Elements that move in the same direction tend to be more related than elements that are stationary or move in different directions.	Vehicles driving in one direction will be perceived as a separate group compared to those going in the opposite direction.

It is thus possible to reduce the number of small units by grouping elements or stimuli into units, or grouping several units into larger sets. This can ease the perception process and make the information easier to understand.

2.3.3 Usability principles

Another set of guidance models worth mentioning and related to usability are the *usability principles* developed by Nielsen (1993). The main usability principles are listed in Table 2.3. As seen, these principles are similar to the aforementioned design principles but the usability principles are more prescriptive and mainly used as a foundation to evaluate interactive prototypes and systems, hence heuristics. Whereas the design principles are mainly used for informing a design, although they too can function as heuristics when used in evaluation.

Table 2.3. The main usability principles (Nielsen, 1993), and matching of the design principles

Usability principles by Nielsen	Description	Mapping with the design principle(s)
Visibility	The system should keep users informed of what is going on, by using appropriate feedback within reasonable time.	Visibility and Feedback
Match between system and the real world	The system should speak the users' language, using words, phrases and concepts familiar to the user, rather than system oriented language.	Mapping and Visibility
User control and freedom	Provide ways to help the user escape from unwanted states they unexpectedly find themselves in, such as clearly marked "emergency exits". Support undo and redo.	Mapping
Consistency and standards	Users should not have to wonder whether different words, situations and actions mean the same thing. Follow basic conventions.	Consistency
Error prevention	Develop a careful design which prevents errors from occurring in the first place.	Constraints
Recognition rather than recall	Make object, actions and options visible. Users should not need to remember information used in the same dialogue, if needed instructions of usage should be visible or easily retrievable.	Visibility and Mapping
Flexibility and efficiency of use	Provide accelerators, invisible to the novice user, but allowing experienced users to more efficiently interact and carry out tasks.	-
Aesthetics and minimalist design	Dialogues should not contain irrelevant or rarely needed information. Every extra unit of information competes with the relevant units and diminishes their relative visibility.	Affordance and Visibility
Help users recognize, diagnose and recover from errors	Error messages should be expressed in plain language, describing the nature of the problem and constructively suggesting a solution.	-
Help and documentation	Documentation and information provided to help the user should be easy to search, focused on the user's task and provide help in concrete steps that can be easy to follow, and not too large steps.	-

As seen there are quite a few usability principles that overlap the product design principles which makes it easier for designers to develop and evaluate interactive products and systems, as there are principles in both disciplines which may support the usability of the product or system.

2.3.4 User experience (UX) Guidelines

A more contemporary take on usability is provided in the book *The UX book: Process and guidelines for ensuring a quality user experience* (Hartson & Pyla, 2012). Here the authors thoroughly describe and elaborate on how to create and refine HCI interaction designs which ultimately results in a quality user experience. The authors argue that as usability is essential to making technology transparent, in order to stay head of consumer competition, it is necessary to also consider the user experience. Further, as this book contains almost everything a UX designer needs to know, a few guidelines which were relevant and applicable for this thesis were selected and used. For further information about UX and the complete scope of the UX guidelines, see *The UX book: Process and guidelines for ensuring a quality user experience* (Hartson & Pyla, 2012).

By extending Norman's theory of stage-of-action model, which typically illustrates a generic sequence of user actions when interacting with a machine, Hartson and Pyla (2012) developed the *Interaction cycle*, which also suggests actions that occur in a typical order of interaction between a user and a machine (Figure 2.5).

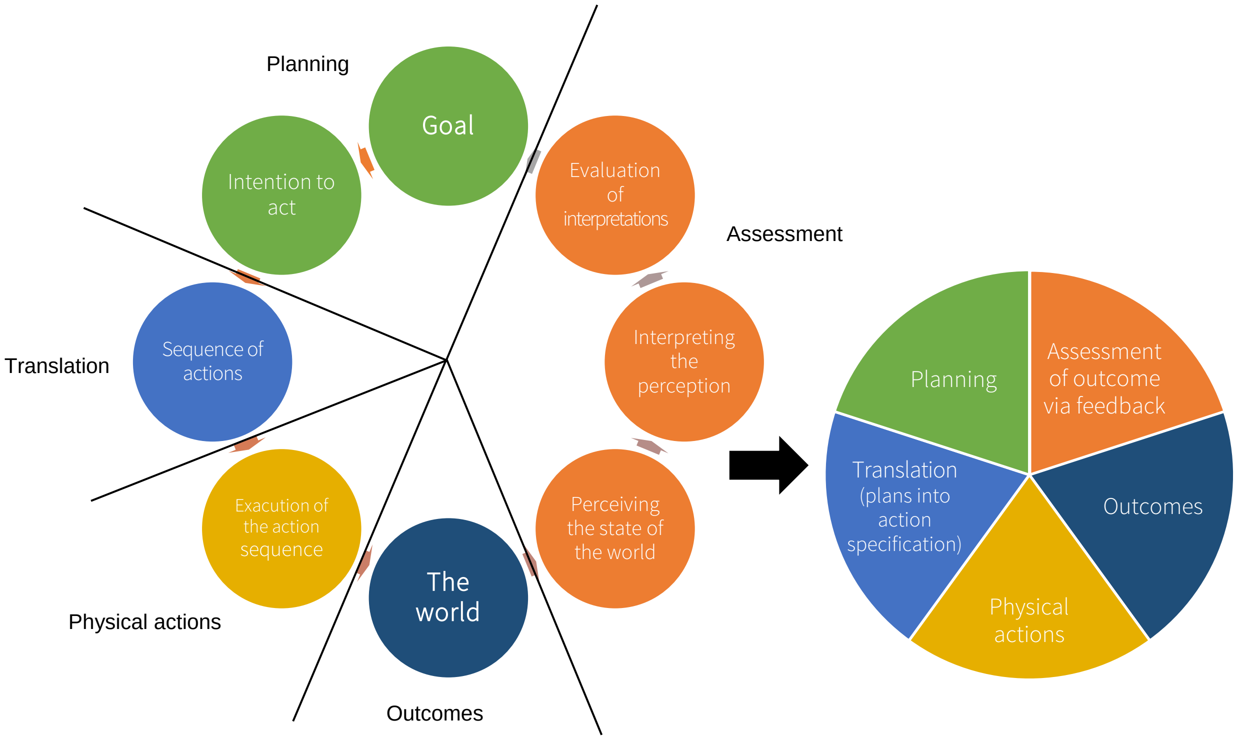


Figure 2.5. An illustration of the transition from Norman's model (left) to the Interaction cycle (right) (modified from Hartson & Pyla, 2012)

As not all phases were of equal relevance to this thesis, only the phases of translation, physical action and assessment were explored further. The translation phase comprises everything which involves deciding how you can or should make an action on an object, including users' thoughts about which actions to take or on what object to take it, or best next action to take within a task. Consequently the translation phase concerns the cognitive actions where users decide how to carry out the interaction arisen from planning phase.

The physical action phase concerns: i) the use the different human senses to, for instance see, hear or feel the objects in order to be able to manipulate them, and ii) manipulation of the object. The ability of the user to sense the object depends heavily on the object's own physical affordance, such as size, colour, surface, location etcetera. Suggested physical affordance design factors (most relevant for this thesis) include design of input/output devices linked to user actions as well as haptic devices, gestural body movements, physical fatigue and physical human factors such as manual dexterity, hand-eye coordination environment layout (Hartson & Pyla, 2012). Related to this physical action phase is Fitts' law, which states that difficulty is a function of distance of movements and target size (Fitts, 1954). In manual assembly this is of interest when considering the assembly task movement's against the layout and the distance of the components.

The assessment phase refers to how users perform physical and cognitive actions or tasks which are needed to be able to sense and understand the feedback of the system as well as the means to understand the display of changes or outcomes due to previous actions. Here, the user's objectives are to determine if the outcomes of all the previous phases and plans help to achieve the intended task or goal. The assessment phase focuses mainly on the presence and presentation of feedback as well as the meaning and content. This can then clearly be linked to errors in the system, as the whole point with the assessment phase it to understand the 'when' and 'what' of the occurring error, as well as being able to sense the message of the feedback.

A more concrete description of these phases can be found in Table 2.4, where selected guidelines from the phases of translation, physical action and assessment are shown (some guidelines were written together in order to fit properly).

Table 2.4. Selected UX guidelines (Hartson & Pyla, 2012), and the matching of other design and usability principles

Interaction circle phase	Breakdown of phase	Guidelines	Mapping to other design and usability principles
Translation	Existence of cognitive affordance to show how to do something.	**Support users know/learn to carry out actions and to predict the outcome of actions.** Feed-forward cognitive affordance of physical actions.	• Visibility [Norman and Nielsen] • Flexibility and efficiency of use [Nielsen] • Affordance [Norman] • Mapping [Norman] • Matching between system and reality [Nielsen]
		Provide a cognitive affordance for a step the user might forget, such as reminders, cues or warnings.	• Memorability [Preece et al.]
	Presenting of cognitive affordance	**Make cognitive affordance visible and noticeable**. Relevant cognitive affordance should come to the users' attention, without seeking it.	• Visibility [Norman and Nielsen]
		Make text legible. Both through appearance and characteristics such as colour, font type and size.	• Help and documentation • Matching between system and reality [Nielsen]
		Control cognitive affordance presentation complexity with effective layout, organisation and grouping	• Consistency • Mapping [Norman and Nielsen]
		Present cognitive affordance in an appropriate time for it to help users before the associated action. Not too early or too late or with inadequate persistence.	• Effectiveness [Preece et al.]
	Content, meaning of cognitive affordance	**Design cognitive affordance for clarity**. Use and create correct, complete and sufficient expressions of content and meaning.	• Visibility • Aesthetics and minimalism design [Norman and Nilsen]
		Make choices distinguishable. Support user ability to distinguish between two or more possible choices or actions, by expressing meaning in their cognitive affordance.	• Affordance [Norman and Nielsen]
		Consistency of cognitive affordance. Use consistent wording In labels, buttons etc. Similar names for similar things.	• Consistency • Mapping • Affordance [Norman and Nielsen]
		Controlling complexity of cognitive affordance content and meaning. Decompose complex instructions into simpler tasks, group together objects and design elements with related tasks and functions.	• Mapping [Norman] • Matching between system and reality [Nielsen]
		Support human memory limitations in cognitive affordance. Support users' memory limit with recognition over recall.	• Memorability [Preece et al.] • Recognition rather than recall [Nielsen] • Visibility • Mapping/ Matching [Norman and Nielsen]
		Avoid cognitive indirectness. Use natural mapping, for instance when designing knobs and other controls.	• Mapping [Norman]
		Be complete in your design of information, include enough information for users to determine correct action.	• Help and documentation [Nielsen] • Visibility • Aesthetics and minimalism design [Norman and Nielsen]
		Find ways to anticipate and avoid user errors when designing.	• Error prevention [Nielsen] • Constraints [Norman and Nielsen]

	Task structure, interaction control, preferences and efficiency	**Design task structure for flexibility and efficiency.** Support user with effective task structure and interaction control.	• Flexibility and efficient to use [Preece et al. and Nielsen]
		Keep users in control. Avoid the feeling of loss of control.	• User control and freedom [Nielsen] • Mapping [Norman]
Physical action	Sensing user interface object	**Support users to make physical actions with effective sensory affordance for sensing physical affordance**. Visible, discernible, legible, noticeable and distinguishable.	• Visibility [Norman and Nielsen] • Help and documentation • Matching between system and reality [Nielsen]
	Manipulating user interface objects	**Support user with effective physical affordance for manipulating objects, help in doing actions**. Help with issues like manual dexterity and Fitts' law, haptics and physicality.	• Effectiveness and efficiency [Preece et al.] • Flexibility and efficiency of use [Nielsen] • Mapping [Norman]
		Use physicality and haptics when designing, if the alternatives are not as satisfying to the user.	• Visibility • Mapping / Matching • Affordance [Norman and Nielsen]
Assessment	Existences, presentation, content and meaning of feedback	**Provide feedback for all user actions and make it visible, noticeable, clear and comprehensible.**	• Feedback [Norman] • User control and freedom • Error prevention [Nielsen]

As seen, there are many usability and design factors that comply with the UX guidelines, which is natural as they originate from Norman's design principles.

2.4 Concluding the literature review

This chapter has reviewed and investigated usability and cognitive aspects of human performance both derived from the field of HCI and product design, but also included factors related to the manufacturing and manual assembly work environment. All of these factors were compiled into a framework of factors where the frequently used factors found within manufacturing and manual assembly were used as a basis. Against this basis, the most relevant factors found in the various models and methods were mapped, to investigate the similarities between all of the different factors, in order to perhaps find factors or areas that were more commonly used (Table 2.5). Furthermore, in some cases several factors were merged, before mapping onto the manufacturing factors.

Table 2.5. Frame work of investigated factors

Main factors within manufacturing	Complexity model	Complexity dimensions	CLAM	Usability goals	Design principles	Usability principles	UX Guidelines
Tools & support tools	• Dexterity • Strength	• Size • Value	• Difficulty of tool use • Number of tools available	• Safety	• Constraints • Consistency	• Flexibility and efficiency	• Consistency • Ways to anticipate and avoid errors
Product variants		• Variety • Concurrency • Variability • Improving uncertainty	• Variant flora • Production awareness	• Learnability • Memorability	• Consistency • Affordance	• Consistency and standards	• Cog. affordance presentation • Distinguishable • Consistency • Cog. affordance for meaning • Ways to anticipate and avoid errors
Transfer of training		• Value	• Level of difficulty	• Learnability	• Mapping • Consistency	• Matching • Consistency and standards	• Consistency • Avoid cog. indirectness
Workstation layout	• Cleanliness • Confined space • Procedures	• Variability • Improving uncertainty • Value	• Difficulty of tool use • Mapping of workstation • Information cost • Poka-yoke	• Effectiveness • Efficiency • Safety • Utility • Learnability • Memorability	• Visibility • Mapping • Constraints • Consistency • Affordance	• Visibility • Matching • Consistency and standards • Error preventions • Recognition • Flexibility and efficiency • Aesthetics and minimalism	• Feed-forward cog. affordance • Visible cog. affordance • Cog. affordance presentation • Cog. affordance for clarity • Distinguishable • Consistency • Cog. affordance for meaning • Memory limitations • Avoid cog. indirectness • Ways to anticipate and avoid errors • Manipulating user interface object
Work instructions	• In-process relationships	• Size • Information • Objectives • Variability • Improving uncertainty • Value	• Parts identification • Quality of instruction • Information cost • Poka-yoke	• Effectiveness • Efficiency • Safety • Utility • Learnability • Memorability	• Visibility • Constraints • Consistency	• Visibility • Consistency and standards • Error preventions • Recognition • Flexibility and efficiency • Aesthetics and minimalism • Help and documentation	• Feed-forward cog. affordance • Visible cog. affordance • Legible text • Cog. affordance presentation • Cog. affordance for clarity • Consistency • Cog. affordance for meaning • Memory limitations • Complete in design of info. • Ways to anticipate and avoid errors • Manipulating user interface object

Operator's way of working	- Procedures	- Improving uncertainty - Value	- Saturation - Information cost - Poka-yoke	- Effectiveness - Efficiency - Safety - Utility	- Mapping - Constraints - Consistency - Affordance	- Matching - User control and freedom - Consistency and standards - Recognition - Flexibility and efficiency - Help and documentation	- Cog. affordance presentation - Consistency - Memory limitations - Avoid cog. indirectness - Effective task structure and control - Manipulating user interface object
Feedback	- Performance issues - In-process relationships	- Improving uncertainty - Value	- Parts identification - Information cost - Poka-yoke	- Safety - Utility - Learnability	- Visibility - Feedback - Constraints - Affordance	- Visibility - Error preventions	- Visible cog. affordance - Ways to anticipate and avoid errors - Manipulating user interface object - Feedback for all actions visible, clear etc.
Information syntax		- Information - Improving uncertainty - Value	- Parts identification - Poka-yoke	- Utility - Learnability	- Visibility - Mapping - Constraints - Affordance	- Visibility - Matching - Error preventions - Recognition - Aesthetics and minimalism - Help and documentation	- Feed-forward cog. affordance - Visible cog. affordance - Cog. affordance for clarity - Distinguishable - Memory limitations - Avoid cog. indirectness - Ways to anticipate and avoid errors - Sensing user interface object - Manipulating user interface object

Most of these factors could be linked in different ways, both within the wider research fields of usability and manufacturing, but are also interrelated across the fields. The result of these connections identified common subject areas within manufacturing which could be related and also supported through usability and cognitive aspects (Table 2.5).

These so called main factors within manufacturing (left column) were of interest for further investigation and exploration of how they are handled in reality, hence literature contra reality. Therefore a case study, as well as an investigating study, was performed in order to explore how the factors from the literature matched the ones found in manual assembly (Chapter 3). These factors were then also investigated further during an experimental study (Chapters 4 - 6).

3 EXPLORATION STUDIES

The main conclusion from the literature review (Chapter 2) was that interest in the cognitive aspects of human performance in manual assembly has increased recently, but there is still limited amount of research done in this research field. The aspects of usability and cognition were of highest interest when investigating factors that possibly affect human performance in manual assembly. Several principles were gathered from the field of HCI and product design, but also from complexity models that used factors derived from the assembly context to evaluate human factors.

Altogether, the literature review resulted in several main factors that affect the assembler at manual assembly workstations. Out of these main factors summarised in Table 2.5, four were considered more interesting to further investigate in this thesis, as they involved several usability and cognitive aspects as well as being tightly connected to assemblers' work environment and therefore well-established factors within manual assembly:

- Product variants
- Workstation layout (material presentation)
- Work instructions
- Operator's own way of working

However, workstation layout consisted of how materials (i.e. components) were presented at the workstation, as it was of main concern in the latter investigations, when regarding workstation layout.

As a starting point, these factors were considered valuable input to further investigations which explored the manual assembly context, (section 3.1) and later in a field investigation (section 3.2), to see how they were presented and handled at several different assembly plants.

The research in this thesis was initially inspired by the VINNOVA FFI (Fordonsstrategisk Forskning och Innovation) project FACECAR (Flexible Assembly for Considerable Environmental improvements of CAR's), which ran between 2009 and 2011. The project involved the large automotive companies in Sweden as well as six other universities and companies connected to the Swedish automotive industry. The overall project aimed at improving competitiveness and sustainability in the vehicle industry with an idea of accommodating a large range of different vehicle models in one production line. In order to achieve this, the focus was to conceptualise the transition of a flexible assembly line in the short term (2012) and the long-term (2020) being able to combine existing and future technology in the same production system. A large project like this obviously included several sub-projects or work packages, where the work related to this thesis was connected to the work package called 'information variation in manual assembly processes'.

The purpose of the work package was mainly to simplify the handling of variants in manual assembly for the assemblers and technicians, with the goal of developing an information system that could handle the large number of variants in the manual assembly automotive industry. In light of this, two case studies were performed at two major automotive companies focusing on the introduction of kitting and the relative effects that followed. These case studies gave good insight and knowledge (or rather the lack of) regarding the cognitive aspects of assemblers' performance at manual assembly workstations. These studies also provided a good foundation as to how to conduct an experiment, and thus research methodology, in an industrial context (section 3.1).

To broaden the knowledge and understanding, a field investigation was conducted at several other automotive companies with similar production systems, to explore the current state of the manual assembly industry (and the extent of the lack of knowledge), but also to identify common factors that affect assemblers' cognitive workload at the workstations (section 3.2).

The main purpose with these studies was to:

- Establish the current state of the assemblers' work performance and environment in manual assembly.
- Provide a research foundation for forthcoming research and identify possible knowledge gaps of how usability aspects affect human cognitive performance in current manual assembly.
- Identify factors that affect assemblers at the manual assembly workstation.

This author co-operated in collecting the data and writing a research paper (Hanson & Brolin, 2012) based on the two case studies in section 3.1, whereas the first author of the paper principally planned and analysed the case study. This was however done using mostly a logistic perspective, while the author of this thesis connected the relevant information, such as the workload aspects, from these studies towards the thesis.

Regarding the observational study, in section 3.2, the author of the thesis planned, performed and analysed the work.

3.1 Two case studies investigating cognitive workload in manual assembly

These studies were conducted at two major Swedish automotive companies, focusing on how the different companies replaced the material feeding principle of continuous supply with kitting, and the effects that followed. As both of the companies went from continuous supply to kitting, it was possible to study both of the material feeding principles in the same production setting, based on empirical data. Kitting means that pre-sorted kits of components are delivered to the workstation either by so called traveling kits or stationary kits, see section 2.1 for a more thoroughly description of kitting and continuous supply.

As stated in the literature review, the use of kitting and continuous supply can be associated with several different performance effects. The ones that were originally investigated in these studies were man-hour consumption (time spent on material handling and assembling of product), product quality (number of errors) and assembly support, flexibility (handling of component variation or production volumes) and inventory levels design and space requirements (required space by the assembly station and storage).

However, for the purpose of this thesis, which aims at using a user centred approach to investigate possible affecting factors at the assembly workstation, different approaches of abovementioned performance effects was necessary in order to better relate to assemblers' cognitive workload. In these case studies, the main factors that would be investigated were work instructions and material presentation.

As mentioned in the literature review, information is a frequently used factor that in many different ways affects assemblers' cognitive workload (Bäckstrand, 2009, Thorvald, 2011). It was therefore decided to analyse these case studies on the basis of how information is presented to the assembler at the assembly workstations and in the kitting preparation area, i.e. work instructions or presentation of information, which was one of the main factors obtained from the literature review. Further, since information presentation in these case studies mainly involved instructions as well as presentation of components, i.e. material, (Medbo, 2003), it was decided to include the aspect of material presentation as well.

This resulted in the two main factors: *work instructions*, consisting of how and in what form the instructions were provided to the assembler, and *material presentation* referring to how and in what form components was presented to the assembler.

As mentioned in the literature review, Thorvald and Lindblom (Lindblom & Thorvald, 2014, Thorvald & Lindblom, 2014) have identified several factors that affect cognitive load at the assembly workstation. Here a deeper presentation of the connections is made as they relate very well to work instruction and material presentation (Figure 3.1), which further strengthens the argument for selecting these factors for the analysis in these case studies.

Factors from CLAM:	**Factors used in the exploration studies:**
Mapping of workstation	Material presentation
Parts identification	
Quality of instructions	Work instructions
Information cost	

Figure 3.1. Selected factors from CLAM (Thorvald & Lindblom, 2014), which could be connected to the selected main factors from manufacturing

The selected factors from CLAM which could be connected to material presentation were primarily 'mapping of workstation', which in CLAM is defined as workstation layout corresponding to the assembly sequence, and thus relating to the presentation of, for instance, components. Further relating to material presentation is 'parts identification', which in CLAM is defined as the identification of components. Traditionally, component numbers have been used in combination with the use of a material rack, but as stated earlier this could also include kitting and other material supply methods and component identification syntaxes.

The factors from CLAM that could be connected to information presentation were primarily 'quality of instruction', which in CLAM is defined as the general quality of the instructions provided to the assembler for information about the work. Another factor that could be connected to information presentation was 'information cost', which in CLAM is defined as the amount of physical and cognitive effort that is needed to utilize the information, and is thus highly related to cognitive aspects of information presentation.

Accordingly, the case studies described below in section 3.1.1– 3.1.4, are primarily described from a cognitive perspective, meaning that only the relevant information concerning these effects are presented in this thesis. For further information regarding the entire scope of these case studies, see Hanson and Brolin (2012).

3.1.1 Case description

As mentioned before, these two different case studies at the two different companies, both replaced continuous supply with kitting but each factory plant constituted a number of interesting differences in the way the kits were arranged and located.

CASE 1 involved the manual assembly of instrument panels at an automotive assembly plant. The assembly was performed along a continuously moving assembly line (although this assembly line was a so called sub assembly line, feeding the assembly product into main assembly), using traveling kits. In this case study the introduction was made in two phases, with approximately two years apart which might have affected the results at the end. After the first phase the kitting boxes were hung on the carrier of the instrument panel and only contained a few components (focusing on the components with many variants) and the rest were supplied using continuous supply. After the second phase, two traveling kits were used. The first one was used along the first half of the panel assembly line, but then replaced by the second kit. Also worth mentioning was that in connection with the second phase, a new product model was launched, in addition to the existing product model, which not only increased the amount of assembly components but also affected the work performance at the assembly line.

Prior to the introduction of kitting, all components were delivered using manually operated tugger trains (although some were delivered by manually operated forklift) which delivered components to material racks at the manual assembly stations. Further, sequenced deliveries were used for components with a large number of variants (using the same containers that were shipped from the suppliers). After the second phase of kitting introduction, approximately 90 component variants were supplied by continuous supply, compared to around 200 by kitting. Also, since the assembly object moved continuously during the assembly, the components in the material rack were arranged according to the need of components, thus the components needed early were presented at the front of the assembly station. Those components needed later in the assembly operation were presented further down the material rack, resulting in a relatively short walking distance to fetch a majority of components. One of the aims when using kitting was to present the component as close as possible to the assembly object, within arm's reach. However, the oblong shape of the instrument panel made the walking distance between the end of the kitting box to the other end (or start) of the instrument panel relatively long, resulting in several steps to fetch components in the kitting box.

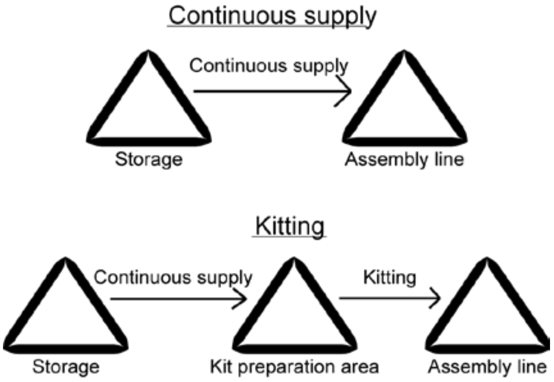


Figure 3.2. An overview of the materials flow

Figure 3.2 shows the difference in the material flows, which were the same except that for kitting the first delivery was made to the kitting preparation area. The preparation area was located just beside the instrumental panel line, about 8 meters way. This made it possible for the assemblers from the assembly line to prepare the kit themselves, in a rotation schedule (as they already rotated between different assembly workstations before the introduction of kitting). Moreover, the kits were prepared one at a time.

The kitting boxes, consisting of a large plastic box, were constructed so that each component had a specific fixed position and orientation. According to the company this would entail less risk of components being overlooked when preparing the kitting box, which would be visible. Another reason was that the kitting boxes themselves would act as a support to the assembler since they knew where to find each component as they were placed in a suitable orientation for assembly. A further reason for the specific fixed position of components was that many of the components had sensitive surfaces so the fixed positions stopped them from moving around and getting scratched. Components that were too large were not included in the kits as well as fasteners which were presented in small containers by the power tools in the material rack. None of the component variants were used at more than one assembly station.

The information provided to the preparer of the kits, i.e. instructions, first consisted of a traditional picking list (only containing text and numbers), presenting several workstations at a time (each square representing one workstation) and printed for each assembly object. But a few months after the introduction of the second kitting phase, a so called pick-to-light system was implemented consisting of small lamps attached to the component boxes. The small lamps indicated which components should be picked for each kit, see the next chapter (section 3.2.2) for more information regarding pick-to-light and other support systems.

As other companies within the same cooperation group had reported several beneficial aspects of introducing kitting, the company representing case 1, decided to introduce kitting to the instrument panel assembly line as one of the first assembly areas within the factory plant. Initially, in the first phase, kitting was used for components with high variant flora, as it was thought to save space at the assembly stations. In the second phase, space savings were still a strong motive but reduction of man-hour consumption was an even stronger motive, although no clear result of this occurred after the first phase. It was instead believed that the benefits in terms of man-hour consumption were achieved first when the larger proportion of the components were kitted. Consequently, in the second phase, one of the main reasons for switching from continuous supply to kitting was to reduce man-hour consumption, although space savings at the assembly stations and improved flexibility and quality were also strong motives.

CASE 2 involved manual assembly of heavy engines at an engine manufacturing plant. The assembly line consisted of automated carriers intermittently moving the engines. The case study focused on four assembly stations on this assembly line (as these were the only assembly stations that had started to use kitting), as well as the in-plant material supply which was supporting these stations. During the assembly operations, the assembly objects were stationed at the assembly station. This case study concerned the introduction of kitting of some of the components as others were supplied using continuous supply.

Prior to the introduction of kitting, all components were presented in material racks at the assembly line (as in case 1). Components with a high variant flora were supplied to the stations using sequenced deliveries and presented accordingly. Still, the majority of components were supplied using continuous supply and presented in smaller containers made of either cardboard or plastic. A few components were however presented without any container, in line with the minomi concept (components rest on small fixtures, hang from hooks, or are simply handled individually or in stacks) and a few other large and heavy components were presented on larger pallets with frames. As in case 1, the large number of component variants at the assembly stations resulted in some components being presented relatively far from the assembly object, leading to the assembler needing to walk a relatively long distance while having to memorise the component number. Before kitting was introduced, the components were delivered to the assembly stations using manual operated tugger trains. The larger components supplied on pallets were delivered by manually operating forklifts, both before and after the introduction of kitting. Approximately 150 component variants were supplied by continuous supply, still the majority of components were supplied using continuous supply. Components with a high variant flora were supplied by sequenced delivery of individual components rather than kits, both before and after kitting was introduced. The 150 components that were introduced using kitting were, similar to case 1, repacked into kits at a preparation area approximately 30 meters from the relevant assembly stations. In contrast to case 1, operators from the materials handling division were responsible for preparing and delivering the kits, as well as for returning empty kits. As in case study 1, the kits were prepared one at a time, but delivered in batches of two. To save time (e.g. time spent on material handling, transport and replenishment), the company decided to divide the kit preparation area into subsections, with each subsection corresponding to one assembly station on the assembly line, and each kit could thus be prepared within a single subsection. Therefore, instead of presenting each component number in only one location in the kit preparation area, the company decided to present each component number in one location in each subsection of the kit preparation area.

All kitting boxes consisted of plastic containers which were stationary meaning that the kits were addressed to one station each. As aforementioned, at the time of the study both kits and material racks were feeding the assembler with components, but the kits were presented a bit closer to the assembly object. As the components did not have a fixed position in the kit (but sometimes smaller containers within the kits), i.e. an unstructured kit, the preparer of the kits made the decision as to how the components should be organised. As in case 1, components that were too large, were not included in the kits and the smallest components (mainly fasteners) were instead stored in a bunch at each assembly station. Information to the preparer consisted of printed picking list, similar to the first phase in case 1.

In case 2, kitting was mainly introduced due to lack of space to present components at the assembly station (due to high variant flora of components). Prior to kitting, the assemblers had to walk long distances to fetch components. But as a new engine variant was to be introduced (and thus additional component variants) priority was given to the most frequently used components and presenting them closer to the engine, compared to the less frequently used components. This reduced the walking distance for the most commonly used engines, but instead prolonged the cycle time for the less frequently used engine variants (due to longer walking distance).

3.1.2 Method

A lot of empirical data was collected, mainly using direct observation and interviews. The interviews conducted at both companies focused on personnel who took decisions to introduce kitting, with personnel involved in performing the introduction as well as with assemblers and operators responsible for preparing the kits (in case 1, the kits were prepared by the assemblers themselves). The interviews were semi-structured and performed face-to-face. Some interviews required complementary questions which then were done using telephone and e-mail. In case study 2, the observations was also video-recorded which was applied for two of the four assembly workstations where kitting was introduced focusing on two common engine variants. Further recorded observations relevant to this thesis, were conducted at the assembly line as well as the kitting preparation area.

The initial analyses of the recordings resulted in a categorisation of the recorded work into predefined activities regarding time consumption for each activity. At the two studied workstations, those activities related to fetching components (i.e. turning, walking to fetch components, handling packaging, grasping components, walking back to the assembly object) were of concern in these studies, as these were the activities where the difference between kitting and continuous supply was expected to be greatest.

3.1.3 Findings and conclusions

The two cases (case 1 and case 2) both introduced kitting but in different ways, which was very rewarding from a research perspective. Case 1, introduced traveling kits, which moved along the assembly line along with the assembly objects containing components for several assembly stations, where the kit had a fixed structure. In contrast, case 2 introduced stationary kits which only supported one assembly station and where the components had no fixed structure, meaning that the preparer of the kits decided the organisation of the kits. Furthermore, the motives for introducing kitting in the assembly plants varied between the cases. It must also be noted that each of the two case studies focuses on the assembly operations within a limited area of an assembly plant and where the in-plant material supply were supporting these operations.

One finding involved the improvement of component presentation (or material presentation as defined earlier) when using kitting. One reason for this was that kitting enabled components to be presented closer to the assembly object, since not all component numbers needed to be presented at once, as they did with continuous supply. However, kitting also meant that only the components needed were presented to the assembler, thus decreasing the amount of information presented to the assembler. Johansson (1991) states that the amount of components needed at each assembly station is likely to be greatest when the number of component variants is large and the assembly cycle time long, so called heavy stations. At these stations, kitting (compared to continuous supply) would be most beneficial. Related to the space-efficient material presentation associated with kitting, in some circumstances, as in case 1, it is possible to present kits right by the assembly object instead of in a material rack (as in case 2), which often needs to be placed a certain distance from the assembly object. This facilitates the workload for the assembler, although perhaps primarily from a physical aspect but also the cognitive workload as the assembler is only provided with the essential information (i.e. components) when using a kit rather than being exposed to too much information, as when using a kit placed in a material rack.

The introduction of kitting (in both cases) meant that component racks were moved from the assembly line to the kit preparation area. This also meant that a lot of information was also moved to the kitting preparation area, freeing some cognitive load at the assembly workstations. Furthermore, as the components were moved, this also meant that this information (i.e. components) instead affected the preparer of the kits, who then needed extra information support. Within the research field of kitting this issue has been frequently debated (Chapter 2), as this means that the problem of deciding which component to assemble does not disappear but is forwarded in the decision process to the worker preparing the kits. However, it is also argued that even though this decision has not disappeared, it has at least been moved from the assembly line, enabling the assembler to focus only on the assembly task. It can be further argued that at the kitting preparation area, it is then possible to focus mainly on information support systems, at one specific area, and not along the entire assembly line (which is the case when using continuous supply). However, perhaps a better choice would be to automate the entire kitting preparation area as it can be viewed as a non-value added activity (according to Lean principles (Shingo & Dillon, 1989)).

After the introduction of kitting, mistakes sometimes occurred in kit preparation, resulting in incorrect components being included in the kits, i.e. quality problems. Most of these mistakes were discovered at the assembly line, before the components were assembled; however, there was still a risk of product quality deficiencies. Therefore, since there is a risk that mistakes are made in kit preparation, resulting in kits containing incorrect components, it is far from clear that product quality (assembly errors) will actually be improved with kitting compared to continuous supply. In fact, as indicated in the case studies, the opposite may be true. To handle this issue it was decided to add further resources to discover and correct such mistakes made in kit preparation. In case 1, a pick-by-light system was introduced to aid and support in the kit preparation area, resulting in the number of picking errors being reduced substantially compared with printed picking lists.

Furthermore, kit preparation productivity, i.e. assembly time, was found to increase as the operators preparing the kits no longer needed to handle a picking list.

In both cases, it was clear that the assemblers appreciated the support that the kits provided, as the simplified component presentation enabled them to focus on assembly tasks, and not have to think about what components to assemble and pick. This was especially apparent when using a more structured kit, as in case 1, where supporting assembly had been an explicitly stated motive for introducing kitting, the rigid structure of the kits (i.e. structured kit) was appreciated by assemblers.

In case company 2, some difficulties were expressed regarding how the components were presented in the kits. Since there were no instructions on how to manage and structure the kits and the components were not fixed in the box, the structure of the kits varied, and searching for components was sometimes necessary. Furthermore, several similar components were sometimes included in the same kit (e.g. different hoses that were to be assembled on the same engine, at the same assembly station). As the components in the kits were not marked with component numbers or other identification, as when placed in the material racks before kitting was introduced, similar components could be confusing. Moreover, kits sometimes contained the wrong components. In most of these cases, the mistakes were discovered and corrected at the assembly line. Accordingly, it seems that a structured kit can offer better support to assemblers, and thus possibly reduced cognitive load, compared to an unstructured kit.

In case 1, the assemblers (both responsible for preparation of kits as well as assembling of components at the line) thought that kitting was a good way to solve problems where too many components were presented close to the assembly object. The assemblers also valued the fact that the kits eliminated the need to search in the material racks before picking each component for assembly. However, in both cases, assemblers did not find it necessary to kit all components. At least some of the assemblers felt that too many components were supplied by kitting after the second phase. They were of the opinion that as long as it was possible to present all components relatively close to the assembly object, there was less need to increase the number of components supplied by kitting.

One reason for this opinion was that assemblers thought that the time required to pick each component in preparing the kits exceeded the time saved at the assembly line. Instead, the assemblers preferred an approach where kitting was mainly used for solving instant problems of insufficient space and only kit those components with many variants, while retaining continuous supply for the rest. This raises the question of the possibility of finding a specific number of components to put in the kits, which both supports the cognitive load aspect but also favours time spent on preparing the kit and assembling the object. Further, the assemblers also thought that components that were picked and assembled together should also be presented together, i.e. if two components were to be assembled together, they should both be presented either in the kit or in the material racks.

As assembly and picking instructions were restrictively investigated in these studies, and therefore hard to analyse, it was of further interest to explore how information presentation and especially how instructions were designed and displayed to the assembler at the assembly station but also to the preparer of kits.

3.1.4 Main conclusions from the case studies

The main conclusions from these cases studies conducted in two different manual assembly environments were:

- Kitting improved material presentation, due to only presenting the components needed to the assembler, thus decreasing the amount of information provided to the assembler.
- Moving the components (i.e. information) to the kit preparation area and thus the decision of what to put in the kit, meant that the preparer of kits was in need of extra information support.
- Using a pick-by-light system substantially reduced the number of picking errors in the kit preparation area.
- The use of kitting was appreciated by most assemblers, as it simplified the material presentation and enabled the assembler to focus on the assembly task.
- The use of either unstructured or structured kits affected the assemblers' performance.
- Further investigation is required regarding the possibility to find a specific number of components to put in the kits, which both supports the cognitive load aspect but also favours time spent on preparing the kits and assembling the objects.

- Further investigation is required regarding how instructions can be designed and displayed to the assembler at the assembly station but also to the preparer of kits.

3.2 Observational study

From the previous case studies several factors were identified as affecting assemblers at the workstations or in the kit perpetration area, categorised as material presentation and information presentation. As the previous study mainly concerned how material was presented to the assembler, it was of great interest to also focus on the instructions provided to the assemblers regarding what component to assemble.

The primary purpose of this study was therefore to further investigate how these factors were used in other manual assembly environments, as well as to explore other possible ways to improve the cognitive aspect of assemblers' performance in assembly environments.

3.2.1 Method

This study was carried out as field research, investigating several different Swedish manual assembly factories, with the focus on exploring which methods and equipment were used to support assembly personnel in performing the assembly task. Through the project FACECAR it was possible to visit and observe six different Swedish manufacturing plants, including the two previously described. All of the factory plants had similar assembly environments, meaning that they all had manual assembly workstations involving more or less complex products as well as several product variants.

The methodology used in this field research consisted of observations and semi-structured interviews which were mostly conducted at the assembly stations. The observations were mostly performed with some guidance from a production developer (or similar) that showed the most problematic stations along the assembly line and briefed about the production situation. During these tours, semi-structured interviews were conducted with assembly personnel, technicians and workers preparing the kits, with the focus on matters related to the distribution of information and material to assemblers.

3.2.2 Findings from the observational study

Most of the findings in the field investigation concerned how material and information was presented to the assembler. Almost all the assembly environments visited had introduced kitting as a material feeding supply system, ranging from just a few to almost all components placed in kitting boxes. However, one problem that many companies were facing was that the factory plants and the assembly stations were not constructed to use kitting from the beginning. This had resulted in more or less temporary support solutions for the assemblers, which thus suggested that knowledge of the assemblers' need for good support systems was poor. Instead the companies had provided the assembler with too much information rather the appropriate information. One good example is illustrated in Figure 3.3, where a lot of information is displayed in a small area, making it difficult for the reader to quickly distinguish, extract and interpret specific information which often is the case in the automotive industry. The field investigation showed that the most common information the assembler is in need of concerns the type of product variant, and thus what components, to pick and assemble. However, the observations in the factory plants showed that that the assemblers are often provided with more information than is needed, such as order number and logistic information.

Figure 3.3. An industrial example of displaying too much information

Another example of too much information can be seen in Figure 3.4, where the assemblers were faced with many different components as well as additional related component numbers. If provided with plenty of time, an assembler would probably pick the right component eventually. However, in a time-pressured environment, such as the automotive industry, the assembler needs to quickly make the right decision of what to pick. This will not only take a long time if there is a lot of information to search through, thus resulting in increased time spent on assembling the object (productivity), but also becomes a great risk of picking the wrong component, due to misreading or memory failure (see literature review Chapter), resulting in increased assembly errors (quality). This way of presenting components and associated information also constitutes a substantial risk for cognitive load. For a novice assembler this is especially burdening since the assembler will have no previous memory of the specific placement of components and thus will have to search through all information or components. The experts have in many cases memorised the most common components and their positions resulting in a different search pattern (compared to the novice), if the components have not been moved which indeed might be the case when introducing new products or product variants.

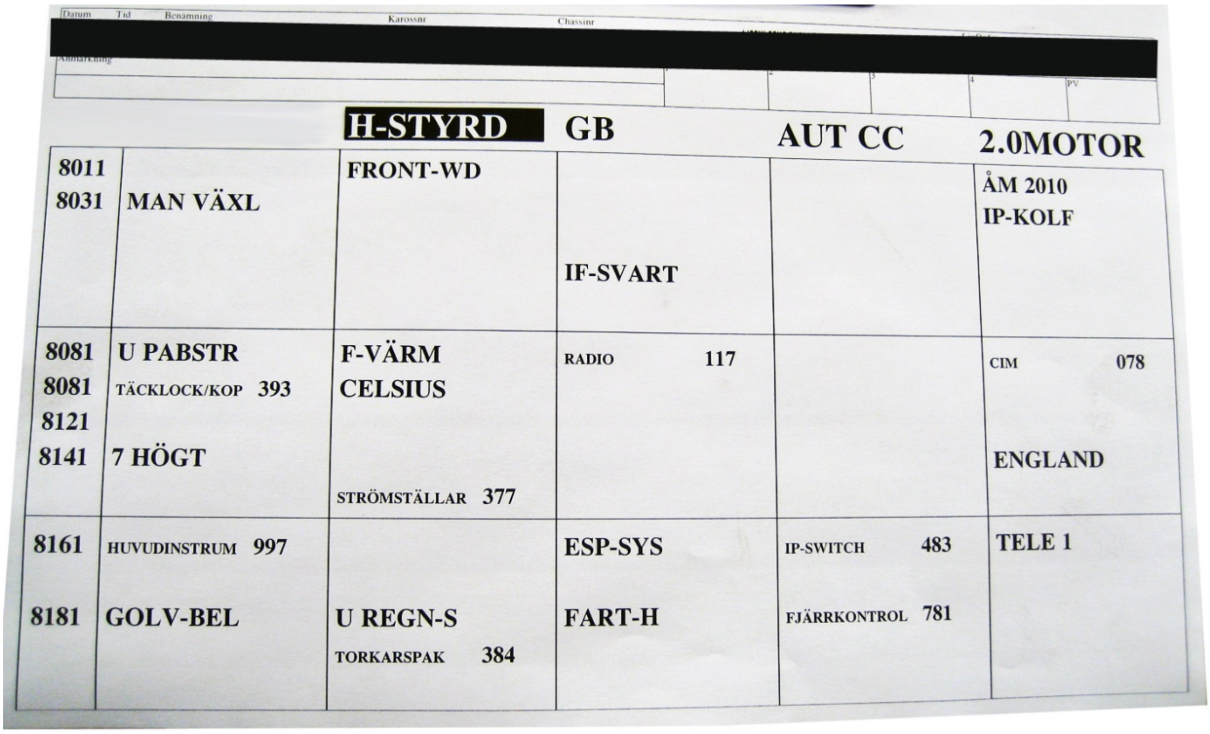
Figure 3.4. An example of a material rack that provides too much information

According to the study, paper instructions were still a common way of distributing information in the factory plants investigated. The instructions usually consisted of a list, displayed on white paper with black text and numbers. In addition, odd component variants were highlighted by inversed text in white with a black box (Figure 3.5). According to the observations, this way of highlighting was not enough for the assemblers, and instead a more distinct way to distinguish variants was desired. If faced with poorly designed instructions, and perhaps also facing a huge variety of components, as in Figure 3.4, the information overload (see further information in literature review, section 2.2) would not only increase the risk of assembly error, but also possibly increase the risk of cognitive overload.

Component number	Description	Amount
127 86 382	Flashers (without speed control)	2
128 01 095	Flashers (with speed control)	2
127 66 978	Keys (model X)	1
127 67 978	Keys (model Y)	1
123 45 678	Bolt	2
123 45 679	Bolt	2

Figure 3.5. An example of paper instructions

As presented in the two previous case studies (section 3.1), there were several other ways of presenting instructions to assemblers, all similar to the one described above using text & numbers in different layouts, which to most assemblers were, again, unwanted and unstructured (Figure 3.6).



Datum Tid Benämning Karossnr Chassinr

[redacted]

1 2 3 4 PV

		H-STYRD	GB	AUT CC	2.0MOTOR
8011 8031	MAN VÄXL	FRONT-WD	IF-SVART		ÅM 2010 IP-KOLF
8081 8081 8121 8141	U PABSTR TÄCKLOCK/KOP 393 7 HÖGT	F-VÄRM CELSIUS STRÖMSTÄLLAR 377	RADIO 117		CIM 078 ENGLAND
8161 8181	HUVUDINSTRUM 997 GOLV-BEL	U REGN-S TORKARSPAK 384	ESP-SYS FART-H	IP-SWITCH 483 FJÄRRKONTROL 781	TELE 1

Figure 3.6. Example of a paper instruction

A most common way of presenting information to the assembler was by using computer monitors (Figure 3.7). They were mainly used to show component variants, number of components to assemble, component numbers and in what order they should be picked, which the previously paper instructions also provided. However, compared to several paper instructions, the computer instructions often displayed information in a more structured way, using a distinct highlight (colour) of the assembly task currently being performed (which was one of the features to be improved from the paper instructions). It also had the possibility to display symbols of a simpler kind.

However, one problem with this way of presenting information was that it still contained a little more information than was needed, for example component numbers and order numbers (as already pointed out when using paper instructions). This led to the belief that poorly constructed instructions had merely been transcribed from paper to computer screen, still including unnecessary and unclear information such as component numbers.

Order id: 99258542

Header	No.	Instruction text	Bcode	Confirm	Tight.	Du Tigh
364025	1		✓		✓	x 3
946671 SCREW M8*30	3					
20411113 CONSOLE	1				⬡	x 2
1547252 SPACER	1					
1546531 LOCKING SHIM	1					
977977 CLIP	1					
946440 SCREW M8*16	2					
STATION COMPLETED				●		

Figure 3.7. An example of a computer monitor displaying information (Bäckstrand, 2009)

Another very common way of presenting information was with so called pick-by-light and pick-by-voice systems. A pick-by-light or picking indication system (Figure 3.8) is a light system that quite recently had been introduced in manual assembly. The study showed that pick-by-light systems were used in different configurations and in different areas in the assembly environments. In some systems the components were lit one at a time (when one component had been picked, another lamp/indicator was lit), leading to a controlled picking routine which beforehand had been calculated to be most time efficient. At the same time some assemblers stated that this way of using pick-by-light controlled the preparer a bit too much as not all might use the same picking routine or structure. Another way of using pick-by-light was to light up all lights simultaneously, leading to the preparer/assembler to choose their own routine of picking. The control was that missing components resulted in lights still being on.

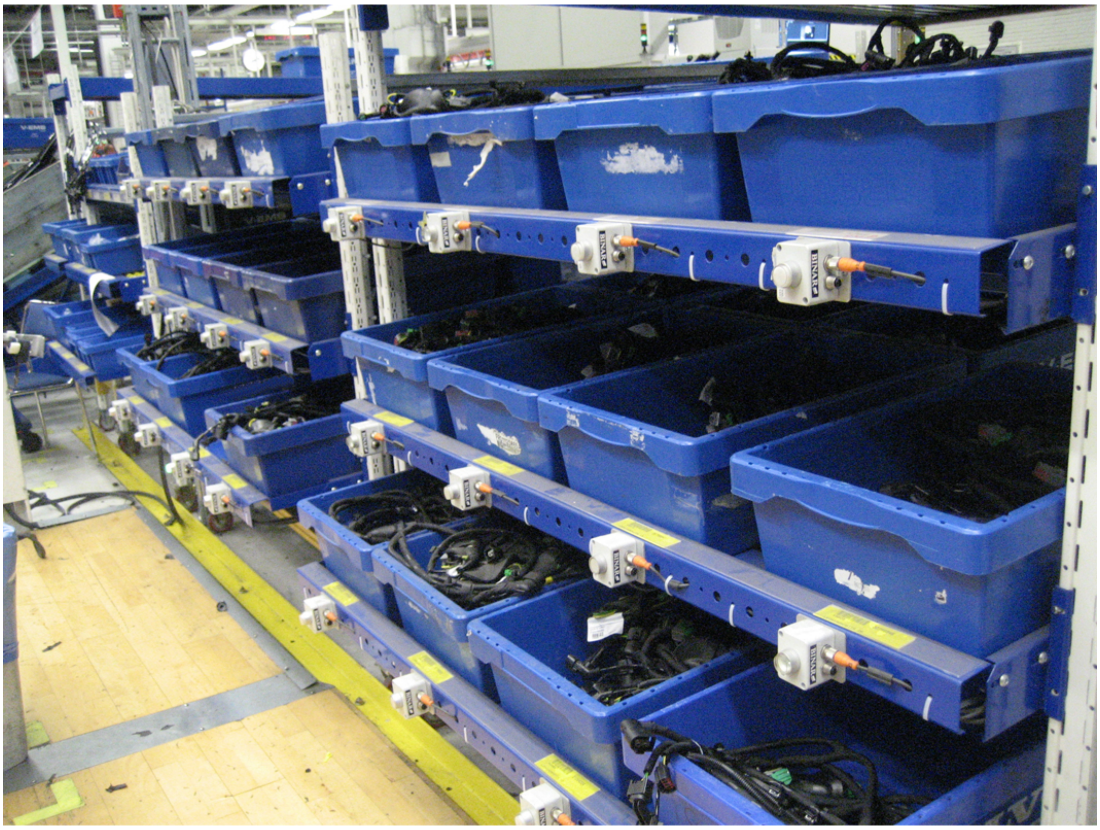


Figure 3.8. An example of a pick-by-light system

Depending on the supply systems that were used, the pick-by light systems were either used by the assembly line, in a kitting preparation area or even a storage area, or at several areas at the same time. To ensure quality, i.e. picking the right components, many pick-by-light systems used an embedded verification function. This either required the preparer/assembler to press a button which then turned off the lamp (which was more or less appreciated, depending on how many components that needed to be picked), or the system used sensors or photocells which indicated that components had been picked (Figure 3.9).

Figure 3.9. An example of pick-by-light system including a photocell verification (Bäckstrand, 2009)

One of the benefits with this system was that the assembler or preparer did not have to actively interpret information and store it in memory, instead the assembler could search for a light (see section 2.2 for more information related to active and passive attention). This resulted in a shorter time spent on picking components (as seen in the previous case studies, section 3.1), which did not stress the mental capability in the same way as when using paper instructions or an ordinary material rack and therefore constituted a smaller risk for cognitive overload. The problem with this system was that it was not very flexible, which was a clear motive for introducing kitting, as stated in case 1 (section 3.1). Supposing that the assembly line is rebalanced, which happens once in a while, or a new product is introduced the material rack (including all the lights) then needs to be rearranged and the lights reprogrammed. In addition, the maintenance of this sort of system is quite extensive. But from a cognitive perspective this system is better than having to read and interpret text and numbers within the same time interval.

Another interesting observation during one of the visits was that one assembler disregarded the pick-by-light process (the system lighted one lamp at a time) and picked the components based on an own routine with the opinion that the lights were too slow. However this also indicated that the assembler had profound experience, while a novice assembler would have difficulty in performing in the same way. This also highlights the aspects of inflexibility within the system and further shows that the system needs to be adapted to the user who is working at the moment.

Another verification system, which was used either in combination with previous material supply and feeding systems and/or with some picking indication systems was to scan codes attached to the assembly object, using a scanner (Figure 3.10). There were however some split opinions regarding this system, as some assemblers found it difficult to find all scan codes, some found it hard and tedious to scan all codes (as some assembly stations needed many components) and some assemblers simply forgot to scan all codes. It is therefore possible to state that such a system probably adds more cognitive workload than it actually reduces.

Figure 3.10. A component with attached scancode and an example of a scanning device connected to the workstation

The pick-by-voice system was also a relatively new system in the assembly environment at the time of this field research. With this system, the worker used a headset which received a number (referring to a specific component number), that corresponded to a component's location. When a component had been picked out of a box, the assembler then verified the location and action usually by pressing a button or stating a check digit (Figure 3.11). The pick-by-voice system was however mostly used beside the often enormous material racks placed in the warehouse or storage area, where there was also a bit less background noise.

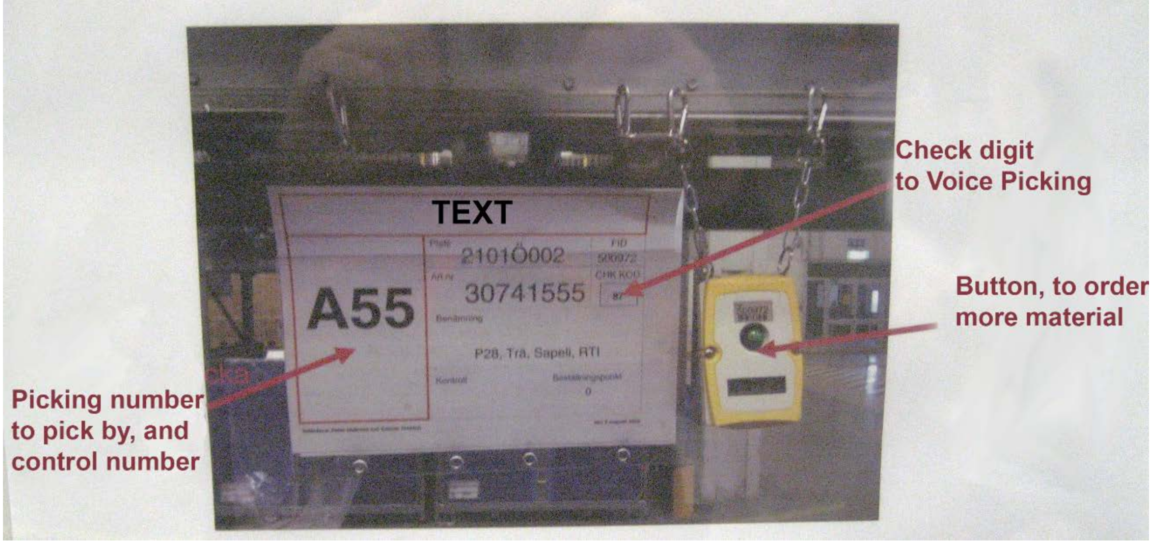


Figure 3.11. An instruction of how to use the pick-by-voice system, located in a storage area

As with the pick-by-light system, the worker did not have to remember a large amount of information by heart but could instead focus on the instructions from the head-set. One problem that assemblers stated could occur with this system was that the worker would get instructions of a location for a component, and be asked to pick several of the specified component variants. But since the worker only had to verify once with the button, it was possible to forget to pick several components. Another problem that had occurred was that the workers had forgotten to verify (using the button), and thus just carried on with the picking routine. However, the assemblers stated that the lack of feedback usually was discovered when new instructions were absent. This is however interesting, since it raises questions of whether or not a feedback signal to the assembler/picker should be an active action or occur automatically. If a feedback signal is automatic, such as a sensor, the worker does not need to actively think or perform the action, but rather can focus on the task at hand. On the other hand, depending of the placement and surrounding activities, it is possible to trigger a feedback signal by accident which could lead to assembly errors etc., if not noticed. If the feedback is an active action, such as a button, the feedback (hopefully) makes the worker aware and observant which may result in fewer assembly errors due to accidently accessing the feedback button (or similar trigger). This however places a higher demand on the attention of the worker, which over a longer period of time might increase the cognitive load (see literature review on active attention, section 2.2).

Most of the support systems above were however usually used in combination with kitting, to support the preparing personnel, as mentioned previously. For the preparer of the kit using these support systems replaces the need for perceiving the sought after component as well as the searching and fetching. During the interviews, most assemblers consequently stated that they were positive towards the introduction of kitting. However, several assemblers stated that their work was made less demanding, both physically and mentally, when introducing kitting and that they wanted to be able to easily make changes in the presented information themselves and not be dependent on other departments (such as the IT department), which is the case when using paper instructions (list of text & numbers) combined with material rack. Depending on the assembly environments, there were different ways of managing the kitting boxes. As stated in case 2, in the previous case studies (section 3.1), some preparers were given unclear instructions on how the kits should be structured. Since the components were not fixed within the kitting boxes, the structure of the kits varied and the assemblers sometimes needed to search within the kits in order to locate a certain component. This aspect highlights the importance of having structured and defined information for the assembler, as well as for the preparer, whether the information consists of words, images or components.

As acknowledged through the previous case studies (section 3.1), it was also evident in this field investigation that the use of kitting made it possible for inexperienced assembly personnel to perform the assembly tasks since they only had to know *how* to assemble and not *what* to assemble. This could be as most assemblers' perceived kits as structured information and that structured kits were able to present distinct information at a certain place to the assembler (as was highlighted above), which in turn reduced the searching for components, and thus reduced cognitive workload. As this issue has been highlighted several times in all of the studies, it was decided to further investigate this in experimental studies (Chapters 5 and 6).

Figure 3.12. An example of a kitting box with cut-outs for the components

In other factories, the kitting boxes had cut-outs in a foam material (Figure 3.12) for specific placement of the components which gave the assembler a clear structure and usually also a process to follow. In addition this also provided the assembler with feedback of missing components. Unfortunately, presumably to save space and time, cut-outs in the boxes were made to fit several different components (and not just that assembly station) which possibly could confuse the assembler and the preparer as to what components to put in the box and what components had been assembled, as seen in Figure 3.12.

As in case 1 (section 3.1), in other manual assembly environments there was a preference to place fasteners and other smaller objects by the material rack or workstation (Figure 3.13).

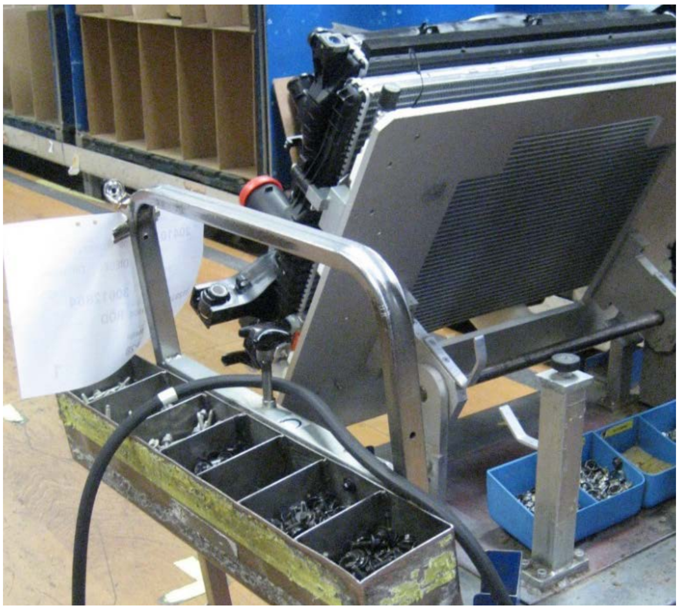


Figure 3.13. An example of fasteners provided by the assembly workstation

Another finding which was observed was that the number of components needed at an assembly workstation was stated by the assembler to affect the cognitive aspect of the assembly performance. If this factor was also combined with time pressure (stress), the assembler would most likely experience increased cognitive load. An additional possible affecting factor was the number of component variants. Hence, if both these factors occurred at the same time at an assembly workstation, called a heavy station, cognitive load would probably increase even more. Therefore it is important that the workers shift to another less cognitively demanding workstation after a while, e.g. by using job rotation.

3.2.3 Main conclusions from the field investigation

The main conclusions from this field research within the different assembly environments were:

- Too much information was provided to the assembler at the assembly stations, both regarding information presentation and material presentation.
- The most common ways of presenting information (and thus support) to the assembler and the preparer of kits was either by a list of text & numbers, a computer screen and / or pick-by lights.
- Using structured and defined information for the assembler was of vital importance when faced with many components and especially many component variants.
- Most assemblers perceived kits as structured information and that structured kits were able to present distinct information at a certain place to the assembler, which in turn reduced the searching for components and thus also reduced cognitive workload.
- If a large number of components, and especially component variants, were needed at the assembly workstation, combined with time pressure, this presumably affected the cognitive aspect of the assembly performance.

3.3 Main findings from exploration studies

Although literature provided extensive information concerning assemblers' performance in the manual assembly context this was usually related to the characteristics of production outcome, e.g. quality and productivity related benefits. But studies investigating the cognitive aspects of the assemblers' performance in manual assembly environments are rare.

Thorvald et al. (2010) state that the information systems used in today's manual assembly environment is missing in usability in many ways. One of the reasons is that the assembler is provided with too much information (information overload, see literature review section 2.1) rather than the appropriate information. As a result, the assemblers fail to assemble the correct and required components in spite of the available information and this also leads to unnecessary cognitive workload and ultimately assembly errors (Bäckstrand, 2009). However, information that is presented at the right time, with the right content, in the right layout and in a perceivable way will ease the workload for the assembler (Wilson, 1997, D'Souza & Greenstein, 2003).

Another conclusion that emerged from these studies was that the factory plants need to start viewing support systems as an investment rather than direct costs, especially due to the increase in product variants. Investing in good support for the assembler will benefit quality (assembly errors) and productivity (time spent on assembly objects), which ultimately results in increased profits. Picking support such as pick-by-voice or pick-by-light systems, may be useful in this context, as can training of operators in the kit preparation area. Furthermore, as suggested in previous research (Brynzer & Johansson, 1995, Baudin, 2004), picking accuracy is likely to be higher when assemblers, who are familiar with the assembly operations, are responsible for kit preparation. This approach was used in case 1 but not in case 2, (section 3.1). However, based on the two cases, it was not possible to determine whether or not picking accuracy is in fact affected by whether or not assemblers prepare the kits.

It was interesting to observe that there appeared to be a potential conflict between production flexibility and assembly support, in terms of whether or not the kit should be structured. A structured kit seems to provide better information to the assembler, in terms of presenting distinct information in a certain place, but on the other hand can restrict flexibility, which, as mentioned in the previous case studies, was a strong motive for introducing kitting. An unstructured kit does not need to provide the assembler/preparer the same amount of support and can be done in a more time-efficient way. This highlights the need for companies to carefully consider which performance areas that should be prioritised before deciding which materials feeding principle to use and also what kind of information system to use.

However, it should be noted that in each of the manual assembly environments, kitting was introduced in an existing factory plant that had previously primarily used continuous supply, which could have affected the outcome of these investigations. Furthermore, neither of the case companies had much recent experience of kitting at the time of the investigations, which possibly affected the way the companies handled kitting and thus material and information presentation, at the time the studies were conducted.

From a cognitive perspective, one of the most interesting findings was that the assembler perceived the kit as a box that carries information of what components to assemble. The assembler was then able to replace the need for perceiving what product variant to assembly, since the right component variant was already were displayed in the box and the need for searching and fetching for component variants was no longer necessary. In placing components in the kit in a manner that reflects the assembly operations, kitting can facilitate learning and consequently reduce learning times and improve production quality, i.e. reduce assembly errors (Johansson, 1991). Another conclusion from these studies was therefore that there is a connection between information presentation and assembly errors and that kitting provides a tool for decreasing the stressors such as information overload and how information is presented.

In addition, when performing observations at the various factory plants it was possible to get a more holistic perspective of the often very complex settings. Modern production systems differ greatly depending on, for instance, company and factory size, product complexity and economics. This provided the insight that it is not only one factor at a time that affects the assembler but several combined factors that form the complex manual assembly environment.

As material and information presentation was investigated mostly using a cognitive aspect of workload in these studies, it was of interest to included assembly time and assembly error as measurement in the forthcoming experimental study, as done previously within this research field (Bäckstrand, 2009, Thorvald, 2011).

This case study provided great insight and an enhanced understanding concerning factors that affect the cognitive aspect of assemblers' performance in manual assembly. Thus, the primary factors chosen for further investigation were:

- information presentation, i.e. the design of information presented to the assembler at the manual assembly workstation.
- material presentation, i.e. how components are presented to the assembler at the manual assembly workstation.

Further, two types of kits were defined: unstructured and structured kits, both of which were perceived as carriers of information, albeit differently organised. However, do the discrepancies and argued effects differ, in terms of cognitive aspects, as well as assembly time and assembly error? To investigate this, these kits should be tested against the use of material racks (referring to information overload) in the forthcoming experimental study, using assembly time and assembly errors as dependent variables, along with a qualitative investigation of the effect of these factors on cognitive load.

The main conclusions from the exploration studies were:

- The way material and instructions (information) is presented to the assembler at the manual assembly station greatly affects the cognitive aspects of assemblers' performance. Hence, material presentation and information presentation will be used as factors in the forthcoming experimental study.
- Unstructured kits and structured kits should be tested against material rack, using both qualitative and quantitative data gathering.
- The most common ways to aid assemblers and preparers of kits in picking components was either by a list of text & numbers, a computer screen (configured in a similar way as the list) and/or using different configurations of pick-by light with additional verification functions.
- As anticipated, there are presumably several factors that affect the assembler at a workstation at any point in time.
- A situation involving many components, and especially component variants, combined with time pressure, presumably affected the cognitive aspects of the assembly performance.

4 PILOT STUDY

During the exploration studies (Chapter 3) different ways of presenting both assembly material and information were found that possibly affected productivity, quality and assemblers' workload. As mentioned before in the literature review (Chapter 2), in this thesis productivity was measured through assembly time and quality was measured through assembly errors. In Chapter 3, two ways of presenting assembly material were defined: unstructured kit and structured kit. As the kits were different and arguably had different effects on the assemblers' workload, as well as the productivity and quality of work, it was of interest to explore their differences further. For instance, was using either of the kits better than using the more traditional way, a material rack? As these kits differed in information content and layout, compared to each other, and had not been tested to a great extent before, it was of great interest to investigate how assemblers handle these different kits and also to compare them to the traditional way, such as using a material rack. Hence, using material rack, unstructured kit and structured kit constituted the levels within material presentation.

Moreover, as found in the exploration studies (Chapter 3), it was also of interest to investigate if different forms of instructions had an effect on the assembler, as the information presentation in manual assembly in current industry plants are lacking in usability in many ways. Therefore using text & number instructions as well as photograph instructions constituted the different levels within the information presentation factor.

The main purpose of the pilot study was thus to assess the feasibility of the experimental methodology:

- To test if the factors (material and information presentation) had any effect on the assembler.

- To test if the levels within each factor were comparable.
- To test if the measurements (assembly time and number of errors) worked in this experimental set-up.
- To identify weaknesses which might occur when using the proposed methodology.

4.1 Method

The assembly task in this pilot study consisted of assembling a LEGO moon car (Figure 4.1), as fast as possible. All of the subjects assembled the same product, consisting of 37 components, at three different workstations.

Figure 4.1. The assembly product – a LEGO car

The study was carried out with 18 subjects, all engineering staff and students, with three subjects assembling simultaneously, one at each station. Since this was a pilot study, with the primary focus on testing the factor effects and the test methodology, no extensive selection of subjects was made. All subjects were aged 18 – 60.

The surrounding environment, in which the pilot study took place, was located in a quite large meeting room (about 45 m^2), with rearranged tables as workstations (Figure 4.2). Each station contained a material presentation option and an assembly instruction option. However, all of the assembly stations used the same assembly product.

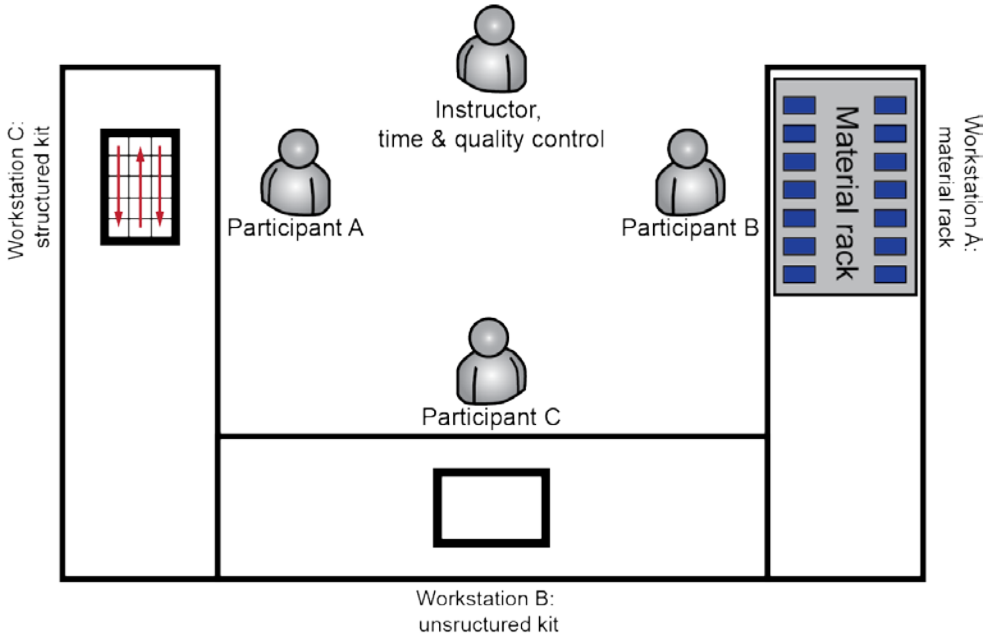


Figure 4.2. An overview of the environment and the workstations

As mentioned before, the factors that were tested in this pilot study were material presentation and information presentation. It was decided to compare not only the different kits with each other but also with using a material rack. The levels within the material presentation used in this pilot study were consequently:

- Material rack – containing several small boxes with necessary and unnecessary components.
- Unstructured kit – containing a large box with only necessary components.
- Structured kit – containing a structured box with only necessary components.

This pilot study was based on quantitative measurements where the dependant variables were:

- Time – time refers to the time it takes for each subject to assemble the entire assembly product.
- Error – number of errors in assembled product.

4.1.1 Set up of pilot study

Workstation A emulated a traditional assembly station where material was presented through a material rack, including several small boxes with attached component numbers that indicated a certain component (Figure 4.3). The material rack also contained false components with associated component numbers that were not included in the assembly task. The purpose here was to simulate an assembly situation as observed in manufacturing plants where product variants and thus component variants are common.

Figure 4.3. The material rack used at workstation A

The assembly instructions for workstation A were illustrated in a traditional way, given on a paper sheet that contained the component numbers and a brief description of each component, given in the right process order with 33 steps. The instructions also included a picture showing the end result of the assembled product (Figure 4.4).

Steps	**Component number**	**Description**
1	138005968	2x8
2	138005989	2x4
3	138005989	2x4
4	138005989	2x4
5	142101043	2x4
6	143494689	1x2
7	129622207	1x2
8	142101044	2x2
9	126087316	1x1 (gripper)
10	129622277	1x1 (handle)

Finished result:

Figure 4.4. Part of the text & number instructions provided at workstation A (picture from LEGO.com)

Workstation B, the unstructured kit, presented all the relevant components in one box without any false components (Figure 4.5). This set of material presentation suggests that the assembler only has to search for components in one focused area.

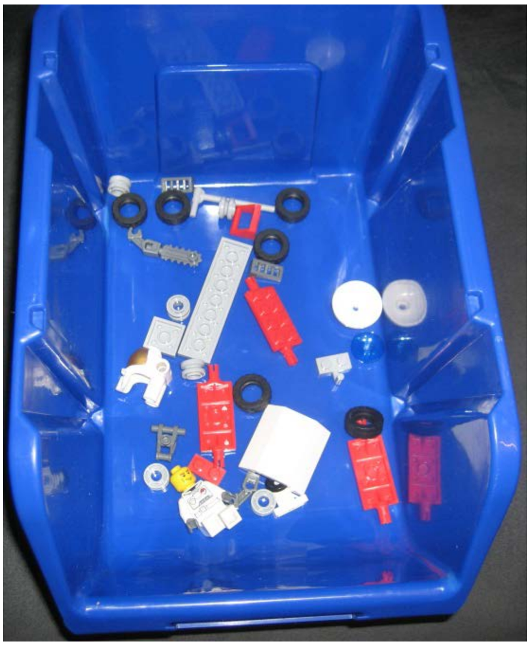


Figure 4.5. The unstructured kit used at workstation B

The instructions used step-by-step pictures, which were digitally collected from LEGO.com and put together to be similar to the LEGO instructions that often are spoken of as being clear and easy-to-use (Figure 4.6). In this way, the instructions had the same overall format (an A4 format with white background) as the text and number-instruction.

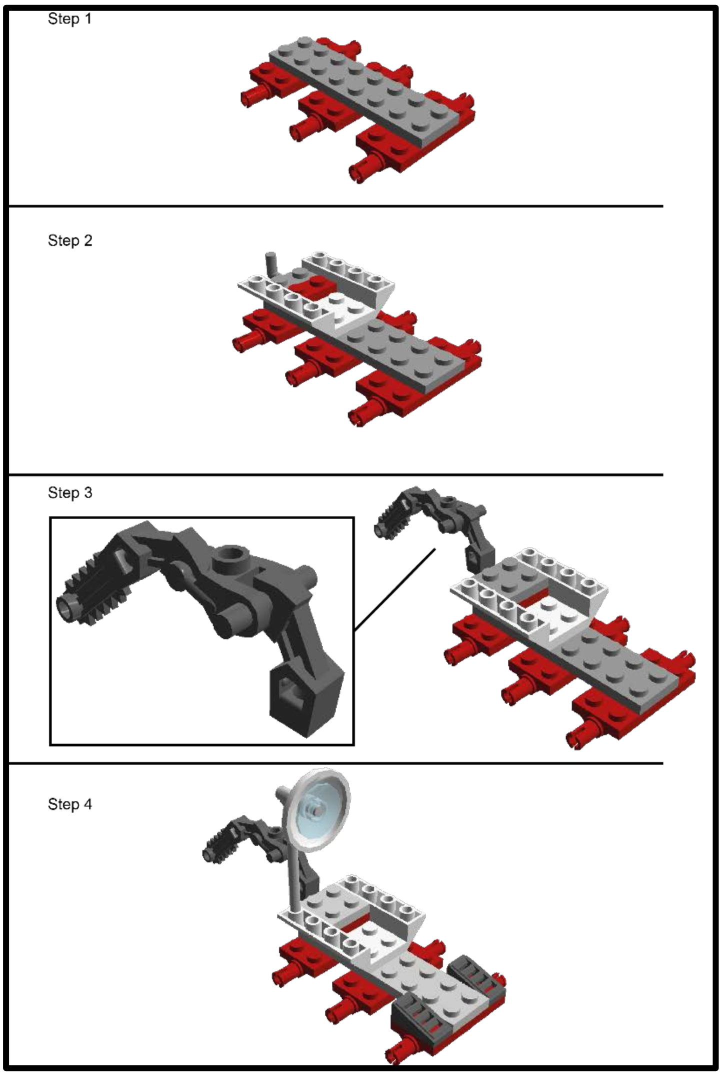


Figure 4.6. Part of the picture instruction used at both workstation B and C

Workstation C used a similar setup as station B (unstructured kit), presenting one box with all the relevant components. However, the box at this station contained separate sections where each component was placed in the same process sequence as the assembly operation, i.e. a structured kit (Figure 4.7). The process was further highlighted through signs, consisting of arrows which acted as process guidelines for the assembler. The assembly instructions were the same as when using an unstructured kit.

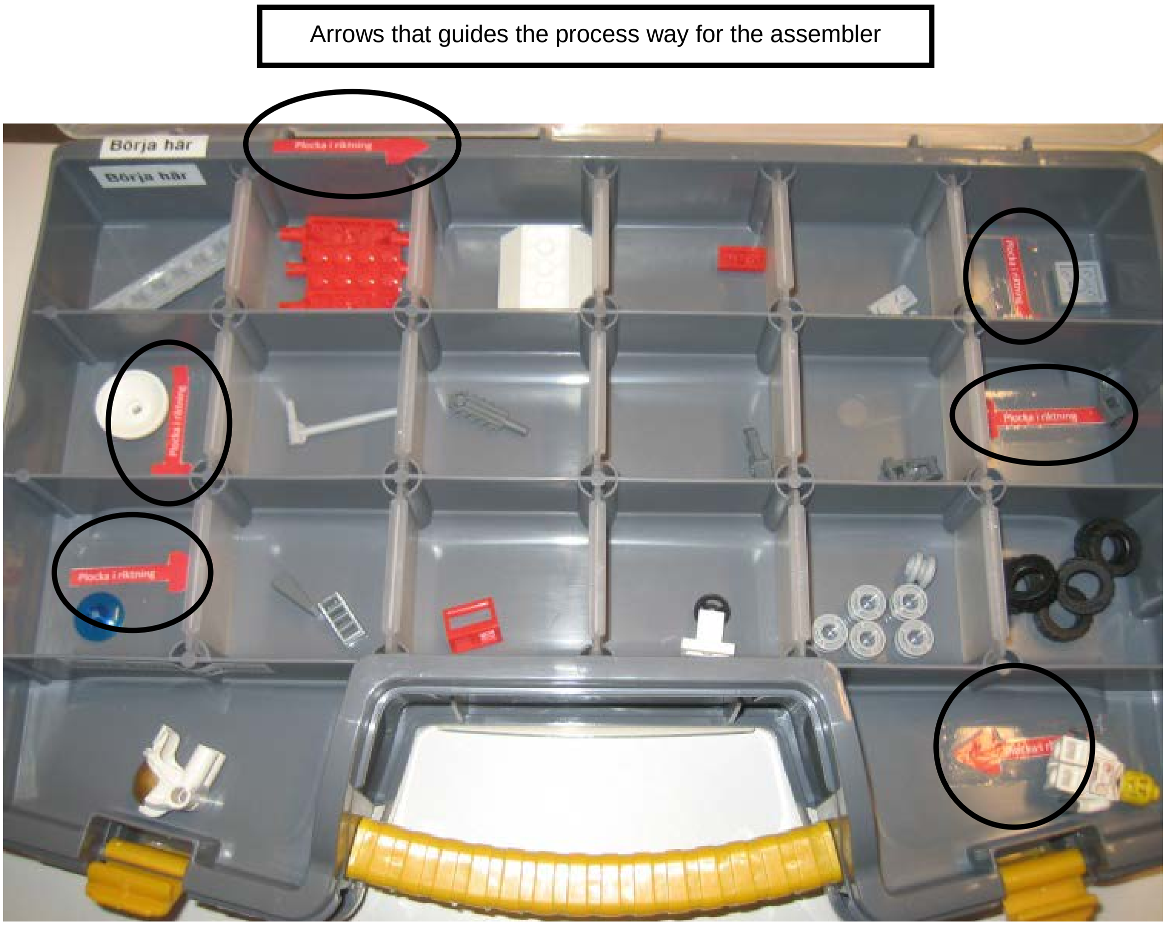

Arrows that guides the process way for the assembler

Figure 4.7. The structured kit used at workstation C

4.2 Results

A total of 18 subjects took part in the pilot study, 3 in each round. Table 4.1 shows the time it took for each subject to assemble the product.

Table 4.1. Results of the pilot study, measured in minutes and seconds (mm:ss)

	Rounds						Average	Median
Workstation / round	1	2	3	4	5	6		
A. Material rack	*	*	*	*	*	*		
B. Unstructured kit	2:37	3:27	4:51	8:31	3:27	4:32	**4:34**	**4:00**
C. Structured kit	2:54	4:27	2:33	2:06	4:00	2:55	**3:09**	**2:55**

*Did not assemble within reasonable time (> 9 min)

The results showed that none of the subjects assembling at workstation A, using a material rack, were able to finish assembling the product (or assembled for more than 9 minutes which was set as the maximum time). This showed that this was a relevant issue that deserved further investigation, especially since this can be argued to still be the dominant way of presenting material in manual assembly. The remaining results therefore only related to unstructured and structured kits.

In this pilot study the descriptive statistics were of highest interest. Table 4.1 shows that the mean assembly time when using an unstructured kit was 4:34 minutes, resp. 3:09 minutes when using a structured kit, giving a mean difference of 85 seconds. Another interesting result was the difference in median, 4:00 minutes (unstructured kit) and 2:55 minutes (structured kit). Further, the maximum and minimum assembly times were 8:31 minutes and 2:37 minutes for the unstructured kit and 4:27 minutes and 2:06 minutes for the structured kit.

Although the assembly time differed considerably between the different workstations, the number of errors were too few across all of the workstations. As a consequence this dependent variable was not reported.

4.3 Discussion and conclusion

The results show that the overall experimental methodology worked.

The results of the pilot study indicated that the way the assembly material and information were presented influenced assembly time, i.e. productivity. When using either of the kits combined with the picture instructions, the subjects were able to assemble the product more quickly, compared to when using the material rack combined with text & number instructions. The lowest assembly time was achieved when using a structured kit combined with the picture instructions.

It should be recognized though that workstation A was provided with both of the hypothetical worst levels of factors such as the material rack and the text & number instructions. This was done primarily to test if there was a difference at all between the hypothetical worst combination and either of the kits combined with the picture instructions, which there clearly was. However, it would also have been interesting to test all combinations, for instance using a material rack combined with using picture instructions compared to using an unstructured kit combined with using text & number instructions. Therefore in the following experiment all possible combinations should be evaluated among the different factors.

Having just a few assembly errors in the pilot study made it difficult to assess whether or not quality, i.e. number of errors, was affected by the factors at all. There could however be a number of different reasons for the lack of errors. One possible reason was that the assembly product was too simple. Therefore, in the forthcoming experimental study, it was necessary to include a more time-demanding and perhaps more complex product, which plausibly would generate more assembly errors, as well as a more complex set-up. This would also be a better reflection of the actual circumstances within assembly in the automotive industry.

Although this pilot study explored the two very different ways of presenting material and information, these factors, and primarily their levels, constituted a difference and thus were kept as factors in the forthcoming experimental study.

Another interesting finding was the assemblers' reaction after they had all finished the experiment. Each subject was facing towards the assembly area and so the subjects were not able to see each other or the other workstations during the experiment. Afterwards, when facing each other, the subjects that had worked at the workstation with the material rack (workstation A) were all of the opinion that the other two workstations were easier. Furthermore it was interesting that until then, the subjects assembling at station A, using the material rack, were of the opinion that they themselves were being slow and were not reflecting on the poorly designed and presented information. This was also the case when subjects from several Swedish automotive companies subsequently performed this pilot study at several industrial workshops. All company subjects in those workshops expressed a great interest, which shows the importance of improving the work situation for the assembler as well as an awareness that the way assembly material and information are presented influences productivity and quality.

This pilot study did not attempt to measure or address assemblers' workload, which obviously is something that this research is aiming to explore and improve. Therefore it was of vital importance that a qualitative measurement was included in the following experimental study. Moreover, to simulate a real industrial environment as much as possible, but still being able to control the influential external factors, was something that was also addressed in the forthcoming experimental study.

Despite some flaws in the experiment within the pilot study, there was still much that was very interesting and worth studying further in a larger context.

The main conclusions from the pilot study were:

- The overall experimental methodology worked.
- The factors, material presentation and information presentation, should be investigated further in a larger experimental study.
- The experimental method should contain both qualitative and quantitative measurements, to assess productivity, quality and assemblers' workload.
- A more complex product and set-up was needed to assess quality.
- The experimental study should, if possible, take place in a controlled environment with as few external factors as possible that would affect the result, but still simulate a real assembly environment to a great extent.

5 EXPERIMENTAL STUDY

One of the major starting points of this thesis, and many others in the field, was that the complexity of work arises from several different sources. For example, an assembler receives information, not only from the instructions but also from the assembly material, environment and peers. It is usually not only one isolated factor at a time that affects the work situation, but several factors in different combinations. Thus, this experimental study explored how different factors and combinations of factors affected the assembly operator at a workstation.

As a result of the pilot study (Chapter 4), material and information presentation were selected for further investigation. Since the pilot study was quite limited in many aspects, these factors were deemed deserving of a larger scale experiment. Aside from the two factors already mentioned, it was noticed that component variation also was a factor that potentially could affect the assembly operator. It has also been suggested in earlier studies that high component variation greatly increases complexity of work (Bäckstrand, 2009, Thorvald, 2011, Mattsson, 2013, Lindblom & Thorvald, 2014, Thorvald & Lindblom, 2014). In the pilot study, factors from CLAM were connected to the factors being investigated in the study. Appropriately enough, the CLAM tool also includes the factor *Variant flora*, as identified in the literature review (section 2.2.3). Based on this, the factor of *Component variant* was included in the experimental study (Figure 5.1).

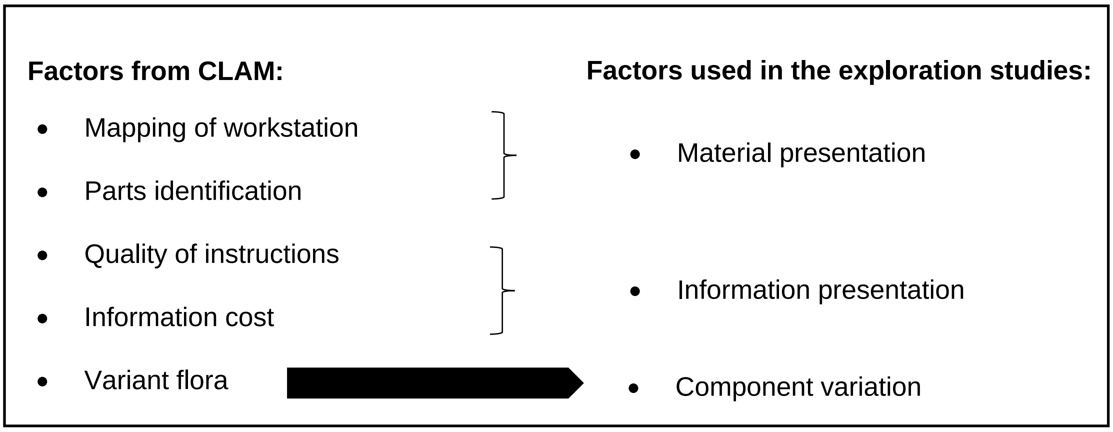


Figure 5.1. Updated figure with selected factors from CLAM (Thorvald & Lindblom, 2014), which could be connected to information and material presentation, and thus also component variation

This experiment used a mixed method design (Creswell & Clark, 2007) which included both a quantitative study, including time and errors as dependant measures, and a qualitative study, including workload ratings and a questionnaire. The quantitative study acted as a base for the hypotheses whereas the qualitative data mostly acted as support to verify and strengthen the quantitative study and thus the hypotheses.

The experiment took place in an advanced assembly laboratory environment. The experiment made use of an assembly workstation at an assembly line laboratory where a pedal car was partly assembled (Figure 5.2).

Figure 5.2. The assembly product used in this experiment, a pedal car

5.1 Hypotheses

The hypotheses (HA to HE) used for this factorial experiment were based upon the results and conclusions from previous studies (Chapters 3 and 4) and concerns the different levels of the factors: Material presentation (HA-HC), Information presentation (HD) and Component variation (HE). As previously mentioned, the hypotheses are based on time, as time spent on task, and errors, as in number of errors.

H_1A: The performance when using a structured kit is better than the performance when using a material rack.

> **H_0A**: The performance when using a structured kit is worse than or equal to the performance when using a material rack.

H_1B: The performance when using an unstructured kit is better than the performance when using a material rack.

> **H_0B**: The performance when using an unstructured kit is worse than or equal to the performance when using a material rack.

H_1C: The performance when using a structured kit is better than the performance when using an unstructured kit.

> **H_0C**: The performance when using a structured kit is worse than or equal to the performance when using a structured kit.

H_1D: The performance when using a photograph is better than the performance when using text & numbers.

> **H_0D**: The performance when using photography is worse than or equal to the performance when using text & numbers.

H_1E: The performance when assembling products with no component variation is better than the performance when assembling products with components variation.

H_0E: The performance when assembling products with no component variation is worse than or equal to the performance when assembling products with component variation.

These hypotheses were tested through a full factorial experimental design, consisting of 2x2x3 factors, where the levels of the three factors involved in the hypotheses were combined in all possible combinations to be able to reject the null hypotheses for each factor (Figure 5.3).

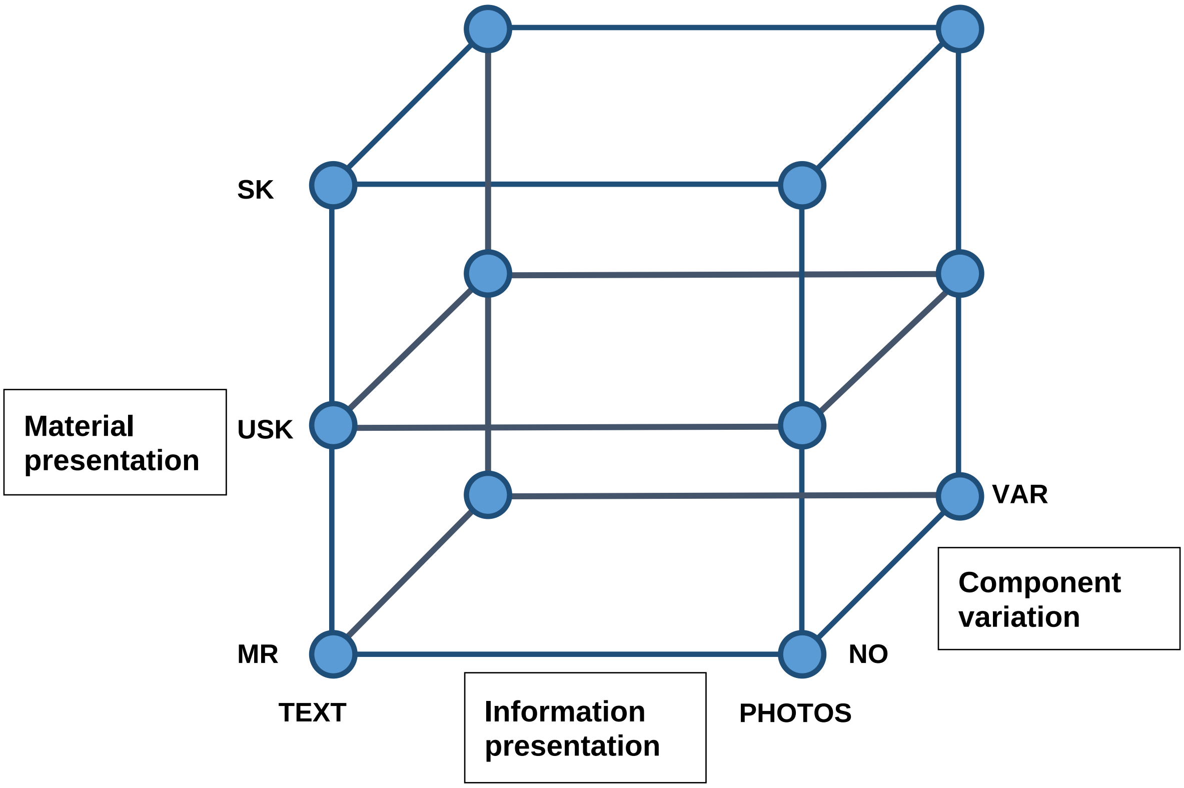


Figure 5.3. Illustration of the involved factors and the possible combinations

5.2 Variables

As identified in Chapters 3 and 4, the **independent variables** that were used in this experiment were (also see Figure 5.3):

- **Material presentation**;
    - Material rack (MR)
    - Unstructured kit (USK)
    - Structured kit (SK)
- **Information presentation**;
    - Text & numbers (TEXT)
    - Photographs (in combination with a brief descriptive word or number) (PHOTOS)

- **Component variation**;
    - No component variation (NO)
    - Component variation (VAR)

These factors represent common ways of presenting information to the assembler, which is needed to perform the assembly tasks. The first factor, material presentation, refers to the way the assembler is provided with the components needed for the assembly task. The observations in the assembly industry, presented in Chapter 3, showed that there were several ways of presenting material to the assembler, three of which were tested in this experiment:

- Using a traditional material rack where material was presented in boxes on a shelf.
- Using an unstructured kit where the required components were presented in a large box with no unnecessary components.
- Using a structured kit where the required components were presented in a box and placed in the box according to the assembly sequence.

The observations also showed that the instructions of what to assemble traditionally consisted of using a list with article numbers and a brief description. The article numbers usually consisted of 6-8 digits, which were often shortened to the last three digits for better and faster interpretation, as used in this experiment. Another way of presenting information was through pictures or photographs, which potentially may ease and speed up the interpretation of information. This difference was considered interesting to test in the experiment, making the two different levels of information presentation:

- Using a traditional sheet of paper containing component text & numbers.
- Using photographs depicting the correct assembly.

In the pilot study it became apparent that the material rack contained several components that were not used in the assembly product. These redundant components could however potentially be used in other assembly products (which is the case in the assembly industry), which would add another complexity to the assembly worker. It was therefore decided to test this in the experiment, making component variation the third factor. But in order to have a manageable experiment and thus analysis, the level of component variation was only set to two levels:

- Using no component variation, assembly according to a standard pedal car.
- Using component variation (5 variants out of a pool of nine).

As for measurement, the **dependent variables** in the experiment were the following:

- *Assembly time*; how long it takes for one person to assemble a pedal car, measured in seconds (*s*).
- *Assembly error*; number of errors that occurred during the assembly task.

The primary measurement used in this experiment was *time*, since it was considered reliable and easiest to measure but also expected from industry in terms of productivity. Since productivity is such an important aspect in the automotive industry, it can be argued that stress, and subsequently workload, comes along with this, making this a valuable measurement.

Another measurement was *error*, which is very common measurement in the field (Bäckstrand et al., 2008, Thorvald et al., 2010) and also introduced in the literature review, Chapter 2. In this experiment there were two types of errors that were recorded: picking the wrong component while assembling it correctly and/or picking the correct component but assembling it incorrectly.

To verify and strengthen the results of the quantitative study, additional qualitative data was gathered to capture the user experience and assemblers' opinions.

- *NASA TLX workload rating,* a workload assessment tool to assess both the mental and physical workload that the subject perceived during the assembly task.
- *Questionnaire*; gathering the users' opinions and experience regarding the different ways of presenting and perceiving the information and material.

The NASA TLX workload assessment method (Hart & Staveland, 1988, Hart, 2006) was also used as a semi-objective measurement which estimates workloads according to a predefined template. This mental assessment tool aims at rating the performance of a task on six different workload subscales: *mental demand*, *physical demand*, *temporal demand*, *performance*, *effort* and *frustration*. Each scale was divided into 20 intervals. These ratings were then converted into scores that vary from 0 to 100. The outcome provides an overall workload score, based upon the weighting of the different subscales.

The questionnaire contained both ratings and open questions regarding to what extent the instructions and the material presentation affected the assembly operation as well as which instruction was easiest or hardest to understand. The questionnaire was written in Swedish, since all of the subjects spoke Swedish. An English translation can be found in Appendix I.

5.3 Subjects

Thirty-six subjects volunteered for the experiment. Most were engineering students at the University of Skövde, but there were also a few students from the computer science department as well as some teachers. The ages ranged from 19 – 62 years. A few subjects had previously taken a course on production engineering, which involved assembling pedal cars in this specific laboratory and had therefore gained experience of the product and the assembly operations. The subjects consisted of 19 women and 17 men, which is a slightly more even gender distribution in this experiment compared to the reality in the automotive industry, where men are overly represented. No disabilities were reported that would have any effect on the outcome.

5.4 Equipment and environment

The experiment took place in a production laboratory at the University of Skövde. The room was equipped with hand tools and machines (Figure 5.4) and there were safety rules that had to be followed.

Figure 5.4. The environment in which the experiment took place including an example of hand tool

Besides the subject that performed the assembly operation, there were two researchers present. One manually timed the assembly of each pedal car using a Polar watch (RS800x). A video camera was also recording the entire experiment, and was mostly used as a backup to measure time, where the time between the subject's first and last touch on the pedal car was recorded. The second researcher made a quality check and disassembled each pedal car (Figure 5.5).

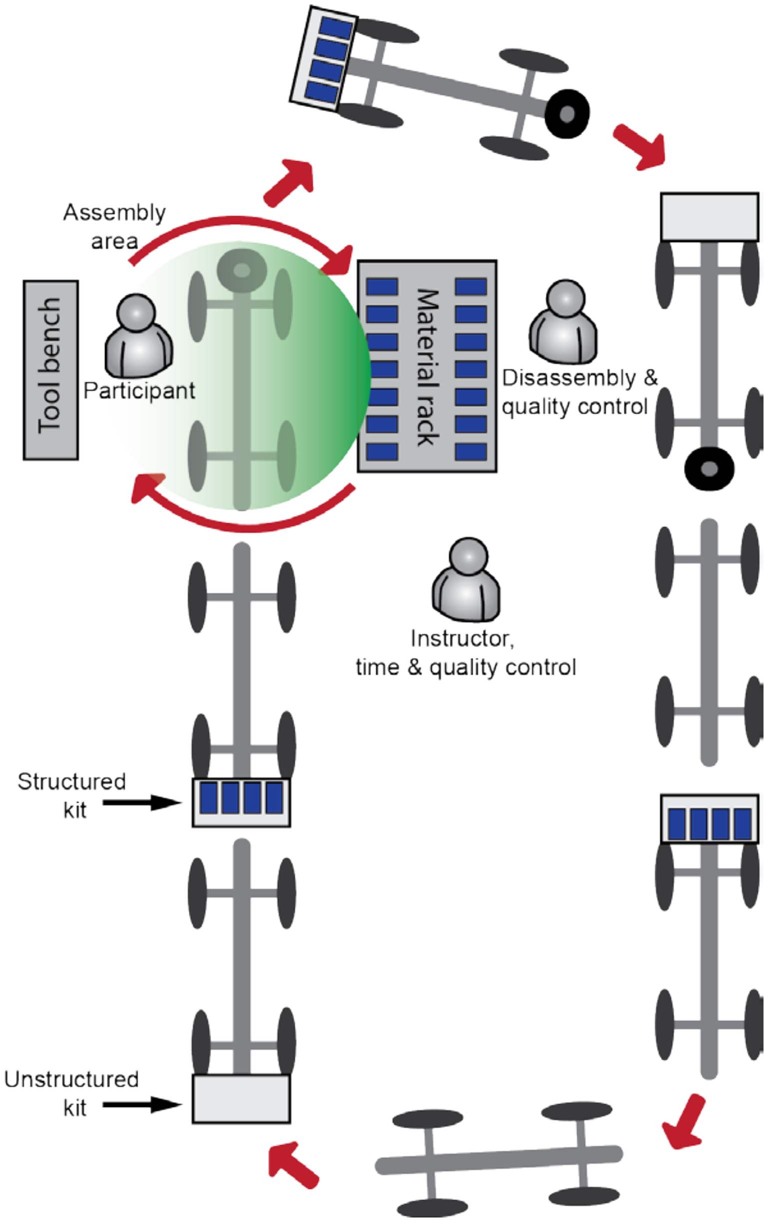


Figure 5.5. An overview of the experimental environment and the process flow

The material rack used in this experiment consisted of two bookshelves and a table, where everything from bolts and nuts to larger components such as steering wheel were placed in small blue boxes on the shelves or in larger boxes on the bottom shelf (Figure 5.6). Two large transparent boxes containing steering wheels and wheels were placed on the floor beside the bookshelves. Each box, i.e. each component, had three digits that matched the assembly instructions. As within the automotive industry, these numbers then communicated with the assembler on what component to use for the assembly task.

Figure 5.6. Material presentation through material rack

In one of the case studies (section 3.1), one company used following kits (the kit is attached to the assembly product and thereby follows the product through the assembly line), which was considered advantageous. Therefore, in this study, two different kits were used but both kits were following kits. Both kits consisted of a large transparent box that was attached at the back of the pedal car. In the structured or sequenced kit, the components were placed in small blue boxes that in turn were placed in the correct assembly order inside a large transparent box (Figure 5.7).

Figure 5.7. Material presentation through a structured kit

The unstructured kit had all of the components directly placed in the large transparent box, forcing the assembler to search for the right components in the right assembly sequence (Figure 5.8).

Figure 5.8. Material presentation through an unstructured kit

The second factor, *Information presentation,* refers to the instructions that were presented to the assembler on what to assemble. As seen in previous studies, one way of presenting these instructions is by using an ordinary table containing text and article numbers (an identity code for the specific component), which was also the case in this experiment. These instructions also contained a brief description of the components (Table 5.1).

Table 5.1. Assembly instructions used in this experiment, consisting of text & numbers

	Assembly steps	**Component number**	**Amount**	**Description**
1	Secure the pedals			Safety strap
2	Pick material	141	1	Parking brake
3		522	1	Locking nut, M8
4		631	3	Disc, 9/25
5	Assemble parking brake			
6	Pick material	490	1	Drive wheel
7	Put on drive wheel, left back			
8	Pick material	483	1	Wheel
9	Put on wheel, right back			
10	Pick material	405	2	Disc, 10/30
11		753	2	Screw, M10*16
12	Assemble both wheels			
13	Release security strap			
14	Pick material	577	2	Hubcap
15	Assemble hubcap			
16	Pick material	166	1	Steering wheel
17		318	1	Disc, 10/26
18		372	1	Screw, M8*35
19	Assemble steering wheel			
20	Pick material	597	1	Steering wheel hubcap
21	Assemble steering wheel hubcap			

The second way of presenting the instructions to the subjects in this experiment was by using photographs of the components with, if necessary, a word or the article number attached to make it more descriptive. An example is presented in Figure 5.9.

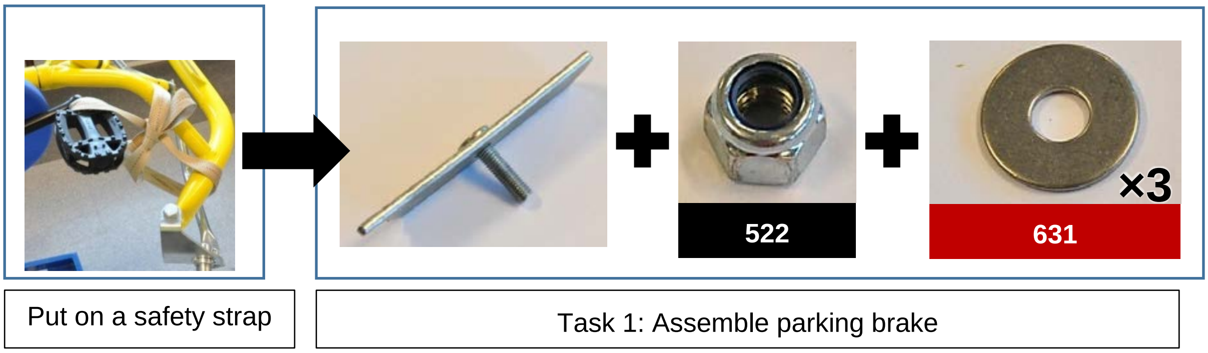


Figure 5.9. Assembly instructions used in the experiment, consisting of photographs

The third factor consists of *Component variation*, which means in this experiment that each pedal car was either assembled according to the standard specifications or could contain 5 varying components. All subjects assembled a total of six standard cars and 6 variant cars, where all of the variant pedal cars each contained five component variants. These variants were however taken out of a pool of nine variants, where all had the same shape but mostly differed in colour and/or material:

- Locking nut, M8
- Disc, 9/25 or 10/30
- Screw , M8*30
- Screw, M10*16
- Hubcap, silver or gold
- Hubcap for steering wheel, red or green

The variants were then randomly assigned to each variant pedal car, so it would be possible to avoid a learning effect on which variants to pick. Figure 5.10 illustrates an example of photo-instructions for a component: Hubcap, using the standard component (to the left) and a variant component (to the right).

Figure 5.10. An example of two different hubcaps used in this experiment

5.5 Setup and performance of experiment

Before the experiment the subjects were instructed that the experiment was aimed at measuring workload and that it consisted of assembling twelve pedal cars of varying kinds, and was estimated to take about an hour. They were also informed that they would get practice on three cars before the experiment started and after the experiment, they were required to answer a questionnaire. The experiment would also be recorded and all information about the subjects would be kept confidentially. What the subjects were not told was that the test also investigated time and error, since this might have made the subject focus on other things rather than making a good job of assembling the pedal cars (this is further discussed in section 8.1.4). The subjects were also told that they could abort the experiment whenever they wanted, but none of the subjects ever did so.

After the presentation of the product, the different types of instructions as well as an example of a component variant were shown to give an idea of what they would assemble. Next, the subjects were placed at the workstation followed by a thorough demonstration of the required assembly operations from one of the experimenters. The assembly operation of the pedal car consisted of:

- Securing the pedals with a safety strap
- Picking material and assembling parking break
- Picking material and assembling both rear wheels
- Releasing the security strap
- Picking material and assembling hubcaps
- Picking material and assembling steering wheel with hubcap

It was important that the subjects really knew how to assemble the product since there would be no instructions informing them on *how* to assemble during the experiment, only *what* to assemble. Therefore each subject had a training session before the experiment started. The instructor first showed how to assemble one car and afterwards each subject got to train on three cars, including different instructions and variants. According to the supervisor of the production laboratory, that is how long it usually takes to learn the assembly operations and sequence.

The subjects towed the cars to the assembly station (the subjects were continuously supplied with cars from one of the researchers). Then they would either notice a kit that was hanging at the back of the car or the subjects would pick the components in the material rack. The pedal cars were then gathered and disassembled by an experimenter on the other side of the material rack, ultimately placing the cars back in the assembly queue. A total of twelve cars were assembled by each subject. The order of the cars in the experiment was randomised to avoid a learning effect having a larger impact on later cars than earlier ones and also to simulate an authentic assembly environment.

After the entire assembly operation, which was estimated to take about 60 minutes, all of the subjects answered a questionnaire. A few randomly selected subjects also answered the NASA TLX workload rating so in these cases experiment time would probably take 20 minutes longer.

With three factors, consisting of 2-3 levels, it was advantageous to perform a 2x2x3 full factorial design, meaning that each subject performed a combination of all factors. Table 5.2 shows the layout of a general factorial experiment consisting of 2x2x3 factors and how the factors were combined.

Table 5.2. The layout of a general 3x2x2 experimental design

Car nr.	Factor 1	Factor 2	Factor 3
1	+	+	+
2	-	+	+
3	+	-	+
4	-	-	+
5	+	+	0
6	-	+	0
7	+	-	0
8	-	-	0
9	+	+	-
10	-	+	-
11	+	-	-
12	-	-	-

Factor 1 (component variation);

+ No component variation
\- Component variation

Factor 2 (information presentation);

+ Photographs
\- Text & numbers

Factor 3 (material presentation);

+ Structured kit
0 Unstructured kit
\- Material rack

In this case the car numbers were also randomised in order to get data that was not affected by the order in which the different assembly tasks (pedal cars) were performed, since the cars differed in combination of levels of the different factors and thus potentially also in difficulty. Table 5.3 shows the entire design of experiment.

Table 5.3. The design of the factorial experiment, including the factors and possible component variants

Car nr.	Component variation	Information presentation	Material presentation
1	No component variation	Photographs	Structured kit
2	Component variation	Photographs	Structured kit
3	No component variation	Text & numbers	Structured kit
4	Component variation	Text & numbers	Structured kit
5	No component variation	Photographs	Unstructured kit
6	Component variation	Photographs	Unstructured kit
7	No component variation	Text & numbers	Unstructured kit
8	Component variation	Text & numbers	Unstructured kit
9	No component variation	Photographs	Material rack
10	Component variation	Photographs	Material rack
11	No component variation	Text & numbers	Material rack
12	Component variation	Text & numbers	Material rack

To be able to obtain relevant results out of all the data, both qualitative and quantitative, it was necessary to figure out the statistical framework in which the analysis would take place. This experiment was a full factorial experiment where each subject performed all possible combinations, and a repeated measure analysis was conducted. This was performed with the quantitative data but also with the NASA TLX workload ratings, even though these measurements mainly acted as a support along with the data from the questionnaire. In the repeated analysis the main effects are of interest since they either confirm or reject the hypotheses, depending on them being significant or not. In addition, it was also of interest to analyse the interaction effects between some or all of the different factors and their levels. This was because, as stated before, in the assembly environment it is usually not one factor that effects the assembler but several factors at a time. In the next chapter, the results of the analyses are presented.

6 RESULTS OF THE EXPERIMENTAL STUDY

Since the results of the factorial experiment were quite massive and contained many analyses, a clear structure for this chapter is needed. First a summary is presented, providing the overall results for assembly times, the NASA TLX workload ratings and the questionnaire. After this a more comprehensive results section is presented, starting with the quantitative data on which the hypotheses were based. Each main effects section ends with confirmation or rejection of the relevant hypotheses. Then the interaction effects, including graphs and contrast charts, are presented along with relevant effect sizes. The chapter ends with the results from the NASA TLX workload analysis and a summary of the questionnaire.

6.1 Summary of results

The dependent variable *error* (number of errors), was omitted from the results as initial analyses showed very few errors made throughout the experiment, which was due to a probable floor effect. There are a number of possible reasons for the lack of errors, such as the assembly product not being complex enough or that the assembly introduction was so thorough that there were insignificant numbers of assembly errors.

A summary of assembly times and NASA TLX workload ratings is found in Table 6.1. The coloured items indicate minimum (dark and light green) and maximum (dark and light red) values of each combination and levels.

Table 6.1. A summary of assembly time and NASA TLX workload rating

	Material rack				**Unstructured kit**				**Structured kit**			
	Photographs		Text & numbers		Photographs		Text & numbers		Photographs		Text & numbers	
	Variants	No	Variants	No	Variants	No	Variants	No	Variants	No	Variants	No
Mean Assembly time (s)	240	238	296	272	224	200	206	216	203	193	211	198
Mean TLX workload rating	22.1	25.1	33.8	25.2	22.7	20.8	22.3	17.8	13.8	13.3	21.3	20.2

Not surprisingly, the time spent on the tasks and the NASA TLX results show that the combination of using a material rack for material presentation, text & numbers as syntax and the added complexity of variants, results in the most challenging scenario. This was also confirmed by the subjects in the questionnaire. Conversely, presenting material in a structured kit and information through images, while not having product variation, seemed to be preferred.

Furthermore, it seems that the product variation effect was small, as the condition "no variation" was the second worst (in the left part of the table) and at least partly second best (in the right side of the table). Meaning that the worst and the best condition were the same, regardless of whether or not product variants were present. This was especially true for the NASA TLX workload ratings.

A visual confirmation of the results regarding assembly time is presented in Figure 6.1. The graph shows that the best way to achieve lowest assembly time was to use a structured kit combined with photographs and no component variation.

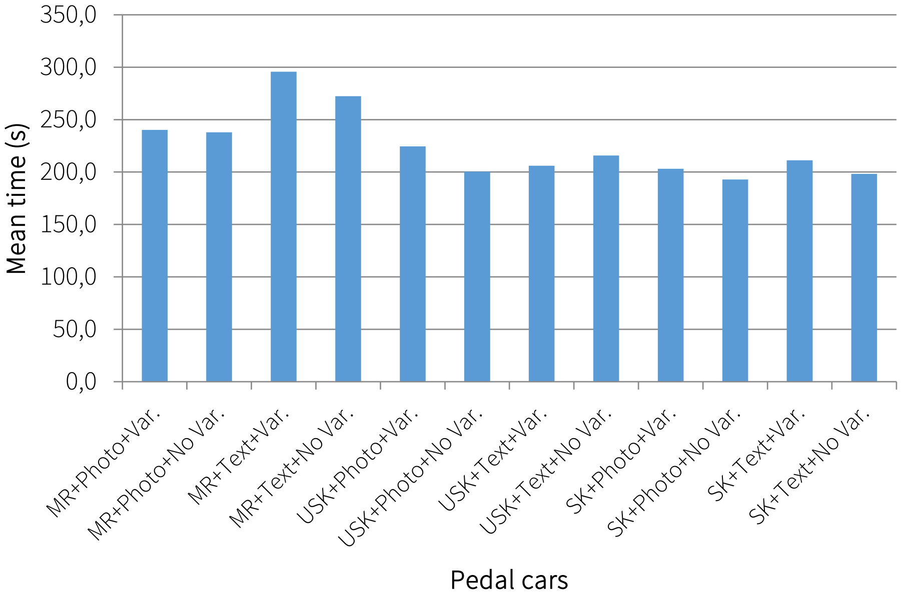


Figure 6.1. Graph showing the mean assembly time for the different cars

In addition, the questionnaire also confirmed that the subjects perceived the use of a structured kit in combination with photographs as the easiest and fastest way to assemble the pedal cars. The hardest perceived combination was when using the text & number instruction format in combination with picking the components from the material rack.

Sections 6.2 and 6.3 below provide a detailed account of the assembly time results. Details of the NASA TLX workload ratings are given in section 6.4 and the questionnaire is presented in section 6.5.

6.2 Results from the quantitative study

Since the sample size was considered large, a normal distribution of the data was assumed (Field, 2014), which was also confirmed by initial analyses. The repeated measurement analysis started with a test of the assumption of sphericity, which refers to the assumption that the variances of the differences between data taken from the same subject (or other similar entity) are equal. In this analysis, Mauchly's test indicated that the assumption of sphericity *was violated* for the main effects of material presentation, $\chi^2(2) = 14.61$, $p < 0.01$. Therefore degrees of freedom were corrected using the Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.74$ for material presentation). With corrected F-value, a summary of the main effects and interaction effects is presented in Table 6.2.

Table 6.2. A summary of the effects and relevant significant statistics

Main effects	Significant[a]	F	Effect size (*r*)
Material presentation (MP)	✓ (0.00)	59.54	0.85
Information presentation (IP)	✓ (0.00)	23.32	0.63
Component variation (CV)	✓ (0.00)	10.37	0.48
Interaction effects			
MP * IP	✓ (0.00)	13.04	0.70
MP * CV	✗(0.77)		
IP * CV	✗(0.59)		
MP * IP * CV	✓ (0.00)	1.78	0.52

a. Computed using alpha = 0.05

The results show that all of the main effects were significant and had a medium to large effect size according to Cohen (1988, 1992). This means that there was a large enough difference between the conditions of each factor, a result which could also be applied in other contexts (outside of this experiment). However, to find out which of these conditions were better than others, further analyses were required, which are presented in sections 6.2.1 – 6.2.3.

There were also two significant interaction effects, between material presentation and information presentation which had a very large effect size. This means that when only information presentation and material presentation were combined, certain combined conditions among these factors were better than other combinations. The second significant interaction effect was between the three-way interaction of material presentation, information presentation and component variation with an effect size which also was regarded as large. This result suggests that when combining all of these combinations it was possible to find a certain combination of conditions, involving all factors, that was better than others. To find out which of these combined conditions were better (in both the two-way interaction and the three-way interaction), further analysis was performed and is presented in section 6.3.

6.2.1 Main effect of Material presentation

The hypotheses for material presentation were:

H_1A: The performance when using a structured kit is better than the performance when using a material rack.

> **H_0A**: The performance when using a structured kit is worse than or equal to the performance when using a material rack.

H_1B: The performance when using an unstructured kit is better than the performance when using a material rack.

> **H_0B**: The performance when using an unstructured kit is worse than or equal to the performance when using a material rack.

H_1C: The performance when using a structured kit is better than the performance when using an unstructured kit.

H_0C: The performance when using a structured kit is worse than or equal to the performance when using a structured kit.

Results

As seen in the introduction of this chapter (section 6.2), all of the main effects were significant. Further analyses on material presentation showed that using a material rack takes the longest time spent on the task compared to unstructured and structured kits (Table 6.3).

Table 6.3. Descriptive statistics for the main effect of material presentation

Measure: Time (s)				
			95% Confidence Interval	
Material Presentation	**Mean**	**Std. Error**	Lower Bound	Upper Bound
Material rack	261.51	12.06	237.03	285.98
Unstructured kit	211.67	9.44	192.50	230.84
Structured kit	201.35	9.69	181.68	221.03

Further understanding of the differences and similarities can also be seen in Figure 6.2. The chart shows, among other things, the differences in variance, where a structured kit has a much lower variance than both a material rack and an unstructured kit. There are however some really extreme values for both material rack and structured kit.

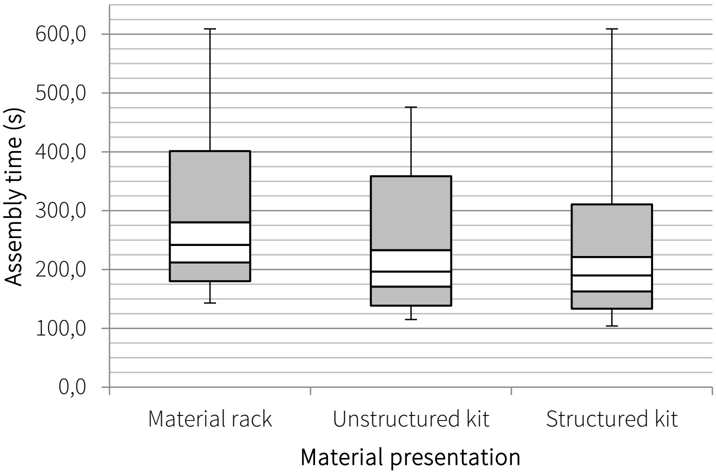


Figure 6.2. Chart showing max and min value as well as 5th, 25th, 50th, 75th and 95th percentile values for different material presentation alternatives

Table 6.4 shows a pairwise comparison analysis for the main effect of material presentation, corrected using a Bonferroni adjustment (Field, 2014). There is a significant difference between material rack and unstructured kit ($p < 0.001$) as well as material rack and structured kit ($p < 0.001$).

But the difference between the kits was non-significant. The table also shows that the mean difference was large between material rack and kits (49.8 *s* resp. 60.2 *s*).

Table 6.4. A pairwise comparison of material presentation, corrected using a Bonferroni adjustment

Measure: Time

Material Presentation (I)	Material Presentation (J)	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
Material rack	Unstructured kit	49.840*	5.290	0.000	36.537	63.143
	Structured kit	60.153	7.412	0.000	41.514	78.791
Unstructured kit	Material rack	-49.840*	5.290	0.000	-63.143	-36.537
	Structured kit	10.312	4.620	0.096	-1.306	21.931
Structured kit	Material rack	-60.153*	7.412	0.000	-78.791	-41.514
	Unstructured kit	-10.312	4.620	0.096	-21.931	1.306

Based on estimated marginal means

*. The mean difference is significant at the 0.05 level.

b. Adjustment for multiple comparisons: Bonferroni

The results clearly show that there was a significant difference between using either kit and the use of a material rack. It was therefore possible to reject the null hypothesis **H$_0$A**, since using a structured kit was better than using a material rack. The null hypothesis **H$_0$B** could also be rejected, since using an unstructured kit was better than using a material rack. The null hypothesis **H$_0$C** could however not be rejected as the difference between using an unstructured kit and a structured kit was not statistically significant.

The effect sizes of the significant effects are based on the contrast analysis since this analysis provides a comparison between all the different levels, between all factors (Field, 2014). These results are presented after the interaction effect, in section 6.3.

6.2.2 Main effect of Information presentation

The hypothesis for information presentation was:

H$_1$D: The performance when using a photograph is better than the performance when using text & numbers.

> **H$_0$D**: The performance when using photography is worse than or equal to the performance when using text & numbers.

Results

Analyses on the main effect information presentation showed that using text & numbers required a longer time to be spent on the task compared to using photographs (Table 6.5).

Table 6.5. Descriptive statistics for the main effect of information presentation

Measure: Time				
			95% Confidence Interval	
Information Presentation	**Mean**	**Std. Error**	Lower Bound	Upper Bound
Text & numbers	233.231	10.207	212.510	253.953
Photographs	216.454	9.881	196.394	236.514

More information is provided in Figure 6.3, where the differences in mean time were not large, but an interesting observation was that the variance and the extreme values were higher when using text & numbers compared to photographs.

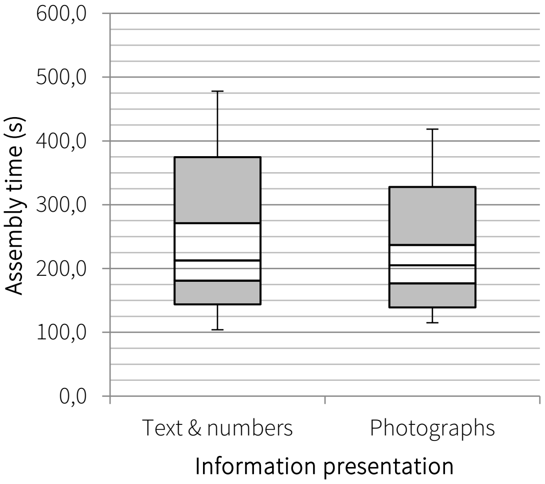


Figure 6.3. Chart showing max and min value as well as 5th, 25th, 50th, 75th and 95th percentile values for information presentation

Table 6.6 shows a pairwise comparison analysis for the main effect of information presentation. There was a significant difference between text and numbers compared to photographs ($p < 0.001$), where the mean difference was 16.8 *s*.

Table 6.6. A pairwise comparison of information presentation, corrected using a Bonferroni adjustment

Measure: Time						
					95% Confidence Interval for Difference[b]	
Information Presentation (I)	Information Presentation (J)	Mean Difference (I-J)	Std. Error	Sig.[b]	Lower Bound	Upper Bound
Text & numbers	Photographs	16.778*	3.474	0.000	9.725	23.831

Based on estimated marginal means

*. The mean difference is significant at the 0.05 level.

b. Adjustment for multiple comparisons: Bonferroni.

The results clearly show that there was a significant difference between using photographs compared to text & numbers, meaning that using photographs was better than using text & numbers, and therefore it was possible to reject the null hypothesis **H_0D**.

6.2.3 Main effect of Component variation

The hypothesis for component variation was:

H_1E: The performance when assembling products with no component variation is better than the performance when assembling products with component variation.

> **H_0E**: The performance when assembling products with no component variation is worse than or equal to the performance when assembling products with component variation.

Results

Initial analyses on the main effect of component variation showed that no component variation results in shorter time to assemble compared to component variation (Table 6.7).

Table 6.7. Descriptive statistics for the main effect of component variation

Measure: Time				
			95% Confidence Interval	
Component Variation	**Mean**	**Std. Error**	Lower Bound	Upper Bound
No variation	219.579	10.375	198.516	240.641
Variation	230.106	9.669	210.477	249.736

Further information is provided in Figure 6.4, where the overall differences seem small between using no component variation compared to using component variation. To determine the significance of the difference, a pairwise comparison analysis of the main effect component variation was needed.

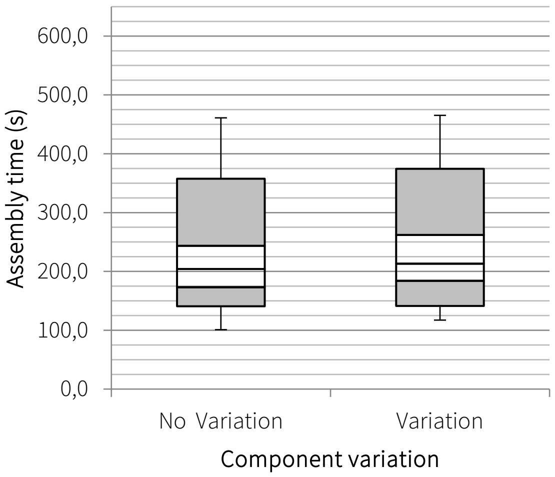


Figure 6.4. Chart showing max and min value as well as 5th, 25th, 50th, 75th and 95th percentile values for component variation

The analysis in Table 6.8 showed that there was a significant difference between using products with no component variation compared to products having component variation ($p < 0.001$), where the mean difference was ~10.5 *s*.

Table 6.8. A pairwise comparison of component variation, corrected using a Bonferroni adjustment

Measure: Time						
					95% Confidence Interval for Difference[b]	
Component Variation (I)	Component Variation (J)	Mean Difference (I-J)	Std. Error	Sig.[b]	Lower Bound	Upper Bound
No variation	Variation	-10.528*	3.270	0.003	-17.166	-3.890

Based on estimated marginal means

*. The mean difference is significant at the 0.05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Since the results show that there was a significant difference between using no component variants compared to using products with component variants, i.e. the use of no component variation was better than the use of variants, it was possible to reject the null hypothesis **H_0E**.

6.2.4 Summary of the main effects

- All of the main effects were significant.
- Assembly time was significantly lower when using a structured kit compared to a material rack, i.e. it was possible to reject the null hypothesis **H_0A**.

- Assembly time was significantly lower when using an unstructured kit compared to a material rack, i.e. it was possible to reject the null hypothesis **H_0B**.
- There was no significant difference between using an unstructured kit and a structured kit, i.e. the null hypothesis **H_0C** could not be rejected.
- Assembly time was significantly lower when using photographs compared to text and numbers, i.e. it was possible to reject the null hypothesis **H_0D**.
- Assembly time was significantly lower when using no component variation compared to using component variation, i.e. it was possible to reject the null hypothesis **H_0E**.

6.3 Results of the interaction effects

This section analyses the interaction effects of the entire three-way interaction between material presentation, information presentation and component variation, and a further analysis of the interaction effect between material presentation and information presentation. These analyses were carried out since these interactions were significant and therefore deserved further analysis, as stated initially in section 6.2.

An interesting finding presented in the interaction graphs in Figure 6.5 shows that the resulting time when photographs were used (compared to text & numbers) and at the same time no variants were used (compared to using variants) was different for unstructured kits compared to structured kits. This is explained by the fact that the difference between the data points in the unstructured kit condition is larger than the distance between the data points in the structured kit condition. This is especially apparent in the bottom right graph of Figure 6.5.

Another interesting finding was that when using an unstructured kit, assembly time was shorter when using text & numbers (compared to photographs) combined with using component variation (compared to using no component variation).

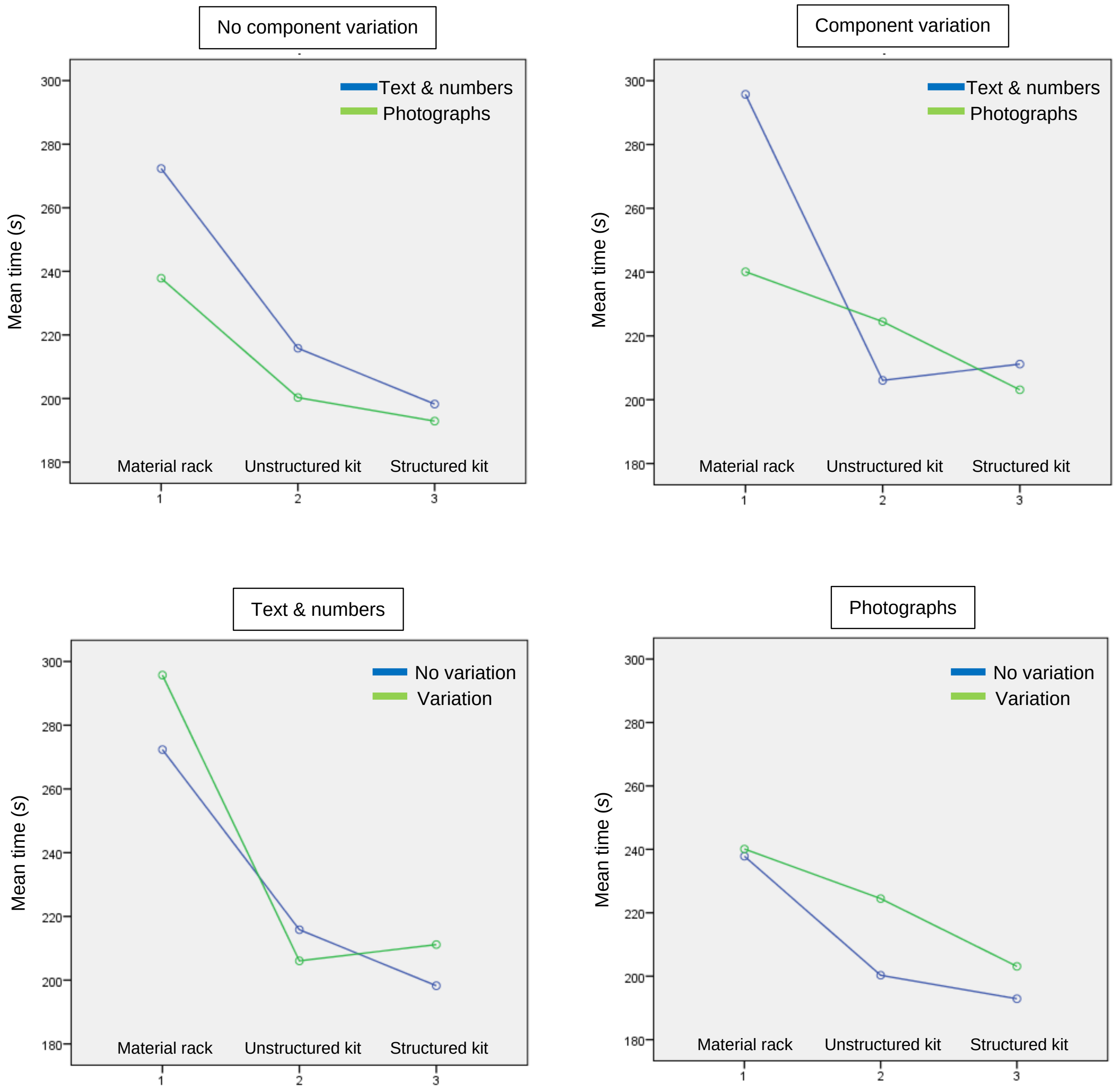


Figure 6.5. Interaction graphs for material presentation, information presentation and component variation

To verify the interpretations from the interaction graphs it is necessary to consider the *relevant* contrasts, i.e. the interaction effects between component variation and material presentation as well as information presentation were not significant (as stated earlier in Table 6.2) thus these contrasts were disregarded and not presented in Table 6.9.

Table 6.9. Contrast analysis regarding the main and interaction effects, as well as the effect size (r)

Measure: Time							
Source	**Material presentation**	**Information Presentation**	**Component variation**	**df**	**F**	**Sig.**	***r***
Material Presentation	USK vs. MR			1	88.752	0.000	0.85
	SK vs. MR			1	65.858	0.000	0.81
	USK vs. SK			1	4.98	0.032	0.35
Error (Material Presentation)	USK vs. MR			35			
	SK vs. MR			35			
	USK vs. SK			35			
Information Presentation		Photographs vs. Text & Numbers		1	23.322	0.000	0.63
Error (Information Presentation)		Photographs vs. Text & Numbers		35			
Component variation			Variation vs. No variation	1	10.367	0.003	0.48
Error (Component variation)			Variation vs. No variation	35			
Material Presentation * Information Presentation	USK vs. MR	Photographs vs. Text & Numbers		1	32.889	0.000	0.70
	SK vs. MR			1	13.051	0.001	0.52
	USK vs. SK			1	0.63	0.433	
Error (Material Presentation* Information Presentation)	USK vs. MR	Photographs vs. Text & Numbers		35			
	SK vs. MR			35			
	USK vs. SK			35			
Material Presentation * Information Presentation * Component variation	USK vs. MR	Photographs vs. Text & Numbers	Variation vs. No variation	1	13.152	0.001	0.52
	SK vs. MR			1	1.776	0.191	
	USK vs. SK			1	4.556	0.04	0.34
Error (Material Presentation* Information Presentation* Component variation)	USK vs. MR	Photographs vs. Text & Numbers	Variation vs. No variation	35			
	SK vs. MR			35			
	USK vs. SK			35			

As Table 6.9 provides the effect sizes, it was first necessary to check if it was possible to confirm the hypotheses concerning the main effects.

Using a material rack (MR) compared to a structured kit (SK) was significant with F (1, 35) = 65.86, $p < 0.001$ and $r = 0.81$, which was a very large effect size according to Cohen (1988, 1992), where $r > 0.5$ is regarded large, $r > 0.3$ = medium and $r > 0.1$ is regarded small. With an effect size considered as large, the hypotheses **H_1A** could be confirmed meaning that *using a structured kit was better than using a material rack*.

Using a material rack compared to an unstructured kit (USK) was significant with F (1, 35) = 88.75, p < 0.001 and *r* = 0.85, which also was a very large effect size. This also confirmed the hypothesis **H_1B**, meaning that *using an unstructured kit was better than using a material rack*.

Using an unstructured kit compared to a structured kit was significant with F (1, 35) = 4.98, p = 0.032 and *r* = 0.35 which was a medium effect size. This contradicted the post hoc test pairwise comparison (see section 6.2.1, Table 6.4) which stated that the difference between the kits was non-significant. Consequently, this result did not confirm the non-rejection of hypothesis **H_1C,** but rather showed that there was a difference between the kits, i.e. a structured kit was better compared to an unstructured kit. Consequently, this result needed to be interpreted and handled carefully, and was therefore analysed further in Chapter 7, Major findings of the experimental study.

Using photographs compared to text & numbers was significant with F (1, 35) = 23.32, p < 0.001 and *r* = 0.63, which was a large effect size. This confirmed the hypothesis **H_1D**, meaning that *using photographs was better than using text & numbers.*

Using no component variation compared to products with component variation was significant with F (1, 35) = 10.37, p = 0.003 and *r* = 0.48, which was a medium (almost large) effect size. This confirmed the hypothesis **H_1E**, meaning that *using no component variation was better than using component variation.*

Furthermore in Table 6.9, the *three-way interaction* showed that assembly time using photographs (compared to text and numbers) for products with no variants (compared to variants) was significantly different when an unstructured kit was used compared to when a structured kit was used (*F* (1, 35) = 4.56, *p* = 0.04, *r* = 0.34). The same goes for when using an unstructured kit compared to a material rack while at the same time using photographs (compared to text & numbers) as well as using products with no variants (compared to variants), (*F* (1, 35) = 13.15, *p* = 0.001, *r* = 0.52). Both had medium to large effect sizes.

The third contrast in the three-way analysis between material rack and structured kit, when using photographs (compared to text & numbers) and products with no component variation (compared to variants), was not significant, *p* = 0.191. This indicated that the pattern of decrease in time when photographs was used (compared to text & numbers) for products with no variants (compared to using variants) was similar for both material rack and structured kit, i.e. there was no interaction effect.

The relevant *two-way interaction* of material presentation versus information presentation shows that the decrease in time, when using photographs (compared to text & numbers) was significantly different when a material rack was used compared to a structured kit and also when a material rack was compared to an unstructured kit, F (1, 35) = 13.05, $p = 0.001$, $r = 0.52$, resp. F (1, 35) = 32.89, $p < 0.001$ and $r = 0.70$. Both of these interaction effects had a large or very large effect size. This can also be seen in the interaction graph of Figure 6.6. The distance between the data points in the structured kit condition is significantly smaller than distance between the data points in the material rack condition.

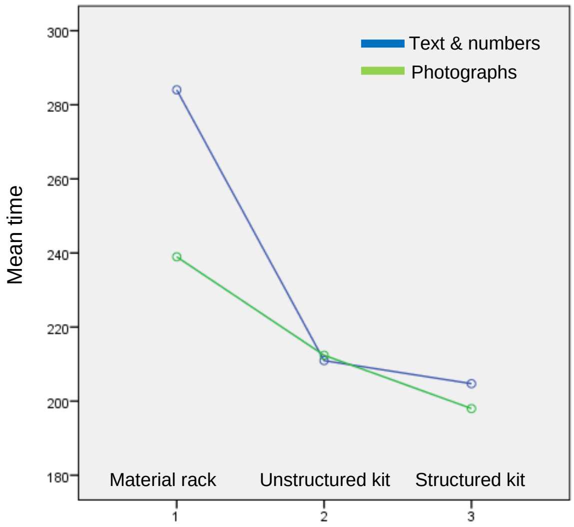


Figure 6.6. Graph showing the interaction effect between material presentation and information presentation

The graph also shows that the patterns of assembly time across different material presentations were similar in that both showed the longest time for material rack, and then the time reduced for unstructured kits and even further for structured kits. The data points that represent text & numbers are higher than the data points for photographs when using material rack and structured kit but not when using unstructured kit. Therefore photographs had the desired effect on material rack and structured kit but not on unstructured kit. This is analysed further in Chapter 7, Major findings of the experimental study.

However, the decrease in time when text & numbers was used (compared to photographs) was approximately the same for unstructured kits and structured kits, p= 0.433. As such, the distance between the data points in the unstructured kit condition is approximately the same (parallel) as for the structured kit condition, indicating no significant interaction effect. Hence, the decrease in time due to using text and numbers compared to using photographs was not affected whether unstructured or structured kits were used.

Summary of the interaction effects includes:

- Contrast analysis confirmed all hypotheses, even the hypothesis **H_1C** (stating that using a structured kit compared to an unstructured kit is better).
- Using photographs was significantly different (compared to text & numbers) when a material rack was used compared to a structured kit and also when using a material rack compared to an unstructured kit.
- Photographs had the desired effect on material rack and structured kit but not on unstructured kit.
- Using text & numbers compared to using photographs was not affected whether or not unstructured or structured kits were used.
- Photographs (compared to text & numbers) for products with no component variants (compared to products with component variants) were significantly different when using an unstructured kit compared to a structured kit.
- Photographs (compared to text & numbers) for products with no component variants (compared to products with component variants) was significantly different when using an unstructured kit compared to a material rack.
- Photographs (compared to text & numbers) for products with no component variants (compared to products with component variants) was not significantly different when using a material rack compared to a structured kit.

These findings were analysed further in Chapter 7, Major findings of the experimental study.

6.4 Results regarding NASA TLX workload rating

In addition to the use of assembly time as a performance measure, the NASA TLX workload assessment tool was used to assess both the mental and physical workload that the subject perceived during the experiment. Twelve subjects were asked to rate their perceived workload on six different scales; *mental*, *physical*, *temporal*, *performance*, *effort* and *frustration*, after the assembly of each pedal car. The scales were set from 0 to 100. To highlight the most important aspects of workload, the aspects were weighted in comparison to each other (Table 6.10).

Table 6.10. Different characteristics of workload weighted through pairwise comparison

	Demands						
	Mental	Physical	Temporal	Performance	Effort	Frustration	**Total weight**
Mental		1		1	1	1	**4**
Physical							**0**
Temporal	1	1		1	1	1	**5**
Performance		1					**1**
Effort		1		1			**2**
Frustration		1		1	1		**3**

Since the NASA TLX workload rating was intended to act as a support assessment against assembly time, stress and mental workload were the primary focus. Temporal and mental workloads were consequently weighted as most important and physical and performance were weighted as of lesser importance. After multiplying the weightings with the ratings, the total score of adjusted workload ratings were summed and divided by 15 to give an overall workload rate of the assembled pedal car.

A repeated measure analysis involving all factors was performed to get an overview of significant effects along with relevant statistics (Table 6.11). As in the previous analyses (with time as the dependant factor) Mauchly's test was performed to check for sphericity, but the sphericity was not violated so the F-ratio was in no need of correction ($\chi^2(2)$ = 0.163, p = 0.922).

Table 6.11. A summary of the effects and relevant significant statistics, with TLX workload ratings as measurement

Main effect	Significant[a]	F	Effect size (*r*)
Material presentation (MP)	✓(0.000)	11.959	0.64
Information presentation (IP)	✓(0.020)	7.390	0.82
Component variation (CV)	✗(0.121)	2.829	
Interaction effects			
MP * IP	✗(0.082)	2.814	
MP * CV	✗(0.635)	0.464	
IP * CV	✓(0.022)	7.118	0.63
MP * IP * CV	✗ (0.071)	1.602	

a. Computed using alpha = 0.05

The results show that the main effects of material presentation and information presentation were significant. Moreover, Table 6.11 also shows that the interaction effect of information presentation and component variation was significant. The effect sizes were large for all of these significant effects. In addition, the interaction effect between information presentation and component variation was significant when measuring workload ratings compared to the qualitative analyses. An interaction analysis was therefore prioritised.

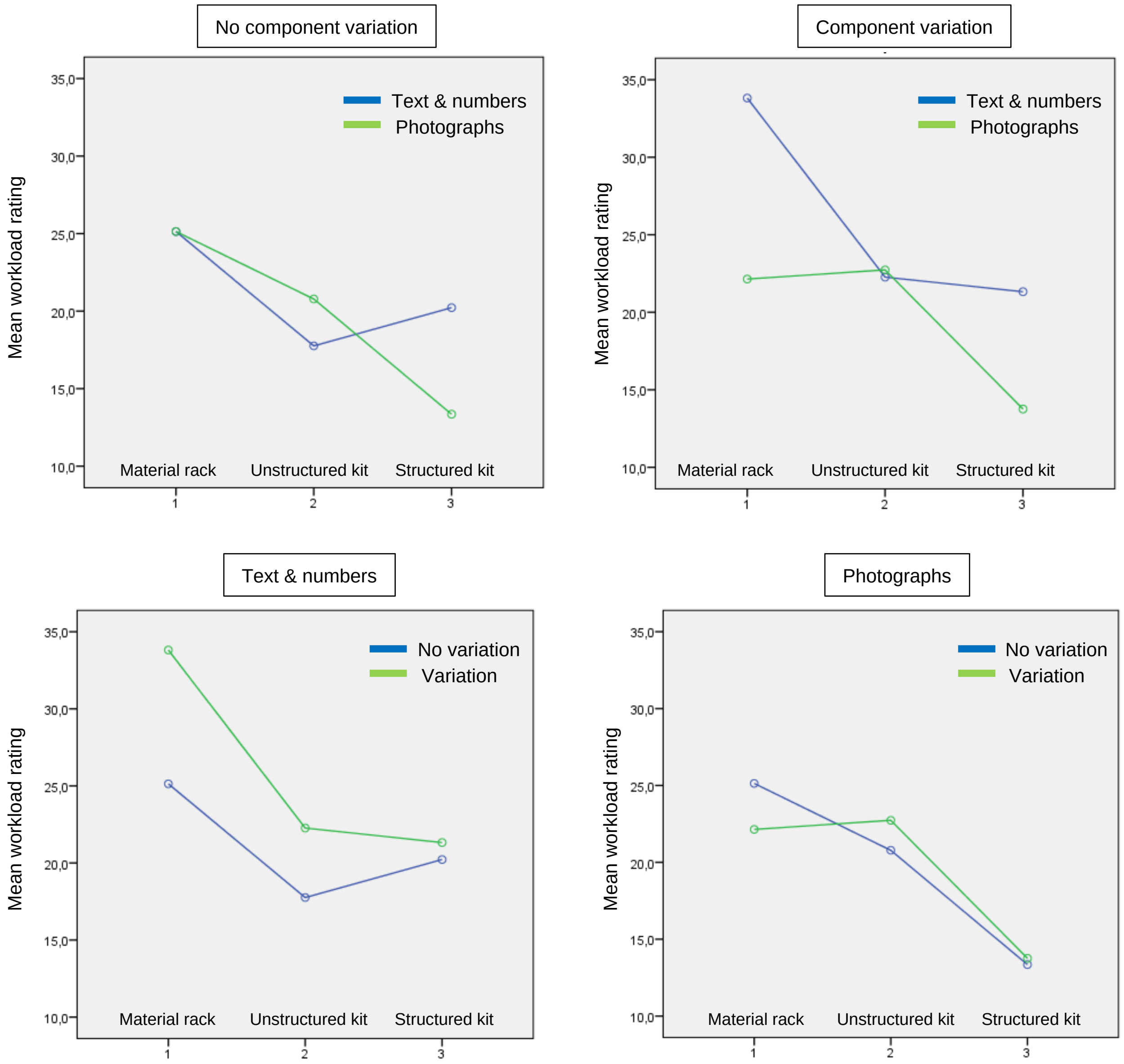


Figure 6.7. Graphs of the mean TLX workload ratings of the interaction effects

Figure 6.7 shows the interaction graphs which indicated that there were interaction effects between information presentation and component variation. The graphs show that the ratings for structured kit stayed consistent when component variation changed (when comparing the two top graphs). As seen when comparing the two bottom graphs, for structured kits ratings decreased at similar rates when changing from text & numbers to photographs and at the same time changing from products with no component variation to products with component variation. Conversely ratings with material racks and unstructured kits both changed depending on information presentation and component variation.

When using material rack and having products with component variation, the ratings decreased when information presentation changed from text & numbers to photographs. However, the ratings stayed consistent when having products with no component variation. On the other hand when using an unstructured kit and having products with no component variation, the ratings increased when changing from text & numbers to photographs, while the ratings stayed consistent when using products with component variation.

To verify the interpretations from the interaction graphs it was necessary to consider the relevant contrasts (Table 6.12).

Table 6.12. Contrast analysis regarding the main effects and relevant interaction effect, as well as the effect size (r) measured through NASA TLX workload ratings

Measure: NASA TLX workload rating							
Source	**Material Presentation**	**Information Presentation**	**Component Variation**	**df**	**F**	**Sig.**	***r***
Material Presentation	USK vs. MR			1	7.775	0.018	0.64
	SK vs. MR			1	23.380	0.001	0.82
	USK vs. SK			1	4.179	0.66	
Error (Material Presentation)	USK vs. MR			11			
	SK vs. MR			11			
	USK vs. SK			11			
Information Presentation		Text & Numbers vs. Photographs		1	7.390	0.020	0.63
Error (Information Presentation)		Text & Numbers vs. Photographs		11			
Information Presentation * Component Variation		Text & Numbers vs. Photographs	No variation vs. Variation	1	7.118	0.022	0.63
Error (Information Presentation* Component Variation)		Text & Numbers vs. Photographs	No variation vs. Variation	11			

The two-way interaction effect, verified in the contrast analysis, showed the decrease in ratings due to using photographs (compared to text & numbers) as significantly greater when using products with no component variants (compared to using products with component variants), $F\ (1, 11) = 7.12$, $p = 0.022$, with $r = 0.63$ which was considered a large effect size.

In addition, both of the main effects of material presentation and information presentation were significant, see Table 6.12. The contrast analysis showed that there was a significant difference between using a material rack compared to a structured kit (*F* (1, 11) = 23.380, *p* = 0.001, with *r* = 0.82, which was considered a very large effect size. Furthermore, the contrast analysis also showed a significant difference between using a material rack compared to an unstructured kit (*F* (1, 11) = 7.775, *p* = 0.018, with *r* = 0.64, which was considered a large effect size. It was therefore possible to conclude that the NASA TLX workload ratings support hypothesis **H_1A** and **H_1B**, but not **H_1C**, as the difference between using an unstructured and a structured kit was non-significant (p = 0.66).

More descriptive statistics of material presentation are provided in Table 6.13. The table shows that using a material rack was rated higher than using either of the kits. The lowest workload rating was assigned to the use of a structured kit.

Table 6.13. Descriptive statistics for the main effect of material presentation, measured through NASA TLX workload ratings

Measure: NASA TLX workload rating				
			95% Confidence Interval	
Material Presentation	**Mean**	**Std. Error**	Lower Bound	Upper Bound
Material rack	26.556	4.449	16.764	36.349
Unstructured kit	20.885	3.516	13.146	28.625
Structured kit	17.165	3.930	8.514	25.815

Further analysis regarding the difference of the main effect of material presentation shows that there was a significant difference between using a material rack compared to using a structured kit (p = 0.002), where the mean difference was ~ 9.4 workload ratings (Table 6.14).

Table 6.14. A pairwise comparison of the main effect material presentation, measured through NASA TLX workload ratings

Measure: NASA TLX workload rating						
					95% Confidence Interval for Difference[b]	
Material Presentation (I)	Material Presentation (J)	Mean Difference (I-J)	Std. Error	Sig.[b]	Lower Bound	Upper Bound
Material rack	Unstructured kit	5.671	2.034	0.053	-0.064	11.406
	Structured kit	9.392*	1.942	0.002	3.914	14.869
Unstructured kit	Material rack	-5.671	2.034	0.053	-11.406	0.064
	Structured kit	3.721	1.820	0.197	-1.412	8.854
Structured kit	Material rack	-9.392*	1.942	0.002	-14.869	-3.914
	Unstructured kit	-3.721	1.820	0.197	-8.854	1.412

Based on estimated marginal means

*. The mean difference is significant at the 0.05 level.

b. Adjustment for multiple comparisons: Bonferroni.

An analysis regarding the main effect of information presentation is also presented in Table 6.15. This analysis shows that using text & numbers (compared to using photographs) generated higher workload ratings.

Table 6.15. Descriptive statistics for the main effect of information presentation, measured through NASA TLX workload ratings

Measure: NASA TLX workload rating				
			95% Confidence Interval	
Information presentation	**Mean**	**Std. Error**	Lower Bound	Upper Bound
Text & numbers	23,421	4,215	14,143	32,699
Photographs	19,650	3,527	11,888	27,412

A more detailed analysis of the significant effect within the main effect of information presentation (Table 6.16) shows that there was a significant difference between using text & numbers compared to using photographs (p = 0.02), with a difference of ~3.8 workload ratings. It is therefore possible to conclude that the NASA TLX workload ratings support hypothesis **H_1D**.

Table 6.16. A pairwise comparison of the main effect information presentation, measured through NASA TLX workload ratings

Measure: Nasa TLX workload rating						
					95% Confidence Interval for Difference[b]	
Information Presentation (I)	Information Presentation (J)	Mean Difference (I-J)	Std. Error	Sig.[b]	Lower Bound	Upper Bound
Text & numbers	Photographs	3.771*	1.387	0.020	0.718	6.824
Photographs	Text & numbers	-3.771*	1.387	0.020	-6.824	-0.718

Based on estimated marginal means

*. The mean difference is significant at the 0.05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Summary of the results from the NASA TLX workload ratings includes:

- Workload ratings were significantly lower when using a structured kit compared to using a material rack.
- Workload ratings were significantly lower when using an unstructured kit compared to using a material rack.
- Using an unstructured kit compared to a structured kit did not result in a significant difference.

- Workload ratings were significantly lower when using photographs compared to text & numbers.

- Workload ratings were significantly lower when using photographs for products with no component variants.

6.5 Results of the questionnaire

After completion of the assembly operations each of the 36 subjects answered a questionnaire. The ages ranged from 19 – 62 years. Only two subjects had considerable experience from assembly work and a few subjects had assembly experience through assembling IKEA or LEGO constructions or some minor previous experience such as summer jobs within the assembly industry. Most of the subjects stated that they had no previous experience of assembly work.

Table 6.17. Summary of how the subjects rated some of the questions in the questionnaire

Ratings range/ initial questions	To what degree did the instruction format affect the difficulty of the assembly operation?	To what degree did the material presentation affect the difficulty of the assembly operation? *	To what degree was the difficulty of the assembly operation affected by the assembly of different variants of the pedal car? *
0-5 (not at all)	1	1	6
6-10	4	1	6
11-15	11	9	11
16-20 (very much affected)	20	25	12

* Only 35 subjects answered this question.

As seen in Table 6.17 almost all the subjects considered that the instruction format and the presentation of material affected the assembly operation. The third question, referring to products with component variation and its effect on the assembly operation, differed a little. One third of the subjects stated that assembling a product with or without component variants, did not affect the assembly operation that much. However, more than 60% stated that component variation affected the assembly operation moderately or greatly. The following section describes the subjects' own views of *how* these factors affected the assembly operation.

In what way did the instruction format affect the assembly operation?

Almost all subjects thought that the assembly operation got better, easier and faster when using photographs compared to text & numbers. Mostly this was because they did not have to read all the lines (compared to the text & number format) and as it was possible to compare the components to the photographs directly, making component identification easier.

Some subjects also stated that when using text & numbers, more controls were needed of whether or not they had read and understood the instructions, which possibly increased the assembly time. Other opinions were that photographs provided a mental preparation for the next assembly task since it was possible to glance at the instructions and thereby get a good overview of the assembly operation, making it a little less stressful.

In what way did the material presentation affect the assembly operation?

The placing of the components seems to affect the assembly operation a great deal, according to the subjects. There were almost unanimous opinions which stated that using a kit in general made the assembly task performance easier, faster and less stressful in finding the right components, especially with the structured kit. Many of the subjects also stated that while using a structured kit, there was hardly any mental workload since there was no disturbance due to reading or searching for components, making it possible to focus more on the assembly task itself. There were some subjects that perceived a decrease in time while using a structured kit (compared to an unstructured kit), but simultaneously also a decreased workload.

A few subjects also stated the very important fact that when using a kit it was possible to interpret when there were no components left in the kits, i.e. all components were assembled. This also however assumed that all components placed in the box were correctly placed.

Further opinions were that using the material rack made it harder to find the right components (mostly because the components were not placed in numerical order nor in sequence) which resulted in a decreased work flow and increased stress and frustration.

To what degree was the difficulty of the assembly operation affected by the assembly of different variants of the pedal car?

Most of the subjects were troubled by assembling a product with component variants. Several subjects stated that this inclusion of variants made it impossible to learn which components to use resulting in not being able to automate the assembly process (assemble without thinking) which would increase productivity. Most subjects also stated that the instructions had to be read thoroughly, to be able to pick the right component, especially when using a material rack.

It was also stated that even though the same assembly tasks were performed (regardless of product with component variation or not) the subjects had to stay alert, since it was easy to start working in the same way as before and possibly miss the material presented in kits behind the car and instead start to search for components all over again. However, some subjects stated that instead of staying alert, it was easy to become careless and not check all component variants, but rather assume standard components, especially when using a text & number instruction format.

Some subjects thought that the work flow was disturbed when having to check for component variants in the instructions all the time, which made the subjects feeling slow and uncertain, which resulted in an increase of stress.

What form of instruction did you perceive as the easiest?

As previously stated, the majority of the subjects thought that using photographs (compared to text & numbers) made searching for components easier, especially regarding subjects with no previous assembly experience. Since the photographs provided visual feedback, the possibility to get an overview of the subtask in the assembly operation increased. Due to this, some subjects also stated that they were able to focus less on the assembly operation, since the tasks spoke for themselves.

The majority also stated that the use of a structured kit made it easier to see where the components belonged, compared to the material rack. Some subjects even stated that they tended not to care about the instructions (even if all cars were provided with instructions) when using a kit. They stated that it was easier that way.

Many subjects tried to optimise the assembly task and process. Some stated that the use of photographs made it easier to view the instructions while at the same time assembling a component, which created a mental representation of what to assemble and what was to come. Furthermore, some stated that using instructions with photographs made it possible to identify differences between the components such as colour, size and material, and thus only search for these exceptions.

It was also thought that using photographs and a structured kit made it possible to read the instructions quickly and that time was not wasted searching for components which were small.

This could however be a bit stressful too, since there was no natural break and the work contained less variation.

Some also stated that using photographs was easier compared to text & numbers, but if not provided with additional component numbers, it could possibly result in errors. It was also stated that the photograph instructions were the best choice in the beginning, but after a while even the photograph instructions did not matter (or were not looked at), except the names beneath the photographs (such as gold instead of numbers).

What form of instruction did you perceive as the hardest?

The hardest form of instructions was seen to be the use of text & numbers. A majority stated that this instruction format made it harder to sweep across the instructions and thereby get an overview and extract the most important information. Instead it was necessary to check the exact component number, which could lead to the possibility of forgetting some steps. There was also the need to know where in the assembly process the subjects were assembling, and this resulted in more time spent on the task.

Some subjects also stated that it was harder to use the text & numbers format (compared to photographs) since it was necessary to remember the component numbers and also that the list of text & numbers did not show irregularities as clearly as using photographs, resulting in too much information which affected mental workload. It was also stated that the hardest components to find were the screws, since they were not only alike but there were many to choose from in the material rack. However, some subjects also thought that using text & numbers was the hardest instruction format, but not that much harder since some learnt the process after a while.

Other comments:

Most subjects stated that they perceived the experiment as interesting and a fun work task. Some also stated that it was interesting to see how easy it was to make assembly errors and thereby cause unsatisfied customers (both externally and internally). Some subjects also stated that they perceived time pressure even though this was not imposed in the experiment. Some also stated that after a while they assembled on pure instinct, which lead to assembly errors since products with component variants were to be assembled. Moreover, some subjects stated that they tried to take as few steps as possible and to think ahead, by perhaps collecting a component that would be used later rather than walking an extra step later.

A few subjects uttered some criticisms regarding too few instructions regarding how to assemble and no clear headings of what each subtask did. At the same time some also stated that they learnt the assembly process when the instructor demonstrated the assembly process in the beginning. Some subjects were also a bit annoyed that the components in the material rack were disarranged and not ordered according to the component numbers. This was however inspired by previous observations in the automotive industry. Further, it was also stated that the table on which the tools were placed was rather small, so some subjects had to be careful when putting down the tools on the table, in order not to drop them on the floor.

Summary of interesting findings from the qualitative results includes:

- A majority of the subjects thought that the instruction format and the presentation of material affected the assembly operation.
- Using a kit in general made the assembly task performance easier, faster and less stressful, especially with a structured kit.
- Using a structured kit resulted in a reduction of reading or searching for components, which led to a better focus on the assembly task itself. However, some subjects also perceived a decrease in time, but simultaneously a decreased workload.
- When using a kit, the subjects got immediate feedback that all components had been assembled, when there were no components left in the box.
- Using a material rack made it harder to find the right components (mostly because the components were not placed in numerical order nor in sequence) which resulted in a decreased work flow and increased stress and frustration.
- A majority of the subjects thought that the assembly operation got better, easier and faster when using photographs compared to text & numbers.

- Photographs provided a mental preparation of the next assembly task and made it possible to identify differences between the components such as colour, size and material.
- Instead, text & numbers resulted in too much information which affected mental workload.
- There were different opinions on whether or not component variation had an effect on the assembly operation.
- The instructions had to be read thoroughly (to check for component variants), to be able to pick the right component, especially when using material rack combined with text and numbers.
- Using photographs and a structured kit made it possible to read the instructions quickly but could also be stressful, since there was no natural break and the work contained less variation.
- In the beginning, photograph instructions were the best choice but after a while even the photograph instructions did not matter, except the names beneath the photographs. Instead, the subjects assembled on pure instinct, which lead to assembly errors since the component variants changed.

6.6 General summary of results

A summary of the effects and whether or not they were significant or not (X = non-significant and ✓ = significant), is presented in Table 6.18, which also illustrates the structure of the summary of results.

Table 6.18. A summary of all effects and their significance (or not), when analysed through assembly time and NASA TLX workload ratings

Main effects	Time[a]	NASA TLX workload ratings
Material presentation (MP)	✓ (0.00)	✓ (0.000)
Information presentation (IP)	✓ (0.00)	✓ (0.020)
Component variation (CV)	✓ (0.00)	✗ (0.121)
Interaction effects		
MP * IP	✓ (0.00)	✗ (0.082)
MP * CV	✗ (0.77)	✗ (0.635)
IP * CV	✗ (0.59)	✓ (0.022)
MP * IP * CV	✓ (0.00)	✗ (0.071)

a. Computed using alpha = 0.05

Based on the results and structure of these effects (Table 6.18), the most interesting findings were summarised as followed:

- Performance, measured in assembly time, was lower when using a kit, when using photographs for information presentation and when not using component variation. The subjects also stated that these conditions made the assembly operation better, easier and faster.

- Using a kit made it possible to interpret if all components were assembled, assuming that all components placed in the box were correct. Using a material rack, made it harder to find the right components, resulting in decreased work flow and increased stress and frustration.

- There were contradicting results between using an unstructured kit and a structured kit, when analysing assembly time either by using pairwise comparison (which resulted in a non-significant difference) or a contrast analysis (which resulted in a significant difference). There were also non-significant results when workload ratings were measured. Subjects stated that using a structured kit resulted in a reduction of reading or searching for components, which led to a better focus on the assembly task itself.

- Performance, measured in workload ratings, supported assembly time analyses in that ratings were lower when using a kit and when using photographs as well as the combination of using photographs for products with no component variants.

- Photographs provided a mental preparation of the next assembly task and made it possible to identify differences between the components such as colour, size and material.

- Using text & numbers made it hard to overview and extract the most important information, when searching for component numbers, leading to loss of track in the assembly process, (especially when combined with using a material rack), resulting in too much information which affected mental workload.

- Using photographs combined with a kit resulted in lower assembly time and the possibility to read the instructions quickly, but could also result in stress (especially with structured kit), since there was no natural break and the work contained less variation. On the other hand, photographs had the desired effect (lower time) on material rack and structured kit but not on unstructured kit. Using text & numbers was not affected by the use of either kit.

- Performance, measured in assembly time, was best when combining photographs with no component variants and when using a structured kit (compared to any of the other material presentation conditions).

These findings were of specific interest and was therefore discussed further in the next chapter (Chapter 7), providing a more extensive analysis and conclusion.

7 MAJOR FINDINGS OF THE EXPERIMENTAL STUDY

This thesis and the experimental results attempts to explain factors affecting human cognitive performance at assembly workstation, such as different ways of conveying information where for instance both instructions and material components need to be considered. The need for information does not go away due to using kits rather than racks, but the way the information is structured and presented creates a more efficient and better workplace which benefits the assembly workers and technicians greatly and is what should be learnt from this experiment.

Accordingly, as the results chapter was too dense and provided a lot of findings in detail, this chapter will only elaborate on the key findings which are based on the effects size of the results as well as the possible impact and interest, observed in the previous studies. Moreover, this will be done by attempting to justify and explain these key findings using a foundation from the literature review presented in Chapter 2, along with the observations from the different studies throughout this thesis.

- Performance, measured in *assembly time* and *workload ratings*, was improved when using a kit, as it was possible to interpret if all components were assembled (assuming that all components placed in the box were correct). Using a material rack, made it harder to find the right components, resulting in perceived decreased workflow and increased stress and frustration.

- Performance measured in *assembly time* and *workload ratings*, was improved when using photographs. Subjects also stated this condition made the assembly operation better, easier and faster, as photographs provided a mental preparation of the next assembly task and made it possible to identify differences between components such as colour, size and material. Using text & numbers made it hard to overview and extract the most important information when searching for component numbers, leading to loss of track in the assembly process, consequently resulting in too much information which affected mental workload.

- Performance measured in *assembly time*, was improved when using products with no component variation. This was also was favoured by the subjects. The *workload ratings* were also lower when using photographs combined with no component variation. According to *assembly time* and *workload ratings*, using either material rack or the kits was not affected by whether the assembly consisted of variants or standard components.

- Contradictory results between using an unstructured kit and a structured kit were found when *assembly time* was analysed. Some analyses showed no significant difference while some showed significant difference between unstructured kit and structured kit. In addition, subjects stated that using a structured kit resulted in lower mental workload due to not having to read or search for components, leading to a better focus on the assembly task itself.

- Using photographs combined with a kit resulted in lower *assembly time* and the possibility to read the instructions quickly, but could also result in stress due to no natural break and because the work contained less variation. Photographs had the desired effect (lower *assembly time)* on material rack and structured kit but not on unstructured kit. Using text & numbers was not affected by the use of either kit. Moreover, according to the workload ratings, using a structured kit combined with using photographs were perceived as the easiest combination to handle, regardless of component variation level.

- Performance, measured in *assembly time*, was best when combining photographs with no component variants and when using an unstructured kit.

The main findings in this experiment were to some extent not that surprising. The fact that using a material rack takes a longer time and generates higher workload compared to using a kit, was to some extent expected. As the subjects stated, this probably had to do with the increased need for searching and fetching components when using a material rack. Instead, when using a kit, all of the components were placed in one small area (attached to the assembly product), the structured kit even had the components order in a structured way according to the assembly process, completely removing the need to search for components. This also corresponds well with what has been described as good usability concerning the goals of efficient and effective to use (Preece et al., 2002) which was explained in section 2.3.1. Moreover, the subjects also said that using a kit made it easier to see if all of the components had been assembled or not. If some remained in the box, an assembly error had probably occurred, i.e. the subjects had failed to assemble all components. Associated with this there was still an issue of whether or not the correct components had been placed in the box by the instructor or experimenter. Related to the manual assembly industry, the idea here is that the decision of what to assemble, and thus which components should be placed in a kit, is moved from the assembly line to a kitting area of some sort (either centralised or locally) in the factory plant. This then makes it possible for the assembler to *only focus on how to assemble*, which is more related to the assembly skills and technique which have been taught to the assembly worker during training sessions at the beginning of the employment. When dealing with the kitting area, it is therefore possible to really focus on appropriate information support to the kitting personnel of what to assemble, or perhaps even making this process automated. In contrast to the use of kitting, subjects said that using a material rack made it harder to find the appropriate components, resulting in perceived decreased workflow and increased stress and frustration. This fails in many usability aspects such as having good visibility, mapping (matching) (Nielsen, 1993, Norman, 2002), and also good efficiency and effectiveness (Preece et al., 2002). In this case this refers to the material rack being perceived as too complex and providing inadequate visibility to be able to carry out the intended assembly task.

Furthermore, using photograph instructions generated shorter assembly times and lower workload compared to using text & number instructions. This could be explained through using photographs provided a mental preparation of the next assembly sub task, as the assemblers were able to get an overview of the entire assembly operation and thus scan through the instructions and extract relevant information. This corresponds to several usability and design principles such as visibility but also aesthetics and minimalist design (Nielsen, 1993), as when using photographs only the relevant information is visible. This in turn made the entire assembly operation not only faster but also easier to handle from a cognitive point of view as it was possible to stay ahead of the information and the task. The focus on the relevant information became better and therefore the opportunity arose to discard unnecessary information. Subjects claimed that photographs made it possible to identify differences between the components such as colour, size and material, and thus only search for these exceptions. This could indicate that the subjects changed their search path, from primarily numbers (when using text & numbers) to visual attributes, as these are more prominent, further enhancing the use of photographs to the design and usability principles of for example mapping (matching) and visibility (Nielsen, 1993, Norman, 2002). In contrast, instructions consisting of text & numbers failed to show irregularities clearly, with the result that it was hard to overview the instructions and extract the most important information when searching for component numbers. Consequently this not only led to loss of track in the assembly process but also too much information which affected the cognitive workload (Lindblom & Thorvald, 2014, Thorvald & Lindblom, 2014).

An additional finding concerned the use of no component variation, which produced lower assembly times (compared to when using component variation). This implies that, as mentioned in the literature (section 2.2), using component variation in manual assembly not only substantially increases the perceived complexity but also the efficiency of carrying out the assembly task, and hence the usability goal of efficiency (Preece et al., 2002). Moreover, the subjects perceived the workload as lower when using photographs combined with no component variation, which can be linked to the usability goal of learnability (Preece et al., 2002). This suggests that good usability in an interactive system is achieved when the user has good support in carrying out the intended task. Thus, this implies that the combination of photographs (or a similar instruction mode) combined with using no component variation is a good working situation for novice assembly workers. Further, according to assembly time and workload ratings, using either material rack or the kits was not affected by whether the assembly consisted of variants or standard components. There could be several potential explanations for this, for instance how often component variation occurred in the assembly flow, or how many component variants were displayed relative to standard components, all which would affect how the complexity of the component variation was perceived by subjects. If the material rack only contained a few component variants, they might appear as irrelevant in relation to the standard components. Another aspect was that when using a kit, the subjects only cared about the components in the box, the decision of picking the right component variants was already taken, which was not the case when using a material rack, i.e. the kits were immune to the change of component variants.

There were contradicting results between using an unstructured kit and a structured kit. Even though the hypothesis **H_1C** was confirmed through the contrast analysis stating that using a structured kit is better than using an unstructured kit, this issue needs to be handled carefully. Moreover, the NASA TLX workload ratings found no perceived difference between using the different kits. Additional information from the contrast analyses showed a medium effect size of $r = 0.35$ and a quite small F-value F (1, 35) = 4.98, indicated that the difference between the kits was not as large as between the different kits and the material rack. However, even a small difference (in this experiment, 5 *s*) can have an impact when applied in a production context where there are short assembly cycles. However, it is probably safe to say that there is a difference between the kits, but the difference is most likely not as big as between the use of kits and the use of a material rack. One can probably say that a structured kit costs more in terms of space, working hours, extra work in terms of picking components and putting them in the box as well as more decisions (although outside of the assembly line). When regarding the unstructured kit one can state that it probably increases the search and thus the number of decisions, but the production system as a whole does not have to provide as much effort for structuring the kit. So what is the difference between the kits, except that using a structured kit in this experiment took about ten seconds less than using a structured kit? One possible difference is that structured information, as a structured kit, provides information about the assembly process to a higher degree and in a more precise way compared to unstructured components. This consequently decreases the need to search and interpret more information other than the kit itself. This in turn not only leads to a better focus on the assembly task but also decreases the information load and thus the cognitive workload for the assembler, which is partly what this thesis set out to investigate. This could be further linked to the usability and design principles of *mapping* (Norman, 2002) and *matching* (Nielsen, 1994). In order to obtain good usability it is important that the control is clear and used consistently as well as positioned logically in order to map to the real-world objects, which in this case means that the components are positioned in a way which logically maps to the intended assembly task. So, how could it be that the effect between the different kits was not that great? And how come the pilot study showed such large differences in assembly time, but not in this experiment? Well, there could obviously be a number of reasons for this but one difference that comes to mind is that no consideration was made in the experiment regarding the number of components that were placed in the kits, which was an error from the research design. The pilot study involved more than twice as many components as the experiment (12 components in the experiment compared to 32 in the pilot study). This may indicate that a structured kit benefits greatly if the assembly operation contains a large number of components, compared to an unstructured kit. Since the assembler then needs to search for components in the unstructured kit, even though this issue is handled far better when using an unstructured kit compared to a material rack. This raises another question of how many components could be placed in an unstructured kit before it becomes too many and thus unorganised. Given the results from the pilot study and the experiment, the limit for the number of components is probably between 12 and 32. Further, since the experiment showed a difference, even though it was small, it is possible to say that the limit for the number of components is probably closer to 12 than 32. In addition, some subjects involved in the exploration studies (Chapter 3) also preferred an approach where kitting was mainly used for solving instant problems of insufficient space and to only kit those components with many variants, while retaining continuous supply for the rest. This was since they perceived that that the time required to pick each component in preparing the kits exceeded the time saved at the assembly line. This would add complexity to the question of finding the magic number of components in the kits, and is also of interest when considering time spent on preparing the kit as well as when assembling the object. Thus, this issue could be something for future work, investigating were the breakpoint of how many components a general kit should contain. When dealing with a structured kit, the main limit concerns the size of the components which should fit into the box and the size of the box. Another reason worth mentioning which might have affected the difference in results when performing the pilot study compared to the experiment, was the components themselves. In the pilot study the components consisted of LEGO and in the experiment the components consisted of pedal car components. Considering of the usability principles of recognition and matching (Nielsen, 1993) as well as mapping (Norman, 2002), LEGO might to some assemblers (or even a majority) be considered more intuitive as they might have grown up with this as toys. On the other hand, the pedal car components can to some extent be considered as intuitive as well. As the design of the component can to a higher degree be connected to the placement and their surrounding context, compared to some of the LEGO components, which are usually standardised.

A further finding was that when using photographs combined with using a kit (either kind), the assembly time was lower as well as providing a clear structure of what and how to assemble, further referring to the design and usability principles of visibility and mapping, but also recognition and feedback (Nielsen, 1993, Norman, 2002, Preece et al., 2002, Hartson & Pyla, 2012). This was due to the photographs providing a mental image (model) of what components to use and how to assemble them, which the kits further reinforced (especially when using a structured kit as this would also reveal the process order). However, using this combination could also result in stress due to there being no need for a so-called natural break, such as stopping to think about what component to pick. Added to this the assembly work contained less variation since, for instance, there was no need to fetch and search. Furthermore, it was interesting that using photographs had the desired effect (lower assembly time) on material rack and structured kits but not on unstructured kits. In addition, using text & numbers was not affected by the use of either kit. Accordingly, using an unstructured kit resulted in lower assembly time when using text & numbers than when using photographs. A possible explanation for this could be that the subjects did not look too carefully at text & numbers instructions, since they would take a long time to go through due to the dense information. Furthermore, since it would be difficult to control if the unstructured kit was prepared correctly, i.e. correct components in the box, they just went along and assembled on previous experience. Compared to when using photographs, which made the information (components) easily interpreted, the assemblers were keener to read the instructions thoroughly to verify and map to the components in the kit, hence taking longer total assembly time. Moreover, according to the workload ratings, using a structured kit combined with using photographs was perceived as the easiest combination to handle, regardless of component variation level. This further strengthens the assumption that structured kits can handle a large amount of component variation, and is perhaps even immune to this variation.

The last main finding concerned the best possible combination of all factors, when performance was measured in assembly time, which were when combining photographs with products having no component variants and when using an unstructured kit. In addition, it was possible to say that when using photographs combined with products having no component variants and when using an unstructured kit, the assembly time was less (compared to the other possible combinations). In contrast, both assembly time and workload ratings showed that the combination of using material rack, text & numbers and products with component variants was the worst of all combinations, as it took the longest to assemble and was rated with the highest workload. This was however not surprising, since all of the null hypotheses connected to the factors were rejected and a combination of these factors could possibly only make it worse.

8 DISCUSSION AND CONCLUSION

The research reported in this thesis has the aim of identifying factors that affected human cognitive performance in manual assembly, and this was achieved through an investigation of the literature and several experimental studies.

The research objectives are to:

- Identify and explore applicable factors for assessing human cognitive performance within the research field of manufacturing.
- Investigate how current manual assembly information systems present information to the assembler at the workstation.
- Identify suitable factors affecting the cognitive aspects of human performance in manual assembly, for deeper study and investigation.
- Investigate how the combination of factors affect the cognitive aspects of human performance in manual assembly.

The first objective was achieved through study of the literature, where the general manufacturing research area was investigated, including logistics and complexity. This was done in order to get an understanding of the factors that had been previously investigated and to see if certain factors were more common than others. The investigation resulted in certain areas of interest, i.e. categories of factors: tools and support tools, product variants, transfer of training, workstation layout, work instructions, operators' way of working, feedback and information syntax. All of these factors were then seen as a foundation when additionally investigating further established models within manufacturing as well as investigating usability and design principles which would aid in the understanding of how to best present information. The result of these investigations was a set of interesting factors that served as input to the exploration studies. The factors considered were product variants, workstation layout (material presentation), work instructions and operators' own way of working.

To achieve the second objective several studies were conducted in different manual assembly environments in industry, with the focus on how information was presented to the assembler at the workstation. Based on the factors found in the literature review, it was possible to establish areas of interest in the manual assembly environment, including the material or components layout at the workstation as well as the design of work instructions. Altogether, this resulted in an insight into how information and material was presented to the assembler at the workstation in several different assembly environments. It also provided input as to what factors were to be investigated in the subsequent experimental studies. The factors considered were:

- Material (i.e. components) presentation
    - Material rack
    - Unstructured kit
    - Structured kit
- Information presentation
    - Text & number instructions
    - Photograph instructions
- Component variation (i.e. product variation)
    - No component variation
    - Component variation

The third and fourth objectives were to a large extent the major objectives that met the aim of this research. The experiments started out with a pilot study which investigated the experimental set-up as well as if and how the factors could be measured. However, only material and information presentation were investigated, partly to ensure that these factors could be used as independent variables. However, in the experimental study component variation was also included.

By primarily measuring assembly time and the perceived workload for each combined set-up, along with an overall questionnaire, it was possible to conclude for instance that it was favourable (both in time and perceived workload) to use a kit compared to using a material rack as well as to use photograph instructions instead of using text & number instructions. However, the most interesting results were how the combination of the independent variables affected the assembly performance.

8.1 Validity

This research has been carried out through various studies, including observations, case studies and a major concluding experimental study. However, in order to assess the overall research process with regards to scientific rigour and validity, Oates (2006) suggests different evaluation guides depending on the type of research that has been performed.

8.1.1 Literature review

Various literature sources were reviewed within the field of manufacturing (Chapter 2), with topics related to manual assembly such as complexity and material supply management. Further investigations were also made within the fields of usability and cognitive load, as these aspects constituted the angle of incidence of the problem. There can of course always be a discussion of whether or not the literature review is broad enough in order to encompass the extent of the problem, but at the same time specific or narrow enough to gain real understanding and to be able to evaluate the problem. Since manufacturing and manual assembly are both extremely broad research fields, there are some topics that were not explored in this. However, through the initial review of commonly used factors in manufacturing and manual assembly, it was possible to navigate in certain directions within the literature review, which helped to get a more comprehensive understanding of the field. The literature resulted in several factors or larger categories that would be investigated further in assembly environments. It is likely that there could be several different ways to create these categories, as for instance some factors would fit under several different main factors and thereby form other categories. Still, the approach used was deemed appropriate for the further research work of this thesis.

8.1.2 Case studies

During the exploration of the background (Chapter 3), two case studies were performed in a manual assembly industry (section 3.1). These cases were mainly selected based on the different strategies of how to introduce kitting in the production system and the possibility to study both continuous supply and kitting in the same production environment. The factory plants, and thus companies, involved in the cases were also part of the FACECAR project (section 1.3), which simplified accessibility to, for instance, documentation. In order to compare how the different plants introduced kitting, the research was performed over time, i.e. using a longitudinal approach. Moreover, the initial strategy was an explanatory multiple case study, where the cases were analysed using a logistical point of view (man-hour consumption, flexibility, space requirements). But when used in this thesis the case strategy was more of an exploratory study, as it was used as background information for the research. However, instead of analysing this through a logistic perspective, the case studies were analysed from a usability and cognitive perspective, to identify and understand how some of the factors from the literature review were used in manual assembly. This meant however that a few years had passed between the analysis and when the case studies were performed. However, as the data collected were still available and not outdated, the analyses were still valid to act as background information. The case studies were based on multiple sources of data, including direct observations, interviews, internal documentation and video recordings. In all of the case studies, representatives from the studied companies have reviewed and approved drafts of the initial case study reports. Since these case studies were used (in this research) to explore the actual settings of manual assembly they were mostly based on qualitative data. The limitation with these case studies was that the cognitive and usability aspects of the analyses were not used initially when conducting the studies which might have affected the result from these cases. But, in order to verify the perspective of the issues found in the cases studies and therefore try to find similar or even other related issues, an additional observational study was performed in other factory plants, which enhanced the generalisation of the issues.

8.1.3 Observational study

The observational studies were performed through so-called complete observation, where the author was overtly observing everything that occurred, meaning that the subjects knew that research was being carried out regarding what and how they performed the tasks but there would be no interference in the assembly proceedings (Oates, 2006). As these observations were made by one person, there are reasons to question the validity since there was a high risk of selective recall and perception. However, one way of ensuring validity was to observe several different assembly environments to see if each environment had the same issues, which would also enhance the generalisation of the issues found in the case studies as well as the literature review. In addition, semi-structured interviews were conducted to further strengthen the validity and reliability and thus confirm the findings derived from observations. Further insights when performing observations at the various factory plants was the possibility to get a more holistic perspective of the often very complex settings. In particular this provided the insight that assemblers are not affected by one factor at a time, but rather several factors combined to form a complex manual assembly environment (section 3.2).

8.1.4 Experimental study

At the beginning of the experiment, several hypotheses were clearly stated, and these formed the bases of the experiment. These hypotheses were derived from the literature review as well as the exploration studies and pilot study, thereby strengthening the reliability and scientific rigour. Since this experiment was performed in an artificial setting, issues can be raised regarding validity related to objectivity and correct measurements (construct validity). In order to obtain validity, several sources of data were used, involving video recordings, quality form, the NASA TLX workload rating survey and a questionnaire.

In the experiment, three independent variables were used (material presentation, information presentation and component variation), each consisting of 2 or 3 levels. Although these factors and their levels were derived from previous studies involving both literature and industry, it is possible to question some of the choices in the levels of factors. For instance, the use of photographs could be further improved by using sketched illustrations of components in the work instructions. The advantage of using simple sketched pictures or illustrations, which primarily consist of contours is that they contain less "noise" and fewer details that are able to distract the perception of the message that are conveying. Consequently, this could possibly have affected the perception of the components and thus the ability to act on the information provided by the work instructions. To some extent, this was considered since the photographs were taken against a white background, in order to reduce redundant information, but using simpler sketches (along the line of IKEA instructions) might have reduced redundant information even more. This is also related to the fact that this thesis to a large extent focuses on and considers usability in order to enhance the understanding of the conveyed information to the assembler, both by investigating literature but also the manufacturing context. However, there were usability aspects that would clarify and enhance certain information both in the pilot study but also in the experimental that can be questioned, as they might not express usability to a great extent. For example, in the pilot study, certain arrows were supposed to guide the assembler into picking in the right sequence according to the assembly process. There were however some assemblers that did not even notice the arrows, which indicated lack of usability, and the same was found with the photographs.

Furthermore, two dependant variables were used, assembly time and perceived workload together with a qualitative survey. The number of assembly errors were also measured, but the errors were too few for statistical analysis as a floor effect was encountered. This is probably due to the task being too easy and also perhaps because the subjects did not feel stressed enough to make assembly errors. Having several independent and dependent factors resulted in the experiment being quite complex, both in the performance but mainly regarding the statistical analyses. As mentioned before, the combination of factors was the main point of interest in the experiment. However, the combination of factors also made it difficult (if not impossible) to distinguish the factors from each other, as they most likely have affected each other. One way to control the variables in the experiment was to use a random selection of subjects which thereby hopefully resulted in the individual factors that might have interfered with the results to cancel each other out across the entire subject group. Since the experiment was a full-factor experiment, consisting of 2x3x3 factors, the statistical analysis became quite complicated, especially considering that there were also several measurements involved. To ensure validity and reliability, rigorous statistical analyses were made as detailed as possible in order to also be able to trace the results.

In addition, as this study was performed in a laboratory setting, it is always an issue of how well the setting can be generalised to other settings such as an actual manual assembly setting. However, as stated in section 5.4, the laboratory environment was set-up to mimic certain elements of a real life assembly environment, in order to enhance validity. However, certain work behaviour is very hard to reproduce in a laboratory setting, such as making the subjects really care for the quality and the results, since the repercussions usually are non-existent. Another ethical issue that arose was that the subjects were only told that the experiment would measure workload (using a waist-strap which was connected to a watch attached to the research instructor's wrist). What the subjects were not told was that the test also investigated assembly time and assembly error, since this might have altered their behaviour and thus made the subjects focus on other things rather than making a good job at assembling the pedal cars. Although this can be seen as violating the participants' 'right to give informed consent' (Oates, 2006), it was believed that the subjects would come to no physical or emotional harm, through participating in the experiment without knowing that they were actually being evaluated on assembly time and assembly error. A further threat to external validity was the use of students and colleagues as subjects in the experiment, instead of using real assembly personnel. It was not possible to get access to real assembly workers, and this could be a cause for questioning the generalisability of the results. However, in several factory plants in Sweden, there are many young people working as assemblers, before moving on to higher education.

Altogether, it should be possible to generalise the finding of the thesis beyond the context of mixed mode assembly, and even beyond the vehicle industry. How to present components and or information, does not necessarily need to be applied within mixed mode assembly but can also support an environment where the fewer components are displayed as well as situations where there are longer cycle times. Moreover, the factors that have been investigated in the vehicle industry can also be useful in other contexts, where for example a large number of components or material is presented at the same time and is perhaps combined with instructions.

8.2 Theoretical and practical contributions

The theoretical contribution in this thesis is focused on the investigation of common factors used in manufacturing as well as within usability. This resulted in common subject areas within manufacturing which could be related and also supported through usability and cognitive aspects (section 2.4, Table 2.5. Investigated factors and their relative resemblance). These so called main factors within manufacturing were of interest for further investigations and exploration of how they were handled in reality, hence considering literature against reality.

Main factors within manufacturing:

Tools & support tools
Product variants
Transfer of training
Workstation layout
Work instructions
Operators' way of working
Feedback
Information syntax

Additional practical contributions involve the results from the various studies, especially the experimental study, for which the aforementioned factors to a large extent formed the basis. Through this experimental study it was possible to conclude both benefits and drawbacks with many of the factors and combinations of factors. In order to provide a better understanding of the concluding results, a few scenarios are established. Observations in the exploration studies (Chapter 3) showed that the assembly environments usually had a few already pre-set of factors such as thinking about using kitting instead of a material rack. These scenarios were consequently an attempt to illustrate possible situations that could occur in the production environment, where several factors in different combinations affect assemblers' performance and work environment and not only one isolated factor at a time. Therefore, based on these factors, a few scenarios could be created to enhance the understanding of what factors to change in order to improve the assembler's work environment and performance.

It is however important to point out that these scenarios primarily were based upon the various studies performed in this research and therefore should be taken as guidelines or directions rather than a state of fact.

In the following set-up times, perceived workload as well as comments about the implementation impact in production systems were summarised and assessed. Here assembly time and workload were assessed as low (**green**), medium (**yellow**) and high (**red**) (Table 8.1). Low-high assembly time and perceived workload ratings were based on the average ratings of each set-up from the experimental study.

Table 8.1. An overview of different set-ups, involving the pre-set of component variants, where high assembly time (s) > 235 and low < 210, and high perceived workload ratings > 25 and low < 18

Set up	Material presentation	Information presentation	Assembly time		Perceived workload		Implementation impact
			Variants	No variants	Variants	No variants	
1	Material rack	Text & nr.	High	High	High	High	Low cost, (lowest effort)
2	Unstructured kit	Text & nr.	Low	Medium	Medium	Low	Relatively low cost, pre-picking
3	Structured kit	Text & nr.	Medium	Low	Medium	Medium	High cost, pre picking and pre-sorting
4	Material rack	Photographs	High	High	Medium	High	Low cost
5	Unstructured kit	Photographs	Medium	Low	Medium	Medium	Relatively low cost, pre-picking
6	Structured kit	Photographs	Low	Low	Low	Low	High cost, pre picking and pre-sorting, highest effort

The different set-ups can be further evaluated regarding their capacity to increase productivity (assembly time) and decrease perceived workload using possible scenarios:

- When situated in mixed mode assembly, products with component variants will generate longer assembly times, and thus an uneven flow leading to bottleneck situations. It is therefore necessary to consider how to handle product variants in the best possible way.

- The exploration studies (Chapter 3) showed that a relatively common scenario within a mixed mode assembly environment was to go from the use of a material rack (i.e. continuous supply) to the use of kitting instead. As previously stated this could be for a number of reasons, for instance an increased number of product variants in the production system. Moreover, as mentioned earlier using a material rack combined with text & number instructions is not good, and being provided with photograph instructions instead does not improve the situation. It can be argued that it is cheaper to invest in good instructions rather than a new material supply system. But a new supply system improves quality, productivity and workload even more. Good work instructions can also to some extent be difficult to develop and be time consuming.

- Unstructured kits can lead to better productivity and reduced perceived workload (compared to a material rack) although they are perhaps not as good as using a structured kit, they most likely bring a lower cost, such as for instance man-hour consumption and space requirements (Hanson & Brolin, 2013). A larger company with a large production system can afford to invest in a structured kitting system along with a support system for the pre-sorting and pre-picking. But a smaller company with a small-scale production might not be able to afford such costs or even have the need. Instead using an unstructured kit, which might not cost as much but still provides better performance compared to using a material rack, may be good enough. Altogether, some companies benefit from using unstructured kits and some from using structured kits and it is difficult to favour one over the other. Perhaps, making a conscious choice at all, is a step forward. There seems to at least be certain aspects that may influence the choice between unstructured or structured kits: *the complexity of the product and the design of the components.*

- In general, using a structured kit needs to be combined with photographs in order to be favourable, otherwise it is only as good as an unstructured kit.

8.3 Future work

Although this thesis has dealt with various studies, both within in real assembly environment and in a laboratory setting, it can still be hard to make generalisations especially regarding the experimental study. Although field studies are expensive and often involve considerable effort, in comparison to many laboratory studies, recommendations for further work are to investigate the findings from this thesis further in the field. This includes for instance the study of a possible limit for the number of components to put in a kitting box. This might be a greater concern when using an unstructured kit, since this kit involves a high risk of searching for components in the box. It is also an issue because the assembly personnel in the case studies perceived that the time required to pick each component in preparing the kits exceeded the time saved on the assembly line. This would add complexity to the question of finding the magic number of components to put in the kits. While discussing the limit of components in the kits, it is also interesting to further study the use of similar components in the kits such as screws or bolts, since this would also add complexity, especially when using an unstructured kit. In the observation studies, it was clear that most workstations contained separate boxes for screws and bolts, regardless of what supply system that were used (i.e. they were not included in the kit), as they were the most used components and therefore needed to be kept near the workstation. It might also be an advantage to not put them in the kitting boxes, since it could lead to difficulties in distinguishing them particularly if there are large numbers. This further adds the question of how much complexity a kit can handle. It might be possible to say that a structured kit can handle more complexity, but this would most definitely also lead to higher cost in terms of, for instance, preparation, i.e. pre-sorting and pre-picking.

This further leads to another interesting issue of what costs are involved when using a kit, especially evaluating the difference in cost between the use of unstructured and structured kits. As this research exclusively evaluated the use of kitting in a laboratory setting it thereby lacked validity regarding cost, it would be interesting to evaluate this difference in a field study which would then also naturally include costs in the production system. Judging from the findings found in this research it might be possible to say that using a structured kit would increase production costs, whereas an unstructured kit which could function almost equally well but perhaps lead to lower costs, especially if it included photograph instructions.

Further investigation of how information should be presented to the assembler is also needed. This research investigated usability principles that were included in the work instructions, where the choice of work instructions was to use photographs. However, the choice of what instructions to use is a very wide subject as it for instance depends on what information is to be conveyed. In this research, photographs were used as a contrast to the traditional text & number instructions. However, as already mentioned, photographs might be subject to issues related to perception of information. Further findings in this thesis, can be related to usability (Chapter 2) which suggest it would be useful to additionally investigate the use of colours in the instructions as well as simpler sketches involving mainly the contours of components. In addition, it would also be interesting to investigate how the use of tactile and haptic feedback could be included in support systems which would for instance enhance the navigation and the user control of the system (Nielsen, 1993), which was one of the main factors found in the literature review (Chapter 2). This could then be used as support to the picking operator but also to enhance certain features of the components themselves.

This leads to another interesting issue of to what degree the components themselves provide enough information to include an assembly instruction. In the consumer industry products are often designed to be intuitive in order for the consumer to understand the usage of the product immediately. For the automotive industry, viewing the assembly operator as the end-user of certain components could be of interest and lead to investigations as to how features of components can be designed in order to better fit the assembly “puzzle”.

Moreover, as this thesis strived to investigate cognitive aspects that affect human performance in manual assembly, further investigation of how to measure cognitive load is needed. Although, this thesis used the NASA TLX workload rating, in order to assess the perceived workload of the subjects in the experimental study along with a qualitative questionnaire, this is still to some extent subjectively assessed. In the experimental study, the subjects heart rate variability (HRV) were also measured, using a polar watch (RS800x) attached to one of the researchers wrist, which in turn was connected to a sensor attached on a chest strap situated around the subject's chest, which was previously mentioned (section 5.4). HRV is the variation of beat to beat intervals, also known as R-R intervals, and indicates the fluctuations of heart rate around an average heart rate. This measurement was interesting since several studies have been able to link measures of HRV to prediction of work stress and other health factors (Kleiger et al., 1987, Chandola et al., 2008). There are, however, divided opinions about the measurement of HRV and if it can be considered a valid method (Nickel & Nachreiner, 2003, Paas et al., 2003). There are also several studies that have used this method and found connections to cognitive or mental load (Orsila et al., 2008). However, the analysis of this measurement was difficult since it was inconsistent in measuring performance, due to a number of reasons. For instance, the chest strap did not fit everyone, (perhaps designed for men as several small women had troubles with making the strap stay up), which resulted in lack of data for several subjects. Further problems were that the sensor range, between the watch and the strap, was too narrow, meaning that if the researcher went too far away from the subject gaps occurred in the data. Since this method was perhaps not the best measurement to use in this laboratory setting, it would be interesting to further investigate possible objective physiological techniques, such as:

- Skin conductance, which has been shown to be a reliable tool in evaluating mental load. One example is the study by Mehler et al. (2009), which focused on using heart rate and skin conductance (sweat gland activity) as primary measures of interest when studying mental workload in a simulated driving environment. The drivers were equipped with non-polarising, low-impedance gold-plated electrodes that allowed electro-dermal recording and the sensors were placed on the underside of the middle fingers of the non-dominant hand. The results of the study revealed a significant main effect of task level that appears on the physiological measures and skin conductance level. The authors state that this study illustrates that skin conductance level can provide an indication of change in workload (Mehler et al., 2009).

- Eye tracking methods have in recent years been used in assessing mental workload. This technology is usually based on video recordings of the eye in real time from cameras that are located on a headband or on a screen that is positioned in front of the subject (Di Stasi et al., 2011). Eye tracking methods introduce three potential sources of information: blinking (rate and duration), eye movements, and pupil size.

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APPENDIX 1: INSTRUCTIONS TO SUBJECTS

- The experiment aims at measuring the perceived workload.
- The experiment will approximately take one hour, including receiving instructions, practise, assembling, rating the workload and answer the questionnaire.
- The experiment consists of assembling twelve pedal cars of varying kind. Three factors will vary to be able to measure the workload: representation format on instructions, material presentation and the number of variants on different pedal cars.
- To get started, you get to practise on three pedal cars before the experiment starts.
- After the experiment, you are required to answer a questionnaire, it is important that you take the time to answer this properly.
- The experiment will also be video recorded.
- All information about the subjects will be kept confidentially, only members of the research team will have access to the video recordings.

APPENDIX 2: QUESTIONNAIRE, ASSESSING WORKLOAD

(Translated from Swedish)

Age: ____________

☐ Female ☐ Male

What kind of previous experience of assembly work do you have?

How long experience regarding assembly work do you have?

☐ 0 – 1 year ☐ 1 – 3 years ☐ 3 – 5 years ☐ 5 – 7 years ☐ 7 years or more

To what degree did the instruction format affected the difficulty of the assembly operation?

Not at all Affected much

In what way did it affect the assembly operation? (If not at all, please go to next question)

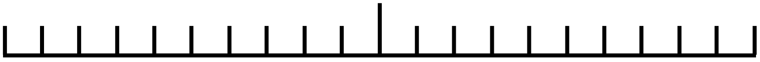
To what degree did the material presentation affected the difficulty of the assembly operation?

Not at all Affected much

In what way did it affect the assembly operation? (If not at all, please go to next question)

To what degree did the difficulty of the assembly operation get affected by that you had to assemble different variants of the pedal car?

Not at all Affected much



In what way did it affect the assembly operation? (If not at all, please go to next question)

What form of instruction did you perceive as the easiest? Motivate!

What form of instruction did you perceive as the hardest? Motivate!

Other comments:

Thank you for your participation!