CHALMERS

Evaluating complexity in manual assembly - Identification of factors influencing quality deficiencies and related costs

An evaluation of assembly complexity in relation to the Robust Index tool at Volvo Cars Corporation

Master of Science Thesis

ANDRÉAS BERGSTRÖM
FREDRIK KARLSSON

Department of Product and Production Development
Division of Production Systems
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2013

MASTER'S THESIS

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ANDRÉAS BERGSTRÖM
FREDRIK KARLSSON

Supervisors:
Ann-Christine Falck, Chalmers University of Technology
Alejandro Vega Galvez, Volvo Car Corporation

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Department of Product and Production development
Division of Production Systems
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

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ABSTRACT

In a recent study, Falck et al. (2012c), complex assembly tasks have shown to result in higher action costs. The same study shows that in order to increase both efficiency and quality, assemblies at high complexity level shall not be accepted.

At Volvo Car Corporation (VCC), a tool called Robust Index Matrix is used to evaluate the robustness of a manufacturing process (Lundell and Nagarajan, 2012).

The purpose of this study has been to investigate potential relations between assembly complexity and Robust Index (RI) to give suggestions to improvements of RI, which could facilitate the prediction of quality deficiencies in early development phases of new car models. This was performed by investigating and answering following research questions:

- *To what extent can the complexity method developed by Falck et al. (2012c) be used to predict the quality outcome and related costs regarding manual assembly operations at VCC?*
- *To what extent does the RI tool consider the complexity factors?*
- *Which complexity factors have major impact on the quality outcome and costs of quality deficiencies at VCC?*

The analyses in this thesis conclude that the complexity evaluation method cannot be used to predict quality outcome and related costs in manual assembly operations at VCC. On the other hand, this conclusion differs from previous studies (Falck et al., 2012c). Therefore, further research is necessary to fully answer the first research question.

In order to answer the second research question, a relation analysis was performed. This analysis shows that almost all complexity factors are included in RI to some extent. The relations between the complexity factors and the RI requirements have been investigated, but there might be aspects that are not considered, as there are no clear definitions of the RI requirements. To conclude, further studies of the RI requirements are needed to fully answer the second research question.

For the third research question, it is concluded that complexity factors: 5 - Resources, 8 - precision, 11 - Adjustments and 12 - Geometric surroundings indicate to have major effect on quality deficiencies. For costs of quality deficiencies, complexity factor 11 - Adjustments indicates to have a major effect.

Keywords: Complexity, Quality, Manual assembly, Robust Index, Quality deficiencies

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ABBREVIATIONS

VCC = Volvo Car Corporation

QDLS = Quality Deficiency Logging System

RI = Robust Index

RIM = Robust Index Matrix

CAI = Concept Assembly Instruction

TQM = Total Quality Management

DOE = Design of experiment

OAI = Operator Assembly Instruction

DPTO = Defects Per Thousand Opportunity

AIM = Affinity Interrelationship Method

SDA-M = System Decision Approval – Manufacturing

GPDS = Global Product Development System

RME = Resident Manufacturing Engineer

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1. INTRODUCTION

This section introduces the thesis work by presenting the background of the project. Thereafter the problem is described and the purpose and goals are stated. This is followed by the scope of the project which describes what will not be included the report.

1.1 Background

Globalization has changed the marketplace from being the sellers' market to becoming the buyers' market (Zaeh et al., 2009). Traditional mass production systems, with dedicated assembly lines where a limited number of product models are produced in large quantity, have been redesigned to focus more on the will and needs of customers (Zaeh et al., 2009). The customers demand customized products at mass production prices, and therefore the modern assembly systems must be robust, flexible, changeable, and at the same time achieve mass production quality and productivity (Zhu et al., 2008). To be effective in this new environment, analytical systems and tools must be used to integrate manufacturing technologies with the capabilities of human workers, in order to evaluate and increase the total performance (ElMaraghy, 2004).

Several Swedish and international studies of manual assembly in manufacturing industries show clear relations between ergonomic conditions and the output of assembly quality (Falck et al., 2010, 2012c) (Hickney, 1994). Manual assembly work, performed in bad ergonomic conditions, is related to an increased amount of quality deficiencies. Other factors that might relate to this and have a substantial impact on the product quality have been identified during the analysis of ergonomics and quality in recent studies (Falck et al., 2010). The relation between assembly complexity and assembly robustness is of great interest to investigate further, together with possibilities to connect assembly complexity with quality deficiencies and quality costs.

Studies show that half of an employee's day is spent either away from the workplace or in the workplace performing tasks that would be unnecessary if the quality of materials, tools, equipment and other process variables are improved (Fuller, 1985). Recent studies on complexity factors in manual assembly indicate that there is a significant correlation between assembly complexity, failures and costs (Falck et al., 2012c). The conclusions of this investigation were that in order to increase the efficiency and decrease action costs of faulty quality in manual assembly, high complexity factors shall be considered.

At Volvo Cars Corporation (VCC) in Torslanda Sweden, manual assembly is used extensively throughout the production system. To assure product quality, the company has developed a tool called the Robust Index Matrix (RIM). The RIM visualizes and calculates the robustness of different manufacturing processes (Lundell and Nagarajan, 2012). Each process is evaluated and given a Robust Index (RI). The RIM aims to help determine which system that has the highest robustness. This is done by visualizing the difference between the systems.

As the earlier performed investigation of complexity factors proved significant correlation between assembly-failures and costs (Falck et al., 2012c), there is a need of investigating how the RI considers the complexity factors. At the same time, VCC wants to improve their process of understanding how to predict quality errors in early development processes of manual assembly tasks.

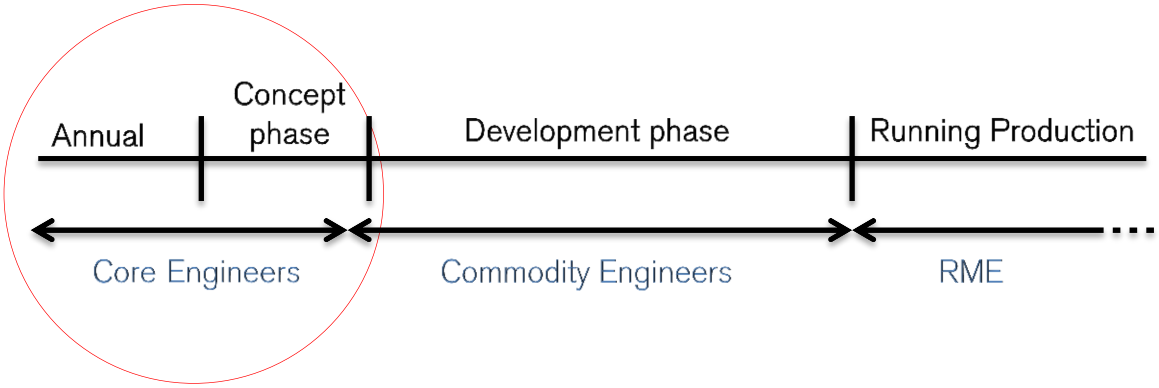


Figure 1- The different phases in the production development. The blue names state who are working in the different phases. This project mostly considered the concept phase.

Figure 1 illustrates different phases when launching a new car model or assembly process. Each project begins in the annual phase where information, knowledge and information from other projects are gained. Core engineers are responsible for the concept phase where concepts of assembly processes are developed. Decisions about which product system solutions to be chosen are also taken, and a RI evaluation is performed on the concept of the assembly process. Commodity engineers are responsible for the development phase, where the concepts are developed and prepared for running production. In the development phase, Concept Assembly Instructions (CAIs) (which are “agreements” between Product Development, Manufacturing Engineering and the Manufacturing Plant (Factory)) are established and handed over to the factory which the resident manufacturing engineers (RME) are responsible for. The agreement lays down instructions for assembly methods and the functional and constructional requirements that apply in order to provide a defined quality (Ortmon, 2007). Throughout the projects representatives from core-, commodity- and resident manufacturing engineers are present in all of the different phases (Lundell and Nagarajan, 2012).

1.2 Problem description

In VCC, Concept Assembly Instructions (CAIs) are developed in the development phase of new assembly processes, before these are introduced in running production. The CAIs act as a starting point when developing work instructions to be used by the shopfloor workers when performing the assembly operations. The intention with the complexity evaluation is to predict quality deficiencies early in the development of assembly processes and the CAIs were therefore considered suitable to examine and evaluate.

To predict the quality of products, influencing factors need to be identified which have an impact on the quality outcome. The intention of the RI tool is to capture these factors and to measure the robustness of the assembly processes. Since recent research has shown significant correlation between assembly complexity, failures and costs (Falck et al., 2012c), it was considered important by the Quality and Geometry department at VCC to examine how the complexity criteria were taken into account at VCC and to see if the RI tool captures all complexity factors in the study.

The results from the relation analysis of RI and the complexity factors are assumed to be used to enhance the RI tool. By improving the RI, the prediction of quality deficiencies at VCC are supposed to be improved which would probably result in further cost reductions.

1.3 Purpose and research questions

The purpose was to examine the relations between manual assembly complexity criteria (Falck et al., 2012a, c) and RI. Through this examination and relation analysis, suggestions for improvements of RI could be identified, which could facilitate the prediction of quality deficiencies in early development phases of new car models.

Hopefully, the outcome of this project will help manufacturing companies in their assembly processes to improve the quality of products and reduce quality related costs in manual assembly.

In order to fulfill the purpose of this study, there are three research questions to be answered.

- To what extent can the complexity method developed by Falck et al. (2012c) be used to predict the quality outcome and related costs regarding manual assembly operations at VCC?
- To what extent does the RI tool consider the complexity factors?
- Which complexity factors have major impact on the quality outcome and costs of quality deficiencies at VCC?

1.4 Delimitations

Due to that the purpose and the research questions are quite extensive there are some delimitations which have to be made:

This master thesis is limited to focus on 28 CAIs at VCC in Torslanda, Sweden.

The used definition of complexity in manual assembly is in line with complexity defined by Falck et al. (2012c).

Quality deficiencies discovered after the cars have left the factory are not taken into consideration.

1.5 Report structure

In this chapter the project has been introduced. The next chapter includes the theoretical framework which provides a general understanding of important subjects related to the project. This is followed by the methodology chapter describing the methods used to understand the concept of assembly complexity and what complexity factors that have a major impact on quality outcome. Furthermore, the relations between robust index and assembly complexity are evaluated.

Thereafter, the results from the used methodology are presented and analyzed. Finally, improvement suggestions of how robust index can be further developed in terms of complexity factors will be discussed.

2. THEORETICAL FRAMEWORK

This chapter includes the theory needed in order to understand the concepts of quality management, robust design methodology, assembly complexity, cost of poor quality, performance measurements systems and Concept Assembly Instructions

2.1 Quality management

Quality management is a philosophy that emphasizes quality improvement principles throughout organizations (Ahmada et al., 2003). The expression “quality”, used in industry, focuses on the savings and possible gains that organizations can realize if they eliminate deficiencies in their operations and produce products and services at the right quality level desired by their customers (Bergman and Klefsjö, 2010).

Bergman and Klefsjö (2010) see “Total Quality Management” (TQM as a holistic concept, where values, methodologies and tools are combined to attain higher customer satisfaction with less resource consumption. According to TQM, to be successful, companies must have a top management that is committed and that continuously and consistently work with quality issues. The improvement work shall rest on a culture, based on the values shown in the cornerstone model (see Figure 2) (Bergman and Klefsjö, 2010).

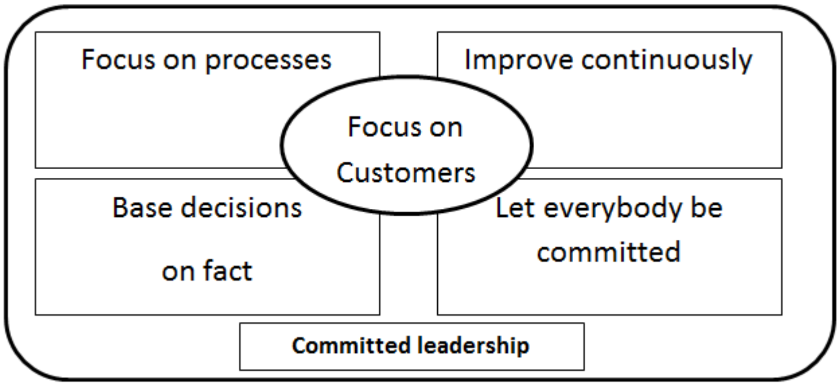


Figure 2 - The values, or cornerstones, which are the basis of Total Quality Management. The model has been named the cornerstone model.

The quality guru Edward Deming said that the only definition of quality that matters is the consumer’s definition (Deming, 2000). Another way of defining quality is described by Hoyle (2007) who defines quality as the degree to which a set of inherent characteristics fulfills a need or expectation that is stated, generally implied or obligatory. Phillip Crosby (1992) defines quality as “conformance to requirements”. This means that when speaking of quality it refers to the extent or degree certain requirements are met (Hoyle, 2007). To make quality measurable and to allow the beliefs that quality deficiencies are not necessary, one method is to develop and use quality requirements and count the number of requirements fulfilled or not

(Crosby, 1979). Quality experts agree that the customers' view of requirements is critically important.

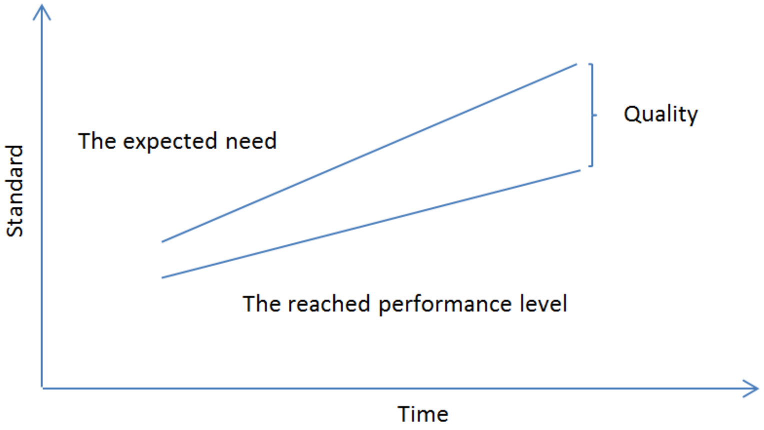


Figure 3 - The meaning of quality according to Hoyle (2007)

The diagram in Figure 3 (Hoyle, 2007) illustrates that customer needs, requirements and expectations are constantly changing. Performance needs to be constantly changing to keep pace with the customer needs and quality is the difference between the specified standard and the standard reached (variation). Quality management needs to enable organizations to close the gap between these variations (Hoyle, 2007).

2.2 Robust Design Methodology

Robust Design Methodology means to consider factors in the developmental phase of a product that are sensitive to variation (Arvidsson and Gremyr, 2008). As noise factors are disturbing the system and are hard to control, the objective of robust design is to design a product that is insensitive to these noise factors.

The objective of robust design is according to Arvidsson and Gremyr (2008) "*Robust Design Methodology means systematic efforts to achieve insensitivity to noise factors. These efforts are based on an awareness of variation and are applicable in all stages of product design.*" This is also emphasized in Phadke (1989) who states that applying robust design improves the development phase of a product in terms of quality and productivity so that high-quality products are produced to a low cost. By performing efforts towards robust design, the goal is to develop awareness of variation in product quality and create designs that are insensitive to noise and variation (Arvidsson and Gremyr, 2008) (Phadke, 1989).

2.2.1 Robust Index

The definition of Robust Design used at VCC is:
"*Design of a product /process so that its functionality is fulfilled the first time despite of disturbing factor influences.*" (Ortmon, 2007). The concept of robust design methodology is considered early in the development process of concepts, and is described in Figure 4 (Ortmon, 2007).

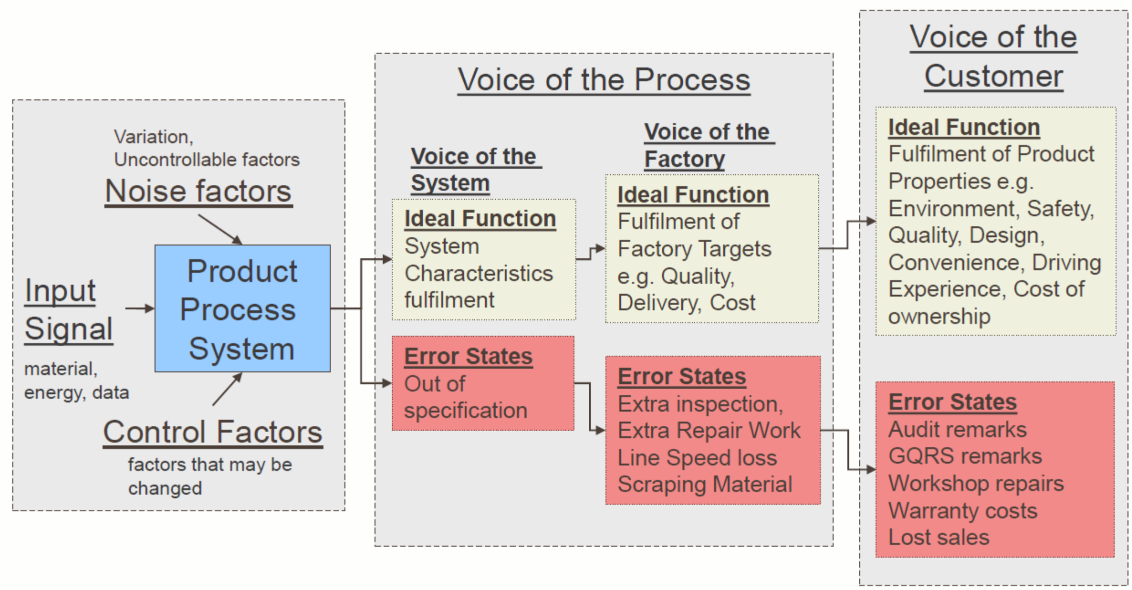


Figure 4 - A description of how VCC is working with the robust design process.

The Robust Index Matrix (RIM) tool was developed at Volvo cars in 2007. The RIM tool focuses on identifying the sensitivity of a system against predefined variations. The sensitivity varies from being a fully robust system to being an extensively un-robust system. The purpose of the tool is to evaluate the fulfillment of the product/process system within the three categories Voice of the System, Voice of the Factory and Voice of the Customer.

- Voice of the System category consists of four manufacturing characteristics which are material, machine, method and milieu. Requirements are set in advance for each of the 4M's and the RI value is dependent on how many of these requirements that are fulfilled, and will indicate how robust the product or process is (Lundell and Nagarajan, 2012). The requirements can be found in Appendix A - RI requirements.

- Voice of the Factory regards cost, quality and delivery aspects at the factory level.

- *Voice of the Customer* regards the customers' opinions with respect to environment, safety, convenience, perceived quality, driving experience etc. (Lundell and Nagarajan, 2012).

2.3 Design of Experiments

It is necessary to collect and treat data systematically to be able to base decisions on facts. Design of experiments (DOE) is a well-established and proven statistical method where well planned experiments provide early knowledge about factors that contribute to the outcome of a process (Bergman and Klefsjö, 2010). Figure 5 illustrates how DOE works, how the inputs affect the outputs so that one can achieve the desirable outputs by changing the inputs.

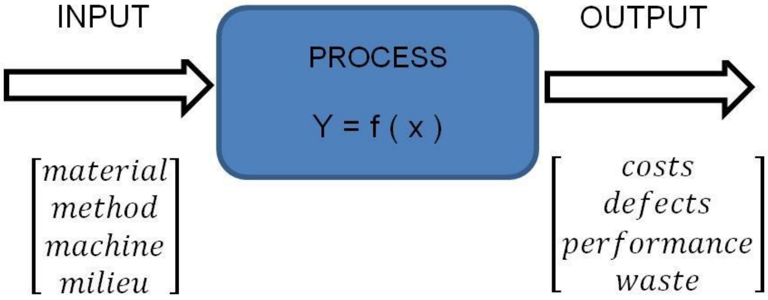


Figure 5 – The figure shows that inputs to a system affect the output. To achieve the desirable output, the input has to be changed.

There are levels of the design that range from the simplest factorial (which includes experiments to identify which factors are most critical) to full factorial (which enables identification of significant interactions between factors) (Winter, 2009).

2.3.1 Normal Probability Plot of factor effects

A main effect plot (Chambers et al., 1983) is a plot of the mean response values at each level of a design parameter or process variable (Antony, 2003). The plot helps to assess whether or not a data set is approximately normally distributed (NIST/SEMATECH, 2012). The plot can be used to compare the relative strength of the effects of different factors. When not knowing the uncertainties of the data set, the estimates from the distributions can be assumed to be close to a normal distribution (Bergman and Klefsjö, 2010).

The sign and magnitude of a main effect plot displays the following (Antony, 2003):

- The sign of a main effect indicates the direction of the effect, i.e. if the average response value increases or decreases.
- The magnitude provides information of the strength of the effect.

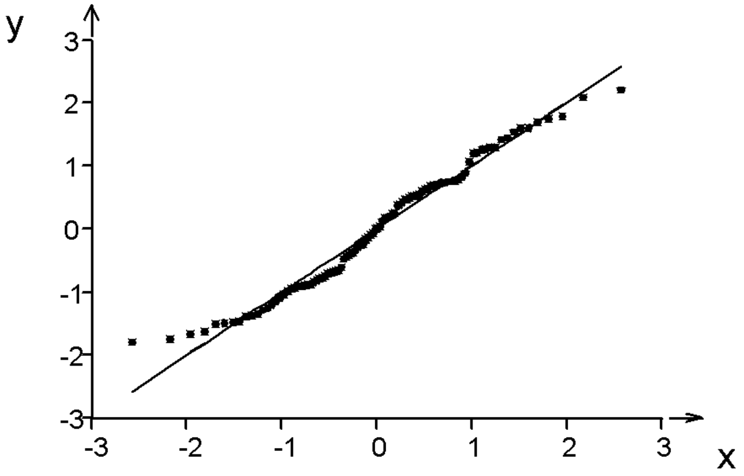


Figure 6 - A normal distributed data set compared to a linear pattern

The example plot (see Figure 6) illustrates that the normal distribution is a suitable model for this data set due to that the points follow a nearly linear pattern. The further the points vary from the line, the greater it differs from normality (Ryan and Joiner, 1976). When plotting the main effects against the cumulative distribution function (which states the probability that x is less than or equal to a value (NIST/SEMATECH, 2012)), factors that are not significant will appear close to the line meanwhile significant factors are points outside the line (Antony, 2003).

2.3.2 Main effect plots

A main effect plot (see Figure 7) provides information about what effect each factor has on the outcome when going from low ("-1", factor not being fulfilled) setting of the factor to high ("+1, factor being fulfilled) setting of the factor (NIST/SEMATECH, 2012).

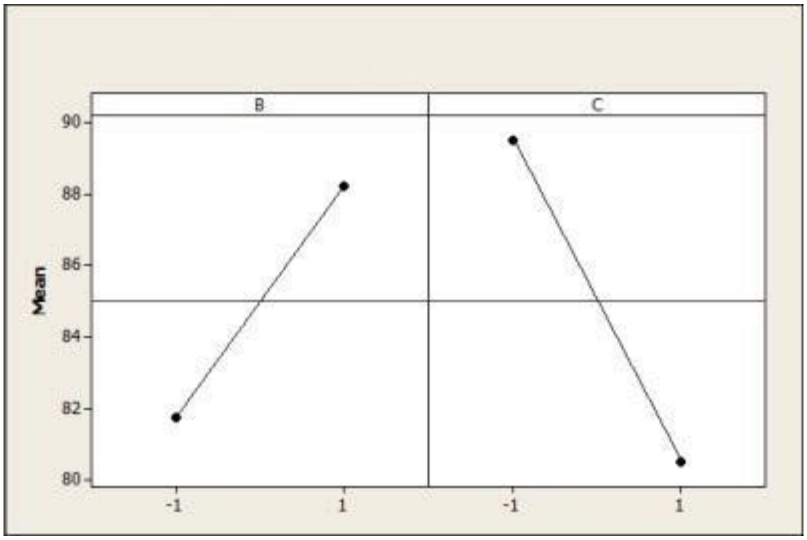


Figure 7 - An example of a design of experiment factor plot

If there are observations of the factors being both high and low, it is possible to calculate the effect of the factor (Bergman and Klefsjö, 2010). This is illustrated through the example given in Figure 7. The slope of the line indicates which factors are important. The factor with the steepest line is the most important factor (NIST/SEMATECH, 2012). A positive slope means an increased effect on the outcome while a negative slope indicates a decreased effect on the outcome.

2.3.3 Interaction effect matrix plots

The interaction effects matrix plot is an extension of the main effect plot and includes both main effects and 2-factor interactions.

When increasing the number of factors, the total number of interactions increases exponentially. The total number of possible interactions of all orders in a k-factor experiment = $2^k - 1 - k$. This means that when having 3 factors (k = 3), the number of possible interactions are: $2^3 - 1 - 3 = 8 - 1 - 3 = 4$. This also means that a slight increase by 4 factors (k = 7) distinctly increases the total number of possible interactions to: $2^7 - 1 - 7 = 128-1-7 = 120$. (NIST/SEMATECH, 2012).

The interaction plot is used to display the combinations between the different investigated factors. If two factors are predicted to have strong interactions, it is necessary calculate the effect of the interactions (Phadke, 1989).

To estimate the effects of interactions between factors, a *design matrix* can be used (illustrated in Table 1). The signs in the columns with interactions are gained through multiplication of the signs for the corresponding factors (Bergman and Klefsjö, 2010). The bottom row indicates the estimated effects. The interaction effect between A and B is estimated as:

$$\mathrm{e_{AB}} = \frac{1}{4}(\mathrm{y_1} - \mathrm{y_2} - \mathrm{y_3} + \mathrm{y_4} + \mathrm{y_5} - \mathrm{y_6} - \mathrm{y_7} + \mathrm{y_8})$$

Table 1- The design matrix for experiments of three factors combined with the results (Output) from 8 runs. The estimated effects are shown at the bottom of the table.

Run no	A	B	C	AB	AC	BC	ABC	Output
1	-1	-1	-1	+1	+1	+1	-1	y1
2	1	-1	-1	-1	-1	+1	+1	y2
3	-1	1	-1	-1	+1	-1	+1	y3
4	1	1	-1	+1	-1	-1	-1	y4
5	-1	-1	+1	+1	-1	-1	+1	y5
6	1	-1	+1	-1	+1	-1	-1	y6
7	-1	1	+1	-1	-1	+1	-1	y7
8	1	1	+1	+1	+1	+1	+1	y8
Effect	e_{A}	e_{B}	e_{C}	e_{AB}	e_{AC}	e_{BC}	$\mathrm{e}_{\mathrm{ABC}}$	

In Table 1, an example of an interaction effect matrix, with three factors, is showing what effect the interactions between them have. The effect of an interaction between two or more factors can be analyzed in the same way as for the effect of a single factor. A steep line indicates that the interaction between the corresponding factors have a high impact on the effect.

2.4 Assembly complexity

Assembly is the process of putting manufactured parts together and making products complete. This process is crucial for the cost and quality performance of a company (Zhu et al., 2008). There are several aspects that contribute to defects in a producing company and complexity is a root source of defects, since it increases deficiencies and variation defects. Complexity is also the least understood source of defects due to the difficulty of defining relative measures of complexity (Hickney, 1994).

The concept of assembly complexity involves several types of aspects that need to be considered. The relation between complexity and product variation has been studied by (Zhu et al., 2008). Mixed- model assembly is described by Zhu et al. (2008) as a flow line system that enables to handle increased variety. The complexity in this kind of system concerns all choices that the assembly operator can make and the risk of defects due to these choices (Zhu et al., 2008). According to Rekiek et al. (2000), in a typical automobile assembly plant, each different car model can reach ten thousands of combinations of build options. This amount of variants makes the designing process and operation of planning of the assembly systems crucial. Therefore, it is needed to organize the production and assembly systems to allow a high product variety with good quality and productivity (Falck and Rosenqvist, 2012a).

Two elements to take into consideration in a man- and machine environment are physical and cognitive human performance models. The physical human performance involves ergonomic analysis and control theory, which address how people interact with machinery and how the user interface should be designed (ElMaraghy and Urbanic, 2004). In a study by Falck and Rosenqvist (2012b) that regards physical human performance, the conclusions are that the ergonomics impact is of great importance. To increase assembly efficiency and quality, assembly at high physical load level and high complexity level should not be accepted. The cognitive human performance deals with how people perceive the surroundings, and how humans react, think and plan (ElMaraghy and Urbanic, 2004). Understanding the cognitive process involved in manual assembly is essential for predicting the worker's task performance (Zaeh et al., 2009).

2.5 Cost of Poor Quality

As the focus in many businesses today is on satisfying external customers, systems or systematic methods to calculate the cost of poor quality are invaluable (Harrington, 1999). The concept "*cost of poor quality*" is something that can be applied to every business area and is described as the cost that is related to quality issues (Schiffauerova and Thomson, 2006). When talking about cost of poor quality, the saved costs of not having poor quality products motivate companies to change the way they think about quality (Harrington, 1999).

There are several ways of defining the cost of poor quality. Sörqvist (1998) expresses in his case studies that one company defines poor quality as "*the total costs which are caused by deficiencies in our processes, goods and services*". Another company mentioned in Sörqvist (1998) considers "*those costs which would disappear if the company's products and processes were perfect*". This means that reduced income from less sold products due to quality problems (because of not satisfied customers) are not taken into consideration.

According to Schiffauerova and Thomson (2006), who have summarized and reviewed several cost of poor quality models, companies are calculating cost of poor quality as preventional, appraisal and failure costs (called the P-A-F model). This means that cost of poor quality includes more than only the direct costs of a new material, plus the cost of additional assembly time. Even though it is relatively easy to calculate the visible and measurable costs, such as scrap, there are more costs to consider like lost sales etcetera (Schiffauerova and Thomson, 2006). Feigenbaum (2004) describes the three types of costs in the P-A-F model, in this way:

- Preventional costs, which mean costs of activities which are aimed at preventing defects that occurs during the development, production, storage and transport of a product. The costs relate to quality planning in the concept phase, before the production start.

- Appraisal costs meaning costs of testing and inspecting products to assure the quality.

- Failure costs, which include internal costs, that relate to scrap and reprocessing, and external costs that are the costs of defects found after shipment to the buyer or consumer.

2.6 Performance measurement systems

Organizations achieve their goals by satisfying their customers with greater efficiency and effectiveness than their competitors (Kotler, 1984). According to Neely et al. (1994), a performance measurement system can be defined as the set of metrics used to quantify goals in terms of both the efficiency and effectiveness of actions. Performance measurement systems are used to work continuously with improvements to reach these goals. The measurement system can be observed in three different levels which are individual performance measures, the set of performance measures and the relation between the performance measurement system and its surrounding environment (Neely et al., 2005), see Figure 8.

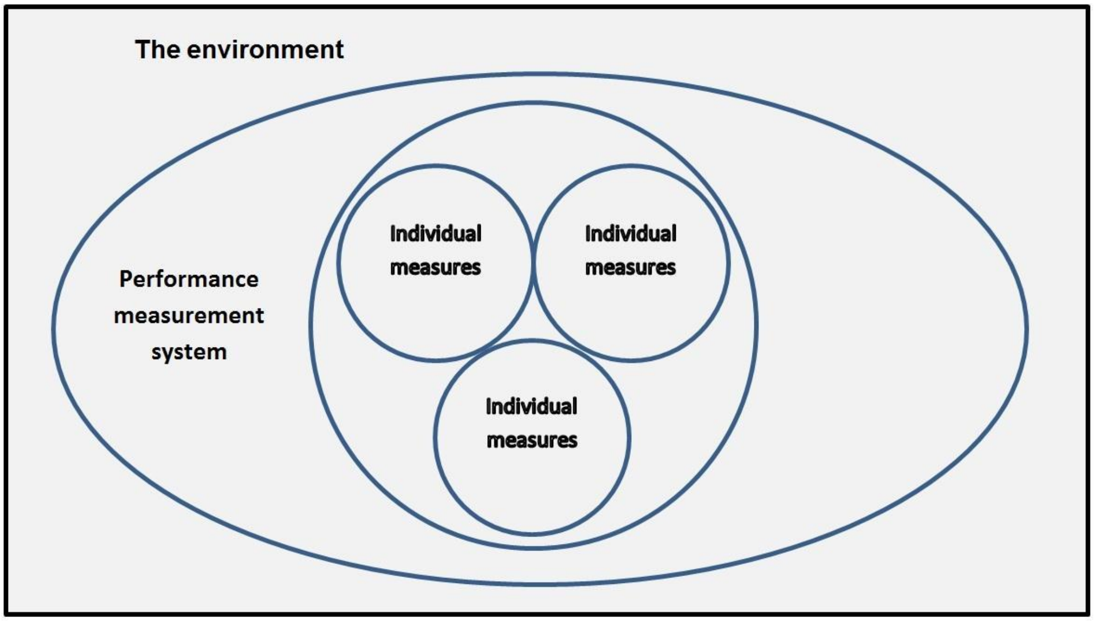


Figure 8 - Example of how to design a performance measurement system according to Neely et al. (2005)

The performance measurement system, together with the individual measures shall reinforce the firms overall strategies and match the organizations culture. According to Neely et al. (2005), it is important to have as orthogonal individual measures as possible, know what they are used for and how much they cost and what they provide.

Another way of measuring performance is described by Kaplan and Norton (1992) who developed a performance measurement framework called the "Balanced scorecard" (Figure 9). The intention of the Balanced scorecard framework is to provide managers with information of how the company look at their shareholders (financial perspective), what the company should focus on (internal business perspective), how the customers perceive the company (customer perspective) and how the company shall work to continuously improve and create value (innovation learning perspective).

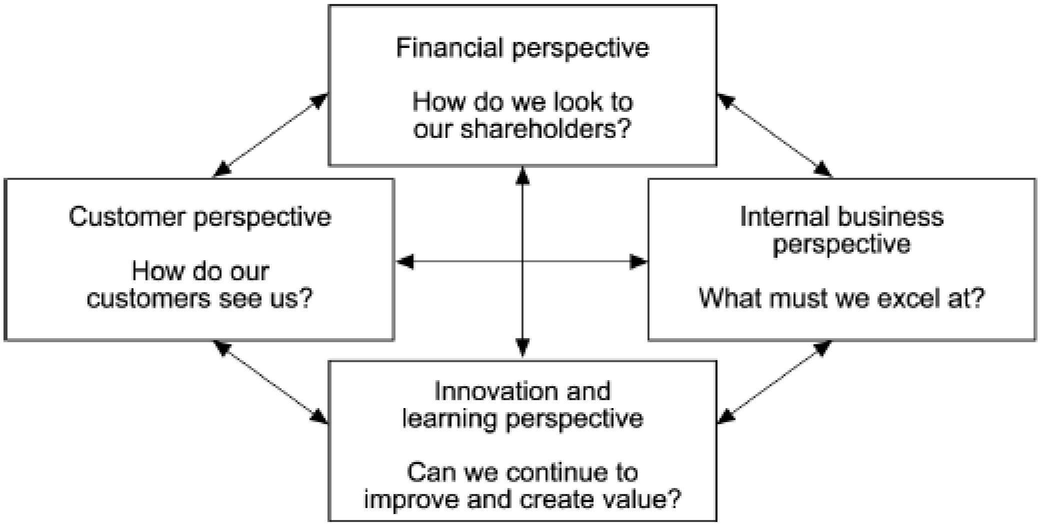


Figure 9 - The balanced scorecard as it was presented by Kaplan and Norton (1992)

Assessing criteria in the performance measurement system design has shown to be a good strategy to track the status of the company's performance. Globerson (1985) suggests a guideline of what such a set of criteria should consider:

- The definition of the criterion must be clear
- The performance criteria must be chosen from the company's objectives
- It should be possible to benchmark performance criteria with other organizations within the same business
- Ratio performance criteria are preferred to absolute number
- Representatives from all involved parties should be included in the development of criteria (customers, employees, managers etc.)
- Objective performance criteria are preferable to subjective ones

When implementing a performance measurement system, Franceschini, Galetto and Maisano (2007) describe in one of five steps how to check how well the performance system works. This test is called the SMART test and investigates if the system is:

S (Specific): The measurement shall be clearly defined so that it is not possible to misinterpret the meaning.

M (Measurable): Is the measurement quantified so that it is possible to measure and compare to anything else?

A (Attainable): The measurement shall be reasonable and it should be possible to achieve to the goal.

R (Realistic): The measurement shall be measuring the thing needed to be benchmarked and improved within the company.

T (Timely): Is it possible to achieve the goals within a reasonable time limit?

2.7 Concept Assembly Instructions

A Concept Assembly Instruction (CAI) is a description of how the assembly is going to be performed at VCC. Each CAI is agreed on between Research & Development, Manufacturing Engineering and the Manufacturing Plant (factory) (Eliasson, 2012). This is an instruction which is developed in the development phase of assembly processes.

Each CAI is described in order to be as efficient as possible while still achieving the correct quality, independent of car type and where it is manufactured (Eliasson, 2012). In general, a CAI contains following parts:

- Operation description - Indicate clearly what is going to be assembled or/and inspected
- Sequence of operations - In what sequence the operations are going to be performed
- Operation type and reference - what kind of operation is going to be done and where
- Multiple pictures - showing the surroundings of the assemblage
- Time setting of the elements- The estimated time it takes to perform the operations,

All parts of the CAI are written according to regulations, in order to be as consistent as possible between different CAIs (Eliasson, 2012). When a CAI is agreed on, the CAI could then be split and distributed on the shopfloor for optimization reasons, depending on the balance of the assembly line. This means that the actual assembly stations may consist of several CAI parts, which later are translated into Operator Assembly Instructions (OAI).

3. METHODOLOGY

In this chapter, the overall methodology used in the project is described. The carried out project can mainly be divided into two steps, see Figure 10. This chapter describes these two steps: Data collection and data analysis.

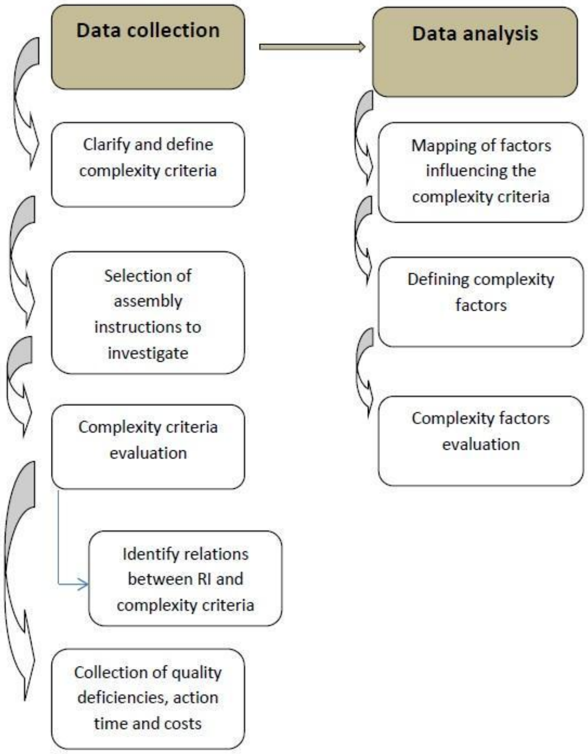


Figure 10- An overall description of the project methodology

3.1 Data collection methodology

Since the project is about examining the relation between assembly complexity criteria (Falck et al., 2012c) and RI, the data collection describes how the complexity criteria needed to be understood. Thereafter, there has been a selection of assembly instructions to evaluate with respect to assembly complexity. Furthermore in the data collection, relations between the complexity criteria and RI are identified in order to understand to what extent RI already considers the complexity criteria, and what improvements that can be made.

Quality deficiencies are also collected to understand what instructions cause most failures and scrap. To calculate the cost for the caused deficiencies, action time for deficiencies and costs of scrapped parts are collected and this section describes how this has been performed in the project.

3.1.1 Development of complexity definitions and complexity evaluation methods

In the study by Falck et al. (2012a), an evaluation of assembly complexity in manual assembly operations was performed. The complexity criteria were obtained through interviews of 64 design and manufacturing engineers with lengthy experience in five Swedish manufacturing companies. Based on their answers, 32 main complexity criteria were extracted -16 at low complexity and 16 at high assembly complexity. These criteria were then used to develop an assessment model that included five complexity levels for evaluation of degree of complexity.

To be able to consistently evaluate the complexity level of each CAIs, the 16 high assembly complexity criteria needed to be clearly defined and methods for evaluating if the complexity criteria were fulfilled or not needed to be established. This was also used to assure the reproducibility of the complexity evaluation method. Quantitative methods for evaluating the CAIs are preferable to use as far as possible, which alines with Globerson (1985). Although desirable, in some cases it was considered hard to get credible results from quantitative methods and qualitative methods were assessed to be a better option. The content in the definitions for each of the criteria was to the utmost quantified and checked through the SMART test (Franceschini, Galetto and Maisano, 2007) (See Appendix B – Definitions of complexity criteria)

When evaluating complexity, Zhu et al. (2008) describes that complexity concern all choices that an assembly operator can make and the risk of defects due to these choices. To consider complexity criteria that regard operators' choices during assembly, there have to be qualitative evaluations. For those reasons, qualitative evaluations were performed through interviews with experts responsible for the CAIs. The evaluation methods used for the complexity criteria can be found in Appendix B - Definitions of complexity criteria.

Since a CAI often contains more than one operation, it was enough with fulfillment of the complexity criteria in one of the operations, in order to make the complexity criteria fulfilled for the CAI. For example, one criterion used in the complexity criteria evaluation was headed "Soft and flexible materials". This criterion is considered high complex if the CAI contains any materials that are soft and flexible. Examples of materials used at VCC that are considered soft and flexible can be found in Appendix B - Definitions of complexity criteria. For a CAI to be evaluated as high complex, it is therefore enough that one operation involves any of the "soft and flexible materials".

3.1.2 Selection of instructions to investigate

To evaluate to what extent the complexity level of manual assembly operations impacts the quality outcome, an even spread of the complexity level (five levels between low and high complexity level, see Appendix G - Evaluation model for the Complexity criteria level) for the chosen CAIs were needed. Since no complexity evaluation had been made for the CAIs before, instead, instructions were chosen that had an equal spread in RI-values, representing both robust and un-robust assembly tasks.

The RI is evaluated for assembly processes and consists of several CAIs. To be able to compare the complexity evaluation with the RI, assembly processes containing one or a few CAIs were chosen. In this way it was easier to make a direct connection between the complexity evaluation and the RI value for that assembly process.

3.1.3 Complexity criteria evaluation

In some cases it is needed to evaluate the CAIs with qualitative methods, therefore experts of the assembly processes are needed to be contacted. The experts of the assembly processes are the core manufacturing engineers, which are responsible for the development of the concepts. The core manufacturing engineers are also responsible for the RI evaluations (See Appendix C – Contacted persons). Interviews with the core manufacturing engineers were held to clarify, and to get an evaluation for the qualitative complexity criteria. For some criteria also an ergonomics expert and a geometry expert were involved in the evaluation. The interviews were performed in person and in a semi-structured way with open-ended questions along with a free-flowing conversation to obtain the interviewees opinion on the subject (Hutchinson, and Wilson, 2006). A protocol in such semi-structured interviews serves as a guide (Flick, 2002), in which the interview is built but one that allows creativity and flexibility to ensure that each participant's story is fully uncovered (Knox, 2009). The scheduled time for the interviews varied between 30 minutes to one hour depending on how many CAIs that were going to be discussed. Answers from the interviewees were noted by one interviewer, while the other one was leading the interview and discussing the CAI. The list of questions used during these interviews is to be found in Appendix D - Interview questions (subjective evaluation of complexity criteria)

During the interviews with the core manufacturing engineers, the definitions of the different complexity criteria were discussed. The results from the interviews were then discussed with the founder of the criteria (Falck et al., 2012c) and agreed changes to the definitions of the complexity criteria definitions were implemented. E.g. one complexity criterion that was discussed with core manufacturing engineers is regarding "*Accuracy/Precision demanding*" (High complexity criterion 11, see Appendix B - Definitions of complexity criteria).

3.1.4 Relations between Robust Index and Complexity criteria

In order to evaluate to what extent the complexity criteria are included in RI, relations between RI requirements and complexity criteria were identified.

For each RI requirement, relations to complexity criteria were made. The relation analysis was performed together with a RI expert at VCC and the founder of the complexity criteria Falck et al. (2012c). Through these relations, an analysis of each RI value and the corresponding complexity criteria level for the CAIs can be done. One example of how to relate the RI-requirements to complexity criteria is shown in table 2.

Table 2 - Example table of relations between RI-requirements and Complexity criteria

RI-requirements	Complexity criteria

When relations between RI requirements and complexity criteria were identified, the core engineer responsible for the RI evaluation was asked, through an interview, why the evaluation is similar or differs from the complexity criteria evaluation. This indicates to what extent RI considers the complexity criteria.

The responsible core manufacturing engineers were contacted in advance for these interviews and the scheduled time for each interview was approximately one hour. When the core manufacturing engineers were contacted, it was said that it would be beneficial to invite also a commodity engineer.

3.1.5 Collection of quality deficiencies

When collecting quality deficiencies, failures occurring online, offline and scrap were retrospectively collected for model year 12 (week 20, 2011 - week 19, 2012). Furthermore, the costs of quality deficiencies were calculated.

The considered costs used in this study are costs that are directly related to manual assembly. Several aspects of the concept of cost of poor quality are thereby excluded.

The quality data is obtained from the assembly line at VCC in Torslanda. During the investigated time period, no new car models were introduced. Furthermore, the takt time was held stable which means there were no deviating changes in the CAIs. Also, many of the quality deficiencies were fixed online compared to previous years (when a major part of the quality deficiencies was fixed offline).

The failure rate data was collected from the logging quality database (QDLS) within VCC. QDLS is a system used in VCC to follow-up and give feedback on quality deficiencies to the assembly teams. Each team leader is responsible for reporting quality deficiencies that occurs in his/her team. Each quality deficiency that occurs is briefly described and stored as QDLS items. The quality deficiencies collected are caused during assembling of five different car models.

The QDLS items were related to the CAIs responsible for the failure. This was performed by sorting the list of quality deficiencies and by relating the QDLS item description to the CAI, where the part was assembled.

The number of cars produced differs between the different models. To keep track of quality deficiencies, VCC uses DPTO (number of failures produced per 1000 cars of the specific type during model year 12). This is to be able to compare how often one quality deficiency occurs compared to another.

The number of, and costs of scrapped parts and components were divided into each CAI. For each CAI, its consisting components were listed. This list was sent to the material coordinators who entered the total number of scrapped parts, during model year 12. The material coordinators also provided the cost for a new part.

The action time for solving errors occurring online was assumed to be 2.2 min (Falck, 2012c). For the errors occurring offline, teams responsible for solving problems offline in the assembly plant were asked. After collecting the problem solving time, an average action time was used to calculate the costs for doing the corrections.

3.2 Data Analysis methodology

This chapter describes how factors that are included in the complexity criteria evaluation are identified. These factors are thereafter defined and an evaluation method of the CAIs, with respect to these new complexity factors, is presented.

3.2.1 Mapping of factors influencing the complexity criteria

During the interviews with the core manufacturing engineers, all notes of the discussed complexity criteria were summarized. In order to understand what factors and how these factors are affecting the complexity criteria, key words from comments during the evaluations were grouped. This was done using the grounded theory method (Glaser, 1999). The grounded theory method is used to find patterns and connections between the criteria that are evaluated using qualitative methods. The aim is to identify how each complexity criterion relates to the other criteria, and to investigate if the criteria are equally important for the total complexity level. This way of clarifying the complexity criteria is similar to the Affinity Interrelationship Method (AIM) (Alänge, 2011) which makes it possible to identify dependence of different factors. The AIM tool is effective when working with complex issues and where there is a need of a shared understanding.

When evaluating the qualitative complexity criteria, the interviewees had the opportunity to freely talk about if the CAI fulfills a complexity criterion or not. This means that the interviewees might motivate their evaluations by using a factor that also affects another criterion. In such case, the interviewee is mixing two criteria, meaning the criteria become dependent of each other and thus are not independent. This constitutes the basis of what can be used in the analysis section (grounded theory), where all comments by the interviewees on a specific criterion are gathered and summarized.

In Table 3, an example of three criteria is visualized. Factors that are related are grouped by getting the same color. In this example, it is shown that several factors are represented in several criteria.

Table 3 - Illustration example of mapping of factors for three complexity criteria. In this example table, the yellow color represents ergonomic factors. The dark blue color is related to the category resources while the light blue color represents feedback.

Example 1	Example 2	Example 3
Long distances	High assemblies	Reference system/pins
Guiding systems	Fixtures	Sound signals
Visible operations	Light signals	Under-up work

When mapping the factors influencing each complexity criterion (see Table 3), it is possible to show the interrelation between the factors and complexity criterion. In this way, improvement suggestions of how to express and use the complexity criteria can be done. By doing this on a whiteboard, it is more obvious to see where the same keywords are represented in many criteria. Table 3 is an example of factors being represented in several complexity criteria. This means that the criteria have to be reformulated.

After the color coding of the different factors, the factors are sorted into categories representing what actually has been evaluated in the complexity evaluation. These categories become complexity factors, see *Table 4.*

Table 4 - Illustration example mapping of sorted complexity factors

Complexity factor 1	Complexity factor 2	Complexity factor 3
Long distances	Guiding systems	Light signals
High assemblies	Fixtures	Sound signals
Visible operations	Reference system/pins	
Under-up work		

3.2.2 Defining complexity factors and evaluating CAIs

As the evaluation of the complexity criteria could be sorted into complexity factors representing all the criteria, the different complexity factors had be specified according to the SMART test (Franceschini, Galetto and Maisano, 2007). The two last parts of the test (which tests if the factors are realistic and timely), are not included, due to that the two last parts need to be adapted to suit each company where the complexity evaluation is going to be performed.

The definitions of the factors were specified based on the SMART test (Franceschini, Galetto and Maisano, 2007), in the same procedure as in chapter 3.1.1.

The definitions of how to evaluate CAIs according to the complexity factors are to be found in Appendix E - Definitions of complexity factors.

With the assistance of the factor definitions (Appendix E- definitions of complexity factors) and the comments gained from the complexity criteria evaluation of the CAIs, the CAIs also were evaluated with respect to complexity factors.

4. RESULTS

This chapter summarizes the complexity criteria evaluation of the 28 CAIs which has been performed outgoing from the complexity criteria definitions (see Appendix B - Definitions of complexity criteria). The relations between the complexity criteria and RI are also presented.

Furthermore, the failure rate for each CAI together with cost calculations for correcting all quality deficiencies is provided.

4.1 Complexity criteria level of the Concept Assembly Instructions

The 16 complexity criteria have been evaluated for each of the 28 CAIs, see Appendix F - Complexity criteria evaluation of 28 CAIs. The criteria have been either considered as fulfilled (high complex) or not fulfilled (low complex). This have been done by using the developed definition and evaluation method, see Appendix B - Definitions of complexity criteria.

A total complexity evaluation of each CAI has been given using the "*evaluation model of assembly complexity"* developed by Falck et al. (2012c), see Appendix G - Evaluation model for the complexity criteria level. This indicates if the complexity level of each CAI is considered low, rather low, moderate, rather high or high.

Three CAIs were considered to be on a low assembly complexity level, one rather high and none of the CAIs were considered to be on a high assembly complexity level. The major part of the CAIs (24 of 28 CAIs) was considered to be on a moderate or rather low complexity level.

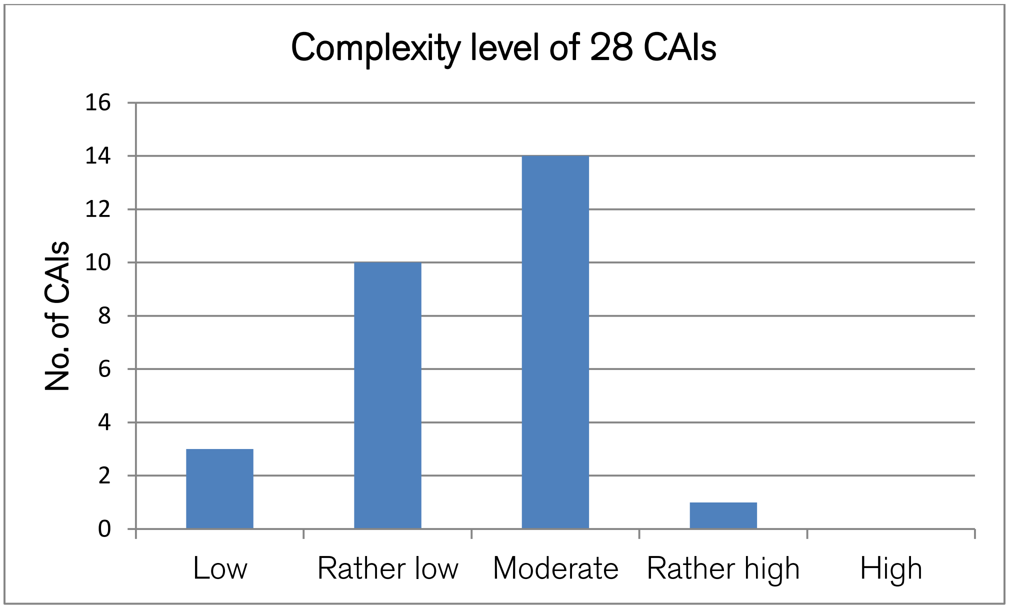


Figure 11 - Complexity level of the 28 CAIs

The information from the column chart (Figure 11) is also shown in Table 5 which indicates how many complexity criteria that are fulfilled to be represented in each complexity criteria level.

Table 5 - Summary of the complexity level for 28 CAIs

Complexity criteria Level	High Complexity criteria fulfilled	No. of CAIs (Assembly tasks)
High	15-16 (94-100%)	0
Rather High	12-14 (75-88%)	1
Moderate	8-11 (50-69%)	14
Rather low	4-7 (44-25%)	10
Low	0-3 (0-19%)	3
All		28

4.2 Relations between complexity criteria and RI requirements

In order to understand how the complexity criteria and the RI requirements are related, the relations were investigated. The founder of the complexity criteria and the Quality Engineer responsible for RI are giving their opinions, through interviews, of how the complexity criteria and RI requirements might be related. The results from the relation analysis are shown in Table 6.

Table 6 - Relations between high complexity criteria and RI requirements

RI requirements	Complexity criteria
Material	
K1:	15. Soft and flexible materials
K2:	
K3:	11. Accuracy/precision demanding
K4:	15. Soft and flexible materials
K5:	14. Need of in detail described work instructions
K6:	
K7:	
K8:	12. Need of adjustment
K9:	10. Visual inspection of fitting and tolerances, i.e. subjective assessment of the quality
K10:	
A1:	
A2:	9. Operations must be done in a certain order
A3:	6. Hidden operations
Method	
K1:	11. Accuracy/precision demanding & 4. No clear mounting position of parts and
K2:	5. Poor accessibility
K3:	
K4:	16. Lack of (immediate) feedback of properly done work, e.g. a click sound and/or
K5:	12. Need of adjustment
K6:	7. Poor ergonomics conditions implying risk of harmful impact on operators
K7:	
K8:	10. Visual inspection of fitting and tolerances, i.e. subjective assessment of the quality
A1:	
A2:	
Machine	
K1:	
K2:	
K3:	
K4:	
A1:	
Milieu	
K1:	
K2:	
K3:	
K4:	
A1:	
A2:	
A3:	

The complexity criteria are only related to RI requirements in the method and material sections. Complexity criteria 1, 2, 3, 8 and 13 were not possible to relate to any of the RI requirements. These five complexity criteria are:

- Different ways of doing the task
- Many individual details and part operations
- Time demanding operations
- Operator dependent operations requiring experience/knowledge to be properly done
- Geometric environment has a lot of variation (tolerances), i.e. level of fitting and adjustment vary between the products

This means that complexity seems to be considered in RI to some extent, but that RI includes more factors than the 16 complexity criteria cover.

4.3 Failure rate and costs related to each CAI

Each CAI has been related to number of quality deficiencies and the costs of quality deficiencies during model year 12. Both the number of quality deficiencies and the costs of quality deficiencies are divided into online or offline, depending on where they are corrected. Furthermore, the costs of scrapped parts for each CAI are shown (see Table 7).

Table 7 - Cost calculations for all assembly instructions

CAI number	DPTO	Number of quality deficiencies online	Online: Cost (SEK) 360 SEK/h	Number of quality deficiencies offline	Offline: Cost (SEK) 360 SEK/h	Number of scrapped parts	Cost of scrapped parts	Total Cost (SEK)	Total cost per produced car (SEK)
1	19,6721	264	3485	0	0	0	0	3485	0,26
2	69,481	4462	58898	23	1380	2	347	60626	0,94
3	40,5854	2196	28987	6	360	0	0	29347	0,54
4	0,5898	31	409	1	180	21	5813	6402	0,12
5	0,74424	31	409	0	0	9	3619	4028	0,10
6	2,58602	167	2204	0	0	0	0	2204	0,03
7	1,32424	69	911	3	360	0	0	1271	0,02
8	0,03678	2	26	0	0	0	0	26	0,00
9	0	0	0	0	0	7	189	189	0,00
10	10,105	770	10164	18	3660	51	6139	19963	0,26
11	63,0115	3411	45025	15	1572	72	3910	50507	0,93
12	18,0257	978	12910	0	0	1	15	12924	0,24
13	120,119	1609	21239	3	540	18	2489	24267	1,81
14	6,89912	538	7102	0	0	15	147904	155006	1,99
15	4,56126	214	2825	34	5790	30	12845	21460	0,39
16	0,77411	41	541	1	90	0	0	631	0,01
17	0,29491	23	304	0	0	24	507	811	0,01
18	1,56681	21	277	0	0	0	0	277	0,02
19	1,71603	23	304	0	0	0	0	304	0,02
20	16,0581	786	10375	6	420	78	407	11202	0,23
21	21,0852	1143	15088	1	60	180	9887	25035	0,46
22	17,8017	509	6719	1	60	40	1445	8224	0,29
23	0,88496	69	911	0	0	56	2023	2934	0,04
24	1,64166	127	1676	1	360	0	2091	4127	0,05
25	5,49961	333	4396	22	2340	44	6980	13715	0,21
26	2,08644	28	370	0	0	5	183	553	0,04
27	0,77459	41	541	9	2970	2	29	3540	0,05
28	0,07452	1	13	0	0	0	0	13	0,00

The table indicates that the total cost for quality deficiencies varies from 0 SEK to 2 SEK per produced car. The total costs of quality deficiencies have been divided into costs of quality deficiencies corrected online, costs of quality deficiencies corrected offline and costs of scrapped parts. The distribution of the total costs of quality deficiencies are shown in Figure 12.

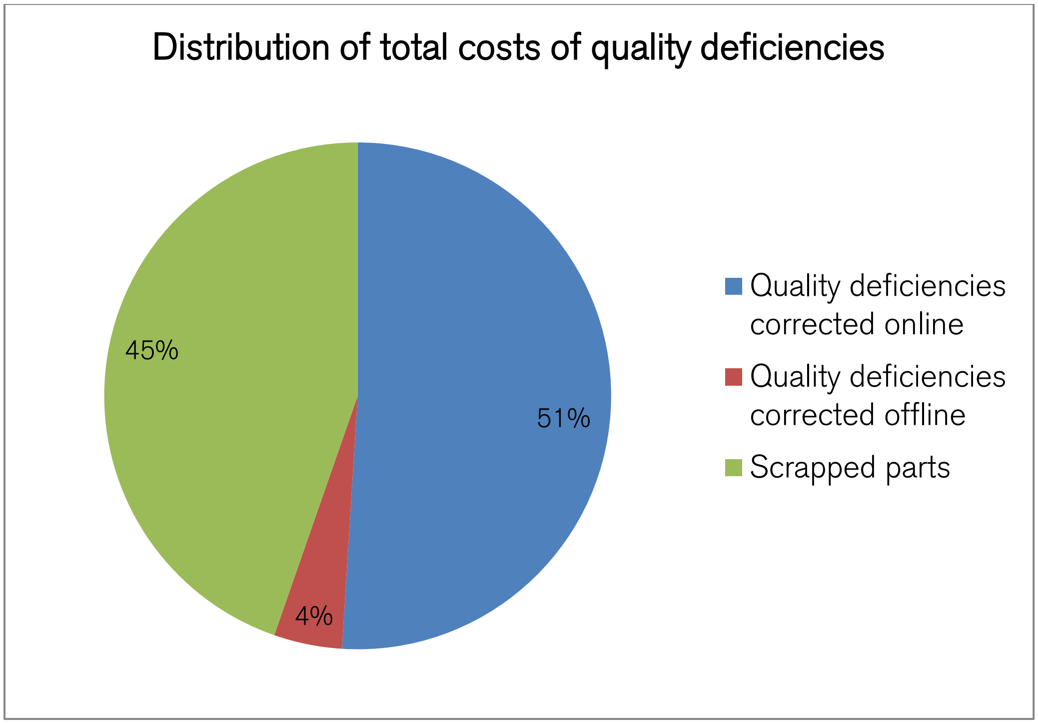


Figure 12 - Distribution of total costs of quality deficiencies

The pie chart in Figure 12 shows that 4 % of the total costs are related to costs of quality deficiencies corrected offline. Furthermore, 51 % of the total costs are related to costs of quality deficiencies corrected online and 45 % are related to cost of scrapped parts.

5. ANALYSIS OF RESULTS

This chapter analyzes how the complexity criteria and RI are evaluated, perceived and interpreted. This chapter further maps relations between complexity and RI, in order to decide to what extent RI includes the complexity criteria.

This chapter also includes an analysis of quality deficiencies that are compared between the CAIs. Besides, costs related to the CAIs were calculated. An analysis of the costs and quality deficiencies related to the complexity is then presented, which leads to identification of important factors to consider when predicting quality deficiencies.

5.1 Analysis of failure rate and costs related to complexity criteria level

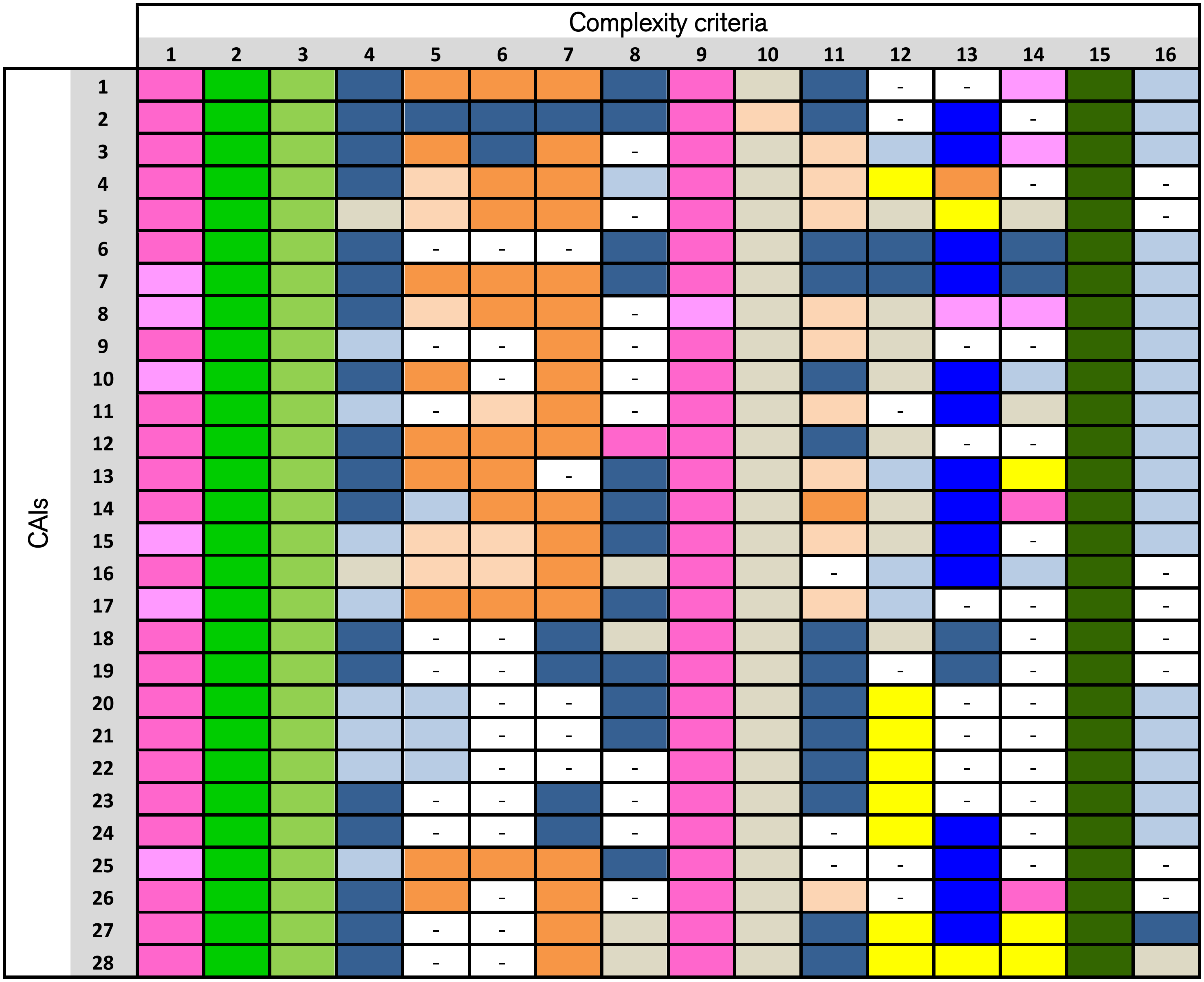
A correlation analysis and a statistical significance analysis were performed in Statistical Package for the Social Sciences software, a software for statistical analysis. Fisher (1935) asserts that a fixed number, for example 0.05 or 0.01, is to be set by experimenters to be referred to as a significance level to indicate if the test is significant.

The correlation analysis shows no correlation between the complexity criteria level and quality deficiencies (DPTO) (see Appendix H - Correlation analyses between complexity and quality deficiencies and complexity and costs of quality deficiencies). The results are significant at the 0,399 significance level and are therefore considered as not significant. The results from a correlation analysis showed either no correlation between the complexity criteria level and costs of quality deficiencies. The significance level from these results is at the 0,442 significance level which indicates that the results are not significant (see Appendix H - Correlation analyses between complexity and quality deficiencies and complexity and costs of quality deficiencies).

To sum up, the correlation analysis between the complexity evaluation and quality deficiencies did not show any significant result. No significant correlation could either be identified between the complexity evaluation and costs of quality deficiencies. Therefore, further analyses of how to interpret the different complexity criteria were required.

5.2 Perception of the complexity criteria

The results from the evaluation of the complexity criteria and how they are related is shown in Figure 13. Both quantitative and qualitative methods have been used (See Appendix F – Complexity criteria evaluations of 28 CAIs) and the results indicate that the criteria to a large extent depend on each other.



CAIs	Complexity criteria															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1												-	-			
2												-		-		
3								-								
4														-		-
5								-								-
6					-	-	-									
7																
8								-								
9					-	-		-					-	-		
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24					-	-		-			-			-		
25											-	-		-		-
26						-		-				-				-
27					-	-										
28					-	-										

Figure 13- Mapping of complexity factors affecting the criteria

During the interviews, the core manufacturing engineers were asked about how they interpret the complexity criteria defined by Falck et al. (2012c). The comments collected from the interviews (evaluating complexity criteria) indicate how the evaluation is performed. Figure 13, shows how comments with similar keywords are grouped and color coded. The figure shows that the same color appears under several of the complexity criteria. This indicates that the criteria are overlapping and that same judgments are used to evaluate several of the complexity criteria. Thus, it can be stated that the criteria are not independent.

5.3 Factors influencing the complexity criteria

To gain more independent factors, which are preferable according to Globerson (1985), the color coded comments are sorted in Figure 14. These comments are the results from the evaluation of the complexity criteria. After sorting the colors, 12 different categories (complexity factors) are identified.

These 12 complexity factors are defined using the SMART test. A complete definition of the complexity factors can be found in Appendix E - Definitions of complexity factors. The following complexity factors were identified:

- Assembly order
- How to assemble
- Individual details and part operations
- Time demanding
- Resources
- Feedback
- Ergonomics
- Precision
- Subjective assessment
- Soft and flexible materials
- Adjustments
- Geometric surroundings

These complexity factors (which are more independent than the complexity criteria) indicate what actually has been evaluated in the complexity criteria evaluation.

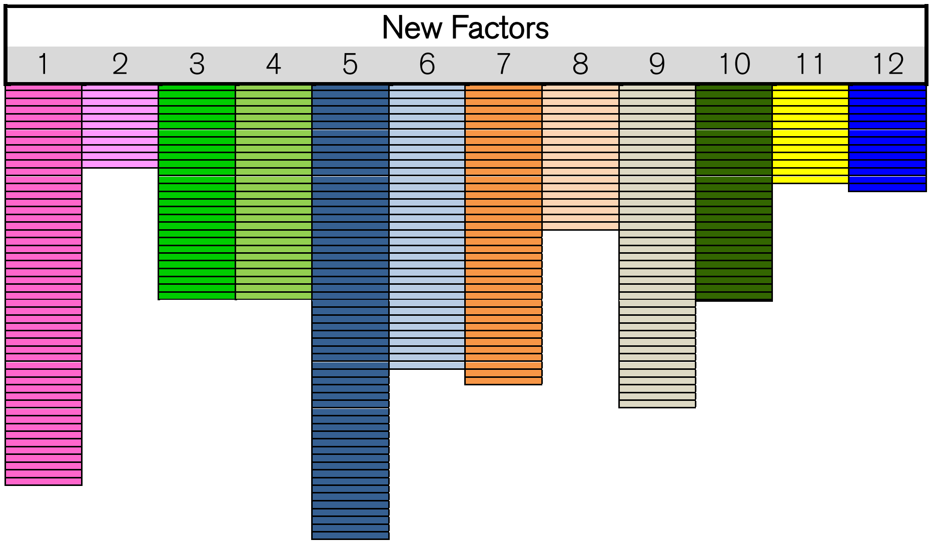

Figure 14- Complexity factors

The fact that the 16 complexity criteria not are independent means that if one complexity criterion is fulfilled, it is possible that another complexity criterion containing the same judgment automatically will be fulfilled. Therefore, the degree of complexity evaluated by using the evaluation model counting the number of complexity criteria fulfilled (Falck et al., 2012c) might give a misleading result. If the 16 complexity criteria are going to be used, an update of the used evaluation model shall be considered. As several other criteria might be fulfilled when one specific criterion is fulfilled, this criterion shall be valued lower.

5.4 Complexity factor levels of CAIs

The results from the evaluation of the CAIs with respect to the complexity factors are shown in Figure 15. The figure shows that 9 of the 28 CAIs had a rather low complexity level (only 0-4 of the 12 complexity factors were fulfilled) while the rest of the CAIs had a slightly higher complexity level (5-8 of the 12 complexity factors fulfilled). The CAI with the highest complexity factor level had 8 complexity factors fulfilled and none of the 28 evaluated CAIs had a complexity factor level between 9 and12.

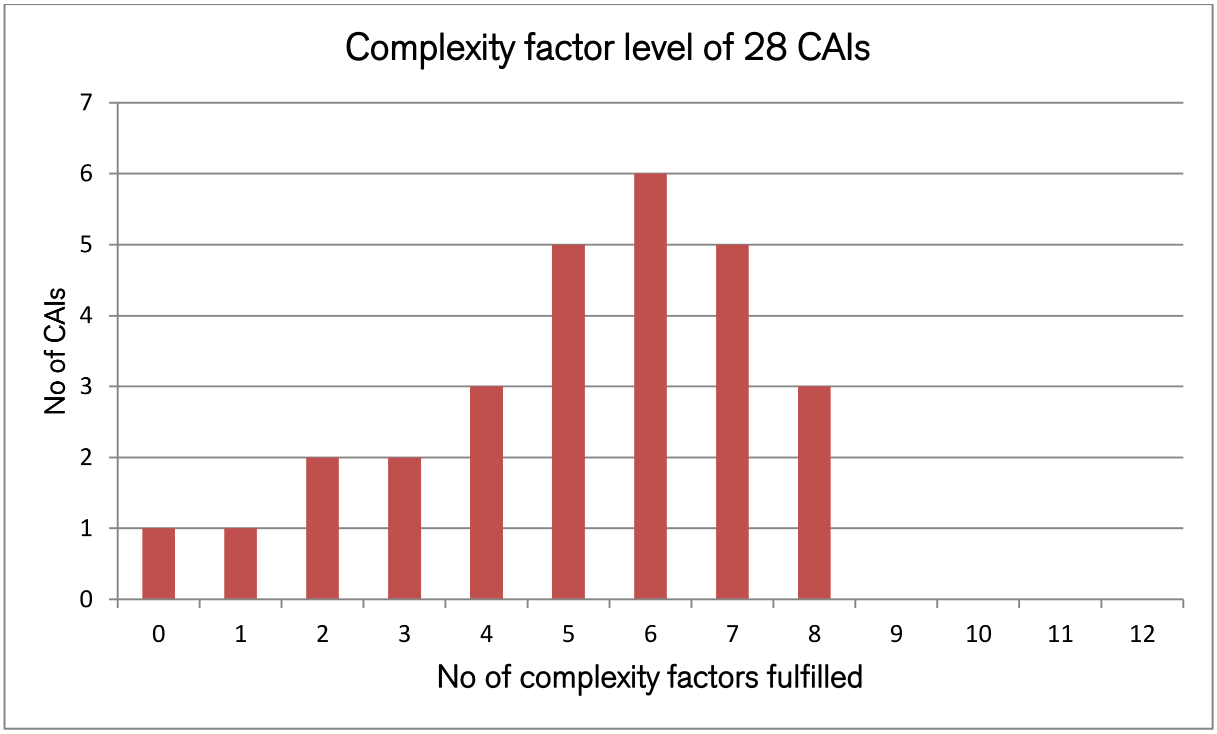

Figure 15- Number of CAIs compared to number of complexity factors fulfilled

When choosing the CAIs to be evaluated, an equal spread in complexity level was desired. In the investigated CAIs, there is no CAI having more than 8 complexity factors fulfilled. Therefore, it is not possible to neither see what quality deficiencies nor what costs the instructions having more than 8 complexity factors fulfilled are causing. This means it is not possible to decide how the number of fulfilled complexity factors affects the quality deficiencies. Maybe the number of complexity factors fulfilled is not what affects the total complexity level of the CAIs. Some complexity factors might have a greater impact on the complexity factor evaluation than others.

All the complexity factors are considered attainable according to the complexity factor definition (see Appendix E - Definition of complexity factors). Furthermore, Figure 16 shows that all the complexity factors are fulfilled at least six times in the evaluation of the 28 CAIs. The figure also shows that the number of times that a complexity factor is fulfilled differs between the complexity factors. As each of the 12 complexity factors are fulfilled at least six times, this proves that all 12 complexity factors are attainable and thus possible to fulfill. Therefore, there might be CAIs available at VCC with a complexity level between 9 and12.

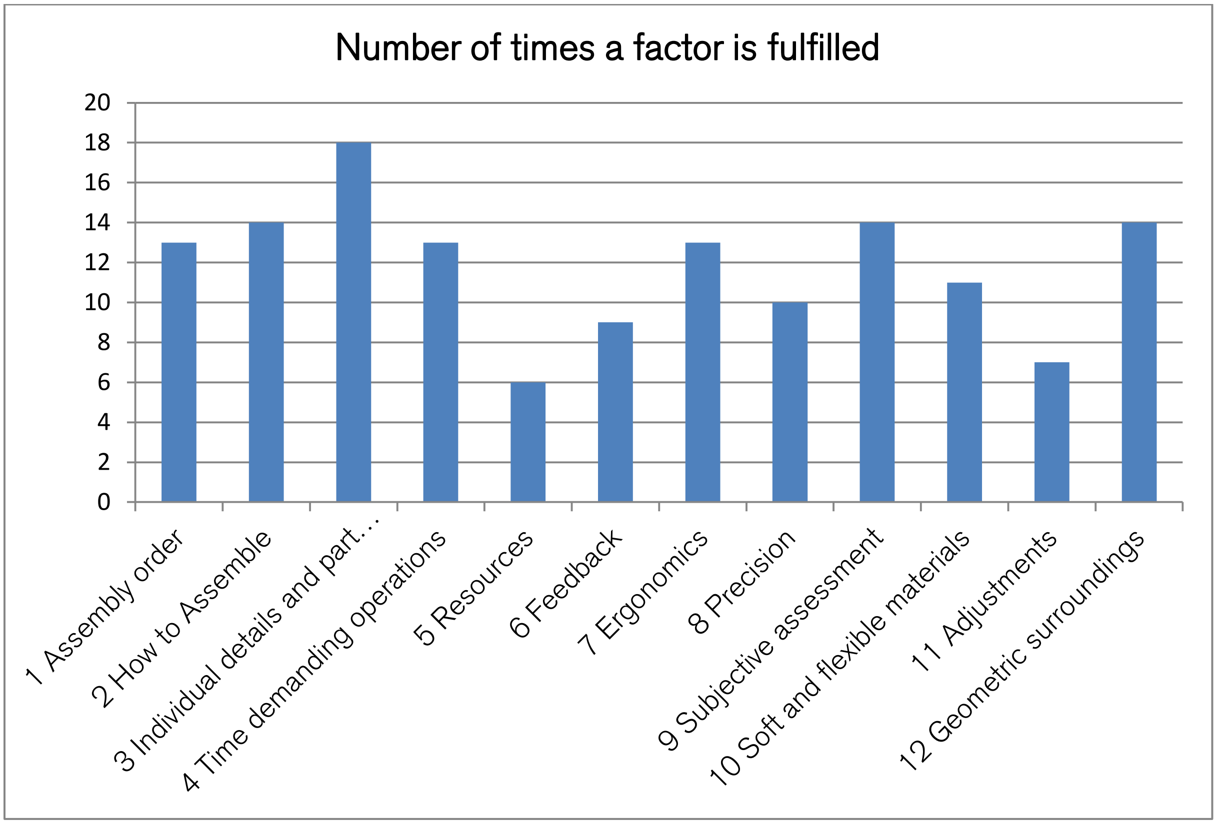

Figure 16- Number of times a complexity factor is fulfilled

Due to that none of the evaluated CAIs had more than 8 factors fulfilled (which was shown in Figure 16), only a comparison between complexity levels from one complexity factor fulfilled to 8 complexity factors fulfilled, and how these levels affect the quality deficiencies and costs could be made. This means that it is not possible to identify how a complexity level with 9 to 12 complexity factors fulfilled affects the quality deficiencies and costs.

To try to understand the results further, a correlation analysis between number of fulfilled complexity factors and quality deficiencies was performed. Furthermore, a correlation analysis between number of fulfilled complexity factors and costs of quality deficiencies was performed. The correlation analysis did not show any correlation between number of fulfilled complexity factors and quality deficiencies. The correlation analysis between the number of fulfilled complexity factors and costs of quality deficiencies neither indicated any clear correlation. The complete results from the correlation analysis can be found in Appendix H - Correlation analyses between complexity and quality deficiencies and complexity and costs of quality deficiencies.

Instead, the individual complexity factors were compared to each other. This was done to identify which factor that contributes the most to quality deficiencies and costs.

5.5 Complexity factors evaluation compared to quality deficiencies and costs of quality deficiencies

To investigate how the individual complexity factor affects quality deficiencies and costs of quality deficiencies, main effect plots (Bergman and Klefsjö, 2010) can be used.
The main effect plots in Figure 17 indicate what impact the different complexity factors have on quality deficiencies.

Main effect plots for quality deficiencies (DPTO)

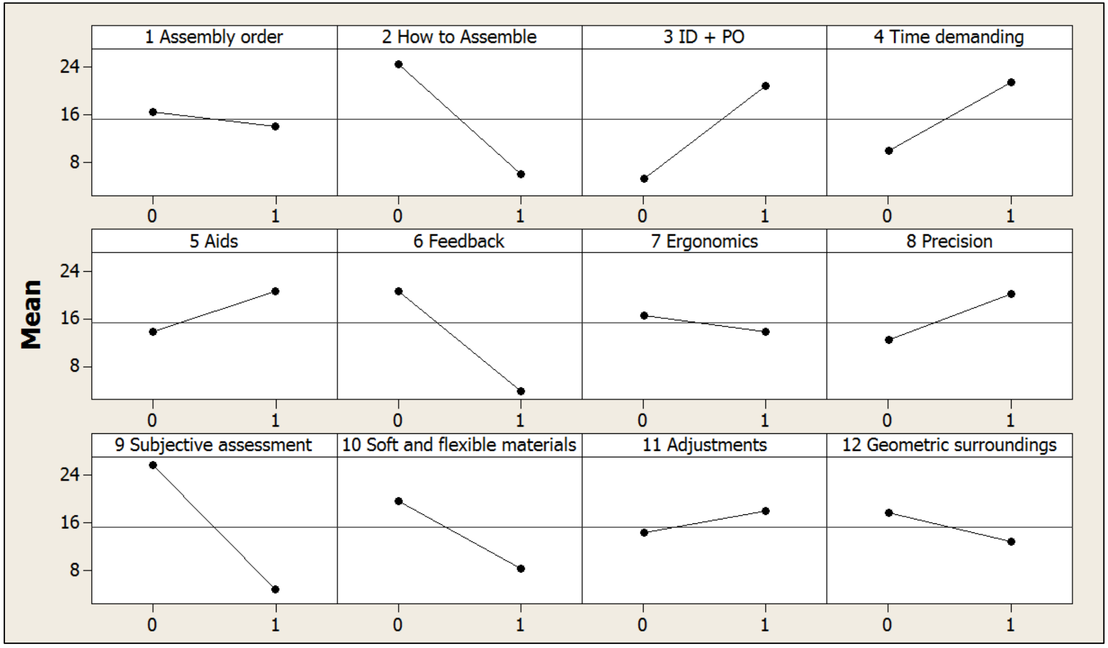

Figure 17- Main effect plots for quality deficiencies (DPTO)

The results shown in Figure 17 indicate that the factors showing most positive main effects for quality deficiencies are complexity factor 3, 4, 5 and 8. The slope of complexity factor 2, 6, 9 and 10 are negative, which means that if any of these factors are fulfilled (which means high complexity), the quality deficiencies will decrease.

The main effect plots in Figure 18 show what estimated effect the different factors have on the costs of quality deficiencies.

Main effect plots for costs of quality deficiencies (per produced car)

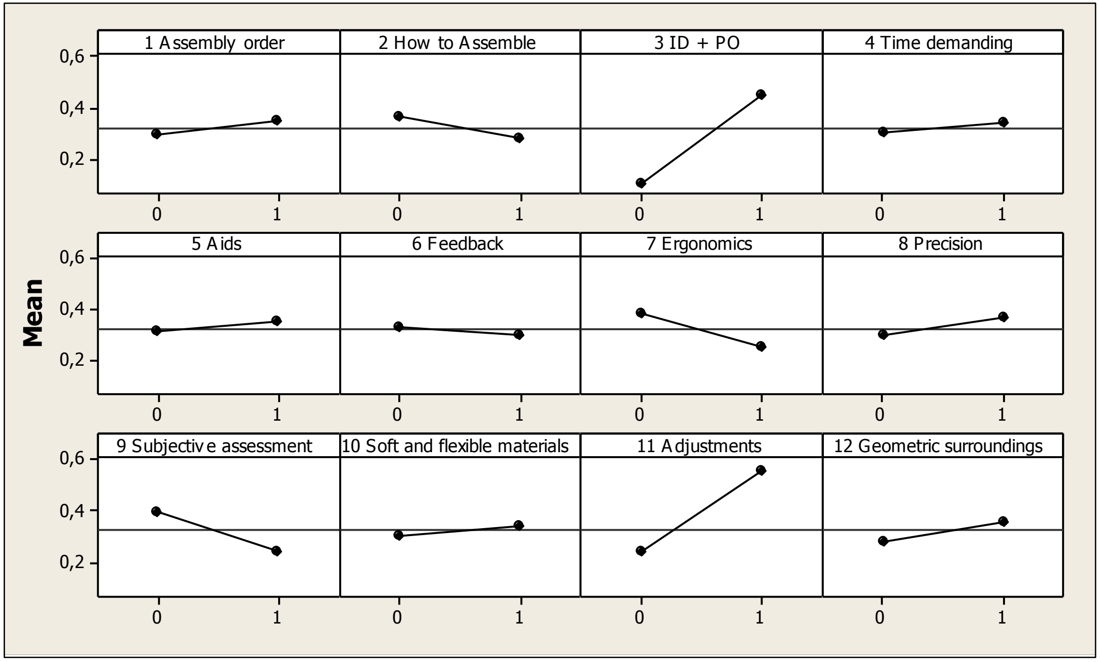

Figure 18- Main effect plots for costs of quality deficiencies (per produced car)

Since factor 3, 7, 9 and 11 have the steepest slopes of the lines (see Figure 18), these factors should be considered as most important for the effect of the quality deficiencies. The slopes of factor 3 and 11 are positive which indicate that if factor 3 or 11 is fulfilled (high complexity), the number of quality deficiencies will increase. On the other hand, the slope of factor 7 and 9 are negative, which means that if any of these factors are fulfilled (high complexity), the quality deficiencies will decrease.

To determine whether one factor or a combination of factors is significant or not, normal probability plots have been performed (see Appendix I - Normal probability plots).

The results from the normal probability plot for quality deficiencies do not show any indications of significant complexity factors (on 0,05 level, see Appendix I - Normal probability plots). The normal probability plot for costs of quality deficiencies per produced car shows that complexity factor 12 (Geometric surroundings) and factor 8 (Precision) are significant at the 0,05 level. The normal probability plot also indicates that the interaction between complexity factor 2 (How to assemble) and factor 4 (Time demanding operations) are significant on the same significance level. A matrix of all two factor interactions can be found in Appendix J - Interaction plots.

The results show a positive effect if factor 4 is going from not being fulfilled to being fulfilled, while complexity factor 2 is kept as not fulfilled.

The results from the interactions plots for quality deficiencies indicate that when complexity factor 2 (How to assemble) is fulfilled and complexity factor 4 (Time demanding operations) goes from not being fulfilled (low complexity) to being fulfilled, the costs will be reduced (have a negative effect). This was not expected. One reason why the results look like this might be that a large amount of the total quality deficiencies collected are caused by semi-automatic screw drivers (see Appendix K - List of quality deficiencies).

Some safety-critical operations are surveyed by so called Poka Yoke systems to make sure that the correct torque is obtained. When the correct torque is not reached in a critical manual screw operation, the screw driver automatically registers this as a quality deficiency in QDLS. However, other quality deficiencies are manually registered as they occur. If the quality deficiencies have to be manually registered, there is a risk of getting problems regarding consistently logging of all deficiencies occurred. When logging deficiencies automatically, all deficiencies are registered. Therefore, manually and automatically registered types of deficiencies should be separated.

The complexity evaluation is investigating what quality deficiencies are caused by manual assembly. This does not consider the semi-automatic screw driving operations. At VCC, the quality outcome of semi-automatic screw driving operations is automatically logged into a system. Therefore, it is expected to be more quality deficiencies detected in these assembly operations. An analysis of the CAIs not containing any screw driving operations, related to the quality outcome without the semi-automatically logged deficiencies is therefore interesting to perform.

5.6 Complexity factors evaluation compared to quality deficiencies and cost of quality deficiencies (excluding screw driving deficiencies)

In the previous section, it was discussed that more quality deficiencies are registered when including screw driving operations, as these operations are automatically logged. Therefore, analyses when removing screw driving related quality deficiencies would be interesting to perform (All deficiencies in QDLS related to screw drivings begin with the character "D", which makes it possible to identify these deficiencies, see Appendix K - List of quality deficiencies). The same kinds of analyses were performed as for the CAIs when screw driving quality deficiencies were included.

When excluding the screw driving deficiencies, the correlation analysis indicates no correlation between the number of fulfilled complexity factors and quality deficiencies (see Appendix H - Correlation analyses between complexity and quality deficiencies and complexity and costs of quality deficiencies). When it comes to costs of quality deficiencies, there was no clear correlation (at the 0,056 level) between the number of fulfilled complexity factors and costs of quality deficiencies per produced car, when excluding screw driving quality deficiencies.

Instead of looking at the total number of fulfilled complexity factors, each factor is now going to be further analyzed individually and compared to each other.

5.7 Complexity factor main effect plots of quality deficiencies and costs of quality deficiencies

The main effect plots (see Figure 19 and Figure 20) describe what effect the different complexity factors have on the quality deficiencies and the costs of quality deficiencies per produced car, when excluding the screw driving related quality deficiencies from the quality deficiencies.

Main effect plots for quality deficiencies (DPTO) (Excluding screw drivings)

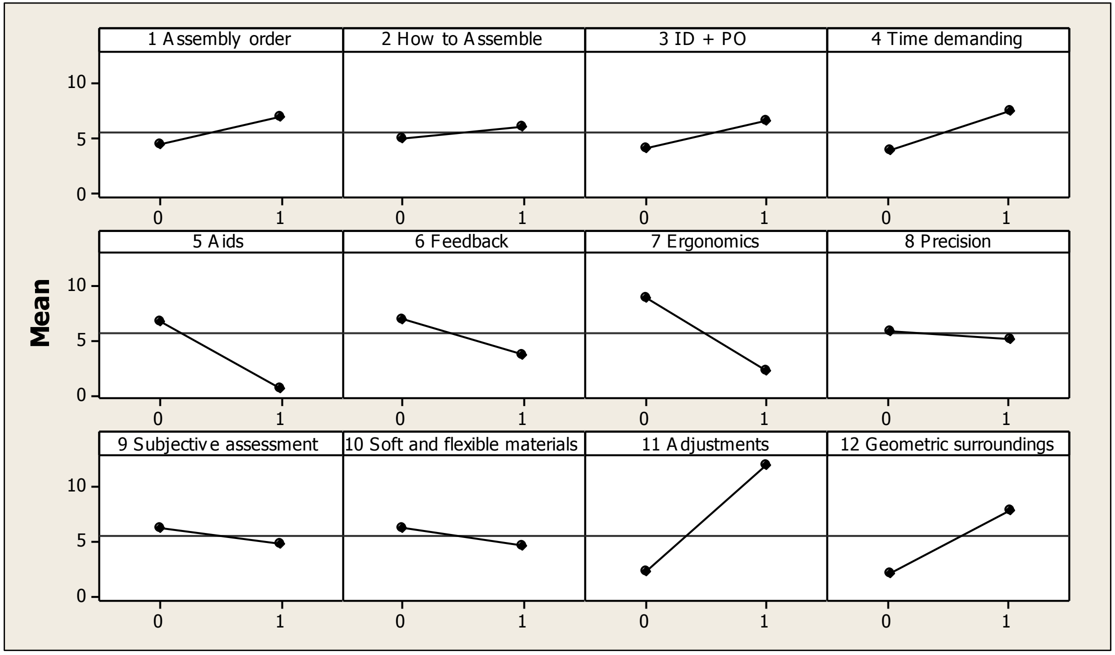

Figure 19- Main effect plots for quality deficiencies (DPTO) (Excluding screw drivings)

Main effect plots for costs of quality deficiencies (Excluding screw drivings) (per produced car)

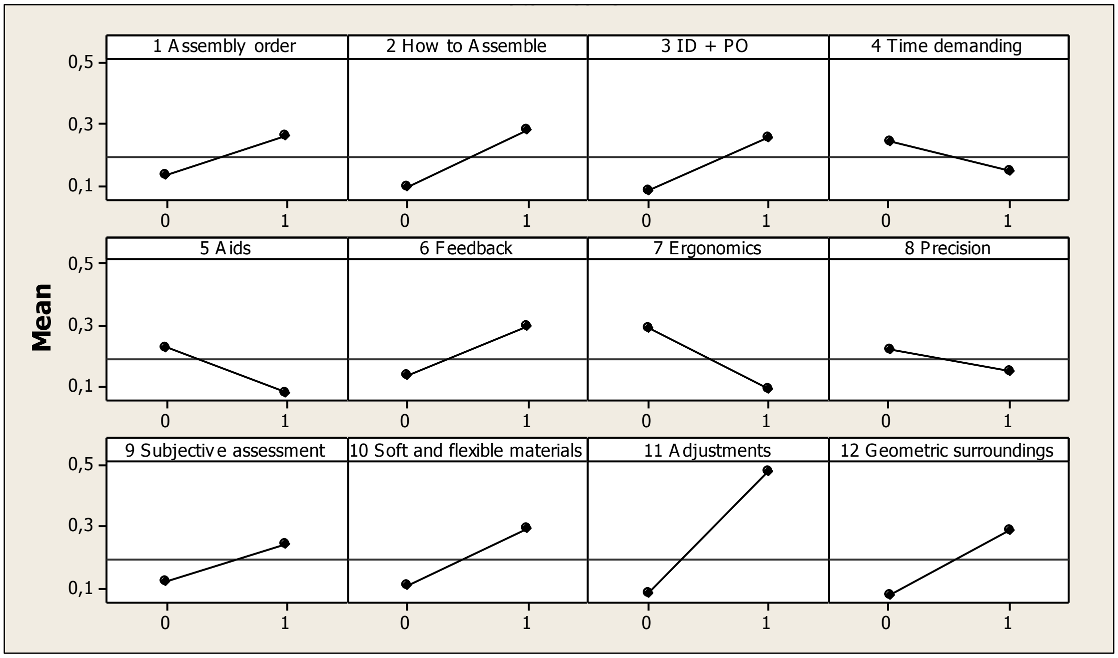

Figure 20- Main effect plots for costs of quality deficiencies (Excluding screw drivings) (per produced car)

Both Figure 19 and Figure 20 show that complexity factor 11 has the steepest line which indicates that this factor is the most important factor to consider. At the same time, there are still complexity factors having a negative effect on both cost per produced car and quality deficiencies. These results are unexpected (due to recent studies by Falck, 2012c). For example, in Figure 19 and in Figure 20 the slopes of complexity factor 7 (Ergonomics) are negative, which indicates that a high complex situation would lead to less quality deficiencies and less costs of quality deficiencies compared to a low complex situation. Therefore, the reason for these results needs to be investigated further.

When removing quality deficiencies related screw drivings, a normal probability plot analysis of the effects of the complexity factors for the quality deficiencies shows that no indications of any significant complexity factor (on 0,05 level, see Appendix I - Normal probability plots) could be identified. On the other hand, when analyzing the normal probability plot for costs of quality deficiencies compared to complexity factors (see Appendix I - Normal probability plots), there are two significant complexity factors and two significant interactions factors. These four complexity factors are:

- Complexity factor 3 - Individual details and part operations
- Complexity factor 4 - Time demanding operations
- Interaction of 1 & 4 combined - Assembly order & Time demanding operations
- Interaction of 1 & 3 combined - Assembly order & Individual details and part operations

These complexity factors are not the same as the significant complexity factors identified in the case with 12 complexity factors including screw driving related quality deficiencies (see *Table 8*).

Table 8 - Significant complexity factors for costs of quality deficiencies with/without screw drivings

Significant factors (including screw drivings) for costs	Significant factors (excluding screw drivings) for costs
12 - Geometric surroundings	3 - Individual details and part operations
8 - Precision	4 - Time demanding operations
Interaction of 2 & 4 - How to assemble & Time demanding operations	Interaction of 1 & 4 - Assembly order & Time demanding operations
	Interaction of 1 & 3 - Assembly order & Individual details and part operations

Removing screw driving related quality deficiencies in some sense impacts the significance of the results. It also impacts which factors that are important. On the other hand, removing screw driving related quality deficiencies does not clearly indicate what factors that are affecting the quality deficiencies either.

The results from the normal probability plot indicated that the interaction between complexity factor 1 (Assembly order) and factor 4 (time demanding) and the interaction between complexity factor 1 (Assembly order) and factor 3 (Time demanding) were significant on the 0,05 level. These interactions are shown in Appendix J - Interaction plots

Interaction between complexity factor 1 and complexity factor 4

The result from the interaction between complexity factor 1 and complexity factor 4 indicates that when complexity factor 1 fulfilled (high complexity) and when complexity factor 4 goes from not being fulfilled (low complexity) to being fulfilled, this has a negative effect, which means reduced costs of quality deficiencies.

Furthermore, the results show that when complexity factor 4 goes from not being fulfilled (low complex) to being fulfilled (high complex), while complexity factor 1 is kept as not fulfilled it has a slight positive effect.

This result also shows that if both complexity factor 1 and complexity factor 4 are being fulfilled, the costs of quality deficiencies will decrease.

Interaction between complexity factor 1 and complexity factor 3

The result from the interaction between complexity factor 1 and complexity factor 3 indicates that when complexity factor 1 is fulfilled (high complex) and complexity factor 3 goes from being not fulfilled (low complexity) to being fulfilled, it has a positive effect, which means increased costs of quality deficiencies.

The results indicate very low effect if complexity factor 3 is going from not being fulfilled to being fulfilled while complexity factor 1 is kept as not fulfilled.

These results show that if both factor 1 and factor 3 are being fulfilled, the costs of quality deficiencies will increase.

5.8 Summary of correlation analysis between complexity and quality deficiencies, and complexity and costs of quality deficiencies

In this section, a summary of the important complexity factors from the previous presented main effect plots and normal probability plots are presented and discussed.

As indicated in the results from the main effect plots, the effect is sometimes reduced for quality deficiencies and/or cost of quality deficiencies (when going from a low complex situation to a high complex situation). These results provide suspicions of that the quality deficiency data is uncertain and needs to be studied further. The only complexity factors that are presented in this chapter are factors that indicate a major positive effect on either quality deficiencies or costs of quality deficiencies.

5.8.1 Quality deficiencies

Table 9 summarizes the identified complexity factors from the main effect plots that have the most effect on quality deficiencies. The table also shows which results that are statistically significant on a 0,05 level.

Table 9 - Summary of factors having the greatest effect on quality deficiencies and significant complexity factors for quality deficiencies

Complexity factors (main effect plot)	Complexity factors (excluding screw driving) (main effect plot)	Significant complexity factors	Significant complexity factors (excluding screw driving)
3 - Individual details and part operations	11 - Adjustments		
4 - Time demanding operations	12 - Geometric surroundings		
5 - Resources			
8 - Ergonomics			

From the main effect plots there were four complexity factors having a major positive effect on quality deficiencies (complexity factor 3, 4, 5 and 8). However, when automatically logged quality deficiencies from screw driving operations were excluded from the quality deficiencies, there were two other complexity factors showing a major effect (11 and 12).

In the main effect plots (summarized in Table 9), complexity factor 3 and 4 were two of the important identified complexity factors. One problem when analyzing these two factors is the fact that the assembly operations in CAIs, which the complexity factor evaluation is based on, are split when CAIs are rewritten into OAI (which are used by the operators in production). Therefore, it is hard to evaluate if these factors actually affect the quality deficiencies or costs of quality deficiencies.

When analyzing the statistical significance on the 0.05 level for complexity factors none of the factors was significance when it comes to quality deficiencies, not even when excluding automatically recorded quality deficiencies from screw drivers, none of the complexity factors were identified. The results from the main effect plots (summarized in Table 9) identified factors 11 and 12 to have high effect on the quality deficiencies when excluding screw drivings. But due to that none of the factors are significant, these effects can therefore only be seen as indications of important factors for the quality deficiencies.

To conclude, complexity factor 5, 8, 11 and 12 seem to affect the number of quality deficiencies in our investigated assembly operations.

5.8.2 Cost of quality deficiencies

Table 10 summarizes the identified factors from the main effect plots that have the greatest effect on costs of quality deficiencies. Furthermore, the table shows which factor results that are statistically significant on a 0,05 level.

Table 10 - Summary of factors having the greatest effect on costs of quality deficiencies and significant complexity factors for costs of quality deficiencies

Complexity factors (main effect plot)	Complexity factors (excluding screw driving) (main effect plot)	Significant complexity factors	Significant complexity factors (excluding screw driving)
3 - Individual details and part operations	11 - Adjustments	12 - Geometric surroundings	3 - Individual details and part operations
11 - Adjustments		8 - Precision	4 - Time demanding operations
		Interaction of 2 & 4 - How to assemble & Time demanding operations	Interaction of 1 & 3 - Assembly order & Individual details and part operations
			Interaction of 1 & 4 - Assembly order & Time demanding operations

From the main effect plots, two complexity factors could be identified to have an effect on the cost of quality deficiencies (complexity factor 3 and 11). When excluding the screw driving operations, factor 11 is still considered having a high effect on quality deficiencies (while factor 3 shows lower effect).

On the other hand, the only results that are statistically significant are those for the factors in the two columns to the right. The results for factor 3 or 11 are not statistically significant, why these results only could be seen as indications. Furthermore, factor 3 can be excluded due to the same reason regarding CAIs and OAI, which was discussed in the previous section about quality deficiencies.

The effect for the statistically significant complexity factors is considered low (see Figure 18 and Figure 20, Appendix J – Interaction plots). No clear indication of what effect the statistically significant complexity factors have on the cost of quality deficiencies can therefore be seen.

To conclude, complexity factor 11 is the only factor which seems to have a major effect on the cost of quality deficiencies in our investigated assembly operations.

5.9 Robust Index

The analysis in this section mainly analyzes the answers from the interviews with the core manufacturing engineers about RI and the RIM. The section also includes an analysis of relations between RI requirements and complexity factors.

5.9.1 Usage of Robust Index Matrix

The interviews with the core manufacturing engineer representatives indicated a shared view of the usage of the RIM. The core manufacturing engineers mainly use the RI value when working towards something called the "System Decision Approval - Manufacturing" (SDA-M). The RI value is used as an incentive for SDA-M to improve concepts and motivate why concepts with certain properties are better than others. The RI value is also used in the Commodity Business Plan, which on commodity level documents technology, contains manufacturing strategies and sets targets towards the research and development department and the purchasing department.

When to use RI in projects is not implemented in the GPDS (Global Product Development System, used at VCC as a cross functional plan to develop vehicles in time with the right quality, see Appendix L - Illustration of GPDS). However, sometimes when milestones are reached in projects, RI values are requested and used to compare the actual status of the project with the predicted status. The interviewees highlight that the RI value, as it is today, is useful in the annual and concept phase of projects. On the other hand in later phases of projects, the RI value is less used. According to the representatives from the commodity engineers, they say that they hardly ever use the RI value.

During the interviews it could be concluded that the latest RI evaluation of the sub-systems was made before the latest update of the RIM. The old RI values for the sub-systems have been transferred from the old version of the RIM to the new version. Some of the old values do not contain any comments or indications of which RI requirements that are fulfilled or not. This means that there sometimes is a RI value, without knowing what the value actually means.

The RIM facilitates the way of commenting on every requirement that is not fulfilled. On the other hand, it is not possible to comment on fulfilled requirements. Even though a requirement is fulfilled, there is a need of documenting the evaluation and understand why the requirement is fulfilled. Otherwise, there is a risk of gradually losing the knowledge about the evaluation.

As the core manufacturing engineers, responsible for the RI evaluation, know when an assembly task is not “robust” enough, it could be stated that they are correcting the RI value in the RIM themselves, if they feel the value does not correspond to the actual level of robustness in running production. This subjective evaluation in combination with lack of instructions of how the matrix is going to be filled in increases the risk of variation in the evaluation results in between the users when filling in the RIM. This was commented by one of the interviewees, who said it is better if everyone only uses the RIM which controls the RI value. Instead of changing the value manually, it would be preferable to try to find another requirement that is not fulfilled in the RIM which indicates the difference between the instructions. If it is not possible to find such a requirement in the list of RIM requirements, an option to leave an overall comment describing the evaluation should be available. This improvement would contribute to the ability to always know what the decisions have been based on, which is important according to Bergman and Klefsjö (2010) who state that decisions shall be based on facts.

The opinions about the RIM indicate that the requirements in the matrix are considered general. As the same tool is supposed to be used for all different car models and all kinds of assembly processes, the requirements need to be generalized to fit all models. The interviewees also say that some requirements are hard to evaluate in early phases, especially the requirements in the milieu (environment) category. In some cases the only information available to make a RI evaluation of is a concept. In best case a CAI and a simulation model of the assembly process is available. Without having more information it is hard to evaluate some RI requirements, e.g. “well balanced ergonomic environment” (milieu K3), due to that knowledge about the surrounding environment is not available.

When performing the RI evaluation, one responsible core manufacturing engineer and one commodity engineer shall be present. During the interviews it was said that the RI evaluations sometimes were done when there was short of time. In those cases, RI is only used as a reporting tool and is filled in because some other departments need the number. During such circumstances, core manufacturing engineers sometimes are doing the RI evaluations themselves. To avoid these situations, the matrix shall be updated on a regular basis in the production development: once in the annual phase and once in the concept phase by core manufacturing engineers, then one year after introduced in running production phase there shall also be an update in the RIM by RME, in order to always catch all aspects that might affect the quality outcome in production.

To be able to compare the different RI values, the interviewees also highlight the importance of consistently evaluating the requirements between the evaluation groups. Out of the interviews, it could be stated that some of the requirements are interpreted differently between the evaluation groups. Therefore, these RI values might not be comparable between the evaluation groups. The question is what requirements shall be used in the RIM to fit all evaluation groups and sub-systems?

5.9.2 Relations between complexity factors and RI requirements

When comparing the complexity factors with the RI requirements, some relations could be identified. This chapter describes these relations.

Both the 16 original complexity criteria and the corresponding 12 complexity factors aim to study the complexity level of manual assemblies in manufacturing companies. The RI tool on the other hand, is focusing on identifying the sensitivity of a system against predefined variation (Lundell and Nagarajan, 2012). The RI requirements are divided into the categories material, method, machine and milieu. These categories cover more aspects than manual assembly aspects. This might contribute to the fact that no clear correlation could be found between the RI value and the number of complexity factors fulfilled for the 28 evaluated CAIs, see Figure 21.

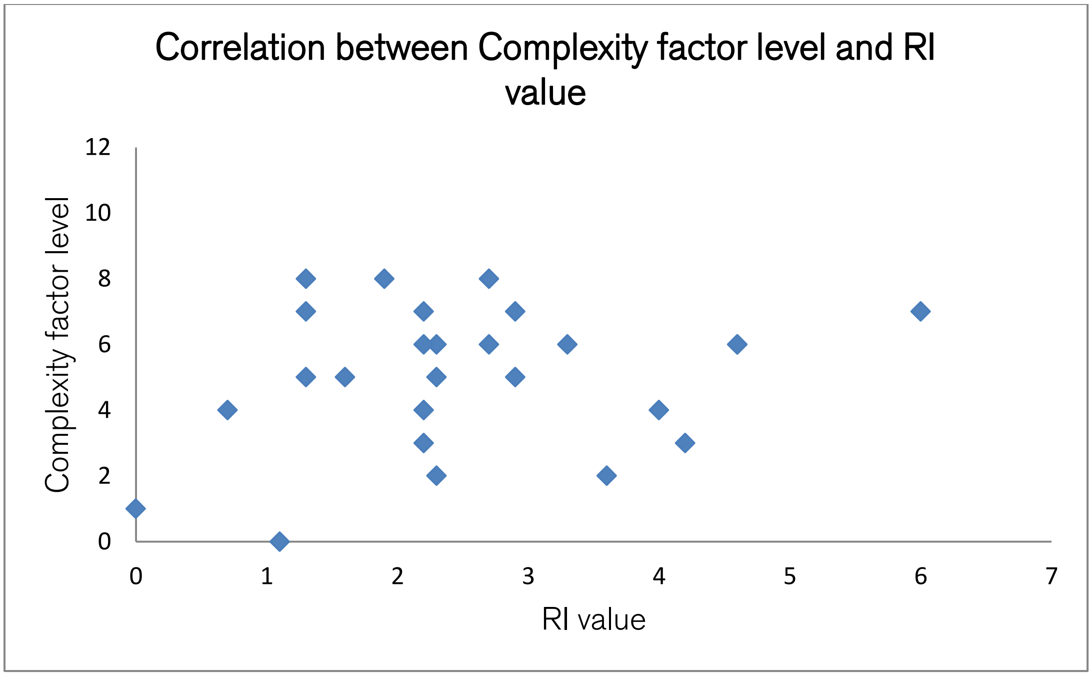

Figure 21- Correlation plot between complexity factor level and RI value

The RIM is developed at VCC and is based on the manufacturing engineering requirements used to develop assembly operations. The complexity evaluation aims to be applicable on companies which include manual assembly work and the original 16 complexity criteria (which later became the 12 complexity factors) are developed from an interview study with representatives from five different Swedish manufacturing companies (Falck and Rosenqvist, 2012a). As the complexity criteria are developed from interviews with several companies, the complexity evaluation method might be applicable on several companies. If comparing results from the complexity evaluations at these companies, it might be possible to get an insight about to what extent the complexity level in manual assembly in general affect the quality deficiencies and costs of quality deficiencies. These results can then be used in benchmarking activities to motivate improvement work, to keep the manual assembly operations as low complex as possible.

The intention should therefore not be to substitute RI for the complexity evaluation method. Instead, it is interesting to investigate and understand how the complexity evaluation method could be used at VCC as a complement to RI. Therefore it is necessary to understand to what extent RI includes the complexity factors.

A relation analysis between the complexity factors and RI requirement was performed in order to understand to what extent RI includes the complexity factors. Table 11 shows the RI requirements that to some extent can be related to a corresponding complexity factor.

Table 11- Relation analysis between RI requirements that have a corresponding complexity factor

RI requirements	New Factors
Material	
K1:	10. Soft and flexible materials
K3:	8. Precision, 5. Resources
K4:	10. Soft and flexible materials
K5:	2. How to assemble
K8:	11. Adjustments
K9:	9. Subjective assessment
A1:	9. Subjective assessment
A2:	1. Assembly order
A3:	7. Ergonomics
Method	
K1:	8. Precision
K2:	7. Ergonomics
K4:	6. Feedback
K5:	11. Adjustments
K6:	7. Ergonomics
K8:	9. Subjective assessment

Table 11 shows that the following complexity factors are not included in the RI evaluation:

- Complexity factor 3: Individual details and part operations
- Complexity factor 4: Time demanding operations
- Complexity factor 12: Geometric surroundings

In the analysis section it has been shown that, when there are quality deficiencies and costs of quality deficiencies, the important factors are:

Table 12 - Important factors for quality deficiencies and costs of quality deficiencies

Complexity factor 5 - Resources
Complexity factor 8- Precision
Complexity factor 11- Adjustments
Complexity factor 12- Geometric surroundings

As the analysis has indicated before, factor 3 - individual details and part operations and factor 4 - time demanding operations are considered not applicable in early development phases. In early development phases, there are no CAIs existing. Therefore, these factors should not be considered to be included in RI. An OAI would better describe these factors from the operators view, as the OAI is describing what the operator actually is doing at the shopfloor. A CAI, is developed before operators' assembly instructions are described, and the CAIs are split into several OAI. In other words, it is not only one operator performing all the part operations in a CAI.

Table 11 shows that complexity factors 5, 8 and 11 to some extent are included in the RI evaluation. Complexity factor 5 - Resources is partly, together with complexity factor 8 - Precision, related to Material K3. Complexity factor 8 - Precision, is also related to Method K1 in the RIM. Complexity factor 11 - Adjustments, is related to Method K5 and Material K8.

To understand the extent of the relations, the definition of the related complexity factor and the definition of the RI requirements need to be further analyzed. The lack of documented definitions of the RI requirements makes this analysis difficult. Therefore, the definitions of the RI requirements need to be clarified and documented, in order to understand to what extent RI includes these important complexity factors.

In the analysis of complexity factors relations to RI requirements, no relations could be identified between complexity factor, 12 - Geometric surroundings and the RI requirements. This complexity factor has been identified as one of the most important complexity factors, which has a major effect on number of quality deficiencies. Therefore, this complexity factor needs further investigations to understand to what extent it is included in RI or how it could be included in the RI evaluation.

6. DISCUSSION

The purpose of this thesis has been to examine the relation between assembly complexity criteria and the RI. This chapter includes a discussion about the analysis results and the methods used to obtain the analyzed results. Furthermore, the credibility of the results is discussed and several aspects that might affect the results are presented. In the end of the discussion, the RIM is discussed and to what extent RI includes the complexity factors.

In this study, the complexity evaluation method (Falck et al. 2012c) has been used as a starting position. The intention with the complexity evaluation method is that it shall be applicable on several companies. The complexity evaluation method was developed through an interview study performed at five different Swedish companies. The interviewees in the companies were considered to be highly experienced and able to provide credible answers to the questions asked about complexity. The complexity criteria used in this study are the results from this interview study, but there might be other aspects that affect complexity which were not identified in that interview study. As complexity in this report is defined as the 16 complexity criteria, these other aspects have not been covered in this study, (See Appendix B - Definitions of complexity criteria).

The complexity criteria have been used to evaluate 28 CAIs. The results did not show any significant correlation between the number of fulfilled complexity criteria and quality deficiencies or costs of quality deficiencies. The fact that the complexity criteria did not correlate with the quality deficiencies, does not correspond to earlier studies (Falck, 2012c), where a correlation between the number of fulfilled complexity criteria and the quality deficiencies collected during year 2010 showed significant results at 0.01 level. Maybe this has to do with the definitions of the complexity criteria developed in this project, which are developed to suit VCC. If the complexity criteria method is going to be used in other companies, the definitions might need to be adapted to suit the investigated company's assembly tasks. The lack of documented definitions in the earlier complexity evaluations by Falck et al. (2012c) (describing whether the criteria are fulfilled or not) makes it hard to explain the difference in the results.

Another aspect that might affect the difference in the results is how the quality deficiencies data is obtained. In this study, the quality deficiencies related to the CAIs were collected by the responsible quality engineers for exterior and interior assemblies. Maybe this way of collecting the quality deficiencies differs from the way these were collected in the earlier studies Falck et al. (2012c), which might explain the differences in the results.

When it comes to the complexity criteria evaluations of the CAIs, several experts have been contacted. Some of the criteria were evaluated by responsible core manufacturing engineers of the assembly instructions. During some evaluations, also a commodity engineer was present. The experts were asked to motivate their evaluation in detail, but some aspects that might have had an impact the evaluation might not have been covered. Therefore, there is a risk that the mapping of different factors in the complexity evaluation does not show all factors included in the complexity evaluation. These aspects might affect the complexity factors and the question is if the complexity factors really are independent? There is a risk that the complexity criteria definitions are interpreted differently by the experts and therefore the CAIs might have been evaluated differently.

The analysis section revealed that it is not always possible to evaluate complexity of a CAI, in the development phase and that subjective evaluation was needed to perform the evaluation. The complexity evaluation is more suitable in later phases of the development process or in running production. As this is the case, the complexity evaluation might be used to facilitate the follow-up work with the calculated RI-values.

In running production at VCC, operators are performing assembly tasks according to an OAI. As an OAI is based on the CAIs, the question is if the results would have been different if the complexity evaluation had been performed on the corresponding OAI for the CAI. In this thesis, it is supposed that the CAIs are followed during the assembly. Hence, one interesting question to investigate is how to assure that the CAIs are correctly transformed into OAI?

In order to investigate and understand if similarities and differences between a CAI and an OAI affect quality deficiencies, one suggestion for further studies is to deeply analyze one certain kind of quality deficiency, that have occurred at the shopfloor, to understand the root cause. If understanding the root cause of one kind of quality deficiency, it would probably be possible to identify if the translation from a CAI to an OAI affects the quality deficiencies. Maybe the root cause also can be related to complexity factors. That would probably make it possible to further decide what of the complexity criteria that are important to consider in early development phases.

In this study 28 CAIs have been evaluated. This is a small part of the total number of CAIs at VCC. If other CAIs had been chosen, other results might have been obtained. A recommendation for further studies is to use a larger selection of CAIs to verify the results. On the other hand, the results from the investigated CAIs provide an indication of how to continue the investigation of factors important for quality deficiencies and costs.

After an analysis of the complexity evaluation, it was shown that several of the complexity criteria were overlapping (see Figure 13). Therefore 12, less overlapping, complexity factors were developed out of the complexity criteria evaluation. These complexity factors are the results from the complexity evaluation at VCC. A complexity evaluation at another company might result in other factors. Therefore, more studies must be performed on other companies to be able to identify which factors that can be generally used between all kinds of companies that include manual assembly.

The 12 complexity factors were developed from the evaluation of the complexity criteria to be less overlapping. After analyzing the results, no correlation could be shown between the number of fulfilled complexity factors and quality deficiencies or between the complexity factors and cost of quality deficiencies either. Therefore, the different effect of each factor was analyzed.

Each of the 12 complexity factors was analyzed to understand the effect of each factor in correlation to both quality deficiencies and costs of quality deficiencies. For the different main effect plots assessing the different factors, there were some factors showing the opposite effect than expected. In the chapter presenting "*Complexity factor main effect plots of quality deficiencies and costs of quality deficiencies",* Figure 17 for example indicated a negative effect for factor 7 (ergonomics), which is contradictious compared to previous studies (Falck et al., 2012c). One hypothesis regarding the effect of this factor is that a high ergonomic load level in this case have made the operator more focused on doing the assembly task correctly, as the operator knows that a bad posture increases the risk of doing mistakes.

Figure 17 also indicates a negative effect for complexity factor 9 (Subjective assessment). One possible hypothesis to this result would be the same as for factor 7 (ergonomics). If the operator on its own shall determine whether the assembly operation is correctly performed, he/she is more aware of doing correct than if no subjective assessment was needed.

Another aspect that might have influenced the results from the analysis (see Figure 13) is the dependence between factors. When Design of Experiments is used as a method to evaluate the different complexity factors compared to each other, this requires independent factors (Reddy, 2011). Even though the complexity factors are developed from the complexity criteria evaluation (made at VCC) to be independent to each other, there is still a risk of having dependency. Therefore, the way of using Design of Experiments can be questioned. On the other hand, this way of analyzing suggests a way of working in the future to identify factors important for quality deficiencies and costs of quality deficiencies.

In the end of the analysis section, important complexity factors to consider in the RIM when it comes to quality deficiencies and costs of quality deficiencies were identified. The relations shown in Table 11 showed that several of the important complexity factors to some extent were considered in the RI requirements. On the other hand, the relations between the complexity factors and the RI requirements maybe have to be revised. As there are no existing definitions of the RI requirements, those needs to be clarified, established and documented in order to understand to what extent RI includes the important complexity factors.

In the analysis, other aspects about the RIM and the usage of the RIM were also identified. Due to that the same requirements are used for all different car models and all kinds of sub-systems, the RI requirements need to be generalized. An option is to consider grouping of similar sub-systems, and developing requirements suited for the different sub-system groups. This would make the requirements less general and more related to the sub-systems. If the same RI requirements are to be used for all assembly tasks and car models, the question is which requirements shall be used in the RIM to fit all evaluation groups and sub-systems? This needs to be agreed on between representatives from quality, core, commodity and RME. Also, definitions of the RI requirements and how they are to be interpreted and evaluated should be established. During the evaluations of the RI requirements, representatives from core, quality, commodity and RME departments need to be present to get as reliable evaluation results as possible. Having representatives from all referred departments would maybe also make the RI value more recognized in the company.

When performing the RI requirement evaluation is important to motivate and document the evaluation, so that the users of the RIM and future evaluation groups understand the current evaluation. By always leaving a comment when a requirement is either fulfilled or not fulfilled is one way of documenting the evaluation, and would make the RI value more understandable.

During the interviews with the core manufacturing engineers, questions regarding the RI evaluations that differed from the related complexity criteria evaluation were asked. A main reason for the difference is the lack of RI requirement definitions and different interpretations of RI requirements. The relations identified (see Table 11) also indicate that the complexity criteria are related to RI requirements, but only in the method and the material categories. No relations between the complexity criteria and the RI requirements could be identified in the machine and milieu categories. This indicates that RI considers more aspects than manual assembly. This partly describes why the results of the RI evaluation and the complexity criteria evaluation of the CAIs differ (see Figure 21).

In this discussion chapter, several aspects that might have affected the results have been mentioned. To sum up the discussion chapter, RI shall still be used to evaluate concepts in early development phases. As the tool to some extent includes almost all of the complexity factors, the focus should be to make sure that the complexity factors that were shown to be important are included in RI (Table 11). The way of evaluating an assembly instruction using complexity criteria evaluation method might be used to confirm the evaluation of the concept considered in RIM.

7. CONCLUSIONS

The purpose of this study has been to investigate relations between manual assembly complexity and RI. This has been done in order to evaluate how RI can be improved, in order to better predict quality deficiencies at the assembly line in early development phases. This Chapter presents the conclusions from this study.

In this study, 28 CAIs have been evaluated both with respect to the 16 complexity criteria and the corresponding 12 complexity factors. Several correlation analyses have been performed between complexity and quality deficiencies, and between complexity and costs of quality deficiencies. Out of this study, the three research questions have been answered. The first research question was:

"To what extent can the complexity method developed by Falck et al. (2012c) be used to predict the quality outcome and related costs regarding manual assembly operations at VCC?"

None of the analyses in this study show any obvious correlation - neither for the complexity criteria evaluation and costs, nor for the complexity criteria and number of quality deficiencies.

The correlation analysis between complexity factors and costs of quality deficiencies did not either show any correlation. The same was for complexity factors and number of quality deficiencies.

The correlation analyses indicate that the complexity evaluation method cannot be used to predict quality outcome and related costs in manual assembly operations at VCC. On the other hand, this conclusion differs from previous studies (Falck, 2012c). Therefore, further research is necessary to fully answer the first research question.

The second research question was formulated as:

"To what extent does the RI tool consider the complexity factors?"

In order to answer to what extent the complexity factors are included in RI, a relation analysis was performed in chapter 5.9.2. This analysis shows that almost all complexity factors are included in RI to some extent. Even though the relation between the complexity factors and the RI requirements is investigated, there might be aspects that are not considered, as there are no clear definitions of the RI requirements. To conclude, further studies of the RI requirements are needed to answer the research question.

The complexity factors that are not included in RI are shown in Table 13:

Table 13 - Complexity factors included in RI

Complexity factor 3: Individual details and part operations
Complexity factor 4: Time demanding operations
Complexity factor 12: Geometric surroundings

The third and last research question is about factors having a major impact on quality outcome and costs of quality deficiencies:

"Which complexity factors have major impact on the quality outcome and costs of quality deficiencies at VCC?"

In this study, it can be concluded that the complexity factors showing a major effect on the quality deficiencies are the ones shown in Table 14.

Table 14 - Important factors for quality deficiencies

Complexity factor 5: Resources
Complexity factor 8: Precision
Complexity factor 11: Adjustments
Complexity factor 12: Geometric surroundings

For the costs of quality deficiencies, it is concluded that complexity factor 11 - Adjustments shows a major effect. In this study, it has been shown that all factors in Table 14 except complexity factor 12 - Geometric surroundings, to some extent are included in RI. Further investigations are necessary to make sure that these factors are fully considered and included in RI.

In this study, the complexity criteria evaluation method has been used to identify important factors for quality deficiencies and costs of quality deficiencies. It is not possible to replace RI with the complexity evaluation method. Instead, RI can be complemented with the identified important complexity factors.

8. FUTURE RESEARCH

In the analysis section, there were several aspects related to complexity and robust index pointed out as interesting for future research, which are presented in this chapter.

In this thesis, the results from the complexity evaluation method differ from Falck et al. (2012c). Therefore, further studies are needed to understand why these evaluations differ. One way to understand the difference between the studies is to perform a complexity evaluation on a larger selection of CAIs. Then it might be possible to verify the results both from this study and from Falck et al. (2012c). As there are two years between this study and Falck (2012c), it also has to be investigated if a complexity evaluation of CAIs is necessary to be performed more often than every second year.

Another aspect that would be interesting for further research is to investigate if the correlation between assembly complexity and quality deficiencies or the correlation between assembly complexity and costs of quality deficiencies differs if investigating an operator's instruction sheet instead of a CAI. This could be investigated together with deep analyses of quality deficiencies where root causes are identified. If understanding the root cause of quality deficiencies, it might be possible to understand which deficiencies that actually depend on the complexity factors. The deficiencies that depend on other aspects than complexity can then be sorted out from the deficiencies, to not be included in the correlation analysis. That would probably further give answers to how well the complexity evaluation method can predict quality deficiencies.

During some of the complexity evaluations in this thesis, it was difficult for the engineers responsible for the CAIs to decide whether a complexity criterion was fulfilled or not. Furthermore, the main effect plots indicated complexity factor 3 – (Individual details and part operations) and complexity factor 4 – (Time demanding operations) as important. These factors are depending on how CAIs are split into OAI and are thus hard to evaluate in early development phases. In future research it would be interesting to interview people both from the shopfloor (assembly operators and engineers working close to the shopfloor) and engineers working in early development phases of new assembly processes. This might make it possible to relate specific complexity criteria to root causes of quality deficiencies. This might also reflect upon how lessons are learned from identifying root causes in the assembly of previous car models, and how those lessons are considered as early as possibly in development phases.

One other factor that is identified as important in this study, and not could be related to any RI requirement, is complexity factor 12 – (Geometric surroundings). Further research is therefore necessary to study how the variance in geometric surroundings actually affects the quality outcome of products, and how the complexity factor can be included in RI. The other complexity factors that are identified as important in this study could to some extent be related to RI requirements. These relations are interesting for further research, in order to investigate if the RI requirements completely consider these complexity factors. This requires deep knowledge about both the definitions of complexity factors and the definitions of the RI requirements.

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10. APPENDIX

In this chapter all appendices referred to in the report are presented, these are:

Appendix A - RI requirements

Appendix B – Definitions of complexity criteria

Appendix C - Contacted persons

Appendix D - Interview questions

Appendix E - Definitions of complexity factors

Appendix F - Complexity criteria evaluations of 28 PIIs

Appendix G – Evaluation model for the Complexity criteria level

Appendix H - Correlation analyses between complexity and quality deficiencies and complexity and costs of quality deficiencies

Appendix I - Normal Probability plots

Appendix J - Interaction plots

Appendix K - List of quality deficiencies

Appendix L – Illustration of GPDS

APPENDIX A – RI REQUIREMENTS

Here the RI requirements for each of the four categories Material, Method, Machine, milieu presented.

Material
K1:
K2:
K3:
K4:
K5:
K6:
K7:
K8:
K9:
K10:
A1:
A2:
A3:
Method
K1:
K2:
K3:
K4:
K5:
K6:
K7:
K8:
A1:
A2:
Machine
K1:
K2:
K3:
K4:
A1:
Milieu
K1:
K2:
K3:
K4:
A1:
A2:
A3:

APPENDIX B – DEFINITIONS OF COMPLEXITY CRITERIA

The definition of the 16 complexity criteria are presented below. First the High Complex (HC) criterion is stated followed by its Low Complex (LC) opposite.

1 (HC) Different ways of doing the task

(LC) Clear assembly order

Interpretation:
Are there different ways to assemble the part correctly?

Evaluation:

- Do any of the operations (in the CAI) specify how the assembly should be performed and where to start the operation, e.g..
    - Low Complex (Fasten the part with four screws) -
        - what should be assembled
    - High Complex (fasten the part with four screws, begin with the top right corner) -
        - what should be assembled
        - how, in detail, should it be assembled

If any part operation not is considered as intuitive how to assemble → High complex.
Then there might be different ways of doing the task.

If it is possible to assemble parts in different ways, and achieve the correct result. → High complex. (It is important to follow the instruction)

2 (HC) Many individual details and part operations

(LC) Few parts/components to mount; preassembly; module solution (integrated assembly)

Interpretations:

There is a difference between details and part operations. Both have to be taken into account.

Evaluation:

Remember that some operations at the CAIs are divided into several stations at the line
Individual Details (ID): All parts that are going to be mounted/ fastened on the car during this CAI are taken into account.
Calculate the number of individual details in the CAI
E.g. 4 screws = 4 details,
(Reference pins are not included as details)

Part operations (PO): All part operations taking time = part operation
Calculate the number of operations described in the CAI
Operations where pre-mounted details are handled are not included.

Use a scale to evaluate this criterion.
Low amount of ID + PO (0-8)
High amount of ID + PO (>=9)

Update the numbers of the scale for your sample of CAIs.
For each CAI:

- Count the number of ID
- Count the number of PO
- Add ID + PO

Then:

- Calculate the median (M) from the sum of all ID + PO
- The (M) then indicate what is considered as many individual details and part operations

Low amount of ID + PO = (0 - (M-1)), High amount of ID + PO (>=M)

3 (HC) Time demanding operations

(LC) Simple plug-in/ click-in solutions that are easy and quick to assemble

Evaluation:
The criterion is evaluated by using the following steps.

<u>For each CAI</u>

- Find the part operation with the longest time

<u>Then</u>

- Calculate a median value from the longest time of all CAIs
- Evaluate the CAIs

High complex:
The CAI includes at least one part operation with a longer time than the median value.
Low complex:
The CAI does not include any part operation with a longer time than the median value.

4 (HC) No clear mounting position of parts and components

(LC) Clear mounting position of parts and components

Evaluation:
This criterion is considered HC if none of the following is included in the CAI to facilitate the assembling of components.

- Guiding/controlling ("*instyrning*")
- Reference systems
- Reference pins ("*styrpinnar*")
- Fixtures
- Clips/screws
- Latches ("*snäpp-system*")
- Controlling spline ("*Styrlister*")
- Rotation stop ("*rotationsstopp*" / "*stoppklack*")
- Snaps ("*Hakar*")
- T-studs (uses an integrated reference system)
- Tracks / cuts ("*spår*" / "*urgröpning*")

Note: the quoted words are the Swedish words used in the CAIs at Volvo Cars Corporation
Ask experts, core engineers etc. in order to determine if the complexity level for each CAI with respect to this criterion.

5 (HC) Poor accessibility

(LC) Good accessibility

Comment:

Poor accessibility means to not be able to access the place where assemblages are going to be performed with the hand, tool, body or part.
For this criterion there are already evaluations existing.
(the clearance criterion in ergonomics evaluation).

- What posture does it take to do the assemblage?
- Use criterion from Ergonomics papers
- Material for discussion: Integrate this criterion with poor ergonomics condition.

Evaluation:

The criterion is judged by an ergonomics expert who is highly experienced, and know how the part operations in the CAIs.
In situations when the ergonomics expert does not know how to evaluate the CAI, the instructions are evaluated by observing what it looks like on the assembly line.

6 (HC) Hidden operations

(LC) Visible operations

Interpretations:
What does hidden mean? Documents from Ergonomics expert (Ergonomics paper, holistic view of....)
"Is the mounting place (where the parts are going to be assembled) in the field of view when directly looking at the car?" (Yes/no)

Evaluation:
The criterion is judged by an ergonomics expert who is highly experienced, and know how the part operations in the CAIs.

7 (HC) Poor ergonomics conditions implying risk of harmful impact on operators

(LC) Good ergonomics conditions i.e. no harmful impact on operators.

Evaluation:

The criterion is evaluated by an ergonomics expert, who has great experience from the assembly operations and CAIs, and preferably also has worked in the production himself

8 (HC) Operator dependent operations requiring experience/knowledge to be properly done

(LC) Non-operator dependent operations not requiring much experience to be properly done

Interpretation:
Is any type of expertise knowledge required to perform the assembly operations in the CAI? Are there any critical operations involved which highly affect the outcome of the product if they are not properly done?

Evaluation:
This is going to be evaluated by the responsible core engineer.
Ask core engineers:

- Is this a station where newly employed begin?

Use several statements that all needs to be fulfilled if the criterion is considered as fulfilled.

E.g. does the CAI involve any of the following? :

- Is there any additional training/practicing necessary, apart from the common introductory sessions? (expert knowledge necessary)
- Is this a station where the newly employed are being placed the first time after the introductory session?

If you are not able to assemble properly after the introductory session, the work cannot be done by everyone. Then the operation needs an experience worker or a worker with special skills to be properly done.

9 (HC) Operations must be done in a certain order

(LC) Independence of assembly order (could only be done in one way)

Evaluation:
Read the CAI and see if there is any detailed description that regards assembly order e.g.
Does the CAI involve terms similar to:

- "Start with...then do..."

The criterion is considered high complex if you have to follow the described order to get a correct result (otherwise it is not possible to assemble).

Notice!
Evaluate the assembly order (sequence) e.g. is it possible to switch place on the part operations?

The part operation sequence matters but do not consider symmetries (right/left).

Comment from the evaluation at VCC:

- Volvo standard- *" we don't want the operations to have a certain assembly order"*

- Don't Include the severity of what happens when doing wrong

- This criterion is similar to the first criterion

The criteria are written by several core manufacturing engineers. Some criteria are very specific and while other are not. Hence there is no uniform way of write CAIs even though there are documents specifying what has to be included in the CAIs. This makes it hard to evaluate the criteria.
The difference between this criterion and the high complexity criterion #1:

10 (HC) Visual inspection of fitting and tolerances, i.e. subjective assessment of the quality results

Interpretations:
Visual inspection means: There is subjective assessment if the task quality is ok.

Evaluation:
If anything of following exists in the CAI:

- "Feel"
- "See"

The responsible core engineer is to be contacted to help evaluating if there is a subjective assessment in the CAIs.

Comments from the evaluation
This requirement only considers what is written in the description of the CAI. Maybe this criterion is fulfilled all the time, subconsciously, on the assembly line during manual assembly. However, it is only considered if "feel"/"see" is explicitly written in the CAI.

11 (HC) Accuracy/precision demanding

(LC) No precision-demanding operations, "no fitting"

Comment:
(This requirement is similar to the tenth complexity criterion "no clear mounting position")

Evaluation:
If any operation in the CAI contains anything from the following list, the CAI is considered precision demanding.
Requiring precision:

- Assemble & Inspect
- No specific markings of where the part is going to be assembled
- Fitting (fitting the detail within millimeters)
- Reference systems which are clear and easy to use to ease the precision demanding work.
- Bad working position/posture
- Tottering material ("*sviktande material*")
- Assembling with long distance to the detail

12 (HC) Need of adjustment

(LC) No adjustment needed

Comment:

Depends on how often there are deficiencies in the related to the CAIs. It is necessary to be able to refer the deficiencies occurring to the specific station where the deficiency was made.

Interpretations:

This criterion regards adjustments of the own work at the station.

Evaluation:

This complexity criterion is evaluated by the responsible core manufacturing engineers.

The responsible manufacturing engineers are contacted and the following questions are asked:

- How often are adjustments needed?
- Where are the adjustments needed?

13 (HC) Geometric environment has a lot of variation (tolerances), i.e. level of fitting and adjustment vary between the products

Comment:

This complexity criterion is evaluated by a geometry expert.

The expert evaluating the CAIs at VCC (the founder of the criterion) provided this explanation of how he is evaluating the criterion:

- Check the tolerances.
- Are the products within the tolerance limits?
- Is there a risk the parts cannot be assembled due to the tolerances?
- Tolerances close to/outside the limits.

In cases when the geometry expert did not know the operations in the CAIs, the mentioned questions are asked to the responsible core manufacturing engineers who then perform the evaluation.

Evaluation:

If the surrounding environment, where things are going to be assembled varies, it is considered as high complex.

If the detail you are assembling is depending on the surrounding components, it is considered as high complex.

Examples of where geometrics environment has a lot of variation:

- Several holes that has to overlap
- Components that are not joined
- Components that are moving relative to each other

If there is a fixture, this criterion is not satisfied (low complexity). The purpose of the fixture is to remove the influencing surrounding environment.

14 (HC) Need of in detail described work instructions

(LC) Self-evident operations that do not need written instruction

Evaluation:

Reflections about what an in detail described work instruction contain:

- In what order are components going to be assembled?
- How is the assembly going to be done?
- With what tools/components?

If there is a risk of assembling wrong if the work instructions are not followed.

The responsible Core engineers are contacted for the evaluation of this criteria for all CAIs.

Summary of key words to discuss with the core manufacturing engineers:

- Does it have anything to do with risks of what happens if the work instruction is not accurately followed?
- Does it have anything to do with the assembly sequence?
- Is it severe to use the right torque when screwing the screws?
- Related to need of adjustments?

15 Soft and flexible material

(LC) Form-resistant material that do not change shape or form during assembly

Evaluation:
If anything of the following is included in the CAI, the criterion of using ”soft and flexible material” is considered high complex:

Materials that not shall be used:

- Rubber splines (”*Gummilister*”)
- Rubber plugs (”*Gummipluggar*”)
- Cables (”*Kablage*”)
- Carpets (”*Mattor*”)
- Some of the panels (for example “*A- stolpe panel*”)
- The belt (*“bälte”*)
- Tubes (in this specific case, the Swedish word “*Spolarslang*”)
- Tottering assemblage (”*sviktande montering*”)
- Coverings (“*Täckningar*”)
- Wires (“*Vajrar*”)

Summary: Things that are not keeping its shape all the time during assembly.
The list might have to be updated when evaluating other CAIs. Then look for materials that can be considered to be soft and flexible, and discuss them with responsible core engineers if they are to be added to the list or not.

16 Lack of (immediate) feedback of properly done work, e.g. a click sound and/or compliance with reference points

(LC) Immediate feedback of proper installation e.g. a click sound and/or compliance with reference points

Evaluation:
The evaluation is done by experts knowing the instruction:

- Responsible Core Manufacturing Engineers.
- Ergonomics expert

Comment:
This criteria is closely related to the tenth complexity criterion “visual inspection of fitting and tolerances”. Maybe this requirement can be integrated into that criterion.

APPENDIX C - CONTACTED PERSONS

In this appendix a lists of involved persons are presented.

List of Interviewees

Mikael Karlsson	Core Mfg Eng. Interior
Bengt-Arne Henning	Core Mfg Eng. Trim and Final
Marcus Jonasson	Core Mfg Eng. Exterior
Daniel Svensson	Core Mfg Eng. Interior
Mikael Rosenqvist	Simulation engineer
Sari Rosenström	Core Mfg Eng. Ergonomist /specialist
Ove Fransson	Manager. RME
Alejandro Vega Galvez	Quality Engineer. TVQ
Per Åslund	Commodity Mfg Eng. Interior
Mattias Eliasson	Plant Man hour Control

Involved persons

Ann-Christine Falck	Researcher. PhD, Eur. Erg.
Roland Örtengren	Professor
Roy Börjeson	Quality Engineer. TVQ
Anna Bergelin	Quality Engineer. TVQ
Christer Carlsson	Quality Engineer. TVQ
Liselotte Johansson	Quality Engineer. TVQ
Anders Ortmon	Quality Core Manager, TVQ
Nina Honkonen	Material Coordinator
Mats Frösemo	Material Coordinator
Bojka Tesanovic	Team developer
Daniel Svennson	Production Supervisor
Mirko Marjanovic	Production Supervisor

APPENDIX D – INTERVIEW QUESTIONS

Here a guideline of questions regarding the subjective complexity criteria is provided. The questions are asked to the core manufacturing engineers responsible for the CAIs. The purpose of asking the questions is to evaluate whether the criteria are fulfilled or not. When the comments regarding the criteria are summarized it is also possible to evaluate how the criteria are evaluated and if some of the criteria are overlapping.

Under the headings of complexity numbers, the questions for respective questions are summarized.

HC 8 – Operator dependent operations requiring experience /knowledge to be properly done

- Would you say that there is a need of additional training or experience to perform this assemblage, beyond the common introductory session?
- Is this an assemblage/instruction, which a new employee can start with?
- What would you say characterize an operator dependent operation?

HC 9 - Operations must be done in a certain order

- In the CAI it is stated: “start with, and then do”. Is it important to exactly follow this order specified in the CAI or is it possible to assemble correctly in another way?

HC 11 - Accuracy/precision demanding

- Would you say this CAI is precision demanding?
  - Are there any specific markings of where the part is going to be assembled
  - Does the assembler need to inspect the assemblage every time to know it has been placed correctly?
  - It there any reference system to use that eases the precision work?
  - How is the working posture during assemblage?
  - Are any tottering material used that are sagging?

HC 12 – Need of adjustment

- Is there any need of adjustments when assembling?
- Is the detail that is assembled positioning correctly at the first time?

HC 14 – Need of in detail described work instructions

- What is written in the CAI seems to require an in detail described work instruction. Would you say this CAI needs a clear work instruction in order to be correctly performed?

APPENDIX E - DEFINITIONS OF COMPLEXITY FACTORS

The definitions of the 12 Complexity factors are developed by the use of SMART test and presented below.

1 Assembly order

Definition

S. Are there any part operations in the work instruction that need to be performed before the others.

M. Identify terms as “start with”, “first grab this” and so on.

A. The factor is attainable, look in the work instruction are any of the terms included in the instruction.

2. How to assemble

Definition

S. Read the work instruction, does it say anything about how the part operations shall be performed?

M. Look at how the part operations are written, e.g. “Tighten the screw” or “tighten the screw by doing …”

A. The factor is attainable, does the work instruction include part operations which are described in detail.

3. Many individual details and part operations

Definition

Same definition as for the second complexity criterion, see Appendix B - Definitions of Complexity criteria.

4. Time demanding operations

Definition

Same definition as for the third complexity criterion, see Appendix B - Definition of Complexity criteria.

5. Resources

Definition

S. Are there any kind of aids or resources to help guide the parts who is going to be mounted available?

M. Are there fixtures, reference systems, fitting tools available at the assembly station?

A. Attainable, read the work instruction and look for guiding tools, aids or resources to help guide the part that is going to be mounted.

6. Lack of feedback

Definition

S. Does the operator achieve any feedback or recognition when the part operations are fulfilled? If any of the part operations provide the operator with feedback, the factor is considered as not fulfilled.

M. Feedback in this context means a sound and/or light signal that indicate when the assembly operation is performed correctly.

A. Are there anything that signals that the part operations are correctly assembled?

7. Ergonomics

Definition

S. Does the assembly include operations which are considered bad in an ergonomic point of view, according to the company ergonomics regulations?

M. Use documents, with the company policies that regards ergonomics. A responsible ergonomist perform the evaluation with the help of work instructions and experience.

A. The factor is attainable if an ergonomist are available.

8. Precision

Definition

S. Use the work instruction and ask an experienced engineer if there are any part operations that are considered as precision demanding for the operator.

M. The experienced engineer's subjective evaluation.

A. The subjective evaluation by the engineer makes it problematic to clearly define what can be classified as a precision demanding operation.

9. Need of Subjective assessment

Definition

S. the operator himself judge if the quality of the assemblage is enough. This includes subjective assessment when it comes to part operations and the final results of the assembly task.

M. If the work instruction include the words “feel/ see” when it comes to quality checks, then the complexity factor is fulfilled. All manual quality checks included in the instructions are also considered as “need of subjective assessment”.

A. If there are any manual quality check operations or “feel/see” operations the factor is considered as fulfilled.

10. Soft and flexible

Definition

S. Are there any soft and/or flexible parts/ components included in the assembly task. The material of the part that is going to be assembled and the material of the surroundings are of interest. The factor is fulfilled if any of the following are included in the work instruction:

- Rubber splines
- Rubber plugs
- Cables
- Carpets
- Soft or flexible panels
- The seat belt
- Tubes Tottering assemablage
- Coverings
- Wires

M. See if any of the parts that are going to be mounted or the surrounding material are classified as soft and flexible.

A. Does the work instruction include any of the materials from the checklist? Then the complexity factor is fulfilled.

11. Need of Adjustments

Definition

S. Adjustments are required if assemblages/ operations not are performed right the first time. Tolerances of fitting parts might sometimes contribute to that there will be need of adjustments.

M. Read the work instruction and identify adjustment operations. Ask an experienced engineer if the assembly task often is in need of adjustments. E.g. does the work instruction include ”when needed adjust”,” when needed corrects”, ” be sure that…”

A. It is obvious if the work instruction include adjustment operations. When no adjustment operations are included in the instruction, the operator himself must judge if there is a need of adjustments.

12. Geometric surroundings

Definition

S. If the surrounding environment, where things are going to be assembled varies, it is considered as high complex. If the detail you are assembling is depending on the surrounding components, it is high complex.

M. If there is a fixture, this complexity factor is not fulfilled (low complex). The purpose of the fixture is to remove the influencing surrounding environment.

- Several holes that has to overlap
- Components that are not joined
- Components that are moving relative to each other

A. A geometrical expert evaluates this requirement

Comments from him telling how the evaluation was going to be performed:

- Check the tolerances.
- Are the products within the tolerance limits?
- Is there a risk the parts cannot be assembled due to the tolerances?
- Tolerances close to/outside the limits.

If fitting is needed, the criterion is fulfilled.

APPENDIX F – COMPLEXITY CRITERIA EVALUATIONS OF 28 CAIS

In this appendix the complexity criteria evaluation of the 28 CAIs are presented. Each CAI has been evaluated with respect to each of the 16 complexity criteria. A red mark indicate that the CAI is considered as high complex (HC) with respect to the specific criteria, a green mark indicate that the CAI is considered as low complex with respect to the specific criteria. The appendix also includes a list of the 28 CAIs, some of the CAIs are studied as one due to that they follow each other; this is indicated by a square.

	Complexity criteria															
CAI	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
2	HC	HC	🟩	🟩	🟩	🟩	🟩	🟩	HC	🟩	🟩	🟩	🟩	HC	🟩	🟩
3	🟩	HC	HC	🟩	HC	🟩	HC	🟩	HC	🟩	🟩	🟩	HC	🟩	🟩	🟩
4	🟩	🟩	🟩	HC	HC	🟩	HC	HC	HC	HC	HC	🟩	HC	HC	HC	HC
5	🟩	HC	🟩	HC	HC	🟩	HC	HC	HC	HC	HC	HC	HC	HC	🟩	HC
6	🟩	🟩	HC	🟩	HC	HC	HC	🟩	HC	🟩	HC	🟩	🟩	🟩	HC	🟩
7	🟩	HC	HC	🟩	HC	HC	HC	🟩	HC	🟩	HC	🟩	🟩	🟩	HC	🟩
8	HC	🟩	🟩	HC	HC	HC	HC	🟩	HC	HC	HC	🟩	HC	HC	HC	🟩
9	HC	🟩	🟩	🟩	🟩	🟩	HC	🟩	🟩	HC	🟩	🟩	🟩	🟩	🟩	🟩
10	🟩	HC	🟩	🟩	HC	🟩	🟩	🟩	HC	HC	HC	🟩	HC	HC	HC	🟩
11	HC	HC	HC	🟩	HC	🟩	🟩	🟩	HC	🟩	HC	🟩	HC	🟩	HC	🟩
12	🟩	HC	🟩	🟩	🟩	🟩	🟩	HC	🟩	🟩	🟩	🟩	🟩	HC	🟩	🟩
13	🟩	HC	HC	🟩	HC	HC	HC	HC	HC	🟩	HC	🟩	🟩	🟩	🟩	🟩
14	🟩	HC	🟩	🟩	🟩	🟩	🟩	🟩	HC	HC	🟩	HC	HC	🟩	HC	🟩
15	🟩	HC	🟩	🟩	HC	🟩	HC	🟩	HC	🟩	HC	🟩	🟩	🟩	HC	HC
16	🟩	HC	HC	HC	HC	🟩	HC	HC	HC	🟩	🟩	🟩	🟩	HC	HC	HC
17	🟩	🟩	🟩	HC	HC	🟩	HC	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	HC
18	HC	HC	HC	🟩	🟩	🟩	🟩	HC	HC	🟩	🟩	🟩	🟩	HC	🟩	HC
19	HC	🟩	HC	🟩	🟩	🟩	🟩	🟩	HC	HC	HC	🟩	🟩	HC	🟩	HC
20	HC	🟩	🟩	🟩	🟩	🟩	🟩	HC	HC	HC	🟩	HC	HC	HC	🟩	HC
21	HC	HC	HC	🟩	🟩	🟩	🟩	🟩	HC	HC	🟩	HC	HC	HC	🟩	🟩
22	HC	HC	HC	🟩	🟩	🟩	🟩	🟩	HC	🟩	🟩	HC	HC	HC	🟩	🟩
23	HC	HC	HC	HC	🟩	🟩	🟩	HC	HC	🟩	HC	🟩	HC	HC	🟩	🟩
24	HC	HC	HC	🟩	🟩	🟩	🟩	HC	HC	HC	🟩	🟩	HC	HC	🟩	🟩
25	🟩	HC	HC	🟩	HC	🟩	HC	🟩	🟩	HC	🟩	🟩	🟩	🟩	🟩	HC
26	HC	HC	HC	🟩	HC	🟩	HC	🟩	HC	HC	🟩	🟩	🟩	HC	HC	HC
27	HC	🟩	🟩	🟩	🟩	🟩	🟩	HC	HC	🟩	🟩	HC	HC	HC	HC	HC
28	🟩	HC	🟩	🟩	🟩	🟩	🟩	HC	HC	HC	🟩	HC	HC	HC	🟩	HC

Number	CAI number	Description	Category
1			
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APPENDIX G – EVALUATION MODEL FOR THE COMPLEXITY CRITERIA LEVEL

In this appendix the evaluation model developed in Falck (2012c) is presented.

Complexity level	Level of complexity	Level of fulfillment for 16 low complex criteria		Level of fulfillment for 16 high complex criteria	
Green	Low	15-16	(94-100%)	0-3	(0-19%)
Yellow-green	Rather low	12-14	(75-88%)	4-7	(44-25%)
Yellow	Moderate	8-11	(50-69%)	8-11	(50-69%)
Yellow-red	Rather high	4-7	(44-25%)	12-14	(75-88%)
Red	High	0-3	(0-19%)	15-16	(94-100%)

APPENDIX H – CORRELATION ANALYSES BETWEEN COMPLEXITY AND QUALITY DEFICIENCIES AND COMPLEXITY AND COSTS OF QUALITY DEFICIENCIES

In this appendix the results from the SPSS simulation is presented. A correlation analysis has been performed between the following:

- Number of fulfilled complexity criteria and quality deficiencies (DPTO)
- Number of fulfilled complexity criteria and quality deficiencies (DPTO) (excluding screw driving's)
- Number of fulfilled complexity criteria and costs of quality deficiencies
- Number of fulfilled complexity criteria and cost of quality deficiencies (excluding screw driving's)
- Number of fulfilled complexity factors and quality deficiencies (DPTO)
- Number of fulfilled complexity criteria and quality deficiencies (DPTO) (excluding screw driving's)
- Number of fulfilled complexity factors and costs of quality deficiencies
- Number of fulfilled complexity factors and cost of quality deficiencies (excluding screw driving's)

		Number of fulfilled complexity criteria (16 criteria)	Quality deficiencies (DPTO)
Number of fulfilled complexity criteria (16 criteria)	Pearson Correlation	1	-,166
	Sig. (2-tailed)		,399
	N	28	28
Quality deficiencies (DPTO)	Pearson Correlation	-,166	1
	Sig. (2-tailed)	,399	
	N	28	28

		Number of fulfilled complexity criteria (16 criteria)	Quality deficiencies (DPTO) (excluding screw driving's)
Number of fulfilled complexity criteria (16 criteria)	Pearson Correlation	1	,084
	Sig. (2-tailed)		,671
	N	28	28
Quality deficiencies (DPTO) (excluding screw driving's)	Pearson Correlation	,084	1
	Sig. (2-tailed)	,671	
	N	28	28

		Number of fulfilled complexity criteria (16 criteria)	Costs of quality deficiencies (per produced car)
Number of fulfilled complexity criteria (16 criteria)	Pearson Correlation	1	-,151
	Sig. (2-tailed)		,442
	N	28	28
Costs of quality deficiencies (per produced car)	Pearson Correlation	-,151	1
	Sig. (2-tailed)	,442	
	N	28	28

		Number of fulfilled complexity criteria (16 criteria)	Costs of quality deficiencies (per produced car) (excluding screw driving's)
Number of fulfilled complexity criteria (16 criteria)	Pearson Correlation	1	-,0,25
	Sig. (2-tailed)		,899
	N	28	28
Costs of quality deficiencies (per produced car) (excluding screw driving's)	Pearson Correlation	-,0,25	1
	Sig. (2-tailed)	,899	
	N	28	28

		Number of fulfilled complexity factors (12 factors)	Quality deficiencies (DPTO)
Number of fulfilled complexity factors (12 factors)	Pearson Correlation	1	-,155
	Sig. (2-tailed)		,430
	N	28	28
Quality deficiencies (DPTO)	Pearson Correlation	-,155	1
	Sig. (2-tailed)	,430	
	N	28	28

		Number of fulfilled complexity factors (12 factors)	Quality deficiencies (DPTO) (excluding screw driving's)
Number of fulfilled complexity factors (12 factors)	Pearson Correlation	1	,283
	Sig. (2-tailed)		,144
	N	28	28
Quality deficiencies (DPTO) (excluding screw driving's)	Pearson Correlation	,283	1
	Sig. (2-tailed)	,144	
	N	28	28

		Number of fulfilled complexity factors (12 factors)	Costs of quality deficiencies (per produced car)
Number of fulfilled complexity factors (12 factors)	Pearson Correlation	1	,110
	Sig. (2-tailed)		,578
	N	28	28
Costs of quality deficiencies (per produced car)	Pearson Correlation	,110	1
	Sig. (2-tailed)	,578	
	N	28	28

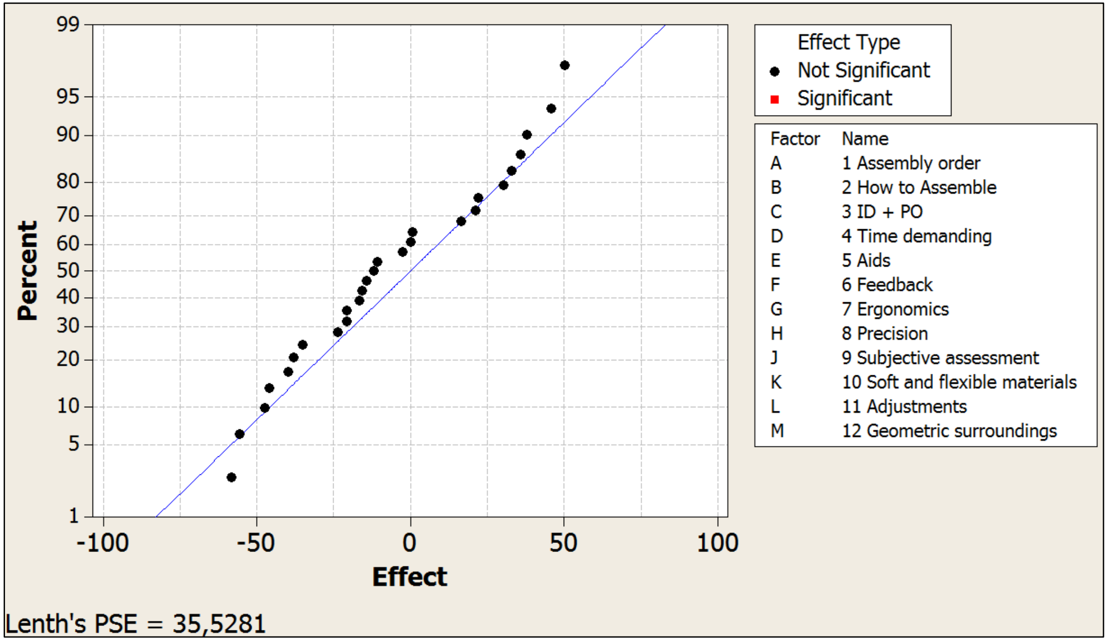
		Number of fulfilled complexity factors (12 factors)	Costs of quality deficiencies (per produced car) (excluding screw driving's)
Number of fulfilled complexity factors (12 factors)	Pearson Correlation	1	,365
	Sig. (2-tailed)		,056
	N	28	28
Costs of quality deficiencies (per produced car) (excluding screw driving's)	Pearson Correlation	,365	1
	Sig. (2-tailed)	,056	
	N	28	28

APPENDIX I – NORMAL PROBABILITY PLOTS

In the appendix the Normal probability plots from the DOE analysis are presented. The results show which complexity factors, or two- complexity factor combinations that are significant.

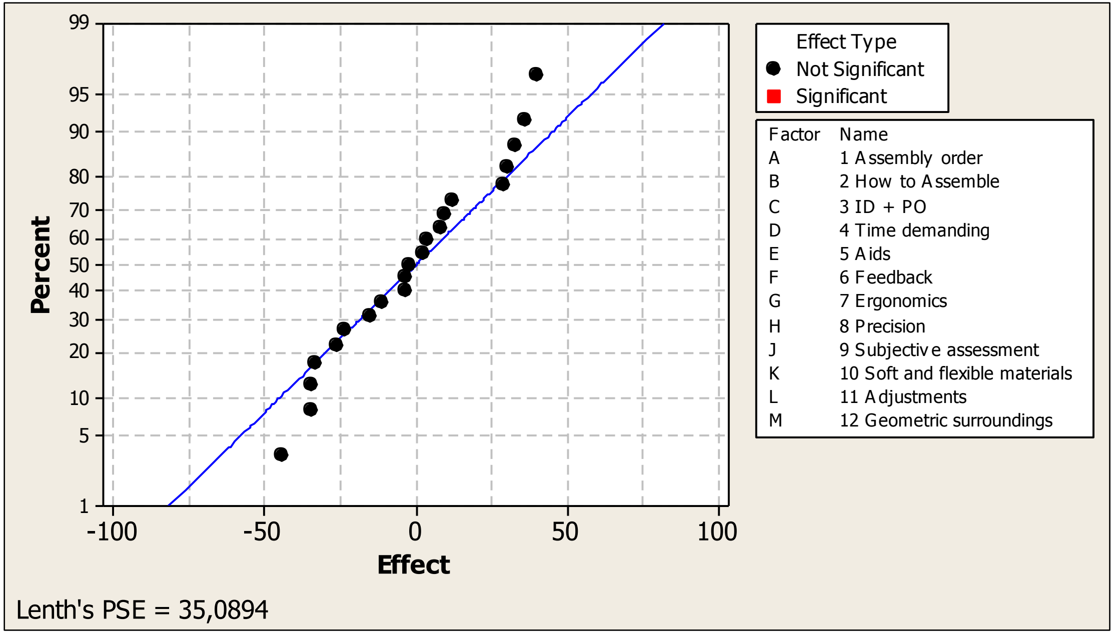
Normal plot of the effects

(Response is Quality deficiencies (DPTO), Alpha =0,05)



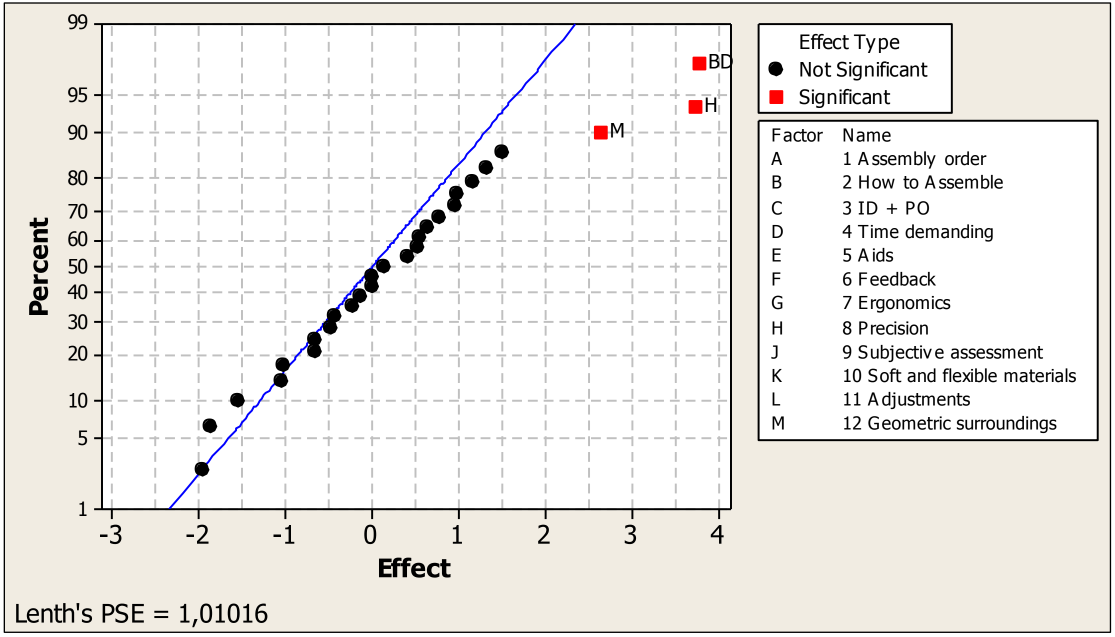
Normal plot of the effects

(Response is Quality deficiencies (DPTO) (excluding screw driving's), Alpha =0,05)



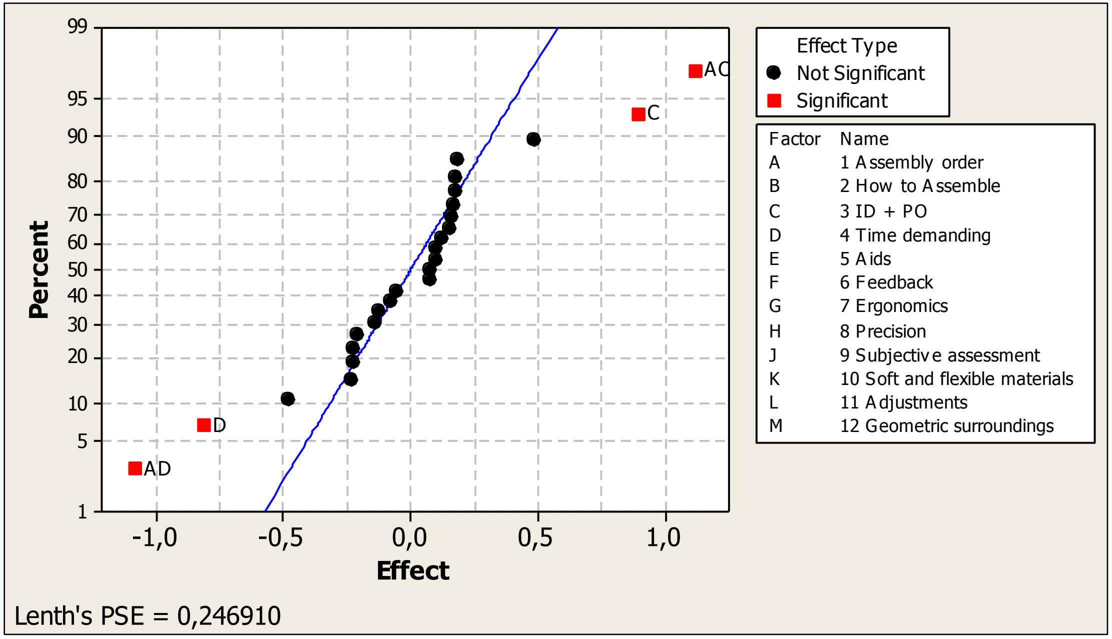
Normal plot of the effects

(Response is Cost of quality deficiencies (per produced car), Alpha =0,05)



Normal plot of the effects

(Response is Cost of quality deficiencies (per produced car) (excluding screw driving's, Alpha =0,05)

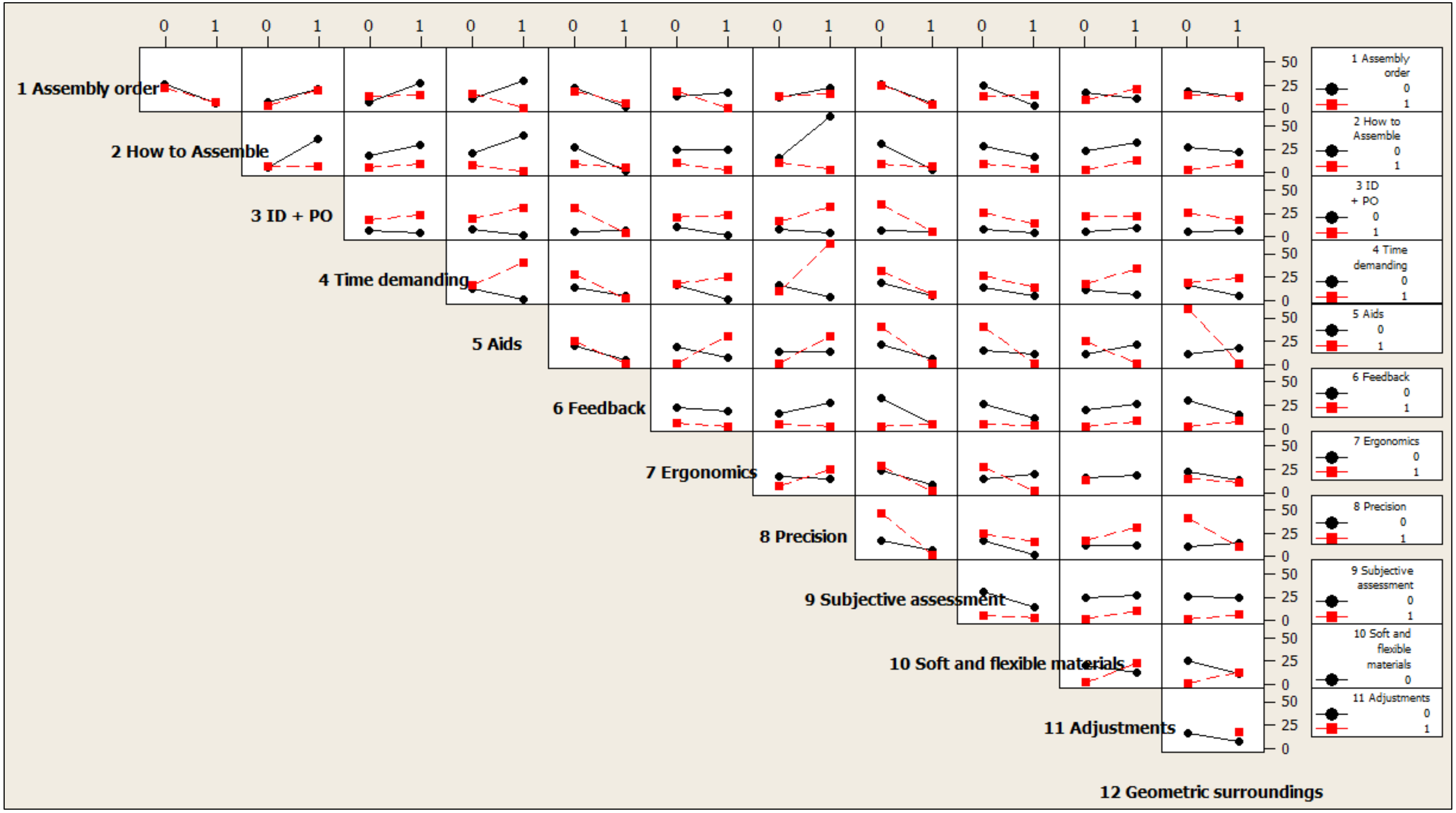


APPENDIX J – INTERACTION PLOTS

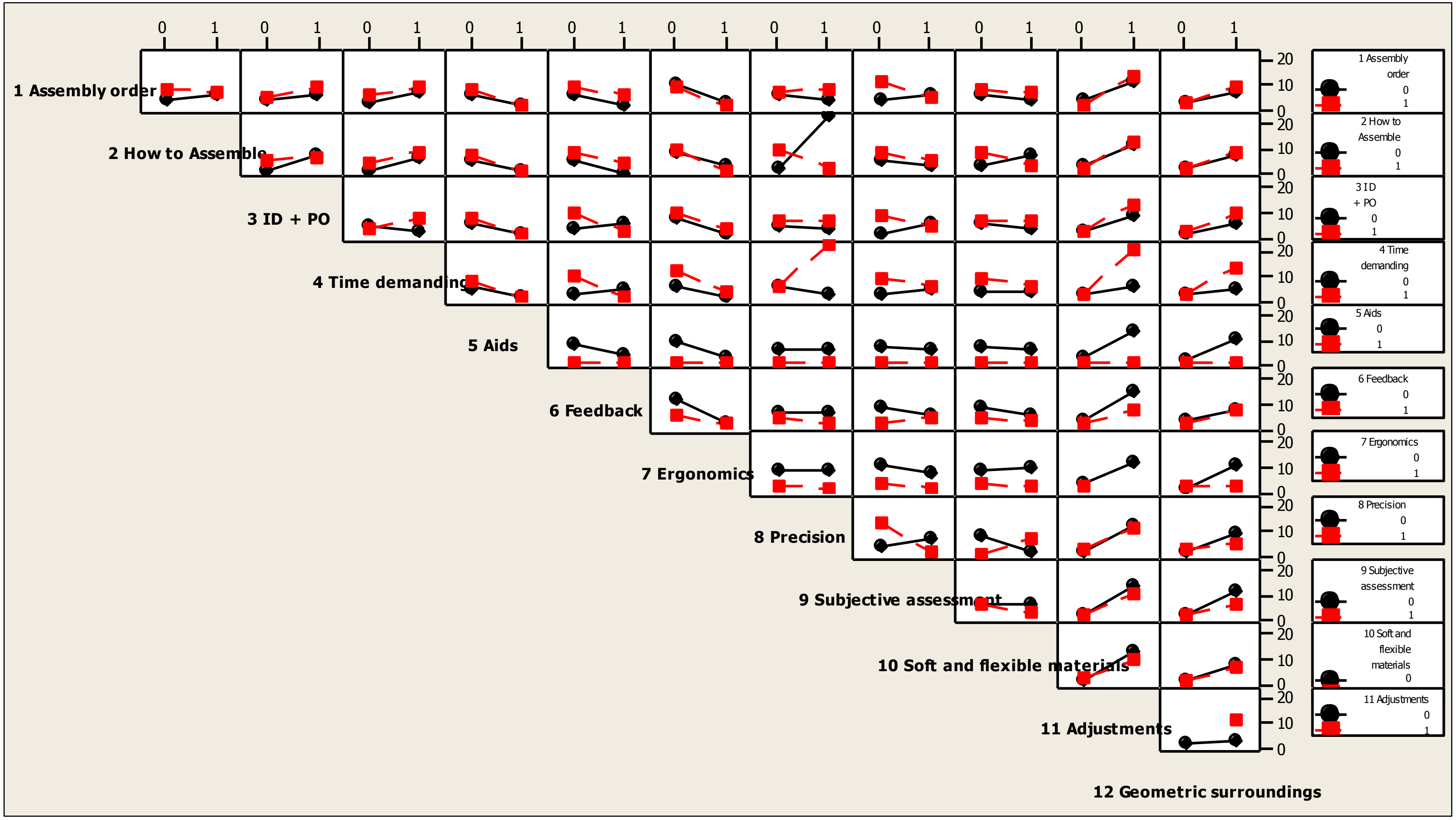
In the appendix the Interaction plots from the DOE analysis are presented. The results show which effect each two- complexity factor interaction have on the response variable.

The red line in the plot shows the effect when complexity factor x is fulfilled (high complexity) and factor y goes from not being fulfilled (low complexity) to being fulfilled. The slope of the red line indicates that when doing this, it will have a negative effect, which means reduced costs.

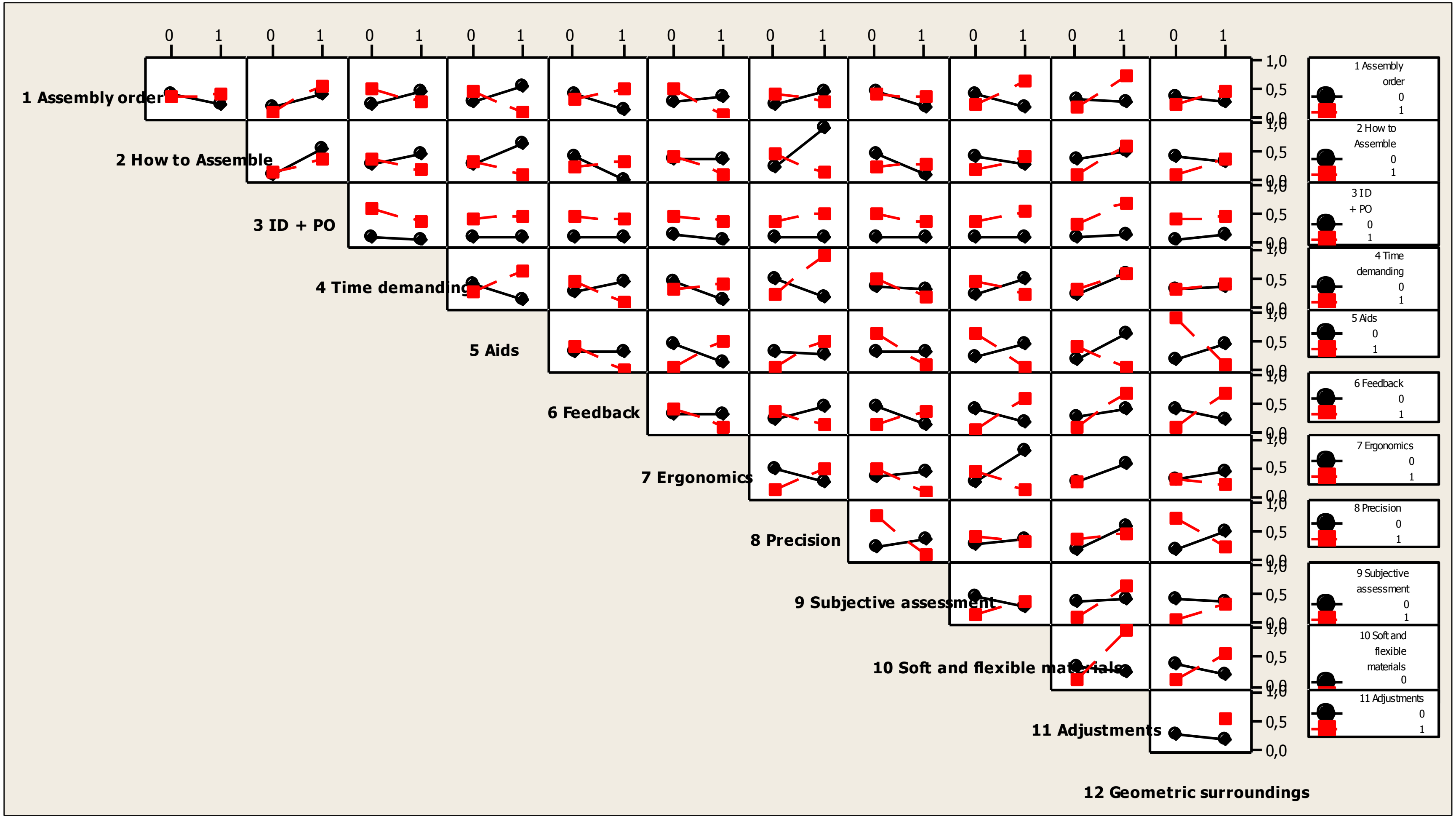
Interaction plot for quality deficiencies (DPTO)



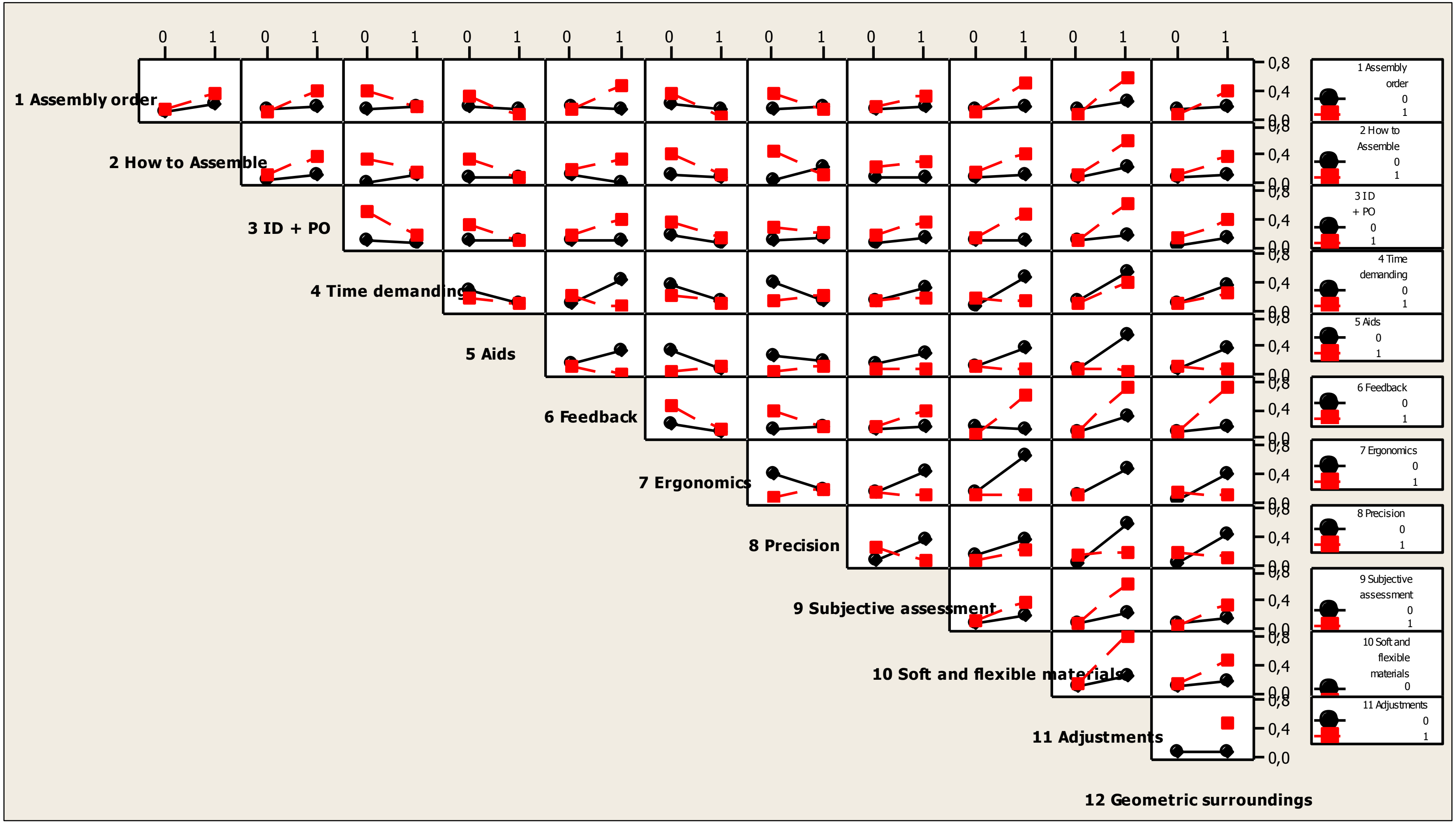
Interaction plot for quality deficiencies (DPTO) (per produced car) (excluding screw driving's)



Interaction plot for costs of quality deficiencies (per produced car)



Interaction plot for costs of quality deficiencies (per produced car) (excluding screw driving's)



APPENDIX K – LIST OF QUALITY DEFICIENCIES

In this appendix a list of the quality deficiencies related to the CAI categories are presented. The Quality deficiencies are gathered from QDLS and the names are the same as the QDLS items. The Names starting with an 'D' are screw driving's deficiencies

APPENDIX L – ILLUSTRATION OF GPDS