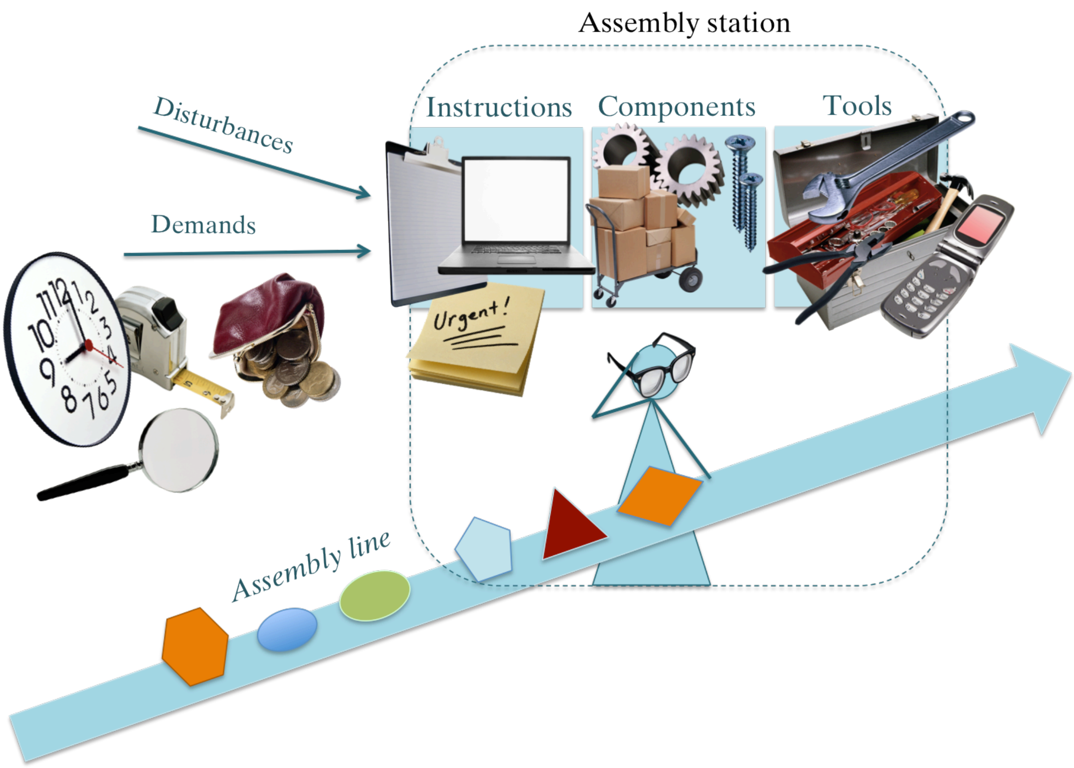
THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING



What is perceived as complex in final assembly?

To define, measure and manage production complexity

SANDRA MATTSSON

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

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Licentiate Thesis
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ABSTRACT

Production complexity affects quality, reliability, performance and production time. Due to the high complexity in final assembly, manual assembly is used to handle the high product variety, flexibility and small batch sizes. To improve and find optimal conditions for the worker is therefore essential. The aim of this thesis is to make production companies more competitive by suggesting how production complexity can be managed i.e. reduce risk, handle uncertainty and catch benefits of having such a system. To manage production complexity it first has to be defined and measured i.e. the objectives are to **define, measure and manage production complexity**. These have been investigated in a case study and field experiments where theory and empirical data was combined to ensure the quality of the research. Production complexity was defined *as the interrelations between product variants, work content, layout, tools and support tools, and work instructions.* To capture all aspects of the system it was empathized that both subjective and objective aspects should be measured. The subjective production complexity was measured by using the developed method the CompleXity Index (CXI) that *simplifies* complexity by visualizing the interrelations between the identified elements. To manage production complexity CXI could be used in conjunction with an objective method to *prevent* complexity and *avoid* negative effects. Managing production complexity this way could increase quality and productivity, ensure reliability and decrease production time. Future work includes further developing the method and to include organizational and external environmental aspects.

Keywords: Production complexity, final assembly, automotive, socio-technical systems, quantitative methods.

This thesis includes a:

- Definition of production complexity in final assembly
- Description of, and empirical results supporting, how production complexity can be measured using a developed method
- Comparison of nine quantitative methods
- Suggestion of how production complexity can be managed by combining methods

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Last but not least: thanks to my dear cat Starbuck, for being my fluffy and faithful companion.

Thank you all for making it possible for me to write this thesis.

Sandra Mattsson

Högsbo, Gothenburg, July 2013

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LIST OF APPENDED PAPERS

This is a list of the appended papers, which were all part of the COMPLEX project. The contribution of each author varied. In relation to each paper Mattsson's contribution is described.

Paper II: Fässberg, T., Harlin, U., Garmer, K., Gullander, P., Fasth, Å., **Mattsson, S**., Dencker, K., Davidsson, A. & Stahre, J (2011). *An empirical study towards a definition of production complexity,* Proceedings of the 21st International Conference on Production Research (ICPR), 31st July – 4th August, Stuttgart, Germany.

Contribution: Mattsson did the empirical analysis together with Fässberg. Fässberg was the corresponding author and presented the paper.

Paper II: **Mattsson, S**., Gullander, P. &Davidsson, A. (2011), *Method for Measuring Production Complexity*, in International Manufacturing Conference IMC 28 - Manufacturing Sustainability, 30th August – 1st September, Dublin City University, Ireland.

Contribution: Mattsson initiated the paper and wrote it together with Gullander and Davidsson. Mattsson was the corresponding author and presented the paper.

Paper III: **Mattsson, S**., Gullander, P., Harlin, U., Bäckstrand, G., Fasth, Å. & Davisson, A. (2012), *Testing complexity index – a method for measuring perceived production complexity*, Proceedings of 45th Conference on Manufacturing Systems (CMS45), 16-18th of May, Athens, Greece, Elsevier, pp 394-399.

Contribution: Mattsson initiated the paper and wrote it together with the co-authors. Mattsson was the corresponding author and presented the paper.

Paper IV: **Mattsson, S**., Fasth, Å., Dencker, K., Gullander, P., Stahre, J., Karlsson, M. & Davidsson, A. (2013), *Validation of the complexity index method at three manufacturing companies*, Proceedings of the International Symposium of Assembly and Manufacturing (ISAM), 30th July-2nd August, Xian, China.

Contribution: Mattsson initiated the paper and wrote it together with the co-authors. Mattsson was the corresponding author and presented the paper.

Paper V: **Mattsson, S**., Gullander, P., Karlsson, M., Fasth, Å. Landeghem, H. V., Zeltzer, L., Limère, V., Aghezzaf, E-H. & Stahre, J. *Comparing quantifiable methods to manage assembly complexity*. (submitted to) International Journal of Manufacturing Research.

Contribution: Mattsson initiated the paper and wrote it together with the co-authors. Mattsson was the corresponding author.

DEFINITIONS

Assembly is the process where a shape is obtained by joining pre-shaped components to form a new shape. The components can be joined permanently or semi permanently (Groover, 2001) and this is achieved by integrating material, energy and information (Andreasen et al., 1983). The typical assembly plant include the following stages: stamping, body shop, paint and final assembly (Papakostas et al., 2010).

Complicated A complicated problem has a formula that can be carried out by personnel with some expertise. The outcome has a high degree of certainty (Rogers, 2008).

Complexity Complexity in a system can be defined as something that is "*difficult to understand, describe, predict or control*" (Sivadasan et al., 2006). Weaver stated that complexity in a system is, given the systems parts, the difficulty in predicting the system properties (Weaver, 1948). A complex problem cannot be described using a formula (Rogers, 2008). Also even though a formula was followed it does not ensure success i.e. there is a high degree of uncertainty. Also having expertise can assure success but it is neither necessary nor sufficient. This means that every problem complex is unique (Ibid.).

Final assembly is the last stage in final assembly in which all components are put together.

Managing complexity means to reduce risk, handle uncertainty and catch benefits of having such a system (ElMaraghy et al., 2012).

Manufacturing *"a series of interrelated activities and operations involving design, material selection, planning, production, quality assurance, management and marketing of the product of the manufacturing industries"* (in this definition the manufacturing system is superior to production system)(CIRP, 2008).

Method A research method provides a specific design for research. The method is based on theory that proves it value and use (Williamson, 2002).

Methodology *"a set of principles of methods, which in any particular situation have to be reduced to a method uniquely suitable to that particular situation"* (Checkland, 1993).

Production is *"the act or process (or connected acts of processes) of actually physically making a product from its material constituents, as distinct from designing the product, planning and controlling its production, assuring its quality"* (in this definition the manufacturing system is superior to production system, http://www.cirp.net, 2008) or A production system is a collection of people, equipment and procedures organised to perform manufacturing operations at a company. A production system covers all steps in the chain from raw material to end customer (Groover, 2001; Löfgren, 1983; Tangen et al., 2008; CIRP, 2008)) (in this definition the production system is superior to the manufacturing system).

Role is connected to a workers work tasks and employment post e.g. assembly worker, team-leader. The role could include different abstraction levels like responsible for quality, health issues and so on.

Theory is an explanatory viewpoint or perspective (Williamson, 2002).

Qualitative research implies a focus on the meanings and the processes in a studied area. This is different from **Quantitative research** that focus on measurement and analysis of causal relationships (Denzin and Lincoln, 1998).

ABBREVATIONS

CXB Method for measuring complexity, developed at Chalmers

CXC CompleXity Calculator, developed in the Belgian COMPLEX-project

CXI CompleXity Index, method developed in this thesis

INUS Insufficient but Necessary part of an Unnecessary but Sufficient

OCC Operator Choice Complexity

RI Robustness Index, developed in-house at Volvo Car Corporation

i.e. Id est (that is)

e.g. Exempli gratia (for example)

et al. Et alia (with others)

Ibid. Ibidem (the same place)

PREFACE

The research project COMPLEX[1], *Support for Operation and Man-hour Planning in Complex Production*, was conducted from 2010 until 2013 (in which I took part in the start of 2011). The overall focus was to reduce complexity by developing generic models and methods to support strategies, planning, managing, and optimizing of complex production. The project was funded by Vinnova within the program *Production Strategies and Models for Product Realization* and was carried out in collaboration between Swerea IVF, Chalmers, Volvo Cars, Electrolux, Stoneridge Electronics, and The Volvo Group. Their support is gratefully acknowledged. My contribution to the project research group was in the beginning to simplify and analyse already gathered data (this is also why I am the fifth author of the first appended paper - Paper I). Then I took over a work package, which had the aim to define production complexity and develop a method that could measure production complexity.

In addition, some results from the research project *The Operator of the Future* were included[2]. The project goal is a future toolbox for competent individuals close to production processes. Such operators could have high impact on flexibility, productivity, and quality. The research has been carried out within the framework of the Sustainable Production Initiative, and the Production Area of Advance at Chalmers.

Although my background is in automation engineering, I have also studied psychology (90 academic points). My interest in psychology has concerned how humans perceive the world and which cognitive limitations influence that view. For instance we as humans have difficulty to keep more than 7 plus minus 2 things in our working memory at the same time (Reisberg, 2001). This introduces a challenge when we want to solve a complex problem (such as, for example, those presented in complex calculation). I was therefore interested in how production complexity could be measured and if complexity could be visualized in a simple way so that production companies can better understand and reach the possible benefits of complexity.

> *"We must make the cars simple. I mean we must make them so that they are not too complicated from a mechanical standpoint, so that people can operate them easily, and with the fewer parts the better" (Bak, 2003), pp 38 - Henry Ford, 1903*

[1] http://www.chalmers.se/en/projects/Pages/Komplex-produktion-St%C3%B6d-f%C3%B6r-optimering-av-direkt-och-indirekt.aspx

[2] http://www.vinnova.se/sv/Resultat/Projekt/Effekta/Framtidsoperatoren1/

1 INTRODUCTION

This chapter introduces the challenges of production complexity and explains the importance of measuring and studying the subjective aspects of complexity. Furthermore, the aim and research questions are presented coupled to the continued disposition of the thesis.

1.1 Background

Assembly systems today are complex due to high product variety (Orfi et al., 2011; Schleich et al., 2007; Hu et al., 2008; MacDuffie et al., 1996) and social sustainability (Chui et al., 2012; Regeringen, 2012; ElMaraghy et al., 2012). One reason for the high product variety is mass-customization, which is the strategy to deliver customized products to a cost similar to products that have been mass-produced (Coletti and Aichner, 2011). Mass-customization forces the assembly system to handle high flexibility, small batch sizes, small product volume and a high number of variants (Heilala and Voho, 2001) at a low cost (Schleich et al., 2007) (Papakostas et al., 2010). In addition, the assembly system has demands regarding social sustainability that makes it important for the production companies to be attractive to a workforce with varying age, skills and health issues (Chui et al., 2012; Regeringen, 2012). Increased complexity is one of the biggest challenges in manufacturing today (ElMaraghy et al., 2012).

The assembly system is a crucial part of manufacturing, especially in terms of cost. Approximately one third of the manufacturing workers are involved with assembly tasks (ElMaraghy et al., 2010) and 25-50% of the total cost is spent on assembly (Bi et al., 2007). In the context of automotive industry, which is the main focus of this thesis, 50% of the labour cost is spent on the assembly systems (ElMaraghy et al., 2010).

Effects of production complexity

Production complexity affects quality (Falck and Rosenqvist, 2012; Fässberg et al., 2011), reliability (Grote, 2004), performance (Guimaraes et al., 1999) (Perona and Miragliotta, 2004) and production time (Urbanic and ElMaraghy, 2006; Lokhande and Gopalakrishnan, 2012). Due to that final assembly work is often carried out manually or partly automatic (Fasth et al., 2010; Papakostas et al., 2010) the role of humans is increasingly important (Oborski, 2003) e.g. bad choices are connected to high costs. In a study of 47 manual assembly tasks it was seen that complex assembly tasks were significantly correlated with the cost of correcting the assembly errors (Falck and Rosenqvist, 2012). The cost also included warranty and repair cost. However, a complex and dynamic context also requires human intelligence and expertise (Billings, 1997; Jensen and Alting, 2006; Fasth et al., 2009).

Therefore, managing complexity is connected to improving the operator performance i.e. to decrease process errors, achieve high quality, achieve good working conditions, fast processes, quick change-overs, to decrease cost (Schleich et al., 2007) (Papakostas et al., 2010; Heilala and Voho, 2001).

Need to measure subjective aspects of production complexity

Although complexity has been studied there is no common approach and many models are theoretical (Orfi et al., 2011; Calinescu, 1998; Frizelle and Suhov, 2001; Chryssolouris et al., 2013). Assessing complexity is crucial in order to increase awareness of the problems and also the causes and effects of complexity (Calinescu, 1998).

Chryssolouris et al. (2013) state that in order to manage and consider a complex system the system needs to be quantifiable. However, since existing quantitative methods e.g. the entropy model (Frizelle and Suhov, 2001) and the operator choice complexity (Wu et al., 2007) often assess objective aspects of complexity e.g. number of components and tools, a method was developed in this thesis, that instead measures the subjective complexity.

Studying subjective aspects means to study how different people perceive the complexity e.g. opinions. Personnel working with the assembly system may perceive an objectively simple system as very complex e.g. although a car has few and similar parts it can still be complicated to assemble (Gullander et al., 2011). Studying how the employees perceive their work is crucial in order to successfully manage and design the system (Grote, 2004; Taylor, 1911; Mavrikios et al., 2007).

Managing production complexity

The management of complexity has been considered by different approaches e.g. by (Corbett et al., 2002; Kaluza et al., 2006; Wiendahl and Scholtissek, 1994). The word manage suggests that it is not evident that production complexity should be reduced. This is since many times it is not possible to reduce the complexity due to market demands. Suggested ways to manage complexity are to *prevent* or *avoid* it (Corbett et al., 2002; Kaluza et al., 2006) and Weindeahl and Scholtissek (1994) stated that complexity should be *reduced* and *simplified*.

Although complex systems are unpredictable, it is possible to find strategies to manage complexity i.e. reduce risk, handle uncertainty, control the system and catch benefits of having such a system (ElMaraghy et al., 2012; Kreimeyer and Lindemann, 2011). For instance, in a study including 14 Italian companies, it was seen that the performance of the company was connected to the way they managed their complexity (Perona and Miragliotta, 2004). ElMaraghy et al. (2012) stress that manufacturing companies can reach competitiveness by more effectively managing and innovating socio-technical systems. Final assembly can be seen as a socio-technical system that according to Urbanic and ElMaraghy (2006) should incorporate both human characteristics and skills, as well as the technical capabilities (Ropohl, 1999). This means that when changes are introduced to a system all parts of the sub-system should be investigated to avoid sub-optimization (Hendrick and Kleiner, 2001). Managing production complexity from an assembly perspective can help reduce cost, time and thereby increase productivity, quality, profitability and competitiveness (Samy and ElMaraghy, 2012).

> *"Simplicity is a great virtue but it requires hard work to achieve it and education to appreciate it. And to make matters worse: complexity sells better."*
>
> \- Edsger Wybe Dijkstra

1.2 Aim, objectives and research questions

To avoid the negative effects of production complexity it is important to identify the elements of complexity thereby creating a common understanding, reducing the uncertainties of production complexity. The elements should be measurable and incorporate subjective aspects so that it is possible to better manage production complexity.

The aim of this thesis is to make production companies more competitive by suggesting how production complexity can be managed.

Studying the following objectives can fulfil the presented aim: to define, measure and manage production complexity. The objectives are coupled to a research question respectively. As a simplification, when *complexity* is written throughout this thesis, *production complexity* is intended.

The first Research Question (RQ1) creates a basis for understanding production complexity:

RQ1

How can production complexity be defined in a final assembly context?

Even though there exist several definitions of production complexity, many of them are theoretical models. In a final assembly context the complexity can be high and in order to be competitive and produce high quality products there is a need to be able to share a language for what complexity is (making it possible for people with different roles and experiences to talk about complexity). Therefore it is important to define what production complexity is in a final assembly context.

As there are many definitions of complexity, there are also many ways to measure complexity i.e. quantify complexity. However, most methods focus on objective data. Since final assembly can be understood as a socio-technical system, it is important to study the workers opinion of complexity. Therefore it is important to be able to measure production complexity (based on the definition of production complexity).

RQ2

How can production complexity be measured in a final assembly context?

The third Research Question (RQ3) illustrates the usefulness of the two first questions in an industrial context:

RQ3

How can a measurement of production complexity be used to manage production complexity in a final assembly context?

When a measurement of complexity have been suggested it is important to establish its practical usefulness. It is important that the measurement is easy to understand by different roles and that the workers view can be captured without loosing valuable production time. It is also important to discuss how and when the measurement should be used.

The research questions are connected to the objectives and the disposition, which is presented in Table 1.

Table 1: Research question connected to objectives and chapter

Research Question (RQ)	**Objective**	**Chapter**
RQ1: How can production complexity be defined in a final assembly context?	To define production complexity (in theory and practice)	4.1
RQ2: How can production complexity be measured in a final assembly context?	To measure production complexity (in theory and practice)	4.2
RQ3: How can a measurement of production complexity be used to manage complexity in a final assembly context?	To manage production complexity (in theory and practice)	4.3

Figure 1: Research objectives, questions and process summarize how the objectives are coupled to the research process.

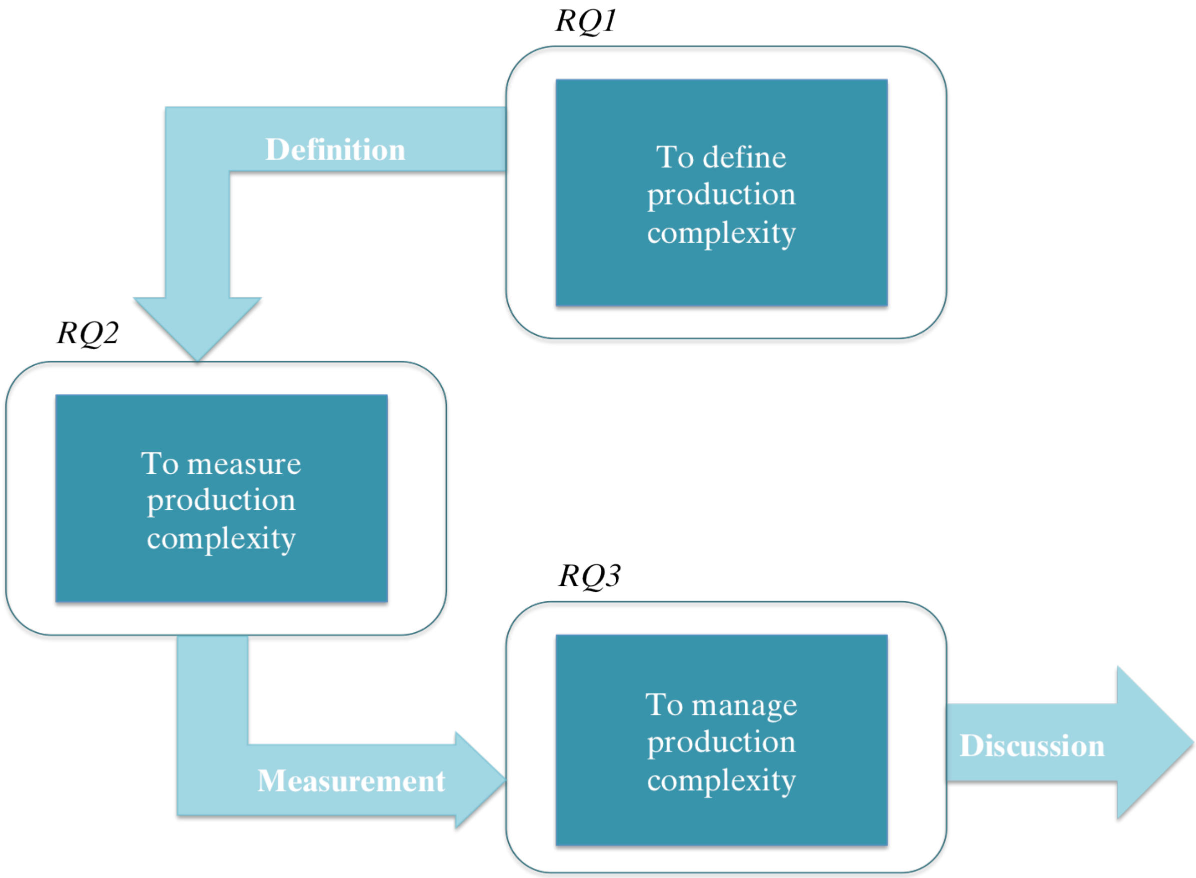

Figure 1: Research objectives, questions and process

1.3 Delimitations

Although a holistic view is emphasized, this thesis is limited to the following:

- Final assembly is mainly studied in an automotive industry context, although other types of companies are included in the studies (project partners are named in Acknowledgements).
- Production complexity is regarded mainly from an operator perspective, where aspects regarding learning, decision-making, motivational factors and stress are delimited. Perception (i.e. information handling and the way humans understand their world), competence and other working roles are discussed e.g. team leader, logistical personnel.
- Production complexity is measured at a station level not including aspects regarding organization or maintenance. Productivity measures e.g. time and quality are discussed briefly.
- Managing production complexity is mainly seen from a team leader perspective i.e. a person responsible for planning the production work at that station according to resources (both material and human). One prerequisite is that this person has the mandate to introduce changes to the station, e.g. changes in the material façade, layout or re-balancing.
- In this thesis management of complexity is considered in terms of simplifying, preventing and avoiding complexity and its negative effects.

1.4 Disposition of thesis

The disposition of this thesis is presented in Figure 2. The research approach and methods used are presented in Chapter 2. As a background the theoretical framework is presented in Chapter 3. Then the answers to RQ1-3 are presented in Chapter 4: TO define, measure and manage production complexity. The results are discussed and compared to theory in Chapter 5: Discussion. A summary of the results is presented in Chapter 6: Conclusions.

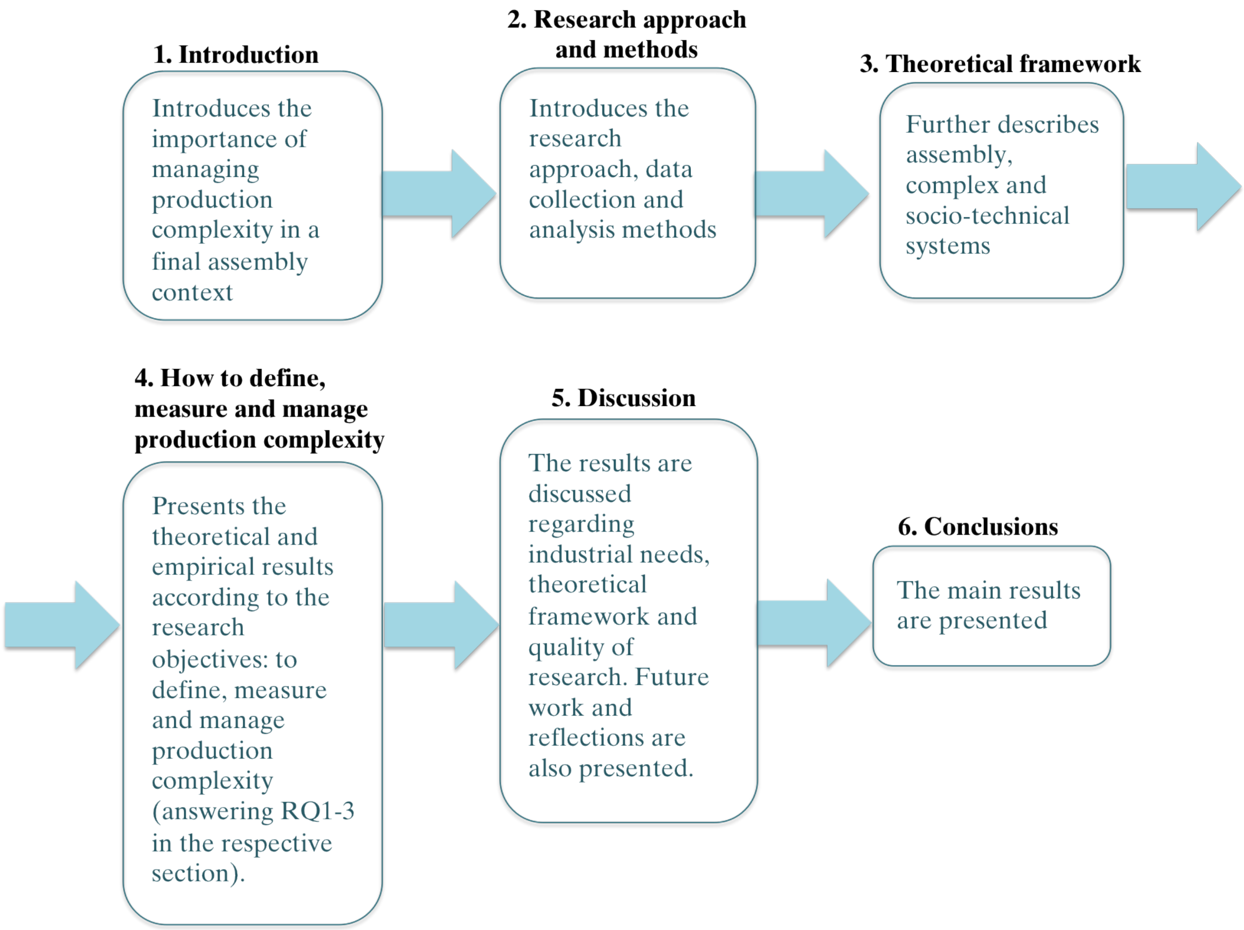

Figure 2: Disposition of thesis

2 RESEARCH APPROACH AND METHODS

This chapter describes the research approach, methods and techniques used to achieve the research aim. The presentation is influenced by a systematic approach for empirical research. First the research activities are presented.

As an overview the research activities are presented, see Figure 3. The activities contribute to the research objectives in various ways, which is the reason for presenting the results according to research objectives instead of according to each of the papers (a small dot for some contribution and a big dot for main contribution).

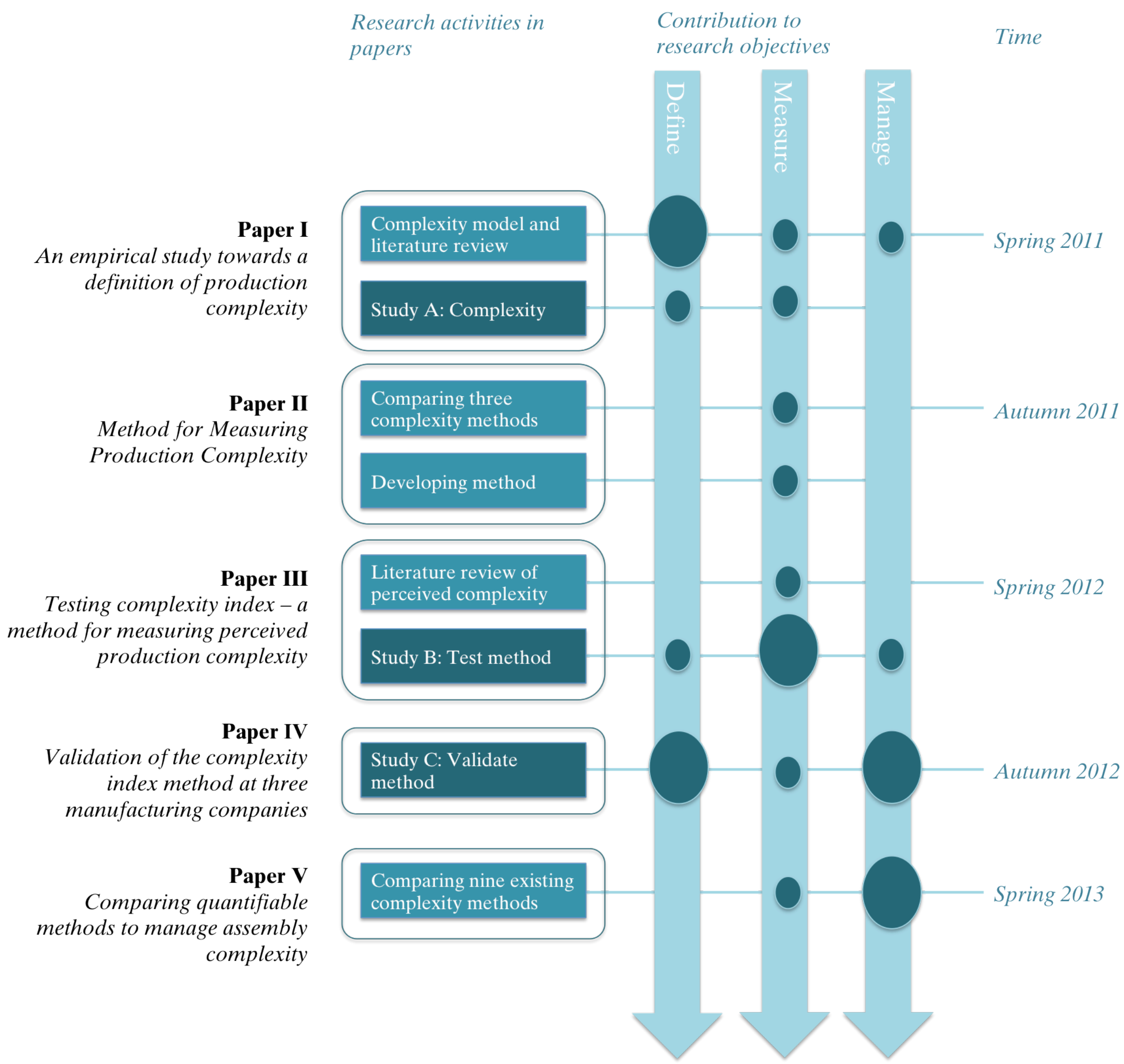

Figure 3: Research activities in this thesis connected to contribution to research objectives and papers (a dot for some contribution and a bigger dot for main contribution)

The activities are three empirical studies Study A-C, marked with a darker colour in the figure (Papers I, III and IV), four theoretical activities (Paper I, III-V) and one activity regarding the development of the method (Paper II).

A summary of the appended papers are presented below:

Paper I:
An empirical study towards a definition of production complexity

The purpose of the paper was to identify the elements of complexity i.e. to find the constructs that would later be used to define production complexity. A theoretical review was performed which together with empirical results (Study A including semi-structured interviews and workshops) resulted in a complexity model and a model for different subjective dimensions that should be included when managing complexity (different time perspectives, abstraction levels and roles).

Paper II:
Method for measuring production complexity

The purpose of the paper was to propose a method for measuring production complexity. In Paper II three of the existing complexity methods found in Paper I were investigated further (further investigated in Paper V). The CXI method was developed based on the Robustness Index method; developed in-house at Volvo Car Corporation. The information of how the method was developed and used was captured through an unstructured interview regarded the development of that method (explained by the developer of the method). The contribution to this thesis is the foundation for the method that was further developed in Paper III and IV.

Paper III:
Testing complexity index – A method for measuring perceived production complexity

In this paper the found elements of complexity were further investigated by including them in the developed method CXI. The purpose of Paper III was to test the developed method at a representative company and included an empirical study (Study B: questionnaire and an unstructured interview) investigating how complexity can be measured. Paper III also included a short review of the perceived complexity. The review was a theoretical basis for the changes made in the method and served as a theoretical background to interpret the questionnaire answers. The review also included comparisons of existing models and methods for perceived complexity. Main contributions are data from the CXI measurement.

Paper IV:
Validation of the complexity index method at three manufacturing companies

The purpose of the paper was to validate the method using three different approaches. The following was investigated: the correctness of the method and how the results of different roles could be included in the measurement. In addition, it was investigated if the method could be used as a predicting tool (measuring the CXI on existing stations to state what future problem areas there might be). The research contribution is the validation of the method and exemplifications of how the method can be used in a practical context.

Paper V:
Comparing quantifiable methods to manage assembly complexity

In Paper V, nine quantitative methods were compared. The chosen methods and models have a manufacturing connection and have been proven relevant in managing assembly complexity. The comparison regarded first the CXI and a method studying objective data, and then they were compared to the other presented methods. The contribution to the thesis is an identified research gap, a presentation and comparison of relevant methods and a suggestion of how CXI could be used in conjunction with the objective method.

2.1 Research approach

This research approach was influenced by Flynn et al:s (1990) systematic approach for empirical research. The approach includes six steps and five of them are used in this presentation, see Figure 4: (i) Establish a *theoretical foundation,* (ii) select a *research design,* (iii) select a *data collection* method, (iv) *implement method* and (v) perform a *data analysis*[3]. A sixth step added in this presentation is: (iv) evaluating the *quality of research.* This step is based on Yin (2009) and Ihantola and Kihn (2010) that suggested ways to evaluate and judge the quality of the research.

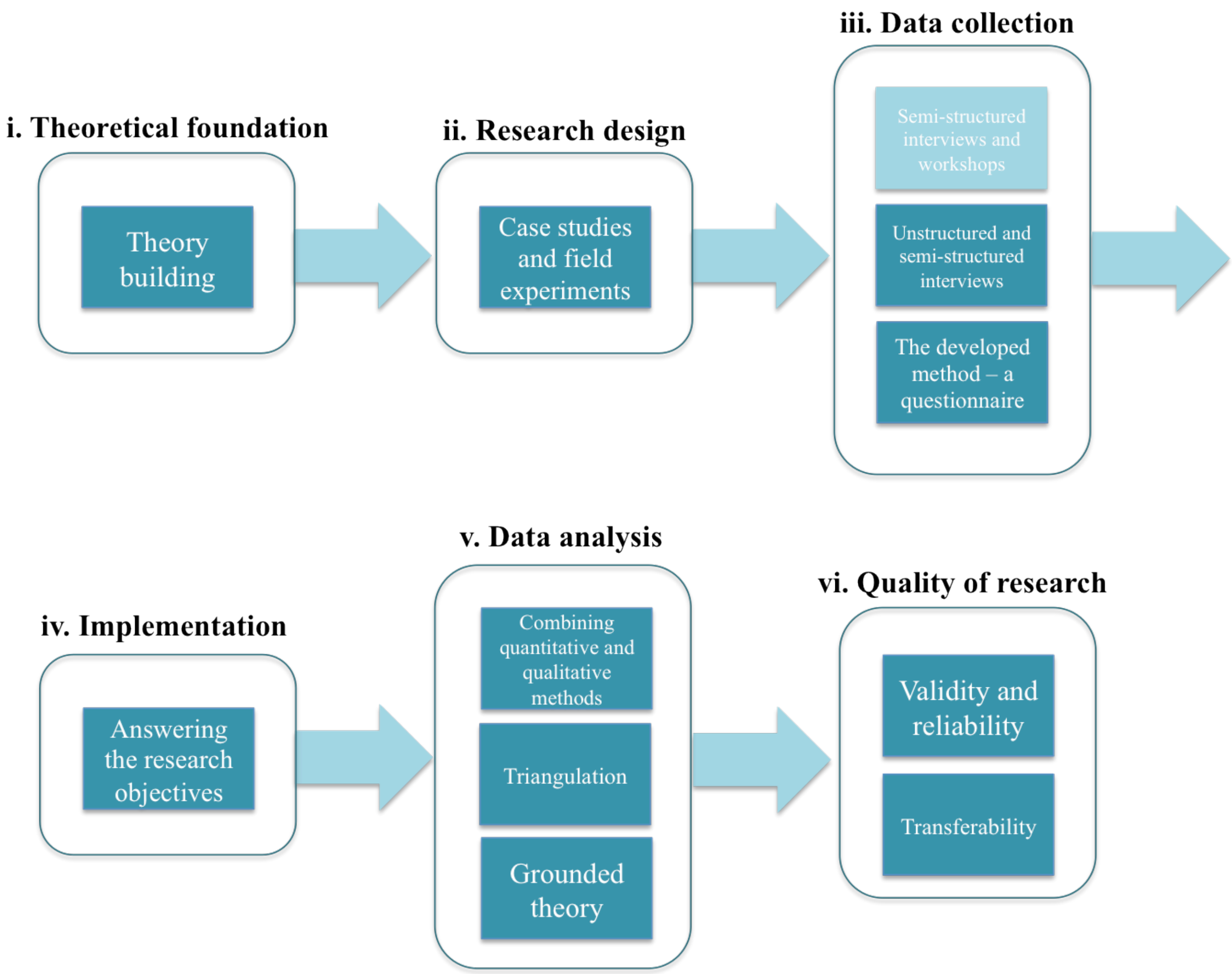

Figure 4: A systematic approach for empirical research, Flynn et al. (1990) edited.

[3] Flynn et. al:s (1990) approach also includes the sixth step publication which was not included in this presentation.

The steps are presented briefly below.

i. In this thesis theory is built, which means that theoretical constructs or models are further developed by empirical studies (Flynn et al., 1990).

ii. In this thesis a case study and field experiment were performed. There are both advantages and disadvantages with this approach. In this study this was handled by carefully designing the data collection methods and that several sources were used to support the relations. In addition, the multiple research designs and data collection methods were used to triangulate findings.

iii. The research approach in this thesis includes both qualitative and quantitative aspects, which complement one another (Williamson, 2002; Yin, 2009). The main data collection methods were questionnaires (quantitative) and unstructured and semi-structured interviews (qualitative).

iv. The research questions/objectives were, according to the suggested research approach, answered by combining results from the research activities (see Figure 3).

v. Both qualitative and quantitative analysis was performed. The qualitative analysis included Grounded Theory and triangulation, and the quantitative analysis included CXI calculations and the comparison of CXI results to objective data.

vi. Yin and Williamson state that the quality of the research can be determined by studying its *reliability and validity* (Yin, 2009; Williamson, 2002). Using triangulation is one way to secure the *reliability and validity* of the data collection and analysis by combining data or methods so that diverse views can be captured on the same topic (Olsen, 2004). In addition, the *transferability* was investigated.

The theory building in this thesis is mostly *abductive* where some aspects can be seen as *deductive* and *inductive*. *Abductive* research means that theoretical and empirical research is alternated in order to draw conclusions from the studies (Alvesson and Sköldberg, 2008). The constructs and models are then tested and formed by the use of empirical studies (see next chapter). Finally theory is built through iterating between shaping and finding evidences for the constructs or models (Eisenhardt, 1989). In *deductive* reasoning, conclusions are drawn from logical statements (Thurén, 2002) i.e. the answer to the research question is formed by studying theory (Starrin and Svensson, 1994). In *inductive* reasoning general results are concluded from empirical data (Thurén, 2002).

The advantages of building theory from empirical cases are that the theory can be tested throughout the analysis and that it is likely that new theory can be created (Yin, 2009; Eisenhardt, 1989). The disadvantages of building theory this way is that the empirical results can lead to intricate theory and that existing theory might be too narrow to be compared to the empirical findings. Also it can be difficult due to problems with differentiating between the cause and effect variables and the context, making it difficult to study the relations (Williamson, 2002).

One of the main points of the research approach is using both quantitative and qualitative data and analysis methods. Studying qualitative aspects means that a phenomenon is studied in its natural setting (in this case complexity) where the aim is to understand or make sense of the phenomenon such as how it affects people or what it means to them (Denzin and Lincoln, 1998). Qualitative data is useful in order to understand why a certain relationship exists and can strengthen already found quantitative result (Williamson, 2002). Quantitative data focuses on things that can be measured in numbers e.g. time relations or the frequency of occurrences (Denzin and Lincoln, 1998). In theory building, quantitative data could be used to indicate a relationship that is not clear for the researcher or to keep him or her from false impressions in qualitative data (Eisenhardt, 1989) thereby complementing the qualitative data (Williamson, 2002; Yin, 2009).

Conducting interviews is a way of obtaining qualitative data and is a common method used in case studies (Williamson, 2002). Often interviews are supplements to survey data i.e. a questionnaire (Ibid.). Interviews can capture complex topics and are motivational for the respondents since they are face-to-face (Williamson, 2002; Yin, 2009). In addition, it is possible to follow up interesting sidetracks in a less structured interview.

Questionnaires are often used to identify user satisfaction regarding, for instance, a specific technical tool (Williamson, 2002). Williamson (2002) state that questionnaires have an advantage since they can be performed whenever the respondents have time (without losing valuable production time). In addition, questionnaires are cheap and much data can be captured in a short time. The analysis of questionnaires is also easy (in comparison to interviews) (Ibid.).

Triangulation was used to analyse the data. According to Deniz, there are four different types of triangulation collections (Denzin, 1970).

- *Investigator triangulation* – Use of several different researchers or evaluators
- *Data triangulation* – Use of a variety of data sources in a study
- *Methodology triangulation* – Use of multiple methods to study a single problem or phenomenon
- *Theory triangulation* – Use of multiple perspectives to interpret a single set of data

Using both qualitative and quantitative methods for data analysis was suggested by Yin (2009) that stated that this analysis could be used to answer questions on different levels. A qualitative method is Grounded theory that is used to develop a set of categories that through theory and literature can explain a phenomenon (Corbin and Strauss, 1990). These categories include concepts that are kept provisional and earn their way to be incorporated in the category after being repeatedly found in the data. The categories are formed iteratively where key-categories have a higher level and include concepts from sub-categories (not all sub-categories will become categories). Each raw data is coded i.e. given conceptualizations, so that they are easier to work with. The significance of the method depends on the quality of the data i.e. scientific literature, the researchers analytical skills (when coding) as well as the sensitivity of using the theory and the action of forming and finding relation between categories (Ibid.). The quantitative approach used to analyse the findings are presented in chapter 2.6 Quality of research.

2.2 Theoretical foundation: theory building

The theory building is described in Figure 5. First a theoretical frame was developed in Paper I, which served as a basis for all objectives. The definition of complexity was developed further and tested in Study A-C. To measure complexity theory from Paper I, II and V were used. To answer the objective existing methods were studied and a method was developed. Empirical test of the method were performed in Study A-C. In Study B and C managing complexity was investigated. Theory was further shaped in Paper V where existing methods were compared.

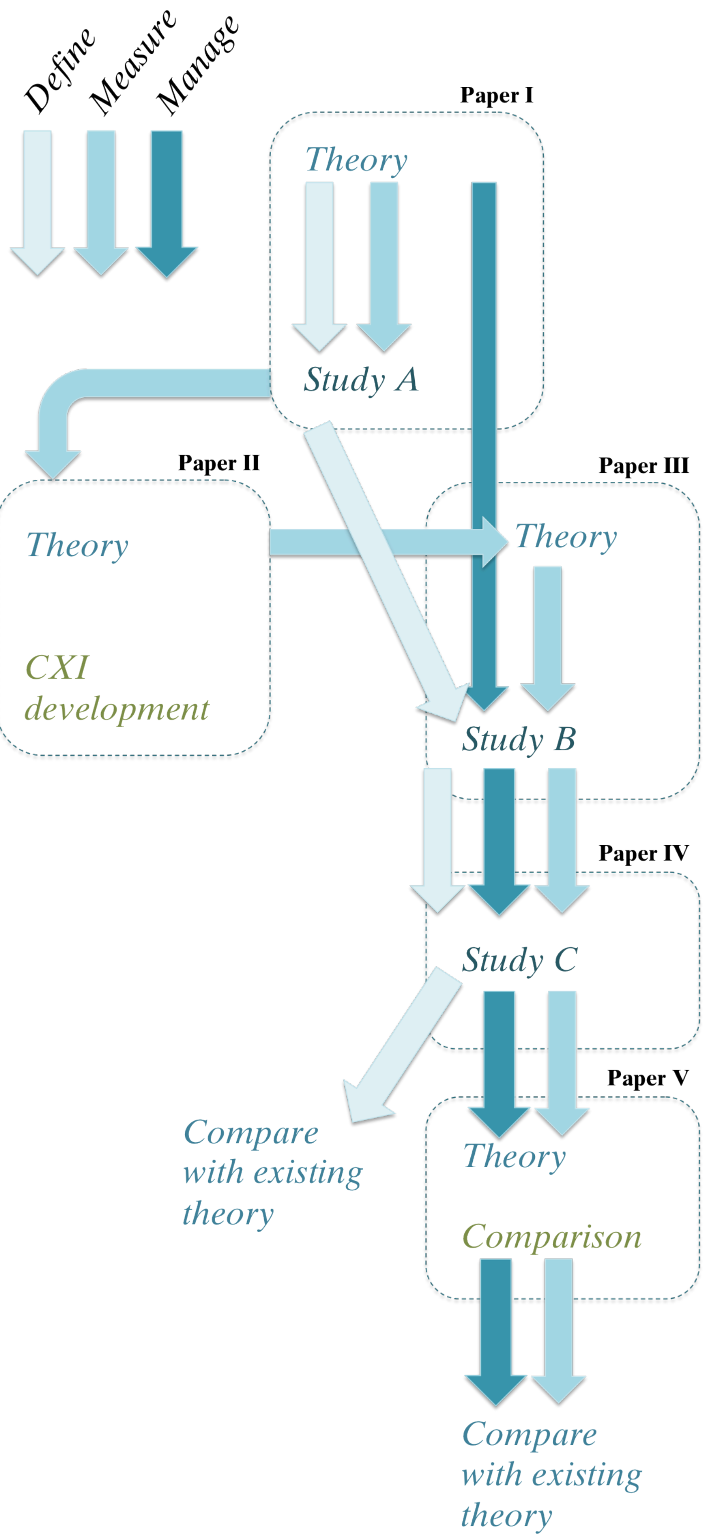

Figure 5: Theory building described using research activities

2.3 Research design

The case study, Study A and the two field experiments, Study B and C are described below regarding unit of investigation and sample (also done in Table 2). Study A and C contributed to defining production complexity, while both Study B and C contributed to measuring and managing complexity.

Study A includes multiple cases and investigates “what is complicated in final assembly work” (unit of investigation). In choosing cases it is crucial to select companies that represent the emergent theory (Eisenhardt, 1989). The sample was a large automotive company and two middle-sized electronics companies (one was a supplier to automotive company). They were chosen since they have final assembly stations that have complexity problems (the companies were research partners). The multiple-case study was carried out as a replication where the same roles were asked the same questions (Yin, 2009). Several different roles were included i.e. management, logistics personnel, operators, production technicians. This is a way to converge the findings to make sure that the views of different companies can be captured and generalized (Yin, 2009). Case studies are suitable since all three questions are how-questions (suggested by Yin, 2009, although Study A mainly answers RQ1) and are useful when studying a topic in-depth and when there are many variables to take into account.

Study B is a field experiment, performed at an automotive company. The unit of investigation was the correctness of the developed method and how complexity can be measured. The company was chosen since it is a representative sample compared to the other companies (choosing a representative company for a single case was suggested Yin, 2009). Since it is a larger company it is difficult to make fast changes i.e. to implement new it-solutions, furthermore it has other characteristics that a middle-sized or smaller supplier does not. The smaller supplier has however other difficulties regarding higher demands on quality and product delivery times.

In Study C, Field experiments were performed at three different companies with the aim of validating the developed method. In this study representative companies were chosen that had different units of investigation. This is called an embedded research design. Embedded research is done to enhance insights from the study (Yin, 2009). The following units were investigated: the correctness of the method and how the results of different roles could be included in the measurement. In addition, it was investigated if the method could be used as a predicting tool (measuring the CXI on existing stations to state what future problem areas there might be). The study included two large automotive companies and one middle-sized electronic company (supplier).

2.4 Data collection

The data collection methods are presented in Figure 6. A qualitative approach was used in Study A where semi-structured interviews and workshops were performed to capture what production complexity means to people with different roles in the company. In addition, interviews were used to strengthen the quantitative results e.g. data from questionnaires in Study B and C (the data captured in the questionnaires are seen as qualitative or subjective but was analysed using a quantitative approach). One question in the questionnaire can be seen as only qualitative since it was open-ended. In addition, quantitative data e.g. the number of components and variants was used to verify the results from the questionnaires (Paper III).

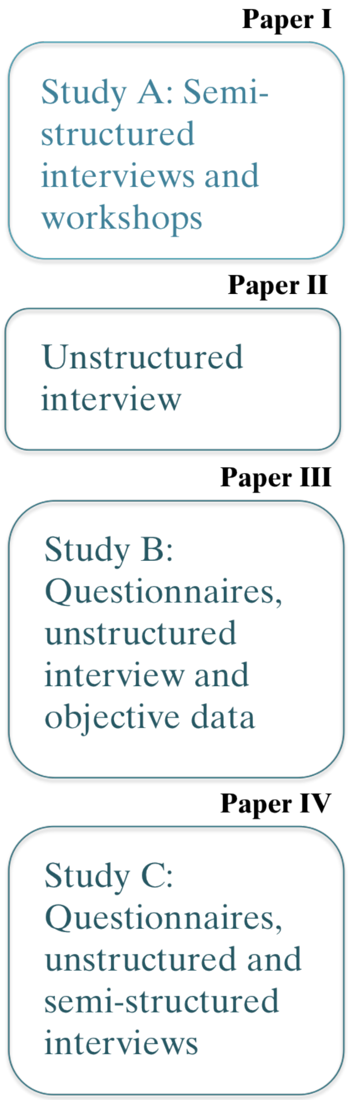

Figure 6: Data collection methods

Semi-structured interviews and workshops were carried out in the research project start (Study A). The author was not part of the data collection design but had access to the results. The author analysed the data together with a co-author. Semi structured interviews were carried out with representatives from operations, internal logistics, production engineering, and from one company, also man-hour planning. Semi-structured interviews are used to explore a topic or to capture in-depth data from experts or key people at a company (Williamsson, 2002). The interview guide addressing perceived complexity aimed to identify subjective complexity parameters related to work tasks, actions taken to minimize or handle complexity, causes and effects/consequences, ways of working, challenges, etc. The interview guide was adapted from a framework developed for investigation of major planned changes in production from the perspective of different functions/roles (Fjällström et al., 2009; Harlin et al., 2007). In order for an interview to be carried out in the best possible way it should be able to give reliable and valid answers i.e. it should be possible to critically evaluate the results. The interview guide for Study A is presented in Appendix D. A workshop was carried out and video recorded. The data collection focused on causes and drivers of complexity from the perspective of operations, internal logistics, and production engineering.

Interviews

Nine interviews were performed; eight investigating if the method achieved the intended measurement (Study C) and one finding out more about the in-house developed method Robustness Index (that the CXI was later based on, Paper II). The interviews were used mainly to triangulate (see Quality of research, Chapter 2.7) the results of the CXI method (i.e. regarding the index of the station and the identified complexity elements). Four of them were semi-structured individual interviews with operators (Company A, Study C, including two researchers and one company representative). First the results of the CXI measurement were presented. Then the respondents were asked if they thought the presented result was reasonable and if it gave a correct picture of the station. They were also asked how the method could be used (for more details see Paper II-IV). Interview guide and field notes for the semi-structured interviews are presented in E. In addition, an unstructured interview was carried out with the team leader, investigating the correctness of the results (Company A, Study C). Another interview was carried out with head of assurance (Company B, where two researchers were present) and one was at a bigger meeting (Company C, including one researcher from the project and two master thesis workers that had performed the study).

The unstructured interview in Paper III was made presenting the results of Study B to the company representatives. The interview took the form of a group meeting where three researchers (one of them a company representative as well), and two company representatives (one mainly connected to quality and one to the assembly of the stations) took part.

The unstructured interviews were not recorded nor transcribed since the aim of them was to validate the results from the CXI method and not to get an in-depth understanding of the topic. The interviews were often very short and several researchers were present. The conclusions were validated letting the company representatives read them and comment on them, before publication (Paper IV). In addition, a representative of the company was part of the research group and could validate the results from that company (in Paper II and Paper III).

One risk with interviews is the interviewer effect, which is the tendency of the respondent to answer in a way that they think the researcher wants them to (this is a threat to the quality of the research)(Williamson, 2002; Yin, 2009). The interviewer effect is avoided since in the semi-structured interviews the results are compared with the workshop results and the unstructured interviews were used to supplement and verify the quantitative data.

The developed method – a questionnaire

When designing the questionnaire it is important to have knowledge of the area and the respondents (Williamson, 2002), this was done Study A and in the theoretical framework. The development of the method was done in five steps: *Concept development* (Paper II)*, Testing* (Paper III)*, Validation* (Paper IV)*, Comparison* (Paper V) and *Use*. The steps are described further in Appendix A. The questionnaire is presented in Appendix B.

The developed method, CompleXity Index (CXI), includes 26 questions: 24 opinion questions, one open and one tick-box question (the respondent could choose from multiple answers what support tools are used at the station, see questions 18 in Appendix B). This means that it is in general quantitative but includes one qualitative question (the open-ended one which is a comment field where the respondent can fill in what possible suggestions they have to improve the station). In opinion questions the respondents opinions are assessed. These are often presented using Likert scales (Williamson, 2002; Dyer, 1995). The answers range from one to five where one is *I do not agree at all* and five is *I fully agree.* Respondents could also answer *I don't know/Not relevant.* An open-ended question means that the respondents can write the answer in their own words). Most of the questions were stated so that the answer five would mean that the station was complex. Some of the questions were reversed to reduce possibilities of bias.

The questions are of the following type:

1. There are many variants on this station

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				*Agree completely*	*Don't know /not relevant*

Even though the topic is intricate, the questions could be phrased in a way that made the questionnaire easy to answer and understand. This made the questionnaire self-administrable (in Paper II the questionnaires were administered by a research colleague, in Paper III they were administered by the team-leader). This meant that operators could fill in the questionnaire in their own time, not causing production disturbances. However, this also presents difficulty in measuring the rate of respondency and whether or not the operators filled in the questionnaires together.

In collecting the data, the stations were selected in cooperation with personnel. In general, the chosen stations were representative of the entire production flow. Some were considered complex and some not complex (Paper III-IV). A questionnaire takes in general 7-13 minutes to complete.

2.5 Implementation

Table 2 describe the research activities, sample and author contribution.

Paper	Research activity	Sample	Author contribution
Paper I	Complexity model and literature review		Part of discussing the results
	Study A: Complexity	Large automotive company, middle sized electronic company (supplier to automotive company) and middle sized electronic company	Analysis of data for two of the companies together with corresponding author
Paper II	Literature review		
	Developing the method		
Paper III	Literature review		Part of discussing the results
	Study B: Test method	Large automotive company	Developed the questionnaire and analysed the data with co-authors
Paper IV	Study C: Validate method	Two large automotive companies and one middle-sized electronic company (supplier)	Gathered data at the larger companies. Analysed data with co-authors. Was part of analysing the data at the third company together with bachelor students
Paper V	Literature review		Did review and discussed the results with the co-authors

Table 2: Description of research activities, unit of analysis, sample and the author's role

The following text describes how the research activities and data collection methods were implemented according to the research objectives.

To define production complexity

First a theoretical framework was used as a base for finding elements that could define production complexity (Gullander et al., 2011). A multiple case study was used to find empirical support for what considered complicated in final assembly work. Several different roles were included i.e. management, logistical personnel, operators, production technicians (Study A, Paper I). The found causes of complexity were tested at a company (Study B, Paper III) to see if it would confirm, challenge or extend the suggested theory. Qualitative data in terms of unstructured interviews were used to support the findings. The elements of complexity were further validated in several companies (Study C, Paper IV) by testing the elements to see if the results of the interrelation corresponded to the opinions of the operators as well as the team leaders/management.

To measure production complexity

In order to investigate how complexity can be measured existing theory was studied. The theoretical framework from Gullander et al. (2011) served as a basis for this. Theory in Paper I is a further development of that, supporting the finding that there is a gap regarding subjective aspects in existing measurements of production complexity. In Paper II, an existing method was used as a basis for the method development (Robustness Index, see Paper II). This was done since the existing method had been developed at Volvo Car Corporation and therefore the new method should be tested there first i.e. it would be easier to implement. The developed method underwent changes before it was tested in Study B. This was done since the first tested operators did not understand how they should answer the questions. The method explanation was simplified so that the questionnaire became self-administrable. By studying the CXI results, compared to the empirical findings given by the unstructured interviews (Study B and C) it was possible to suggest how production complexity could be measured. The elements of complexity are called problem areas in the papers.

To manage production complexity

The theoretical study in Paper I was used as a basis for how production complexity should be managed. Study B and C gave further insights on how production complexity could be managed in practise. Paper V was used to compare existing methods and suggest a way to manage complexity. The comparison between CXI and an objective method gave further insight on the usefulness of the developed method.

2.6 Data analysis

In Study A many authors were part of the data collection and analysis (*investigator triangulation*, while in Study C one additional researcher and one company representative were part of the data collection and analysis. The development of the method was led by the author but the design was discussed in the research group. Eisenhardt (1998) state that *investigator triangulation* is also good for increasing the creativity in the research as well as that several researchers' converged analysis enhances confidence in the study. In Study D, Paper IV, data collection and analysis was performed by the authors independently. All results and conclusions were discussed together in the research group.

Grounded theory was used, in Study A, to form categories that would differentiate complexity elements from the found data. The coding and the first step of forming categories were done by the author together with one of the co-authors of Paper I. This was done for one company and two of the other co-authors did the coding for the other two companies. Then the results were compared and key-categories formed. In Study D the semi-structured interviews were analysed in the research group. The field notes were used as a basis for the analysis (presented in Appendix E).

The method comparison made in Paper V was analysed in a qualitative way. The comparison of the CXI and the method developed within the Belgian sister project CXC is presented in Paper V. The two research groups behind the methods made this comparison jointly. The comparison was made regarding:

1. Purpose of method
2. The contents of the method (what aspects / parameters are covered)
3. The intended usage
4. Methods for calculation and for visualizing the results
5. The methods' validity
6. The added value the method is expected to give the users
7. Prospects for future development

The methods were further classified to enable a comparison with other methods and assess their usability. The criteria used were inspired by Calinescu et al. (1998). The following criteria were used to classify the methods:

1. Purpose of method
2. Type of complexity (static or dynamic complexity)
3. Type of measures (objective or subjective)
4. Results (detailed or holistic)
5. Experience level needed (high or low)
6. Strengths and weaknesses (+ or -).

The quantitative and qualitative analysis of CXI was performed according to the following. After collecting the questionnaires the answers were entered on an Excel sheet (takes approximately 30 minutes for filling in 15-20 questionnaires. In particular the analysis of the questionnaire data in Study B and C was done according to the following steps:

1. What is the CXI for that station?
2. What elements contribute to that CXI score?
3. What are the answers contributing to the score in that problem area/ complexity element?
4. Study the comment-field (last question) and compare with CXI, the complexity elements and the answers to the statements.

The first three are analysed quantitatively while the last step is qualitative. The results from the measurement were compared to the initial view of complexity (made by the company representatives) and objective data (the number of variants and components on each station).

2.7 Quality of research

Validity means that the method or technique measures what it is intended to (Thurén, 2002; Williamson, 2002; Yin, 2009). This can be evaluated by studying the (i) *construct, (ii) internal, (iii) external* and (iv) *contextual validity* (Yin, 2009; Ihantola and Kihn, 2010).

To ensure *validity* the suggested theory building approach was followed i.e. describing the cases in a logical and consistent way (this is called *contextual validity*). Replicating findings in the multiple cases i.e. studying different types of companies to see if the same results are found, can approach the *external validity (*secured by *data triangulation)*. *Internal validity* was increased by validating the quantitative findings by using qualitative data (semi and unstructured interviews: *methodology triangulation*) (Eisenhardt, 1989). *Internal validity* was increased by supporting the findings with theory (Ibid.), This was done through the use of abduction (*theory triangulation*).

Reliability is connected to that the data found is stable and that the results did not occur by chance (Williamson, 2002). In order to secure the *reliability* of empirical data there is a need to store and structure the data so that it is possible to re-visit it (Yin, 2009; called procedural reliability by (Ihantola and Kihn, 2010)). The transcripts of the interviews from Study A are stored together with video material from the workshops. In addition, field notes were gathered and used a base for the analysis made in Paper IV, Appendix E. Lastly, Ihantola and Kihn (2010) suggested that studying the *transferability* of the research could assess the quality of the studied case. This means to provide links between theory and empirical data and to show the practical usefulness of the results. *Transferability* was analysed throughout Study B and C and is the main part of finding a measure that can be used to manage production complexity.

3 THEORETICAL FRAMEWORK

This chapter presents complex systems and how a final assembly system can be characterized. The complex system is described by using general system theory and socio-technical system theory.

This thesis approaches production complexity by studying a subsystem i.e. the final assembly system. According to ElMaraghy et al. (2012) the following views of complexity are found in the manufacturing and engineering design context: *part-, product-, system-* and *system of system complexity*. The characteristics of a complex system are described in Chapter 3.1. The subsystem can be described in terms of a socio-technical system that means studying the interrelationship between humans and technology in final assembly. Socio-technical systems are shortly described in Chapter 3.2. Final assembly is a typical example of a socio-technical system, which is described in Chapter 3.3. A model of the system investigated is presented in Chapter 3.4: Context description.

3.1 Complex systems and general systems theory

Complexity in a system can be defined as something that is *"difficult to understand, describe, predict or control"* (Sivadasan et al., 2006). The term "complex" is often used in everyday language to refer to the difficulty of understanding or analysing a system. Weaver stated that complexity in a system is, given the systems parts, the difficulty in predicting the system's properties (Weaver, 1948).

Objective complexity is important since objective parameters provide a hint of complexity as several experiences it and are independent of which the user is. In final assembly complexity can be divided into two types: *static* and *dynamic complexity* (ElMaraghy et al., 2012; Blecker. T., 2005; Frizelle and Suhov, 2001; Asan, 2009) where static complexity deals with the structure of the product or production processes that are time-independent. This can be for instance the number of variants. *Dynamic complexity* is time-dependent and includes the uncertainties of information and material flow (Sivadasan et al., 2006). Objective data can capture both static and dynamic aspects of complexity. The *static complexity* of a system or a subsystem can be modelled measuring parameters such as number of stations, work tasks, parts, levels of automation etc. The *dynamic complexity* is modelled in order to include time and dynamics, like deviations from plans, and uncertainty.

However, since humans may consider the same system and situation differently it is important to consider how the system is perceived i.e. *the subjective complexity* (Paper III). How the personnel handle the problems with complexity can depend on *subjective* factors for example previous experience, knowledge, training, personality type, background and mind-set. These variations between individuals need to be regarded as well as the work tasks being performed. To grasp the perceived production complexity it is therefore necessary to gain an increased understanding of different functions and their needs in the organization (Ahlström, 2002).

Existing methods can be divided into two approaches: information flow or a computational approach. Below eight relevant methods are presented, see Table 3. The methods were seen useful in understanding how complexity can be measured in a final assembly context (the table is not exhaustive).

Table 3: Existing method names and purposes

Method	**Purpose of method**
Operational Complexity* (Sivadasan et al., 2006) (UK)	To monitor and manage information and material flows
Entropic Measurement* (Frizelle and Suhov, 2001) (UK)	To measure the rate of variety
Manufacturing Complexity Index* (Urbanic and ElMaraghy, 2006) (UK)	To evaluate alternatives and risk with respect to product, process or operation task in a design stage
Operator Choice Complexity (OCC) (Zhu et al., 2008) (Michigan)	To find causes, plan assembly sequences and design mixed-model assembly lines
Knowledge and Technology complexity* (Meyer and Curley, 1993) (UK)	To manage software development
Complexity Measurement* (CXB) (Falck and Rosenqvist, 2012) (SWE)	To support product preparation to increase productivity and decrease costs
Robustness Index (RI) (SWE)	To evaluate risks and problem areas on a management/team leader level
CompleXity Calculator (CXC) (Zeltzer et al., 2012) (BE)	To automatically assess the complexity of stations

* The methods are named by the author according to what they measure and are not their given names. This is done to easier refer to the methods.

To measure complexity Sivadasan et al. (2006) presented a method focusing on monitoring and mapping the information flow The information flow was also considered by Urbanic and ElMaraghy who put forward a model focusing on the information content, where the quantity, diversity and content of information are used as a function related to complexity (Urbanic and ElMaraghy, 2006). Meyer and Curley (1993) presented another view in which the knowledge and technology complexity was studied. Their aim was to manage software development and this was conducted through studying subjective complexity (the other methods have studied objective data in their approach). Another approach frequently adapted to model and measure complexity using the term "entropy" which measures the uncertainty and randomness of a variable in the system. Entropy shows the rate of variety among possible next states, as a system changes state (Frizelle and Suhov, 2001). In production, the entropy of a production system can be applied to states of a station, the tasks/choices in station, or the line/system. The entropy of an operation reflects how uncertain it is that the operation is the next operation on a station. Focusing also on probability Zhu et al. (2008) presented a method which calculates the average uncertainty and risk in a choice for right tool, fixture, parts and procedure for variant. In addition, the Robustness Index (RI) that was developed in-house at Volvo Car Corporation and served as a basis for the development of CXI. The method is based on Lean methodology[4] and is used in early development phases. The purpose of RI is to secure the robustness of a part (system). The robustness is evaluated by every part for each product and then summarized. The aim of RI is to evaluate risks and problem areas on a management or team leader level. Another method developed at Chalmers, Sweden, called CXB, is also an index for measuring complexity in an automotive setting (Falck and Rosenqvist, 2012). In the method stations are judged as having a high or low complexity due to several criteria. The aim of CXB is to support product preparation to increase productivity and decrease costs. Within the Belgian COMPLEX project (see acknowledgements for description of the Swedish sister project), a complexity measurement method has been developed, called the Complexity Calculator (CXC) (Zeltzer et al, 2013). The focus and purpose of the method are to characterize the complexity of manual operator workstations. In CXC objective data is collected from engineering data systems and an algorithm then calculates a complexity measure for all stations, and statistically classifies it as either of High or Low complexity. The operators are thus not involved and the method can easily cover many stations.

Of the methods four come from the United Kingdom, one from the U.S.A. (Michigan), two from Sweden and one from Belgium (a method developed within the COMPLEX sister project in Belgium). All methods are from 2006 or later, except for Meyer and Curley, which were published 1993.

[4] Lean production is a management philosophy developed from the Toyota Production System (Bicheno, J. 2004. *The New Lean Toolbox: Towards Fast, Flexible Flow*, Buckingham: PICSIE Books.) see Liker, J. K. 2004. *The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer p. 303,* USA, McGraw-Hill.

Characteristics

The characteristics of solving a simple, complicated or complex problem were described by Rogers (Rogers, 2008). A simple problem has a formula that is tested and standardized. No experience is needed to follow that formula, and the result is therefore predictable and positive every time. A complicated problem has a formula, which can be carried out by personnel with some expertise. There is also a high degree of certainty in the outcome. A complex problem cannot be described using a formula. Also, even though a formula is followed it does not ensure success, i.e. there is high uncertainty of the outcome. Having expertise could ensure success, but it is neither necessary nor sufficient (Ibid.). This means that every problem is unique.

Kurtz and Snowden (2003) presented another view of the differences between simple, complicated, complex and chaotic problem solving. They emphasized that people can perceive a problem differently, and instead of simple and complicated called it the known and knowable. The characteristics are presented in Table 4.

Table 4: Four domains of how complexity can be perceived (Kurtz and Snowden, 2003)

COMPLEX: Cause and effect occur in retrospect and the relation is not repeated.	KNOWABLE: Cause and effect are separated over space and time. Might be known to a limited amount of people.
CHAOS: No cause and effect patterns can be found	KNOWN: Linear cause and effects relations can be found. They are repeatable and can be predicted

The difference between the right side of the table, Table 4, and the left side is that humans can reach the knowable domain by spending time and energy (from the known domain). The left side is connected to finding patterns. By visualizing the patterns it could be possible to move from the complex domain to the knowable, or from the knowable to the known domain i.e. it is possible to understand a complex problem by making patterns visible.

The characteristics of solving a complicated or knowable problem are similar to how a complicated system is described. Grabowski and Strzalka (2008) suggested that a simple system could be a pendulum that has deterministic behaviours (the pendulum could also behave in a complex manner). A complicated system could instead be a steam locomotive that works according to deterministic laws and has a high number of elements that work together. A complex system has a number of elements that interrelate to one another (Ibid.). It is counterintuitive and has non-linear links (Forrester, 1961). One example is a non-linear differential equation or a social community (Perona and Miragliotta, 2004).

Another example of a complex system is a flock of flying ducks that consists of a small amount of elements, however the elements adapt to the contextual situation (self-adapts to outdoor conditions), depend on each other and do not have a leader - this means that reaching the destination can be done in many ways (Grabowski and Strzalka, 2008).

As kids we are taught that problems can be understood by breaking them down into smaller pieces (Senge, 1990). However, if the problem is very complex, looking at its parts solves the problem but the view of the complete system can be lost (Ibid.).

Complexity elements

When studying production complexity it can be difficult to establish what are the causes and effects of complexity (also see Table 4). Johansson stated that since the causes are interrelated the effects could be hard to predict (Johansson, 1999). This is since humans do not have stable input-outputs, for instance a specific input does not always lead to the same output (Rasmussen et al., 1994). This means that a system including humans and technology cannot include input-output characteristics (Ibid.). Instead of using a cause and effect model this can be described as an INUS-condition which is an "Insufficient, but Necessary part of an Unnecessary but Sufficient condition" (Mackie, 1965). An INUS-condition means that there are conditions that combined are necessary in order for a system to be complex, but if only some of them are present the system will not be complex. For instance a system can be perceived as complex due to that there are a lot of product variants, but having many variants does not imply that the system will be perceived as complex. This can also be due to that each variant has to be assembled using different tools and different components (and also to the similarities of those tools, components and variants). Combined with demands on quality, decreased cycle time and that the layout of a station is poor or ergonomically bad, the station might be perceived as complex.

To consider the systems interrelating elements is described as systems thinking:

"Systems thinking is a discipline for seeing wholes. It is a framework for seeing interrelationships rather than things, for seeing patterns of change rather than static 'snapshots'. Today systems thinking is needed more than ever because we are becoming overwhelmed by complexity" …((Senge, 1990), p. 53-54).

Further, Checkland defined a system as:

"a set of elements connected together which form a whole, this showing properties which are properties of the whole, rather than properties of its component parts" ((Checkland, 1993),p. 3).

This is also one of the main ideas of General Systems Theory, that state that the sum of the system is bigger than the sum of all parts (Skyttner, 2001). Furthermore, the parts are interdependent and they cannot be understood by studying the whole. By studying the whole only the characteristics of the parts can be found. The elements in a system can be physical, social or abstract and have a relationship if they affect each other. The relationship consists of a communication determined by energy, force, information or matter. A systems process can be described as a transformation where the input i.e. energy, force, information or matter is transformed from the surroundings through the systems boundary. The output is energy, force, information or matter that is transformed from the system into the surroundings (Figure 7). The feedback can be a feedback in terms of a specific goal or standard. The system can be open or closed where the surroundings affects the system or does not affect the system. The environment can be internal or external (surroundings in the figure) (Ibid.).

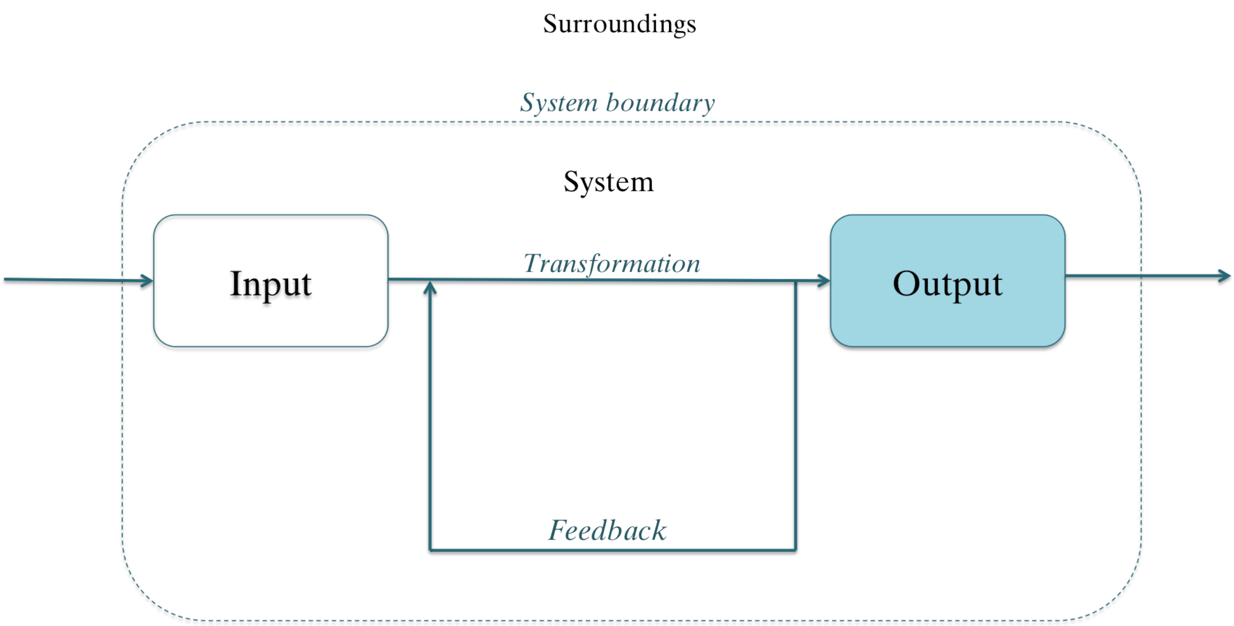

Figure 7: System model

3.2 Socio-technical systems

Socio-technical systems, as a concept, came from the Tavistock Institute when performing field projects in the British coal mining industry in the 1950's (Trist, 1981; Trist and Bamforth, 1951). Since coal was then the main source of power, having a cheap and efficient production of coal was important. However, with the increase of mechanization i.e. new technology, a decreased productivity was found, and the absenteeism increased to on average 20%. This resulted in a change of the organization where the previous self-regulating small groups became bigger groups with one-man-one-task roles and larger operations that was controlled by an external part. The core findings were that the social system and work organization view have been lost when introducing the technology, which reduced the work system's ability to handle uncertainties (Trist, 1981).

Trist and Bamforth, together with their colleagues therefore developed a model for socio-technical systems that included three elements: *the technological subsystem, personnel subsystem and the work design subsystem.* If all sub-systems are not considered when introducing a change, the system will be sub-optimized and may break down (both in terms of performance and safety) (Hendrick and Kleiner, 2001; Trist and Bamforth, 1951). Many times socio-technical systems have been used to describe dysfunctional systems that have been results of this. An example is when a support tool (*technology subsystem*) is introduced on the assembly line by the management (*work design subsystem*), without considering the operators (*personnel*). This may result in a technology that is not used, or that the operators don't know how to use it since it is was not designed in cooperation with the operators. A way to optimize the system is to develop all the described sub-systems together, which means also that all parts are equally important. Although socio-technical experiments have overall been successful, it was seen in a study including 134 experiments, that new technology or technology change innovation is rarely used (Pasmore et al., 1982).

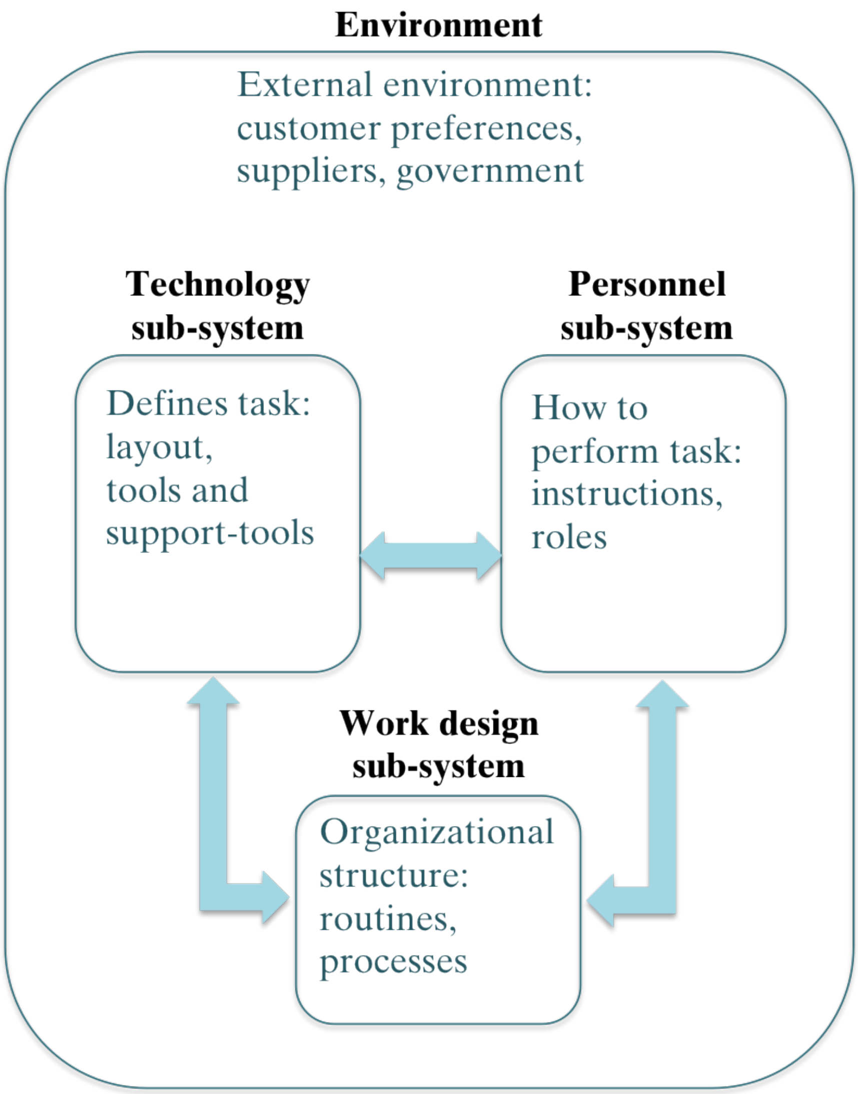

Figure 8: A socio-technical system

These three sub-systems interact in *an environment* (Hendrick and Kleiner, 2001), see Figure 8.

- The *technological subsystem* includes the technology and the task that should be performed. The technology in an assembly station is structured according to *the station layout, the tools and the support tools* given to the personnel. The layout considers if it is a line or a cell and how the material/components are presented to the operator. The tools and the support tools can be screwdrivers, computers where the instructions are placed, or scanners that are used to secure that a specific part has been chosen. Other available technology may be digital boards where production data statistics are presented, and the written instructions that present the task description.

- The *personnel subsystem* includes the humans and how they are organized in order to perform the work. In the final assembly system the humans are often operators that have as their task to assemble something using a work instruction. Connected to the station are also logistical personnel and team leaders. The logistical personnel supply the station with material and remove empty boxes. This is done in daily work as well as for re-balancing situations, i.e. when a new product will be assembled. The team - led by a team leader, who is often also part of the team - structure and plan how the team should work and in some cases in what order products should be produced.
- The *work design subsystem* includes the routines, organizational structure and processes in the system. In many cases the team members have additional roles (for instance first-aid-education or maintenance) that are also connected to different groups in the organization. The work design can depend on how many shifts they have per day and what the working hours are. Some assembly teams have specific routines regarding cleaning and also when and how team meetings are carried out.
- The *external environment* gives feedback to the different sub-systems and is important since it includes laws, regulations and culture and provides a context for the subsystems. At the assembly station, the company culture can determine work ethics and group dynamics; for instance the motivation to help team members, or if a work related injury is reported or not. The environment in the automotive industry is characterized by high demands on quality, short lead times and unexpected disturbances (many times depending on lack of material or changes in orders).

The aim of studying systems in this way is to shape both the technological and social conditions so that both efficiency and operator satisfaction can be achieved (Ropohl, 1999). This means that in a production system context, the tasks that the operator performs need to be re-designed to emphasize job enlargement and more group or team work activities, e.g. to empower the personnel (Jensen and Alting, 2006). This could result in a higher internal motivation, higher quality work performance, higher satisfaction and low absenteeism and personnel turnover (Jensen and Alting, 2006; Pasmore et al., 1982).

3.3 Final assembly systems

The assembly system can be described as a transformation system (Bellgran, 1998; Andreasen et al., 1983; Rampersad, 1994) where each task has a specific and limited task time and is assigned to specific sequences of operations that are performed on the station

(Ghosh and Gagnon, 1989). The assembly line consists of a number of assembly tasks (Ghosh and Gagnon, 1989) that can be divided into smaller elements or stations (Seliger et al., 1987). The tasks on the line are planned so that the work is effective regarding time for re-balancing and the number of workstations available (Ghosh and Gagnon, 1989). The material is transformed into a product through an automated process in cooperation with an operator or manually (ElMaraghy et al., 2010).

The tasks in final assembly are often carried out manually (Fasth et al., 2010; Michalos et al., 2010). Having a high manual assembly is connected to smaller batch sizes, increased number of variants, production volume and flexibility, see Figure 9 (Heilala and Voho, 2001). The role of humans is therefore increasingly important when complicated systems are considered; e.g. high expenses are to be expected if bad choices are made (Oborski, 2003). In the automotive industry 50% of the labour cost (ElMaraghy et al., 2010), and 25-50% of the production cost is spent in assembly (Bi et al., 2007).

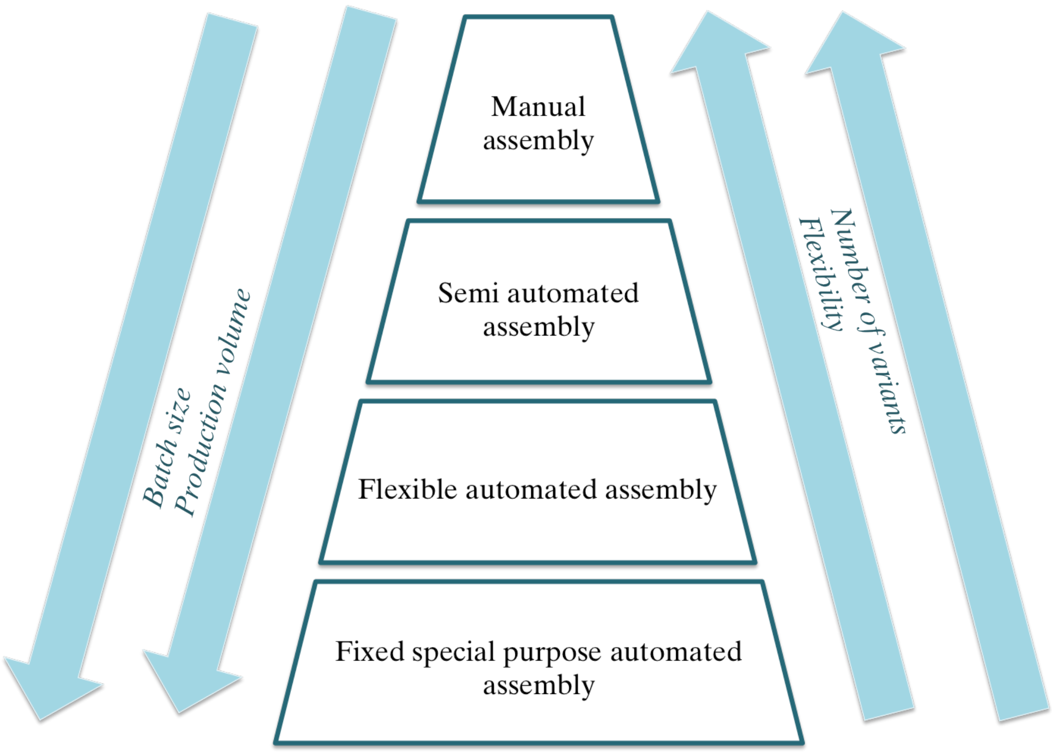

Figure 9: Characteristics of the performance of assembly systems (Heilala and Voho, 2001)

Humans are useful in a complex situation since they are flexible, creative, can utilise all kinds of information (for instance solving a problem they have not encountered before) and can cope with incomplete knowledge, i.e. handle uncertainties (Billings, 1997). Their main task in modern manufacturing systems is to handle disturbances, where the operator needs to combine new information with previous experience (Mårtensson and Stahre, 2003). Therefore, the ultimate goal of measuring and managing complexity in final assembly is to improve the operator performance i.e. to decrease process errors, achieve high quality, good working conditions, fast processes, quick change-overs and to decrease cost (Schleich et al., 2007) (Papakostas et al., 2010; Heilala and Voho, 2001). Management of a system must be done in close collaboration with the workers (Taylor, 1911; Grote, 1994). Grote stated that a systematic approach is needed to manage uncertainties and that it is important to include different organizational domains. This is because:

"..these foremen and super-intendants know, better than any one else, that their own knowledge and personal skill falls far short of the combined knowledge and dexterity of all the workmen under them" (Taylor, 1911, p. 30).

3.4 Context description

The final assembly system can be seen as a socio-technical system that includes humans, technology, work design and the environment. In this thesis the most interesting parts are things that can be easily measured. The system investigated therefore needs system boundaries. The system boundary is described in Figure 10.

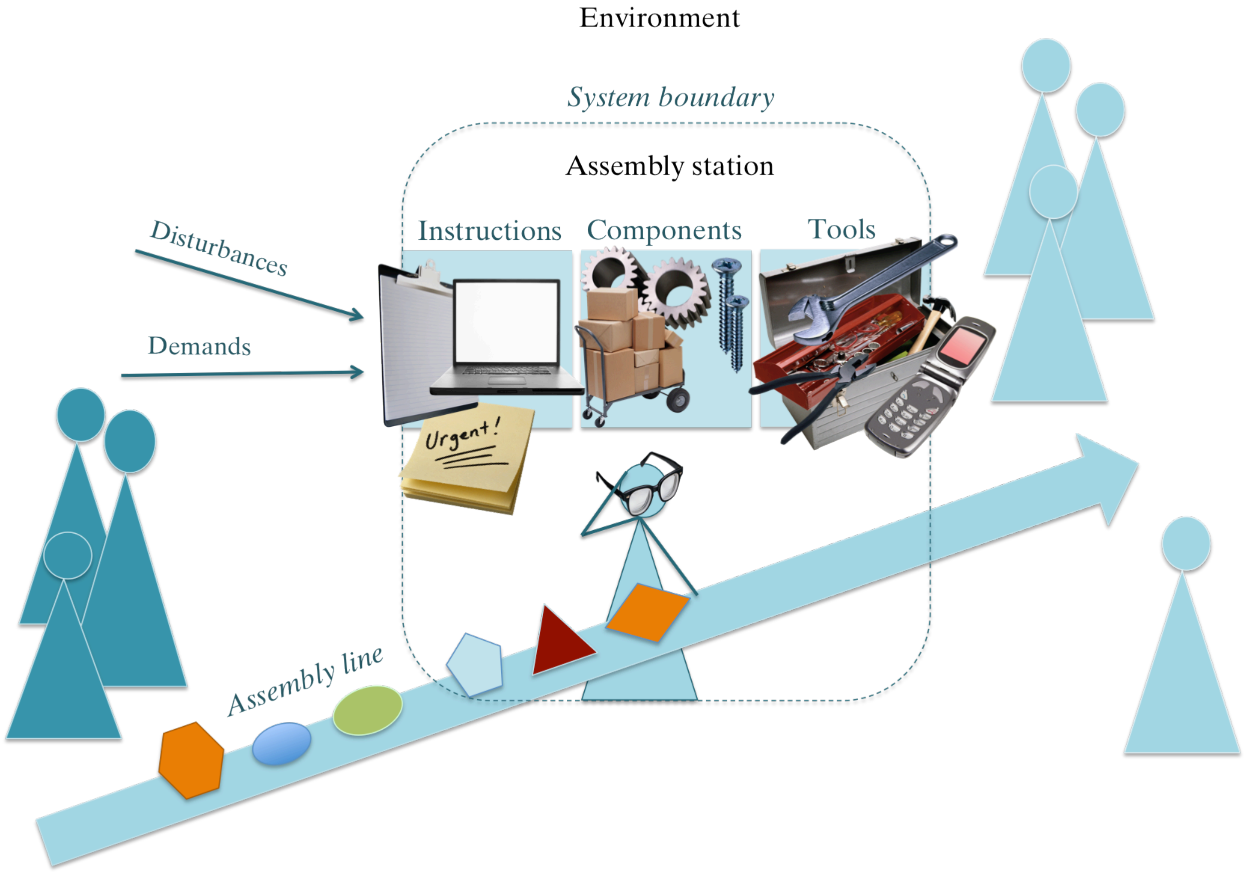

Figure 10: System boundary

The system is limited to one worker performing assembly on an assembly station. The internal environments e.g. the layout of the station or the material routines given are seen to affect the worker. The system can be seen as an open system that interacts dynamically with the surroundings. The external environment can be described such the *external environment* in the socio-technical subsystem. The worker is affected by the organization in the *work design subsystem* but the system only includes elements from the *personnel* and the *technology subsystem*. This describes the system boundaries as well as how the surroundings affect the system. The system can be limited in time to describe the complexity over a specific time-span.

The assembly process within the system boarder is described in the following figure, Figure 11. The process is a transformation of matter and information where the system input is the product variant and the output is the finished product. The feedback given to the worker can be goals or standards or the next task to perform.

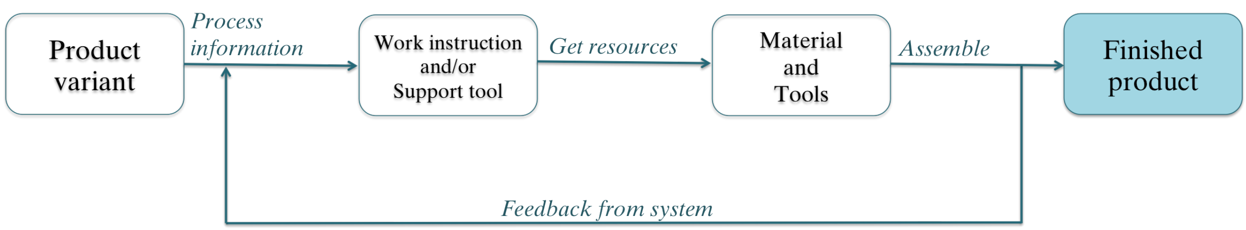

Figure 11: The assembly process

4 HOW TO DEFINE, MEASURE AND MANAGE PRODUCTION COMPLEXITY

This chapter presents the research results according to the research objectives: to define, measure and manage production complexity.

According to the theoretical framework the system boundary is combined with the holistic view of the socio-technical system. The research results are focused on the *technology* and *personnel sub-system,* see Figure 12.

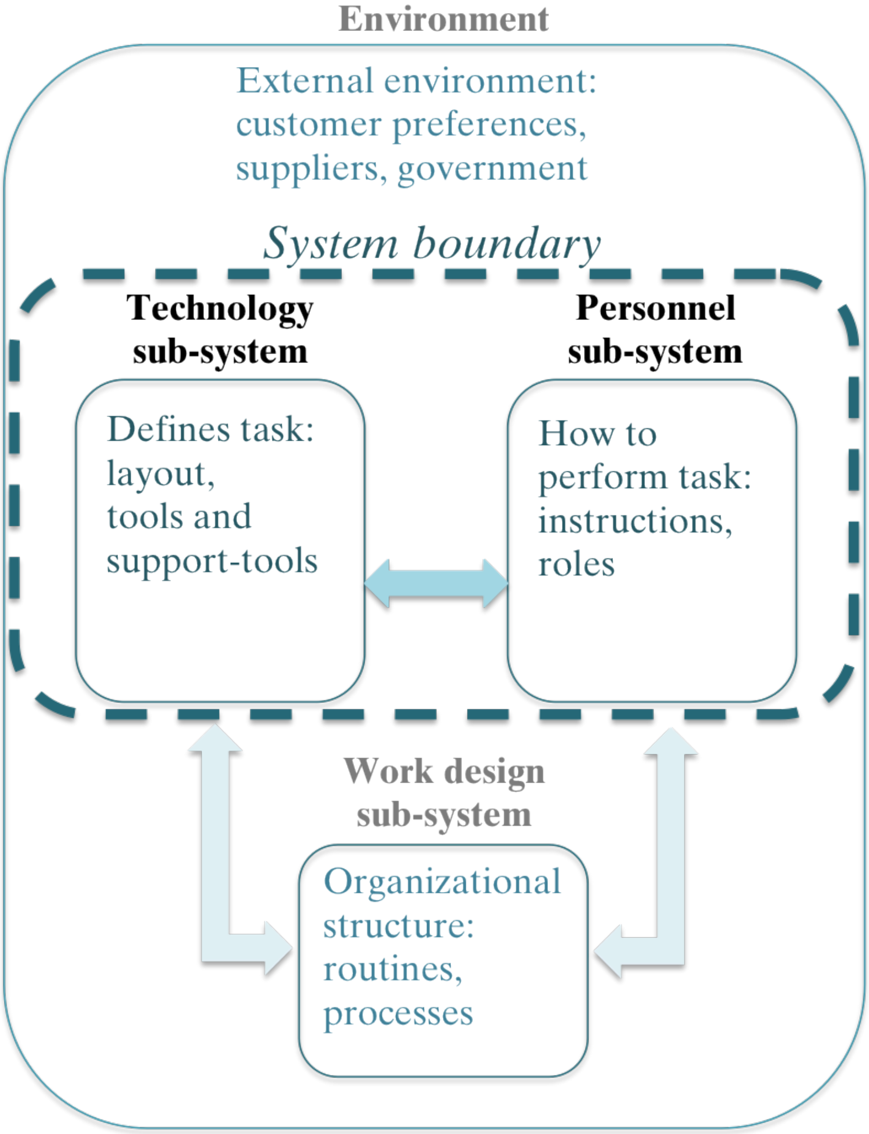

Figure 12: Result scope

4.1 To define production complexity

The final assembly system should be viewed using a holistic systems thinking i.e. a socio-technical approach (Skyttner, 2001; Senge, 1990; Checkland, 1993). The subsystems can then be seen as interrelating parts and it is important to consider all parts instead of sub-optimizing one part (Ropohl, 1999; Trist, 1981) i.e. to consider both *technology* and *personnel sub-systems* therefore it is important to consider both *objective* and *subjective complexity* (Paper I). Supporting the holistic view of complexity a complexity model was presented, see Figure 13 (Paper I). The model consists of the following parts: *causes of complexity*, *objective and subjective complexity* and *complexity management* (management is further discussed in Chapter 4.3).

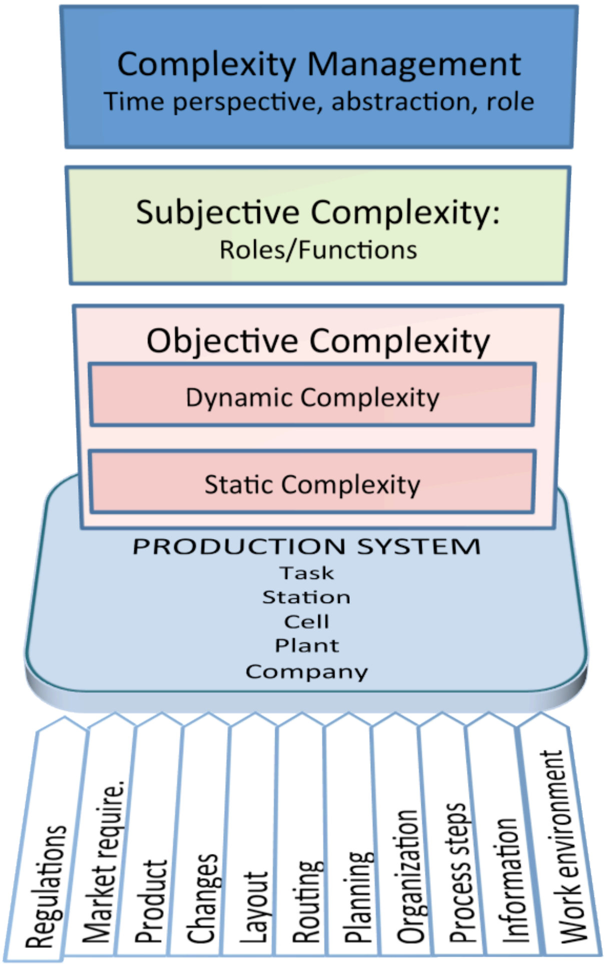

Figure 13: Theoretical framework suggested in Paper I

In the suggested model, Figure 13, the following elements affect production complexity: *regulations, market requirements, the product, changes, layout, routing, planning, organization, process steps, information* and *work environment* (Paper I). The elements were further simplified and grouped throughout the development of the CXI method (Paper II-IV). In Figure 14 the elements are presented in a co-variance model; this is different from a cause-effect model (Holme and Solvang, 1997). In this type of model it is indicated that there is no causal relation between the elements, more than that they all contribute to complexity i.e. it is not specified if one or several elements contribute more or less (Ibid.). The elements can be described as INUS-conditions where the identified elements can contribute to a system becoming complex but do not have to be the cause of the complexity (Mackie, 1965). The suggested elements of production complexity are: *product variants, work content, layout, tools, support tools* and *work instructions*.

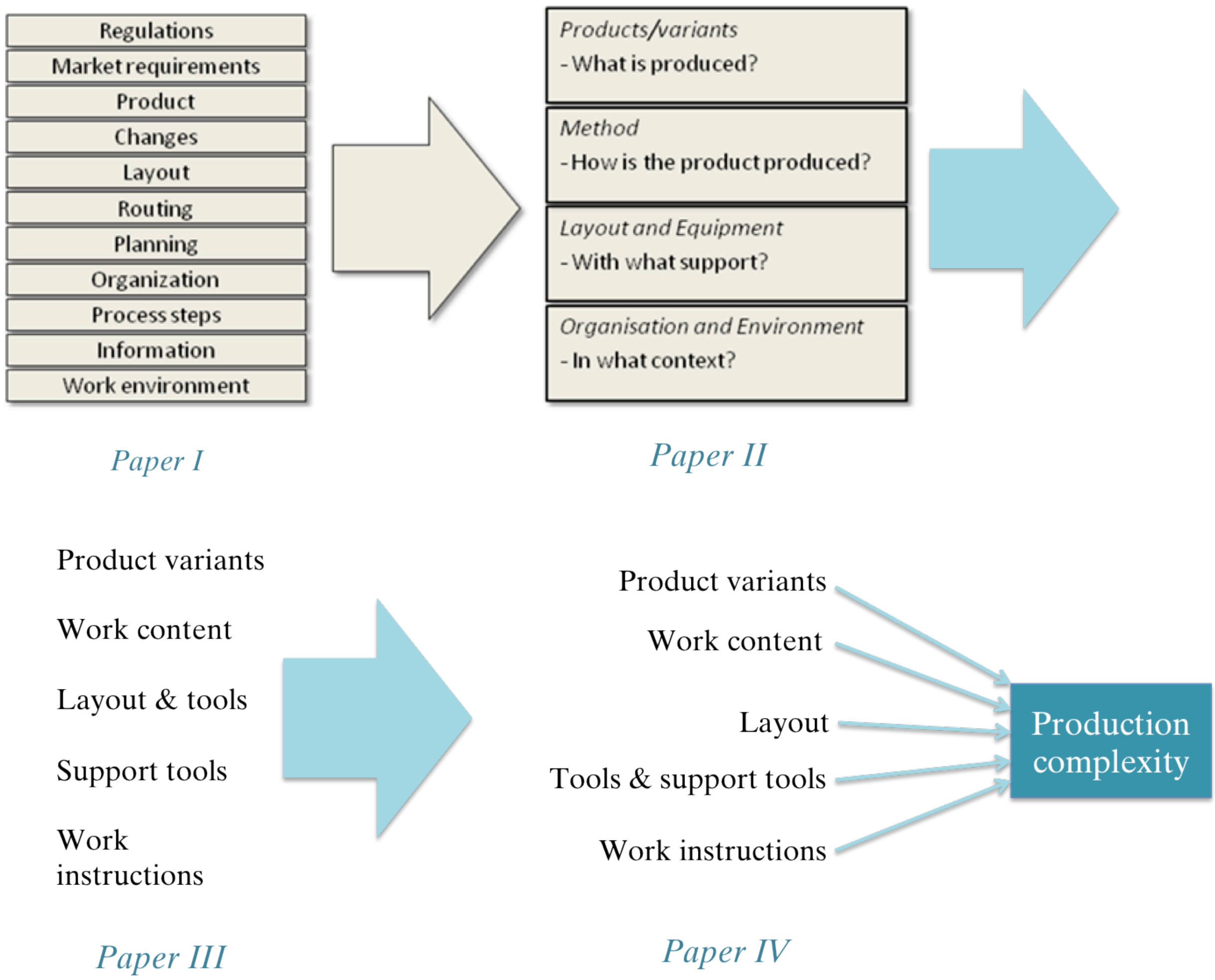

Figure 14: Process of finding the elements of complexity

Summary and how to define production complexity

Based on the theoretical and empirical findings the following definition is presented (thereby answering RQ1):

Production complexity can be defined as the interrelations between product variants, work content, layout, tools and support tools, and work instructions.

4.2 To measure production complexity

Since production complexity should include both objective and subjective aspects, existing methods were investigated further (from theoretical framework). This was done in order to find an objective method that includes the complexity elements and to further show why the development of a method is needed. The subjective complexity was measured using the developed method CompleXity Index (CXI) and empirical results from the measurements are presented.

Comparison of methods

The existing methods are summarized in Table 5 according to: *purpose of method, type of measure/-s (objective or subjective)* and *data gathering method* (see also Paper V and Appendix C). This table could be used to find a suitable complexity measurement depending on research scope and resources. Of the nine methods only three rely on subjective aspects e.g. the CXI, Robustness Index (RI) and Knowledge and Technology complexity method (Meyer and Curley, 1993). Almost all objective methods relied on production data (either observed or collected from data logs). This means that in order to use the methods logged data need to be available. In addition, the aim of many methods was to study complexity from a controller, management or team leader level perspective i.e. not assessing the worker view. Assessing the workers view was only done in CXI and Knowledge and Technology complexity method. The Knowledge and Technology complexity method did however not include all elements in the suggested definition (focuses on knowledge and technology).

Table 5: Complexity method matrix with nine methods that have been used to quantify complexity

Method	**Purpose of method**	**Types of measure/-s (objective/subjective)**	**Data gathering method**
Operational Complexity (Sivadasan et al., 2006) (UK)	To monitor and manage information and material flows	Objective: Amount of information required to describe a state: according to flow variations, products, reasons and variation states.	Observed by a controller in a supplier-customer system during a specific time interval
Entropic Measurement (Frizelle and Suhov, 2001) (UK)	To measure the rate of variety	Objective: Probability of a state to occur according to different time measures.	Production data or measurements in factory
Manufacturing Complexity Index (Urbanic and ElMaraghy, 2006) (UK)	To evaluate alternatives and risk with respect to product, process or operation task in a design stage	Objective: Quantity, diversity and content information in the process	Assessments of elements in system
Operator Choice Complexity (OCC) (Zhu et al., 2008) (Michigan)	To find causes, plan assembly sequences and design mixed-model assembly lines	Objective: Average uncertainty and risk in a choice for right tool, fixture, parts and procedure for variant	Observations or from data systems
Knowledge and Technology complexity (Meyer and Curley, 1993) (UK)	To manage software development	Subjective: Assessment of knowledge and technology complexity	Questionnaires/interviews
Complexity Method (CXB) (Falck and Rosenqvist, 2012) (SWE)	To support product preparation to increase productivity and decrease costs	Objective: Criteria for low/high assembly complexity	Logged data from company databases and assessments of area. Assembly errors from team-leaders
Robustness Index (RI) (Paper II) (SWE)	To evaluated risks and problem areas on a management/team leader level	Subjective: Robustness score regarding material, method, machine and environment	Several specialists gathered, discussed and agreed on index
CompleXity Calculator (CXC) (Zeltzer et al., 2012) (BE)	To automatically assess the complexity of stations	Objective: Probability that the workstation's complexity is high or low	Capture data automatically from systems
CompleXity Index (CXI) (SWE)	To find problem areas at a station level	Subjective: Assessment of product/variants, work content, layout, tools and view of station	Questionnaire made by operators and personnel close to production

To measure production complexity in an objective manner, the complexity elements should be calculated. Although it is stated in the method descriptions, what elements (measures) are used it can be difficult to be sure that the objective data does or does not capture the production complexity elements. The methods that include many of the elements could be used to measure production complexity are the Operator Choice Complexity (OCC) (Zhu et al., 2008) the CXB (Falck and Rosenqvist, 2012) or the CXC (Zeltzer et al., 2012) methods. The OCC method includes the risk connected to the tool, fixture, part and procedure connected to the variant (could represent the elements: *work content, tools and support tools* and *work instruction*). The CXB method includes a number of different variants, which can regard several of the elements of production complexity. The CXC method captures *product variants, work content, layout* in terms of assembly direction, *tools and support tools* as well as *work instructions*. These methods could be used to capture the objective production complexity.

CompleXity Index

The objective of CXI is to assess weather a station has a low, middle, or high complexity and how urgent that problem is. To better visualize the complexity index, the score was divided into three categories: Green, Yellow and Red. Stating for instance that a Red area needs urgent change, Yellow needs change and that Green would mean that no change is needed. The limits for these categories are: Green for CXI < 2, Yellow for 2 ≥ CXI < 3, and Red for CXI ≥ 3, see Table 6 for the score boundaries. The development steps of CXI is found in Appendix A. During the development steps the score boundaries, formula, questions and complexity elements were changed.

Table 6: Score boundaries for CXI

CXI	**Complexity**	**Colour**	**Action**
<2	Low	g (Green)	No action needed
≥ 2 and <3	Middle	y (Yellow)	Need change
≥3	High	R (Red)	Need urgent change

The questionnaire answers are evaluated using a formula (the complete questionnaire is found in Appendix B). The formula consists of two parts:

$$CXI_e = \frac{\sum_{P=1}^{n} M_{ep}}{n} \tag{1}$$

$$CXI = \frac{\sum_{e=1}^{k} CXI_e}{k} + \frac{\max_{e=1..k} CXI_e}{4} \tag{2}$$

Where:

CXI is the total complexity index for the station

CXI_e is the complexity index for complexity element *e*

M_{ep} is the median of the questionnaire answers for complexity element *e* for respondent *p*

k is the number of complexity elements

n is the number of respondents

CXI is measured by first calculating the median for each complexity element (first part of formula (1). The second part of the formula (2) make sure that high values of elements of complexity are captured i.e. individual differences, will be captured in the station CXI. Here the highest median for all complexity elements (the maximum median) is taken and is divided by a four (the highest median can be 5 (because the statements are rated from 1-5) which means that if a five is the highest median the second factor will be 1.25). These are the basics for calculating CXI. The analysis of the index includes also studying the variance between individual answers.

The interrelation between the production complexity elements i.e. *product variants, work content, layout, tools, support-tools* and *work instructions*, were visualized in CXI using a colour-carpet which was as useful in understanding complex final assembly stations (see Papers II-IV). In addition to the elements of production complexity the questionnaire also included *the general view* of the station.

i. *Product variants* are the number of product variants that can be found on the station. The operator is asked if there are less frequent variants, if the product variants have similar components and e.g. if they are different in the assembly.

ii. *Work content* regards if there are many work tasks except for the final assembly, if the operator knows what to do when they come to the station and if they are part of changing or planning work on the station.

iii. *Layout* regards the layout of the station regarding if the material handling, material façade and if ergonomics are well designed.

iv. *Tools and support tools* regards what type of tools they have on the station and if they help the operators in their assembly work.

v. *Work instructions* regards if the instructions are used everyday and if they help the operator in their daily work (this area can be specific for the operator role).

vi. The *general view* of the station regards what the operator in general thinks about the station and here it is possible to comment to suggest improvements.

Measuring the subjective production complexity

The following examples show how the interrelations can be used to characterize the assembly stations (data from Paper II characteristics of stations were not included in the paper), see Figure 15. Stations A-E are explained in detail; stations F-H had similar characteristics to those in Stations A-E and are not exemplified further. Note that the complexity elements are just five (and not six according to the final version of CXI). In this version of the method layout and tools are included in the same problem area. The areas were divided in order to be able to visualize the differences between changes needed in layout and tools.

Example

STATION	A	B	C	D	E	F	G	H
Area i: Product/variants	4	1	4	1	5	5	5	5
Area ii: Work content	1	1	1	5	5	3	1	1
Area iii: Layout and tools	2	1	1	1	2	2	2	3
Area iv: Support-tools and work instructions	3	1	2	1	1	3	1	1
Area v: General	2	1	2	3	5	2	1.5	2.5

STATION	A	B	C	D	E	F	G	H
CXI	3.0	1.3	3.0	2.3	6.3	4.3	2.8	3.8

Figure 15: Results from Volvo Car Corporation

- Station A was not considered complex in the first view given by personnel. Here the station was assessed complex (Red value for CXI ≥ 3) regarding complexity elements: *product variants* and support-tools (there were none). At this station CXI could help discover problems previously not known. As a calculation example the CXI of Station A is calculated by first taking the median of each of the complexity elements, in this case 2. Then the highest median i.e. 4 is divided by the factor 4 and added to the first term resulting in an index for the station 2 + 4/4 = 2 + 1 = 3.
- Station B was not considered complex in first view given by personnel. Although there are a lot of variants on the same line they are assembled in the same way and was not perceived as complex. Here the general view was supported by CXI results.
- Station C was an assembly of small parts. Personnel, in the first view, considered the station complex due to the high variant number. In addition a high rating was given due to problems with ergonomics. Here CXI could give indications of the complexity due to a combination of the complexity elements as an interrelation.
- Station D was not considered complex in first view given by personnel. The station was given Red values for the work content and general view since a lot of time was spent on opening boxes. Here CXI was used to find and visualize unnecessary work.
- Station E was considered complex, by the personnel working there, due to a high variant flow. Confusion due to that some parts are assembled on another station, sometimes but not always, added to the complexity. Here CXI visualizes known and unknown problems.

The results from companies indicate that the respondent's assessments do not vary that much from each other (see Paper III). This was supported by a respondent in Study C: *I think everyone has approximately the same view* (Interview 3). The interviewed respondents state, that although having different skill levels the CXI provide useful information: *If 90% think that the station is easy, why do the others think it is difficult? I think it would be good to know what people think, know why people think differently. I only know my own view.* Several respondents stated that although the station was acceptable to work at, they felt that a new person would have difficulty to learn the work. One operator stated: *It is pretty difficult to learn it, but once you know it, it is okay* (Interview 2). Another operator working on a different station supported this: *as a new employee it is horrible. You have to learn the pace; it does not work to perceive it all at the* *same time. It is frustrating with all the signals, all the new things. For me now: It just flows!* (Interview 4).

The difference in assessment could be found for people with different roles. In Study C The trainers' role at Company B was to teach new trainers how to educate their personnel on the lines (they had deeper knowledge of the station but had not worked there for some years). Results indicate that trainers rated the stations as more complex than the actual operators did (due to the number of product variants). However, the value for the operators was close to red values (CXIA=2.96 and CXIC= 2.90 where the score for a red value is ≥3). The difference could however be due to that they had not worked on the station for some time. In order to further understand the problems identified, a discussion with the associated operators is needed. The differences connected to roles have to be further investigated.

In Karlsson et al., CXI was used in order to gain knowledge of current and future support tool needs (Karlsson et al., 2013)(within the project Operator of the Future, see Preface). Since the method does not take a long time to complete it was useful for the companies in providing a view of the current state (already on the first visit). In total 58 operators answered the questionnaire (9 stations for three companies. The reference paper includes case data from two companies).

Summary of how to measure production complexity

CXI provides a useful, pragmatic and simple view of complexity presented from different peoples' views on a station e.g. the colour-carpet that helps to visualize the patterns between the elements of complexity (thereby making the system knowable or even known (Kurtz and Snowden, 2003)).

CXI can be used to:

- Find problem areas and suggest improvements
- Predict problem areas on new stations by measuring similar existing stations (re-building stations or building new stations)
- As a tool for man-hour planning (having measured several stations)

Objective complexity could be measured by using the OCC, CXB or the CXC method, which capture many of the production complexity elements.

4.3 To manage production complexity

To manage complexity, the personnel working closest to the complexity should be part of the analysis (Grote, 2004; Taylor, 1911). This indicates that the methods should be low in adaptation, which was true for CXI, CXC, OCC and Knowledge and Technology complexity method, see Appendix C or Paper V. The CXC and the CXI were compared, in Paper V, with the aim of investigating if they could complement one another. It was indicated that CXC is a good method for scanning stations and that CXI could be used to study the complexity in-depth at identified problematic stations. The objective data could be done automatically (as in the CXC model), which is fast if all data is logged e.g. a larger company, but could take a lot of time if it has to be gathered by observation (depending also on the number of measures).

To support a holistic management result from the case studies, Paper I shows that production complexity management needs to regard the:

- Global perspective and external challenges,
- Abstraction levels: company/plant, cell, station, task level,
- Time perspectives: Short, medium, long term, and
- Individual perspectives: Function/roles

This is illustrated in Figure 16.

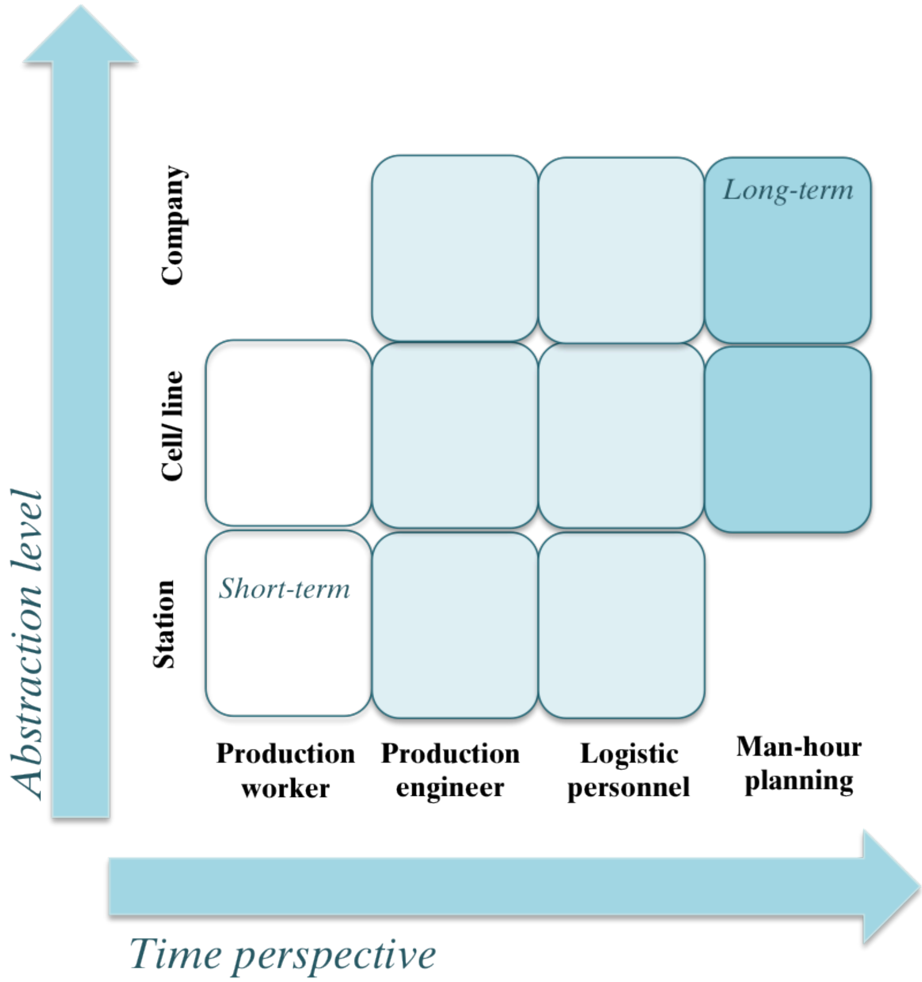

Figure 16: Subjective complexity dimensions

In this figure CXI could support the management of short-term time perspective on a station level whereas the objective data could be used to capture the cell and company/plant level. Objective methods could thereby be used to choose which stations that should be studied in-depth. Thereafter the team leader or manager could discuss the results from the CXI's colour-carpet together with the operator to establish what improvements could be made.

The unstructured interviews showed that the operators thought that the CXI could be used for continuous improvements, specifically if given to all operators after a rebalancing situation. The operators would then have the chance to comment and if in agreement, changes could be implemented directly (Interview 3). One suggestion was to do this once a year in connection to other surveys (regular surveys carried out to establish employees opinions on company culture etc.). The team leader, in the current state analysis completed in Study C, supported this idea: *It would be a good complement to "how are you feeling at work-survey".* One operator stated that it could only be used for re-balancing or in regards to material: *These are areas in which improvements can be carried out without making substantial changes* (Interview 1. The problem on this station was the product variants, which many times cannot be changed without making bigger changes). The production supervisor supported this view and stated that it was not possible for him to make changes. He thought the method could be useful on a higher level since he did not have authority to make changes to respond to the Red values in the CXI.

Summary of how production complexity can be managed

Production complexity could be simplified (Wiendahl and Scholtissek, 1994) by visualizing the interrelating elements of complexity. CXI provides a *simple*, and time-efficient measurement that could improve the management of complex stations. CXI could be used to *avoid* (Kaluza et al., 2006) the negative effects of complexity by performing a current state analysis, facilitate continuous improvements and *prevent* (Corbett et al., 2002) and undermine problems on new stations. The assessment is useful as a visual decision support when it is possible to make changes according to the suggested problem area (complexity elements) i.e. when the team or team leader has the mandate and sufficient funds to do so. In order to identify which stations should be studied in-depth with CXI, all stations could be scanned automatically using objective measures e.g. the CXC or the OCC method. This enables different time perspectives, different functions and abstraction levels (being able to scan the stations mean that cells and the whole plant can be studied) according to the subjective dimensions.

5 DISCUSSION

The main aim of this chapter is to discuss how production complexity can be managed. In addition the research approach and the quality of the research is discussed.

The aim of this thesis was to make production companies more competitive by suggesting how production complexity can be managed. This is presented in Figure 17.

- To *define* production complexity: a definition of production complexity is presented and a research gap was presented: perceived complexity and the use of subjective data. Previous literature, systems thinking and the theory of socio-technical systems pointed to a need for a holistic view.
- To *measure* production complexity the CXI method was developed to resolve the encountered research gap and it was found that there was a need for simple and time-efficient methods.
- To *manage* production complexity: Since the definition of complexity emphasized the combination of subjective and objective aspects it was found that a combination of methods should be useful when managing complexity.
- Reaching competitiveness: To avoid sub-optimization organizational data and different roles should be included. CXI should be complemented with objective complexity and aspects from the *work design sub-system* as well as from the external *environment* (including global challenges).
- Future work includes further developing the method and testing complementary methods that incorporate organizational factors as well as error and quality data.

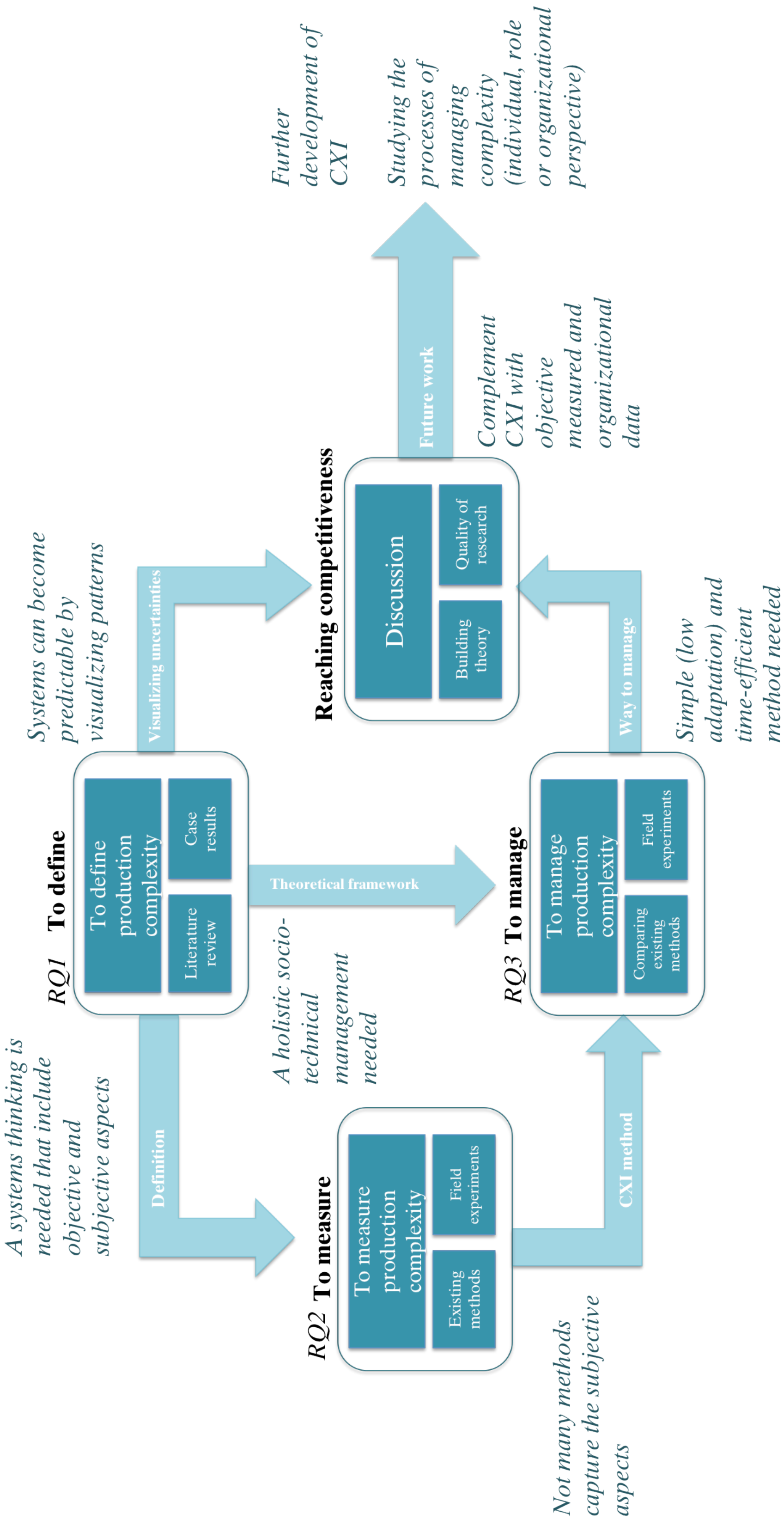

Figure 17: The research process

The research contribution is presented in Table 7.

Table 7: Research contribution of work connected to research objectives

Contribution	To define production complexity	To measure production complexity	To manage production complexity
Academic	Definition of production complexity	Comparison of complexity methods Characteristics of complex stations	Case study results Further comparison of complexity methods
Industrial	Language and structure for talking about production complexity	Description of practical usefulness of CXI and comparison of existing methods Index and visual presentation of problem areas/complexity elements on a station level	Suggestion of how complexity can be managed (for instance by a team-leader)

5.1 Reaching competitiveness

Elmaraghy et al. (2012) stressed that competitiveness could be increased by more effectively managing and innovating socio-technical systems. According to Hendrick and Kleiner (2001) this meant to consider all parts of the socio-technical sub-systems: *the technology, the personnel, the work design sub-system* and the *environment.* The developed method CXI is a step in this direction, including *the technology* and the *personnel sub-system.* CXI is useful to study individual differences between different skilled workers i.e. managing the variation of workers. This also accounts for different roles, which can capture aspects of socio-technical systems to some extent. Understanding production complexity and its interrelating elements could reduce the cost for assembly errors (Falck and Rosenqvist, 2012) and increase the product quality (Fässberg et al., 2011). If complex assembly systems can be better managed this could result in higher company performance (Perona and Miragliotta, 2004), decrease time and assembly errors as well as increase the productivity, quality, profitability and competitiveness (Samy and ElMaraghy, 2012). In addition, it could be used to to better manage the demands of social sustainability i.e. demographical issues (Regeringen, 2012; Chui et al., 2012).

5.2 Quality of research

The quality of the research in terms of validity, reliability and transferability (Yin (2009) and Ihantola and Kihn (2010)) was ensured by using Flynn et al:s systematic approach and triangulation. The chosen approach was useful in building new theory (Yin, 2009; Eisenhardt, 1989) and although the references Eisenhardt and Yin studied how to build theory from case studies, the theories presented can be applicable to field experiments as well. Choosing another approach could have provided other advantages and disadvantages.

The *external validity* was increased studying the phenomenon in several companies. The field notes is presented in Appendix E, which strengthens the *reliability* of the study. The samples were chosen to be representative (Yin, 2009; see Reflections). The empirical data was useful in providing the data needed to validate the elements (data, methodology and theory triangulation). Investigator triangulation contributes to the *reliability* of the results (since co-authors with different backgrounds and experiences were included in different stages of the research). The *reliability* is however reduced due to that unstructured interviews were not recorded or transcribed.

Due to that existing methods were compared and abduction was used the *internal validity* was increased (Eisenhardt, 1989). The *construct validity* is high since the study was described in the research implementation (this also increases the *transferability* and *contextual validity*) (Yin, 2009; Ihantola and Kihn, 2010). The chain of evidence and multiple sources increase the *construct validity, contextual validity* and *transferability.*

The data collection methods were suitable to answer the research questions (qualitative and quantitative data complement one another (Williamson, 2002; Yin, 2009)). This also increased the *internal validity.* In order to study production complexity in a more holistic way, in-depth structured interviews could have been an alternative. This could have given a wider view of other departments, not included in this thesis, e.g. product preparation, product development and quality assurance. Instead of using a questionnaire, structured interviews could be used to fully grasp what problem areas contribute to the complexity. This could have given a more deep and holistic view of the problems but should have taken more time from production and for analysing the data. The CXI method was validated through the use of semi- and unstructured interviews which could be biased according to interviewer effect (Williamson, 2002). This means that the respondent answers in a way he or she thinks the researcher wants them to. This is a threat both to *reliability* and *validity*. However since almost 90 CXI measurements have been made and feedback from the measurements was positive (they thought that the CXI gave a correct view of the station), the results could be viewed as reliable (also increases the transferability of the study). By letting the key informants review the paper, Paper IV, the construct validity was increased. By using field experiments the *internal validity* was increased (validating quantitative results with qualitative data). Comparing existing methods also increased the validity. Although the validation included comparisons to objective data, it did not include organizational data that could have been useful in order to reach a more holistic viewpoint.

The data analysis was performed using both quantitative and qualitative methods, which was supported by Yin (2009). The methods chosen in the method comparison (Paper V) were chosen since they could be coupled to the final assembly situation in some way. The Knowledge and Technology method (Meyer & Curley, 1993) was included, although much older and not as applicable to the assembly situation as the others, since it provided a view of complexity that was not brought forward by the others. The other methods were developed after 2006, which means that it is, with the exception of the Knowledge and Technology method, a review of recent complexity methods. Although there are methods represented from all over the world i.e. the United States, Belgium, the United Kingdom and Sweden, most of the methods originate from the United Kingdom. This could imply a bias in the results.

5.3 Reflections

The main strength in the research performed is that theory is built using *abduction* i.e. by iteratively using both theory and empirical data. This is especially seen for the measurement of production complexity. The usefulness of CXI was proven in the current state analysis measurements done within the Operator of the Future project where 53 assessments were done in three companies. The questionnaires were self-administered and answered with a 100% response rate, which proves that although CXI covers a complex topic it is simple to understand, by the respondents. This was also proven since many different roles have been tested with the method. It is also time-efficient since the operators filled it in in their spare time and the analysis of the questionnaires could be done directly at the company (after approximately 30 minutes of filling in the data in an Excel sheet). Different researchers and evaluators did the analysis, providing indications of the methods low adaptability.

However, the questionnaire has not been tested statistically, which decreases the *reliability* of the method. Statistical test include validating the questionnaire further to study if the questions correspond to the suggested elements of complexity. Also, even though the analysis of the CXI includes studying the variance of individual answers further studies should be performed to ensure that the views of several individuals are correctly captured. This is also why the results were compared to unstructured interviews (to support that the results were correct).

The results are valid in the final assembly context but some results could be applicable to other branches. The chosen delimitations to assembly systems and especially to final assembly could limit the *reliability* of the results of production complexity since the studies only included final assembly. It could be argued that a more narrow view of complexity has been studied e.g. assembly or product complexity (other areas of complexity). However, since Paper I included more roles e.g. man-hour planning, logistical personnel and management and that the continued studies with CXI included additional roles e.g. logistical personnel and productions supervisors, it is possible to argue that production complexity is captured in the study. Also since different types of companies were included in the study (not only automotive companies) and that automotive companies have high demands in both quality and time-efficiency, the results could be relevant to companies with similar contexts. Even though case studies and field experiments introduces difficulty in generalizing results, the CXI method could be used in other branches. For instance even though it was designed for assembly industry it could be tested in process industry (changing assembly to the process investigated).

The result from the CXI is only valid when a specific station during a certain time-span is considered. The results should be studied analysing the roles separately e.g. logistical personnel separated from the operators. If a big variance within role answers is seen complementary interviews are needed to further understand the interrelations.

Managing the complexity in the suggested way could increase communication between roles that normally don't have team meetings together (logistical personnel and assembly operators) and could also increase the worker influence on improvements. In order to successfully implement an objective method and the CXI the personnel should be included in the work design.

The choice of delimiting *work design sub-system* and the *environment,* also make the findings less holistic. This is also one reason that CXI does not incorporate organizational issues (the work design subsystem suggested by Hendrick and Kleiner (Hendrick and Kleiner, 2001)). Also an environmental aspect that could be interesting is the company culture, which should influence the quality and perceived view of the station. If only focusing on one part of the systems complexity, other parts of the process might have to endure an increased complexity.

5.4 Future work

Additional measures are needed in order to complement the results of a CXI measurement (in order to further develop the holistic approach). For instance CXI does not capture connections between Red values in product variants and support tools (Paper IV). In these stations there are a lot of product variants, which were secured via support tools at the station. The tools make incorrect assembly very difficult, even impossible. This characteristic could be included with a complementary statement or via complementary measurements. In order to better capture the holistic view CXI could be measured long-term to see which changes occur in the perceived view of the station (studying the differences in the measurement) or by using other methods in conjunction.

In general, the method developed needs further testing. Although, it has been tested by over 90 respondents that have been positive to the results. The focus has been on operators which means that further studies are needed to make sure that the questionnaire is suitable for other roles and to test that respondents have a similar view on the station investigated (this was found in all studies so far).

By performing the CXI studies the following questions have been raised:

- How can the interrelation between product variants and support tools be better visualized in CXI?
- How can organizational data be captured in a simple way to support a socio-technical view of the assembly?
- Is there a relation between high/low production complexity and satisfaction?
- How is company culture connected to management of production complexity? And how can company culture be affected to better manage production complexity?

The perspective of worker satisfaction has not been included in this thesis i.e. it does not say whether a complex working situation is related to work satisfaction. This could be an interesting further development of CXI. Some parts of this were comprehended in the studies (in comments and interviews) where for instance one station was considered complex due to unnecessary material handling. Reducing this might also increase work satisfaction on the station (however the satisfaction may also be increased due to that their suggestion of improvement was carried out). This should be studied on different roles on different experience levels (a novice worker might find other things satisfying than does a skilled one).

Also, production complexity has not been connected to assembly errors. Even though this was already found in previous case studies it would be interesting to use CXI in a current state analysis while also measuring assembly errors, then introduce some changes according to the identified complexity elements and finally measure the future state (CXI and assembly errors).

The method today is in paper form that could be further developed into software. This would increase the time-efficiency even more and better visualize the interrelations between the complexity elements, the questions and the CXI on that station.

6 CONCLUSIONS

In this chapter the answers to the research questions are presented.

The aim of the thesis is to make production companies more competitive by suggesting how production complexity can be better managed. The aim was fulfilled by answering how to define, measure and manage production complexity in a final assembly context (RQ 1-3):

Define

RQ1: How can production complexity be defined in a final assembly context?

Measure

RQ2: How can production complexity be measured in a final assembly context?

Manage

RQ3: How can a measurement of production complexity be used to manage production complexity in a final assembly context?

A definition of production complexity was found, RQ1. *Production complexity can be defined as the interrelations between product variants, work content, layout, tools and support tools, and work instructions* called the elements of production complexity.

The developed and validated method, the CompleXity Index (CXI) was found to successfully capture the interrelations, which were also visualized, RQ2. The method has low adaptation i.e. is simple and time-efficient which means that it is useful for industrial purposes and could be used by people with different roles. This way production complexity could be captured from the workers point of view and not only from a management perspective (done in existing methods). CXI provides a unique way of measuring the subjective aspects by including different roles, and gives a fast indication of how the complexity elements interrelate and why, on a specific station. Empirical results indicate that CXI could be used for continuous improvements and to predict problem areas on assembly stations.

To manage production complexity, RQ3, complexity should be *simplified* and *prevented* so that negative effects can be *avoided*. This could be achieved by automatically scanning all stations with an objective method and then measure CXI in-depth. In addition, organizational and environmental aspects should be studied. Managing production complexity this way could increase productivity, quality and decrease production time.

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APPENDIXES

Appendix A
Development of the complexity index method

Appendix B
The CompleXity Index questionnaire

Appendix C
Complete matrix from comparison of existing methods

Appendix D
Interview guides for Study A

Appendix E
Interview guide and field notes from Study C

APPENDIX A – DEVELOPMENT OF THE COMPLEXITY INDEX

To meet the apparent need, the CompleXity Index (CXI) was developed to measure perceived production complexity. CXI is a questionnaire-based method and complexity assessment tool that includes 26 statements addressing the following identified complexity elements: *Product variants, Work content, Layout, Tools and support tools, Work instructions* and *General* (general view of the station). The complexity elements are based on empirical work in Paper I. The development of CXI is further explained in Paper II. The complete questionnaire is found in Appendix B.

The CompleXity Index development was done in 5 steps: Concept *development, Testing, Validation, Comparison* and *Use*. The first step included finding complexity elements and building a first draft of the method. The problem areas were found by studying common problems from empirical data in Paper I. The method was created based on an already existing and used method at Volvo Cars Corporation (the description of that method is found in Paper II). Step 2 was a pilot test at Volvo Cars Corporation (Paper III). Step 3 was the validation of the method done at three companies (Paper IV). Step 4 was a comparison with the method developed by the COMPLEX project in Belgium (Paper V) and Step 5 is current state analyses done at two companies included in the project Operator of the future (the perceived need for future operators is described in Grane et al. (Grane, 2012). The development phases of the method is presented in Table 8.

Table 8: Development of CXI

Changes\Step	1: Concept development	2: Testing	3: Validation	4: Comparison	5: Use
Change in grouping of complexity elements	Four complexity elements: Product/variants, method, layout and equipment and organization and environment	Five complexity elements: Product, work content, layout & tools, support tools & work instructions and general (view of station)	Five complexity elements: Product variants, work content, layout, tools and support tools, work instructions and general (view of station)	Same as for step 3	Same as the validation
Statement changes	No statements	23 statements (one statement rephrased)	Question about the respondent' background was added (How many years on actual station?) 23 statements	23 statements	Two new statements regarding ergonomics and if a certain feeling is required to assemble at that station. 25 statements
Change in CXI formula	No formula developed	Formula developed	Calculation of means for several participants instead of medians	-	-
Total number of participants	-	16 (8 team leaders and 8 operators 8 stations	16 operators, 3 trainers, 4 kit operators and 10 logistic personnel 16 stations	Same as case as for step 3	3 operators 5 stations 43 operators 9 stations
Method	Interview	Workshop and objective data comparison	Interviews, workshop with people of different roles	Comparison of added value of the methods	Interviews, workshop
Type of triangulation		Data and methodology triangulation	Data, investigator and theory triangulation	Theory triangulation	Data and methodology triangulation
Comment	RI was not useful, needed a simpler method. Complexity elements based on empirical data	Tested at 8 stations at VCC. Interesting examples, tells characteristics of stations. Validated with company	Validated at three companies	Comparison with Belgian objective method. Methods complements one another	Used for current state analysis at three companies

APPENDIX B – THE COMPLEXITY INDEX QUESTIONNAIRE

(translated from Swedish)

This questionnaire has been designed to find solutions that can simplify and improve your work. The survey is anonymous. When you are filling in the questionnaire it is important that you consider one chosen station.

Chosen station: ___________

Number of years assembling:________years

Number of years on actual station:________years

The questionnaire regards: product variants, work content, layout, tools and support tools and work instructions.

Thank you for participating!

Consider how well the following statements fit with the work you have performed during the last month at the chosen station. The scale is 1-5 where 1 is I agree completely and 5 is I don't agree at all.

A. Product variants

1. There are many different variants on this station

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

2. Many variants are similar to one another regarding function and/or external surface at this station

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

3. There are many variants that are seldom assembled at this station

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

4. The variants at this station require different strategies to assemble (for instance order, difficulty, different amount of operations)

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant
(exactly the same assembly strategy)				(completely different assembly strategy)	

5. The components that belong to the different variants are very similar at this station

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

B. Work content

6. When I work on this station I know what to do

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

7. I often feel that I have time to perform the work at this station

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

8. I have many other work tasks, except for the assembly work at this station (for instance material handling, 5S, documentation etcetera)

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

9. My work at this station is often affected by unplanned changes/uncertainties (for instance change of plans, new instructions/variants, or machine disturbances)

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

10. I am part of the planning for the changes on this station

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

C. Layout

11. This station is well designed regarding reachability

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

12. This station is well designed regarding heavy lifts in the assembly work

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

13. This station is well defined regarding ergonomics in the assembly work (for instance stretching, bending down)

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

14. This station is well designed regarding the material façade (for example type of packaging, placement, simple to pick and sequence material)

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

15. The placement of tools, fixtures and components on this station is generally good

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

D. Tools and support tools

16. The tools/fixtures that are used on this station are well adjusted for the tasks performed there

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

17. Different tools are used for the assembly of different variants at this station

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

18. Which support tools are found at this station?

☐ Pick-by-light (lights are lid for a specific part)

☐ Barcodes and scanners

☐ RFID system

☐ Feedback from screens

☐ Feedback from tools (for example the correct force and correct bit)

☐ Checkpoints (feedback in the assembly work)

☐ Other ___________________

19. The above mentioned support tools helps me to carry out my work on this station

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

E. Work Instructions

20. I often read (every day) the work instructions that are placed at this station

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

21. The work instructions are easy to understand

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

22. The work instructions at this station simplify my work

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

23. It takes a long time to learn the work on this station (compared to other stations in my team area)

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

F. General view

24. At this station a feeling (tacit knowledge) for the work is needed

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don't know /not relevant

25. In general I think this station is well designed

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Agree Completely				Do not agree at all	Don’t know /not relevant

26. Comment (for example a possible improvement, change of the station, work content, support or other)

____

____

APPENDIX C – COMPLETE MATRIX FROM COMPARISON OF EXISTING METHODS

The nine existing methods comparison are presented below (due to size the table was divided into two parts see Table 9 and 10).

Table 9: Comparison of methods – first part

Method	**Aim**	**Type of complexity (Static or dynamic)**	**Types of measure/-s (objective/subjective)**
Operational complexity (Sivadasan et al., 2006)	To monitor and manage information and material flows	Dynamic	Objective: Amount of information required to describe a state: according to flow variations, products, reasons and variation states.
Entropic measurement (Frizelle and Suhov, 2001)	To measure the rate of variety	Static and dynamic complexity (comparison off)	Objective: Probability of a state to occur according to different time measures.
Manufacturing complexity index (Urbanic and ElMaraghy, 2006)	To evaluate alternatives and risk with respect to product, process or operation task in a design stage	Dynamic complexity	Objective: Quantity, diversity and content information in the process
Operator Choice Complexity (OCC) (Zhu et al., 2008)	To find causes, plan assembly sequences and design mixed-model assembly lines	Static complexity	Objective: Average uncertainty and risk in a choice for right tool, fixture, parts and procedure for variant
Knowledge and Technology complexity (Meyer and Curley, 1993)	To manage software development	Dynamic complexity	Subjective: Assessment of knowledge and technology complexity
Complexity method (CXB)(Falck and Rosenqvist, 2012)	To support product preparation to increase productivity and decrease costs	Static and dynamic complexity	Objective: Criteria for low/high assembly complexity
Robustness index (RI) (Paper II)	To evaluated risks and problem areas on a management/team leader level	Dynamic complexity	Subjective: Robustness score regarding material, method, machine and environment
CompleXity Calculator (CXC) (Zeltzer et al., 2012)	To automatically assess the complexity of stations	Static and dynamic complexity	Objective: Probability that the workstation's complexity is high or low
CompleXity Index (CXI)	To find problem areas at a station level	Static and dynamic complexity	Subjective: Assessment of product/variants, work content, layout, tools and view of station

Table 10: Comparison of methods – second part

Method	Data gathering	Results (detailed or holistic)	Experience level needed (High or low)	Strengths and weaknesses (+ or -)
Operational complexity (Sivadasan et al., 2006)	Observed by a controller in a supplier-customer system during a specific time interval	Dependent on scope of study	High: Needs understanding of measures, process knowledge needed	+ Detailed quantitative answers to specific questions. Set boundary's needed
Entropic measurement (Frizelle and Suhov, 2001)	Production data or measurements in factory	Detailed information on the system	High: process knowledge needed	+ Objective data, Valuable for simple systems and line managers - Takes a long time to assess dynamic complexity
Manufacturing complexity index (Urbanic and ElMaraghy, 2006)	Assessments of elements in system	Holistic	Low: can be understood by people from different backgrounds. High: Process information needed	+ Used by people from different background - Understanding of calculation needed (process versus product index)
Operator Choice Complexity (OCC)(Zhu et al., 2008)	Observations or from data systems	Holistic	Low	+ Simple measurement, many possible applications - Not detailed, could require logged data
Knowledge and technology complexity (Meyer and Curley, 1993)	Questionnaires/interviews	Holistic	Low	+ Easy to apply, low cost. Could be used for predictions - Limited to knowledge and technology
Complexity method (CXB) (Falck and Rosenqvist, 2012)	Logged data from company databases and assessments of area. Assembly errors from team-leaders	Holistic	High: Process information and expert knowledge needed regarding ergonomics, geometry assessment	+ Low/high complexity on index on stations - Requires data gathering from expert
Robustness index (RI) (Paper II)	Several specialists gathered, discussed and agreed on index	Detailed (each part evaluated)	High: Experts on products and its parts are needed.	+ Detailed knowledge about parts gathered by experts - Time-consuming and part specific
CompleXity Calculator (CXC) (Zeltzer et al., 2012)	Capture data automatically from systems	Holistic	Low: Assessment based on Likert scale	+ Gives a high/low complexity index on stations implying direct and in-direct costs - Requires logged data
CompleXity Index (CXI)	Questionnaire made by operators and personnel close to production	Detailed	Low: no prior knowledge needed, analysis in Excel	+ Holistic and quick view that visualizes complexity elements. Comments can be included - Language dependent, requires operator time

APPENDIX D – INTERVIEW GUIDES FOR STUDY A

(translated from Swedish)

<table>
<tr><td>Company:</td><td>Respondent:
xx</td><td rowspan="3">Participant from the COMPLEX-project:

xxx</td></tr>
<tr><td>Date:
xxx</td><td>Focus:
Complexity related to x (x = area)</td></tr>
<tr><td colspan="2">Comment:</td></tr>
</table>

Name and work role?

How long have you worked in x? (x = your department)

And what are you working with?

What do you think is complex or what can be complicated in your work?

Do you get good feedback from other roles (for instance logistical personnel)?

How often do you carry out improvement work?

How does the communication work then?

Do you think there are more improvements that can be made to decrease the complexity at these stations?

Are the operators part of the improvement work?

How does your support tools work?

What future challenges are there?

What level of automation do you have? Will humans be needed, not only to supervise but also to control the production?

Is it stressful at times, or do you have time?

What are your goals at this time?

APPENDIX E – INTERVIEW GUIDE AND FIELD NOTES FROM STUDY C

(translated from Swedish)

Present the research topic and the reason for the interview.
Present the CXI Excel sheet (result of the CXI measurement)

- Do you agree with the CXI general values?
- Do you think that the problem areas in general represent the perceived view you have of the station?

Discuss the open-ended question, if there is a comment there.

- Do you think that CXI could be used for continuous improvements?
- Do you think there is something missing, some question that could be included to get a better view of the station?

Field notes – Interview 1:

Many variants: Not that much that can be done; the station is driven by its variants. It is not possible to make mistakes, we scan all the material. It is only the screws that you need to learn.

CXI: Sometimes it is difficult to assemble, it depends on what variants that arrive. Maybe there are 34 variants and that is difficult to learn. When you look at the KPIs they are not studied again (since the instructions are perceived as simple). It is difficult to get into the motor station. We have now 6 stations that we vary between. It would be better with more, for instance eight. When someone new comes here they will stand on the easy station all the time – boring.

You just have to like it. It is not possible to change it. It is not possible to prepare more than one hour ahead (regarding the different product variants).

Material façade: You have to walk over to the other side to pick up material.

Comment: A lifting table could be good. The back gets a lot of weight.

Continuous improvements: Well, there are not a lot that can be changed. There are no direct changes. It is mostly the same thing all the time. The thing you could affect is the re-balancing or the material maybe. These are areas in which improvements can be carried out without making substantial changes

Missing in the CXI survey?: No, I think it considered most of it.

Interview 2

Many variants: There are many, not often occurring variants.

CXI: It is pretty difficult to learn it, but once you know it, it is okay. If you compare it to others that are easy to learn, it should be red (the CXI value of the complete station). But it has a calm pace, if you don't use the lift. The lift is not efficient since it is placed weirdly, so that takes time. Now it is possible to be calm at this station.

I don't read the instructions, maybe you should. In the beginning you did it, but not anymore. Now you know it, and have to keep track of it.

Material façade: It is like that since the last re-balancing. The holder for the screwdriver and so on was moved since it is not possible to have it anywhere else. You could build a small buffer; almost half of us work like that. Before now you didn't have to walk that far, now you have to walk and get things before every new model arrives.

Comment: The lifting tool is not good. I lift by hand, however you cannot drop the AC, then it will get expensive.

Continuous improvements: Good to do it each ¾ years, so that it is possible to see the changes. Maybe perform one after each re-balancing, in that case 2-3 weeks after it.

Missing in the CXI survey?: Not that I could think of

Interview 3:

Many variants: 30 gear boxes and components for those and 20 different engines so that is a lot. But they have pick-by-light t reduce the mistakes. You could make a mistake, but then you had to have picked the wrong piece. It may be difficult to learn.

CXI: Pretty good picture. It depends on how you feel at this moment maybe: if you are negative for instance. I think everyone have approximately the same view. I agree with it. I hardly watch the instructions .. we have pick-by-light. I don't think so much before I stand at the assembly line. It is just to do it really.

Material façade: Things stand far away. There is not enough room to introduce something new. You would like to have everything behind you. I know many people feel like this so that is why I answered like I did plus that there are problems with many of the tools. You need to change the batteries and they are worn out. We don't have many tools but more pre-drivers.

Continuous improvements: It could be used for continuous improvements, if it was given to everyone after a re-balancing situation. So that everyone could comment if they think of anything in particular. If everyone thinks so, then it could be changed. That could simplify instead of holding meetings. There are some people that don't say what they think for instance.

Missing in the CXI survey?: Ergonomic issues: to bend down for instance.

Interview 4:

Many variants: Two XC90 combi cannot come after one another for example, but that has nothing to do with the actual gearbox. There are approximately 50 different, so that is much. You cannot plan which comes after one another. It is possible to pick things in advance, but mentally. You need to be sharp and be completely there.

CXI: The view is correct: with what is red, that the general view is red and that the yellow is yellow. The instructions are green. I don't watch them. For an experienced it looks like this. I know it so I think it is ok to get to it. I have learned. As new it is much more difficult. It can take three weeks to learn the complete area, but as a new employee it is horrible. You have to learn the pace; it does not work to perceive it all at the same time. It is frustrating with all the signals, all the new things. For me now: It just flows!

Yellow for tools and support tools: there is a problem with a screwdriver.

Material façade: The station is crowded; there is no place in the façade to place new things. It is crowded both time and space.

Comment: It is difficult for those who have never seen a gearbox. Partly which one it is, partly it is difficult to see which components there should be and what "stage" (note: a specific tools) it is. Sometimes you have to reduce the ergonomics to reach quality. We cannot have tools that place the O-ring.

Continuous improvements: That would be good, maybe at the same time, once per year, the company survey is carried out. If 90% think that the station is easy, why do the others think it is difficult? I think it would be good to know what people think, know why people think differently. I only know my own view.

Missing in the CXI survey?: It is complex to get a feel for it. There are different angles in the box.

Paper I

An empirical study towards a definition of production complexity

Fässberg, T., Harlin, U., Garmer, K., Gullander, P., Fasth, Å., **Mattsson, S.**, Dencker, K., Davidsson, A. & Stahre, J.

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AN EMPIRICAL STUDY TOWARDS A DEFINITION OF PRODUCTION COMPLEXITY

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Abstract

Mass customisation increases the number of product variants, shortens product cycles, and results in increasingly complex production systems. The complexity needs to be defined, and further operationalized to support management of production complexity. This paper's contribution is the empirical findings of perceived production complexity at three manufacturing companies, from the perspective of different functions/roles within the production systems; production engineers, operative personnel, internal logistics, and in one company also man-hour planning. Data was collected through observations, interviews, and cross-functional workshops. Results show that mass customisation is the greatest driver and cause of complexity. The increase of product variants affects complexity for all three investigated roles in the production system.

Keywords:

complexity, manufacturing, parameters, subjective, management, roles

1 INTRODUCTION

Future production systems need to be extremely flexible but still remain and excel their efficiency. Mass customization of consumer products increases the number of product variants, shortens product cycles, and frequently results in increasingly complex production systems. This is a major contribution to complexity. Assembly complexity is further increased by new product requirements such as hybrid engines. In order to handle challenges related to production complexity new support is needed for measurement and development of work towards efficiency, highly flexible and sustainable production. The production complexity in assembly systems therefore needs to be defined, described and broken down into relevant components that can be used for measurements, analyses and support tool for development.

This work is part of the research project COMPLEX, "Support for Operation and Man-hour Planning in Complex Production", conducted from 2010 until 2013. The overall focus is to reduce complexity by developing generic models and methods to support strategies, planning, managing, and optimizing of complex production. A theoretical framework for complexity was proposed [1], Figure 1. This paper aims to further develop this framework by empirical studies including three case studies in companies with production complexity challenges. In specific, production complexity parameters are investigated from a company and an individual perspective. The case study approach enables mapping of how complexity is perceived by different functions in their work with operations, re-balancing, internal logistics, and man-hour planning. Furthermore, the empirical studies enhance the modelling and development of management of production complexity, development of appropriate information and IT-support tools for calculation of the total requirement of indirect and direct man-hours in production, as well as competence development approaches.

2 THE PRELIMINARY FRAMEWORK

The proposed framework based on a literature study takes a holistic view on production complexity acknowledging the need to account i) complexity drivers; causes/complexity parameters, ii) the production system context, iii) objective, and subjective complexity, iv) impact and effects of complexity, and v) complexity management [1].

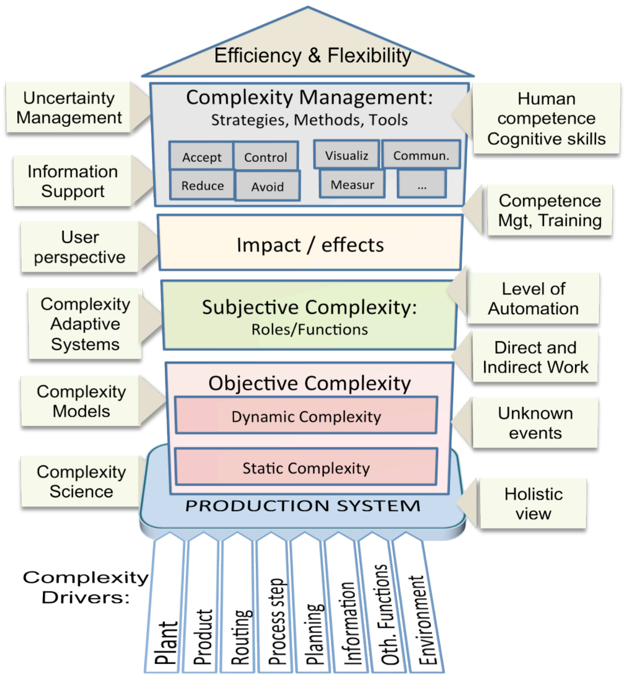

Figure 1. Complexity framework [1]

In the context of the production system, complexity parameters; drivers, causes and effects may be initiated by external changes (e.g. new product, equipment), or from within the system (e.g. schedule or routing changes). There are several factors causing production complexity, which can be operationalized as production complexity parameters.

Previous research emphasise different drivers of complexity in a production context. The relationship between complexity, and variety of products has been investigated by several authors [2-4], and has been referred to as the main driver for complexity within the automotive industry [3]. MacDuffie *et al* makes use of four measures of variety in their complexity model targeting the automotive industry: model mix, part variation, level of content and variability of options [2]. Urbanic *et al* put forward another model where the quantity, diversity and content of information are used as a function related to complexity [5]. Calinescu *et al:s* list of factors causing complexity was used as a basis to form the complexity parameters in the framework. The parameters are: products, plant/shop, planning, information flow, other and environment as seen in Figure 1.

Regarding *objective production complexity*, measurable parameters are important since they provide a hint of complexity as several experiences it and independent of whom the user is. Objective data can capture both dynamic and static aspects of complexity (Figure 1). The static complexity of a system or a sub-system can be modelled measuring parameters such as number of stations, work tasks, parts, levels of automation etc. The dynamic complexity is modelled in order to include time and dynamics, like deviations from plans, and uncertainty. The objective data focus of this paper is on static objective data rather than dynamic.

Regarding *subjective production complexity*, the same production system or situation may be perceived differently depending on a number of different factors such as individuals´ skills, competence and experience. Perceived complexity is in research closely related to managing and handling critical events, production disturbances, frequent changes, unknown situations, unpredicted situations, and difficult work tasks etc.[6-8]. Hence, as production systems become more complex there is more that can go wrong, in several ways, and it is increasingly difficult to predict faults [9]. Human cognitive skills at different levels in the organization are increasingly crucial when manufacturing systems are becoming increasingly complex and subjected to changes and uncertainties [10]. Also development of both reactive and proactive ways of working are needed where many different functions need to collaborate [11].

To grasp the perceived production complexity it is therefore necessary to gain an increased understanding of different functions and their needs in the organization [12]. There is also an increasing collaboration between different functions while handling changes and uncertainties during different phases of product realization [6, 13-15]

Regarding *impacts/effects,* the impact of complexity on the organization (technology, man, organization, methods, tools, etc.) needs to be considered. Challenges related to globalization, market requirements as well as handling critical events during product realization needs to be addressed from a *complexity management* perspective. To run a manufacturing/production system of large scale is a challenging task that requires competent people from different fields of expertise and organizations to join forces, efficiently and effectively. The increased complexity also challenge man-hour planning, on plant, line and station levels, as the indirect work tasks will increase while being insufficiently specified [1]. According to Grote [16] adequate management of uncertainty in complex systems is crucial for safe and efficient system design.

3 CASE STUDIES

Three case studies have been performed at three plants located in Sweden belonging to three global companies: Volvo Cars Corporation (Case A), Stoneridge Electronics (Case B) and Electrolux (Case C). All companies had similar challenges to maintain and increase their, efficiency, flexibility, and sustainability of production, which will be needed to address coming challenges [1]. The case studies have been performed during the fall and winter of 2010.The case study contains of five steps, illustrated in figure 2.

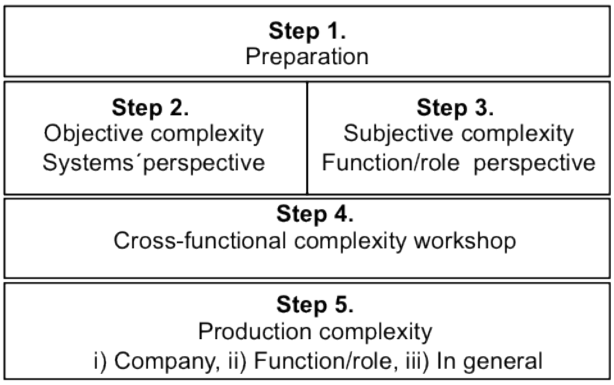

Figure 2 Case study approach

Step 1. Preparation – Initially, the research team planned the study in collaboration with representatives from the company. In this phase, the companies´ needs related to production complexity were defined, followed by a selection of a production unit for the case study. A production unit (a team area/cell) within the final assembly was selected by company representatives and formed the physical platform for the study. The production unit was selected based on that it was experienced as challenging and future complexity challenges were expected.

Within each company, a production unit, and two stations were chosen for further analysis; one station considered to have a high degree of complexity and one station considered to have a low degree of complexity. This was done so that comparisons between the stations easily could be made. The choice of stations was done in accordance with the representatives' perceived view of complexity, which facilitates comparison of subjective and objective complexity. Additionally, an interview guide was designed, participants from the company were identified.

Step 2. Objective complexity (Systems´ perspective) – Quantitative data was gathered using the first two steps in the DYNAMO++ methodology [17, 18] and the further developed concept model [19]. The selected production unit was studied by "walking the process", carrying out open interviews with production technicians, internal logistics and production employees. Further, observation of the two selected stations where done by filming and photographing, this data was then analysed further in accordance with DYNAMO++, i.e. measure Levels of Automation (LoA), both physical and cognitive in the chosen tasks and stations within the cell. The data collection focused on information of the product flow, product variants and families, the Level of Automation, work tasks, time parameters on task, on a station/cell level.

Step 3. Subjective complexity (Function/role perspective) – Semi structured interviews were carried out with representatives from operations, internal logistics, production engineering, and from one company, also man-hour planning. The interview guide addressing perceived complexity aims to identify subjective complexity parameters, which was related to work tasks, actions taken to minimize or handle complexity, causes and effects/consequences, ways of working, challenges, etc. The interview guide was adapted from a framework developed for investigation of major planned changes in production from the perspective of different functions/roles [6, 7].

Step 4. Cross-functional complexity workshop – An industrial workshop was carried out, also video recorded. The data collection focused on causes and drivers of complexity from the perspective of operations, internal logistics, and production engineering. The semi-structured interviews combined with a cross functional dialogue facilitated analyses of perceived complexity from different functions, i.e. roles or departments within the production system; 1) production engineers, 2) operative personnel in the selected production area, and 3) personnel from internal logistics.

Step 5. Analysis of production complexity related to i) each company, ii) function/roles and iii) in general

Results are based on interviews with selected individuals representing different roles and occupational groups. This study included views from operations, production engineering, Internal logistics and, in one company, man-hour planning. The interviews and the workshops were analysed from a company and a role perspective, while the objective data aims to explain the context in which the complexity exists within.

4 RESULTS

All companies had similar challenges to maintain and increase their efficiency, flexibility, and sustainability of production, which will be needed to address coming challenges. The main challenge for case company A is to maintain or even increase efficiency, flexibility, and sustainability of process and operation even with the expected explosion of product variants. The number of components is expected to increase by 50% to 100% within the next three years, and the frequency of changes will increase compared with today. Also the product variants are getting more differentiated. This puts extremely high demands on the ability to design, plan, schedule and balance a mixed model system in order to achieve and maintain an acceptable system performance. It also has a crucial impact on the whole organization and collaboration with different partners.

Case company B is a global company with customers within the heavy trucks and automotive industry, which is a very competitive market with fierce requirements on quality. Therefore, it is of greatest importance to continually improve the production process in order to stay competitive. The challenges associated with complexity are mainly related to an increasing number of product variants, requirements on quality and volume flexibility.

Case company C are operative on a very competitive market with fierce requirements on quality, and the studied plant will go through a large transformation during the next year. The layout will be dramatically changed and new material supply systems will be introduced.

In all three companies, sections within the final assembly have been chosen for further analysis.. The reason for this is that the effects caused by an increasing number of variants are most apparent in final assembly operations.

4.1 Case Study A – Volvo Cars Corporation

Objective complexity – The layout was a takted line containing seven assembly stations. The operators assembled three different products but with 72 (high complexity station) and 32 (low complexity station) variants. Further, in the higher complexity station, more work tasks were performed and there were more variance between the different variants compared with the station with lower complexity. The higher complexity for parts was handled by the use of ergonomic help tools such as lifts, and pick-by-light solutions were used to handle the part complexity. Unexpectedly the cycle time was more evenly distributed at the complex station in comparison to the low complexity station were the cycle time varied greatly.

Subjective complexity – In case company A the perceived complexity was described by representatives from production, production engineering, logistics and man-hour planning. The general production complexity parameters were related to variants, volume fluctuation, the layout, visual indicators, e.g. pick-by-light, ergonomics, changes, deviations and manning, see Figure 3.

Production engineering (PE) specifically addressed the production complexity related to the product platforms, rebalancing, and development of technical support (physical and cognitive automation) for the operators and work in preparation phases. A challenge was the balance of support and flexibility, where stations with a higher degree of assembly support tools were less flexible, and minor changes were harder and more expensive to make. Production focus on: remembering how to assemble the different variants, especially the unusual variants. While internal logistics focus on material handling, foremost how to place the components most effective at the stations.

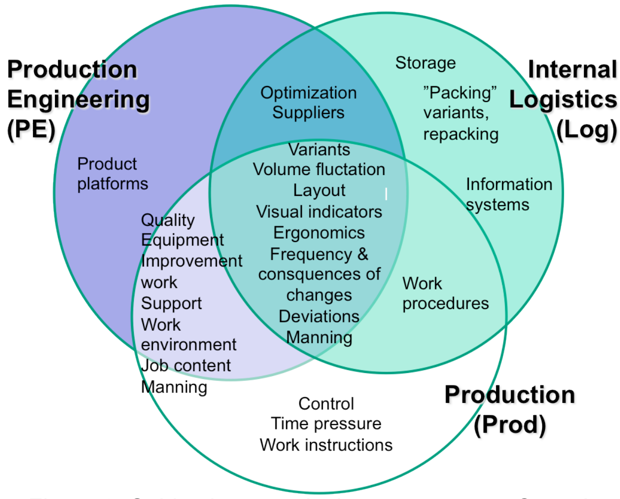

Figure 3. Subjective complexity parameters – Case A

The IT support system was not considered to be adapted to the large amount of variants and variant structure. Representatives from production (Prod), considered the main causes of complexity as the amount of tasks to be performed within a limited workspace regarding both time and space, the need to remember how to assemble different/unusual variants, and the uneven work pace caused by the many number of variants. From the perspective of internal logistics (Log), production complexity was foremost related to how to place the components most efficiently at the stations, i.e. storage, packing/repacking, information systems, and work procedures. In addition to the complexity parameters in figure 3, the company representatives responsible for man-hour planning (MHP) stressed challenges related to different time horizons. MHP specifically focused a long term perspective, i.e. 1 – 5 years, while PE focused a medium perspective (up to 1 year), and production a short term, daily perspective of daily – weekly planning. Further, complexity parameters were from a MHP-perspective related to variants, frequency of new/modified products, increasing product complexity, volume fluctuation, and production planning.

4.2 Case Study B Stoneridge

Objective complexity – Results from "walking the process" revealed that both chosen stations were within U-cell layouts. Each U-cell assembled one specific product family. This decreased the perceived complexity for the operators due to a reduced number of products to assemble. Both U-cells were not takted, operators had to plan the takt time themselves based on the number of pieces demand, hour and shift.

When measuring objective parameters such as number of tasks number of variants etc., differences were found between the U-cells. The low complexity U-cell produced five variants to customer from two motherboards, batch produced earlier in the value chain. But 90 % of the orders were of the same variant. The cell was characterized by stable, low product volume operated by one operator, thus easy to plan. The U-cell with higher complexity produced eleven variants of products to customer, created from four motherboards. It had a higher product volume with higher variation between the variants and volumes, more difficult work tasks, and more personnel in the cell to account for. More material handling and set-ups was needed compared to the low complexity cell. The number of tasks to perform on the two compared stations was 15-20 tasks in the high complexity station and 26 tasks in the low complexity station. The high complexity station had more cognitive support functions and advanced fixtures i.e. higher cognitive and physical Level of Automation (LoA), compared to the low complexity station.

Subjective complexity – In case B, perceived complexity was described from representatives from production, production engineering, and logistics. The general production complexity parameters were related to products/variants, the layout of the plant, and material planning, Figure 4.

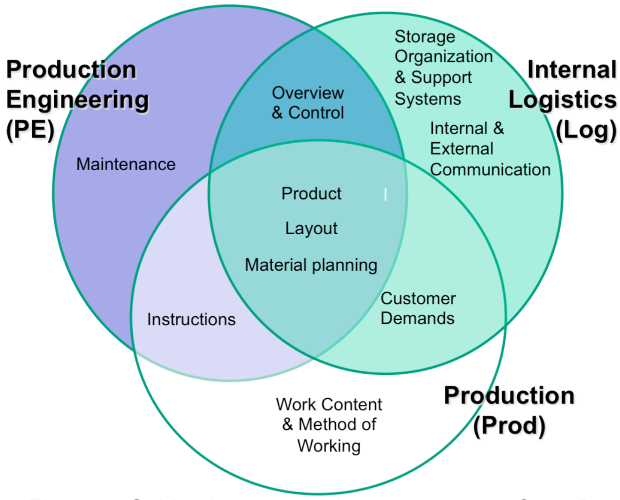

Figure 4. Subjective complexity parameters – Case B

Production engineering (PE) specifically addressed complexity related to sharing of resources, the material flow to the stations and machines. Further PE addressed overview and control, maintenance, and work instructions. Representatives from production (Prod) saw that the main causes of complexity were the distances between functions and the amount of machines. Further production personnel addressed the customer demands, work content and methods of working/work procedures, and work instructions. From the perspective of internal logistics (Log), production complexity was related to the lack of space for supermarkets, the material flow to the stations and machines, as well as a plant perspective of logistics including deliveries to the warehouse. Further, logistics addressed challenges related to customer demands, overview and control, storage organization, support system, structure of material, as well as internal and external communication.

4.3 Case Study C Electrolux

Objective complexity – The case study has mapped the whole assembly system, divided into five sections (or sub-systems). The analysis had a deeper focus on the so-called base assembly, which includes the first nine stations of the whole line (in total 37 stations). Each workstation was analysed and documented by "walking the process". The assembly lines were visualized to bring a rigid understanding of each defined action and transportation that were executed in the production flow. The cognitive instructions placed along the line at each station where used as framework, even though the operation sequence performed by the operators many times differed from the standard instruction.

The low complexity station had very simple operations that did not vary much between variants. The station with higher complexity contained more advanced operations. These operations required more knowledge about effects of the work performed. In addition, the shape of the component making the assembly work more complicated. The same cognitive supports were provided at all the stations even though the work content varied.

Subjective complexity – In case C, perceived complexity was described from representatives from production, production engineering, and logistics. The general production complexity parameters were related to products/variants, the layout of the plant, and material, Figure5.

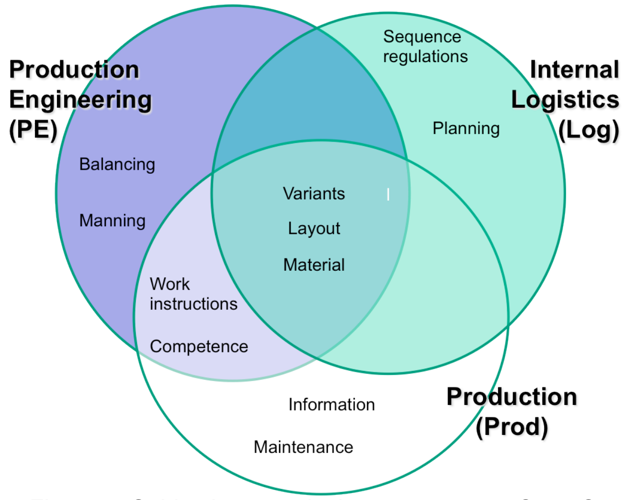

Figure 5. Subjective complexity parameters – Case C

Production engineering (PE) specifically addressed the material handling challenges linked to the variants. The balancing was affected by the variants because all of the models did not require the same manning of stations.

Representatives from production (Prod), found the main causes of complexity to be the scattered information about changes in product and the production line. The assembly work itself was considered quite easy but all of the operator were experienced and could be considered experts. Even though the work tasks were considered easy there were still a lot of variants regarding how the tasks were performed. There was a well-defined "best practise" but the operators still performed the task their own way.

From the perspective of internal logistics (Log), production complexity was related to the shape of the components. Today the logistics are well defined, but in the near future the whole concept will be changed into "train concept".

5 DISCUSSION

In understanding complexity further each companies´ specific challenges were further investigated from different functions perspective. Previous research have emphasised a clear focus on product variety as a cause and driver of complexity [3, 4]. The findings of the case studies described herein are consistent with that, but also indicate that a distinction needs to be made between objective and subjective complexity. The results from interviews and workshops clearly state that a holistic approach needs to be made in order to capture the cause and effects related to production complexity.

5.1 Subjective and holistic perspective

Depending on the individual function and role, the perceived complexity may differ, and the concept of production complexity is described from different time and abstraction levels such as task, station, cell, plant, and business unit/company level. For example, production engineering was mainly affected during ramp ups and re-balancing while assembly operators and internal logistics experience the production complexity more continually. Using subjective description of production complexity complements the theoretical definition of complexity, i.e. theoretically un-complex systems may be considered very complex, or complicated by users. This can be dependent on subjective factors for example previous experience, knowledge, training, personal type, background and mind-set. These variations between individuals needs to be regarded as well as the work tasks needed to be performed. Therefore it is important to capture objective and subjective parameters in order to get a better view of how a problem occurs, how they affect different functions in the production flow, and how production complexity can be managed.

5.2 Complexity parameters

The production complexity parameters, common within all three cases were i) number of variants (which were identified as the main driver of complexity in all three cases), ii) the layout, which was a mean for handling the complexity induced by all the variants, iii) material supply, which was an increasing challenge when the number of parts increase and the batch sizes decrease, and iv) ergonomics and human aspects both physical and cognitive.

They will contribute and expand the theoretical model, Figure 1. However it was seen that customer-oriented assembly and mass customisation are increasing in industry and this is one of the greatest driver and cause of production complexity. This leads to an increase in product variants, which has effect for the three investigated roles in the production system:

- Production engineers – Increased need for advanced methods to rebalance the assembly lines
- The chosen production area – Increased need for better and more functional information flows and to plan the production flow and levels of automation in order to avoid or cope with the increased complexity.
- Internal logistics – Increased need for material handling efficiency.

5.3 Complexity management

The companies had different strategies to handle and manage production complexity. All companies addressed the significance of the layout as a crucial complexity parameter. Company A and C had driven lines with a mixed model assembly, which seemed to cause similar complexity issues regarding balancing, material supply and information support. Company B had reduced the variant complexity by having one U-cell dedicated for each product family. This had different effects for different functions. Production engineers developed technical support (physical and cognitive automation) for the operators at more than one place, thus increasing the cost. Internal logistics had increased challenges with material handling, with more stations to support. This indicates that the production complexity has been shifted from assembly operations towards production engineering and internal logistics, but it is perceived as being easier to handle in this form. Results from the case studies shows that production complexity management needs to regard: i) Global perspective/external challenges, ii) Abstraction level; company/plant, cell, station, task level, iii) Time perspective; Short, medium, long term, and iv) Individual perspective; Function/role/work task. This is illustrated in figure 6.

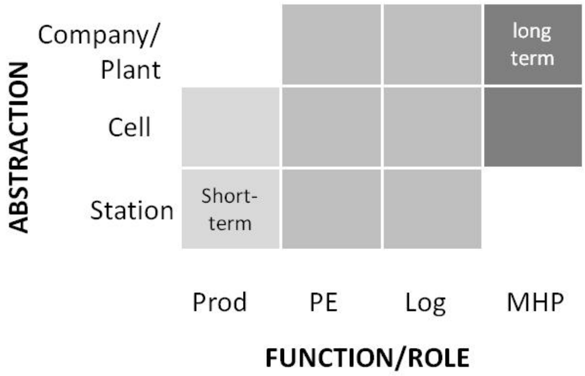

Figure 6. Subjective complexity dimensions

A holistic view needs to be addressed to avoid sub optimisation. If only focusing on one part of the systems complexity, other part of the process might have to endure an increased complexity. One example is the increased need of cognitive support tools to decrease the complexity for assembly personnel. The side effect is an increase of complexity for production engineers who have to manage the extra work associated with these solutions. Kitting could be seen as another example where the complexity has been shifted from assembly to internal logistics. By combining knowledge of both objective and subjective complexity parameters, production complexity can be visualized and measured supporting proactive work. The case studies supports the need of considering different functions and roles in order to get a holistic view of production complexity, illustrated in Figure 7.

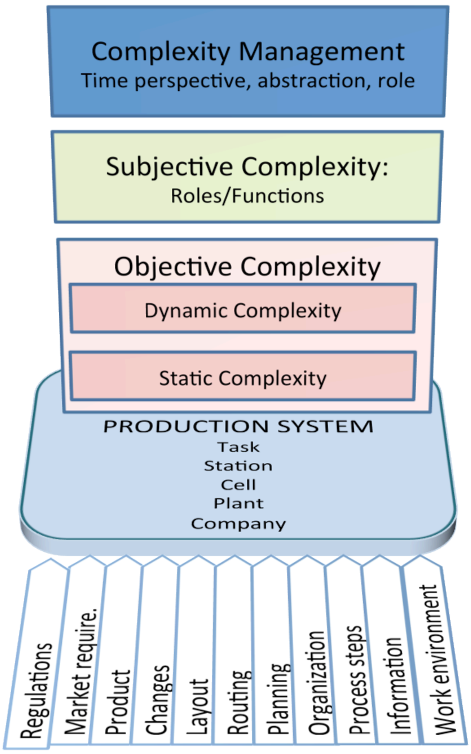

Figure 7. Updated parts of the complexity model

The model in Figure 7 presents additions to the discussed sections of the earlier presented complexity framework. The complexity parameters have been updated based on findings of this empirical study. Another focal point in the model is the need to consider time, role and abstraction levels when managing the production complexity.

6 CONCLUSIONS

The scope of the research project was to contribute to the preliminary framework of production complexity based on a literature study and initial identification of industrial complexity challenges [1]. By additional case studies in three companies, production complexity parameters were investigated. The empirical investigation supports and strengthens the proposed complexity framework by verifying and extending the main complexity parameters: and thereby investigating the drivers, causes and effects of production complexity. Furthermore the study identified the importance to take account for different roles within the production system when addressing complexity. Many complexity parameters are common for the different roles, although the viewpoint on the same parameter can be different regarding time horizon and abstraction level. Methods aiming to visualize, measure and reduce or handle complexity must acknowledge effects for different roles, time perspectives and abstraction levels in order to avoid sub optimization. The empirical study concludes that a holistic view needs to be addressed if the entire complexity is of focus.

The production complexity framework discussed in this paper will be further used within the COMPLEX research project to support complex operation, line rebalancing, and man-hour planning. In specific, following areas of research are planned:

7 ACKNOWLEDGMENTS

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Paper II

Method for Measuring Production Complexity

Mattsson, S., Gullander, P. &Davidsson, A.

International Manufacturing Conference IMC 28 - Manufacturing Sustainability, 30th August – 1st September, Dublin City University, Ireland (2011).

METHOD FOR MEASURING PRODUCTION COMPLEXITY

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ABSTRACT

Many companies today struggle with fierce demands on efficiency, flexibility and sustainability connected to customization and the introduction of new sustainable products. This increases production complexity, which should be managed through a holistic approach in order to avoid sub-optimization, focus usage and support relevant changes in the production set-up. This paper presents a first step approaching such a framework, a method for measuring production complexity specifically on a station level in a line re-balancing scenario. A Complexity Index was developed in analogy with, and as a compliment to, Robustness Index (RI) a calculation method used at Volvo Cars. The RI involves parameters that are ranked by a multifunctional group during several days. Complexity Index should in comparison, be used by one person at a time evaluating four parameters: *Product and variants, Method, Layout and Equipment* and *Organisation and Environment*. The method should be validated empirically through in-depth studies at Volvo Cars Corporation.

KEYWORDS: Complexity, flexibility, sustainability

1. INTRODUCTION

For many years there has been a development towards shorter product life cycles, frequent changes in products, processes and volumes, which increases production complexity. Volvo Cars Corporation (VCC) reports that in a couple of years the number of components will increase by 50-100%, mainly because of the introduction of new sustainable products i.e. electric and hybrid engines. The variants are also expected to be more differentiated e.g. fuel tank or batteries instead of a number of fuel tanks variants. Changing products in production inevitably introduce certain amounts of ramp-up losses and disturbances in running production, which introduces problems related to balancing.

The term “complex” is often used in everyday language to refer to the difficulty of understanding or analyzing a system. When modelling a system’s complexity, there seems to be a common understanding in literature to separate “structural complexity” - which is related to fixed nature of products, structures, processes, and “dynamic complexity” - variations in dates and amounts due to material shortness, breakdowns, insufficient supplier reliability [1-3]. However, since humans may consider the same system and situation differently it is important to consider how the system is perceived. Li & Wieringa [4] presented a conceptual framework for perceived complexity in supervisory control systems, consisting of three factors: a systems technical complexity (machine and equipment), task complexity (volume variety and link dependencies) and perceived complexity in terms of personal factors (knowledge, training, personal type, background, willingness) and operation and management strategy. In handling complexity a theoretical framework was first suggested handling static and dynamic complexity [5]. This model was expanded with empirical data and it was seen that a missing piece of understanding complexity was perceived or subjective complexity seen from different roles in production [6]. In this paper a method, used by different roles connected to production for measuring complexity, is presented.

1.1 Aim and delimitations

In this paper the research question, first stated in Gullander et al. [5] will be followed: *What should be included in a definition and description of "production complexity" to support measurement and development work of efficient, highly flexible and sustainable production?* This paper will focus on analysing existing methods for measuring complexity and concepts similar to it and to suggest a method for measuring complexity at a work-station-level. The research work reported in this paper is conducted within the project "Support for Operation and Man-hour Planning in Complex Production" (COMPLEX) where a holistic standpoint is aimed for.

The main aim of the method under development is to be used for continuous improvements, to suggest a degree of complexity and ways of managing it. In order to develop the method iteratively the method, in this step, will consider how the degree of complexity is measured, specifically for a re-balancing situation. Effects and ways of handling complexity are not considered. The focus of the method lies in subjective or perceived complexity, filling the gap in previous complexity frameworks.

The work is conducted in collaboration with the Belgian Complex project**.**

2. RESEARCH METHOD

Previously used methods or measurements of complexity are investigated to see if they fill theoretical and empirical gaps. In identifying requirements of a company, VCC is considered as a specific example.

In the empirical framework for complexity, by Fässberg et al. [6], the theoretical framework for complexity was updated and the complexity parameters were extended to *Regulations, Market requirements, Product, Changes, Layout, Routing, Planning, Organization, Process steps, Information* and *Work environment.* These parameters will be analysed further in connection to existing literature and methods.

The complexity method will be formed so that it can, after this step, be tested by different roles in order to get their feedback on parameters, the method as a whole and the manual for how to use the method. A request, from VCC, was that the method would result in a complexity number or degree that would say how low or high complexity a station has in order to better choose a way to handle complexity at that specific station. In addition the tool should be easy to grasp and used by people with different roles connected to the direct production.

3. EXISTING METHODS

In literature a number of different complexity models and corresponding methods for calculating complexity measures are presented. These concentrate on the emerging behaviour resulting from a system having a number, variety, strength of interactions and a certain structure. Generally it can be stated that the methods identified are difficult to grasp, requires detailed data on the system to be measured, and are time consuming. Despite the effort required, they do not cover all aspects of complexity, such as the subjective aspects of complexity. The most relevant methods found are seen in Table 1, see full literature review in Gullander et al. [5].

Both the entropy model [2] and the information diversity model [7] have been seen hard to understand and to use; the entropy model has been hard to use by people working on shop floor level. Calinescu et al. [8] compared Frizelle's entropic and the MFC method [9], concluding that the methods complement each other since they differ regarding what types of complexity they show, requirements, and methodology. The entropic method, was much more time consuming and data requiring, but provided more information of the system. However, the MFC method provided more information of the decision-making process, and was faster and easier to use.

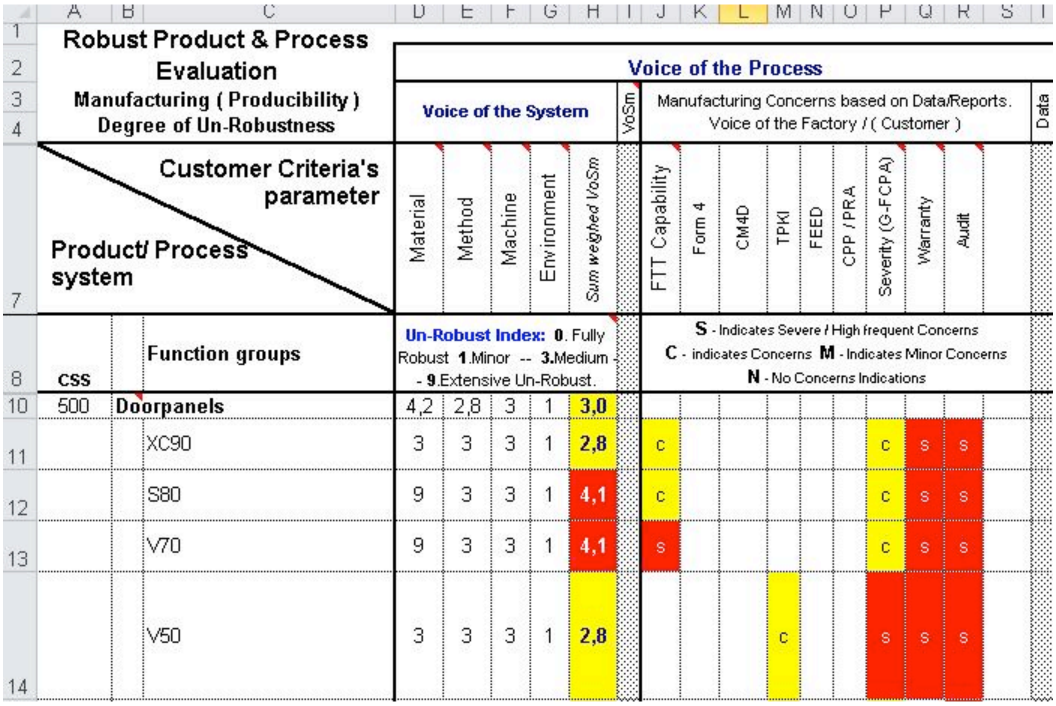
Table 1: Summary of complexity methods and measurements found in literature

Name	Developed by	Focus	Method
Complexity Entropy model	Frizelle and Woodcock [2]	Static and dynamic complexity	Formula that calculates the probability of a state to occur
Information diversity, content and quality	ElMaraghy and Urbanic [7, 10]	Complexity of products, process and operations	Ratio of diversity, content and quantity
Management of software development (MFC)	Meyer and Foley Curley [9]	Knowledge and technology complexity	Interviews and questionnaires on seven scores concerning decision-making and information at hand

Another related method found at VCC was the internally developed Robust Product & Process Evaluation called Robustness Index (RI). The method is based on FMEA methodology and is used in early development phases. RI is useful since it provides a number that you can work on a long-term basis with. The purpose of RI is to secure the producability of a part (system) of the product and to evaluate if the new product has a more or less robust system, see Figure 2.

Each product system is evaluated in a spreadsheet from 3 different aspects; Voice of System, Voice of Production and Voice of Customer. The main parameters: Material, Method, Machine, and Environment, are the same for each of the voices but has its own criteria for evaluation. The robustness is evaluated by every part for one product and then summarized. The parts are judged as, 0 = Fully robust, 1 = Minor robust, 3 = Medium robust and 9 = Extensive un-robust. The method is during ongoing changes where one suggestion is to insert also a 5 in the robustness scale in order to make the gap between 3 and 9 smaller.

The evaluation is made in cross-functional teams in order to gather the total picture.



Robust Product & Process Evaluation Manufacturing (Producibility) Degree of Un-Robustness		Voice of the Process															
		Voice of the System					VoSm	Manufacturing Concerns based on Data/Reports. Voice of the Factory / (Customer)									Data
Customer Criteria's parameter / Product/ Process system		Material	Method	Machine	Environment	Sum weighted VoSm		FTT Capability	Form 4	CM4D	TPKI	FEED	CPP / PRA	Severity (G-FCPA)	Warranty	Audit	
CSS	Function groups	Un-Robust Index: 0. Fully Robust 1.Minor -- 3.Medium - 9.Extensive Un-Robust.						S - Indicates Severe / High frequent Concerns C - indicates Concerns M - Indicates Minor Concerns N - No Concerns Indications									
500	Doorpanels	4,2	2,8	3	1	3,0											
	XC90	3	3	3	1	2,8		c						c	s	s	
	S80	9	3	3	1	4,1		c						c	s	s	
	V70	9	3	3	1	4,1		s						c	s	s	
	V50	3	3	3	1	2,8					c			s	s	s	

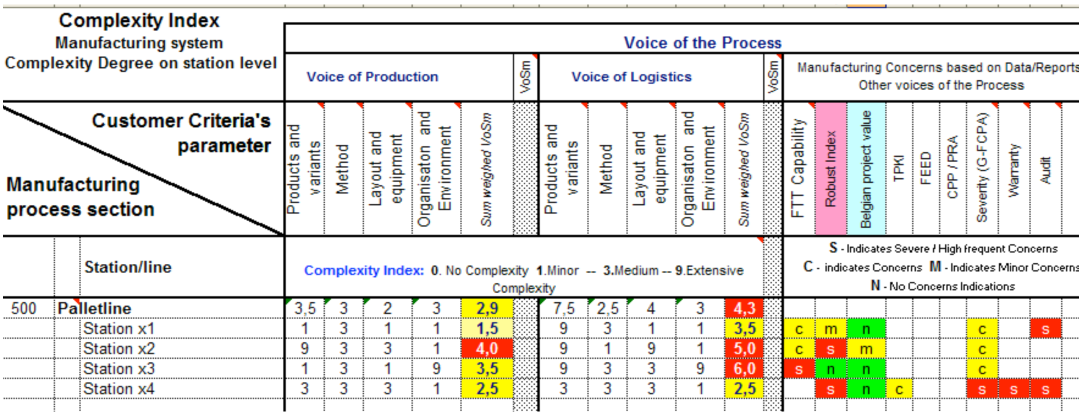
Figure 1: Robustness Index

The sister project in Belgium is developing a method for measuring the objective complexity by collecting a number of parameters for each assembly station. The method is under development and aims at capturing the complexity of direct operator time and focuses on data that can be gathered automatically as it exists today (from computer systems). This method produces a number/degree of the objective complexity and is not yet included in any work procedure or any management concept.

4. METHOD PROPOSED - COMPLEXITY INDEX

The CompleXity Index (CXI) was built on the same principle as RI. In comparison to RI, CXI is simplified in order to be used continuously and by fewer people and focuses on a station or line instead of the product. This means that instead of evaluating every parameter by every part of for example XC90, see Figure 1 and the RI = 2.8, CXI will consider a station or line and all parts/products produced there. CXI has otherwise the same features that RI has; that people should evaluate parts on a scale of 1, 3, 5 and 9 on how complex a certain object is (see Figure 2) and that a manual should be used for explaining the important parameter criteria. The number of parameters used in CXI should be as many, or fewer than for RI.

In this first step it is suggested that people close to production should use the method. In this way three or more people assigned to the same station or line, within different roles, could give their view of how complex a certain station or line is. The index given by all roles are summarized and a final index will be given the station/line so that complexity can be handled accordingly. If there is a big difference in indexes between different roles a further discussion is suggested. Two roles suggested for using the method are internal logistics and production personnel, see Figure 2.



Complexity Index Manufacturing system Complexity Degree on station level		Voice of the Process: Voice of Production					VoSm	Voice of Logistics					VoSm	Manufacturing Concerns based on Data/Reports Other voices of the Process								
Customer Criteria's parameter / Manufacturing process section		Products and variants	Method	Layout and equipment	Organisaton and Environment	Sum weighed VoSm		Products and variants	Method	Layout and equipment	Organisaton and Environment	Sum weighed VoSm		FTT Capability	Robust Index	Belgian project value	TPKI	FEED	CPP / PRA	Severity (G-FCPA)	Warranty	Audit
	Station/line	Complexity Index: 0. No Complexity 1.Minor -- 3.Medium -- 9.Extensive Complexity												S - Indicates Severe / High frequent Concerns C - indicates Concerns M - Indicates Minor Concerns N - No Concerns Indications								
500	Palletline	3,5	3	2	3	2,9		7,5	2,5	4	3	4,3										
	Station x1	1	3	1	1	1,5		9	3	1	1	3,5		c	m	n				c		s
	Station x2	9	3	3	1	4,0		9	1	9	1	5,0		c	s	m				c		
	Station x3	1	3	1	9	3,5		9	3	3	9	6,0		s	n	n				c		
	Station x4	3	3	3	1	2,5		3	3	3	1	2,5			s	n	c			s	s	s

Figure 2: Complexity Index, as suggested

4.1 Parameters for measuring complexity

The subjective parameters found in previous case studies were grouped into higher-level parameters, Figure 3. *Product/variants, Method, Layout and Equipment* and *Organisation and Environment* were formed using data from the empirical studies and framework, see research method.

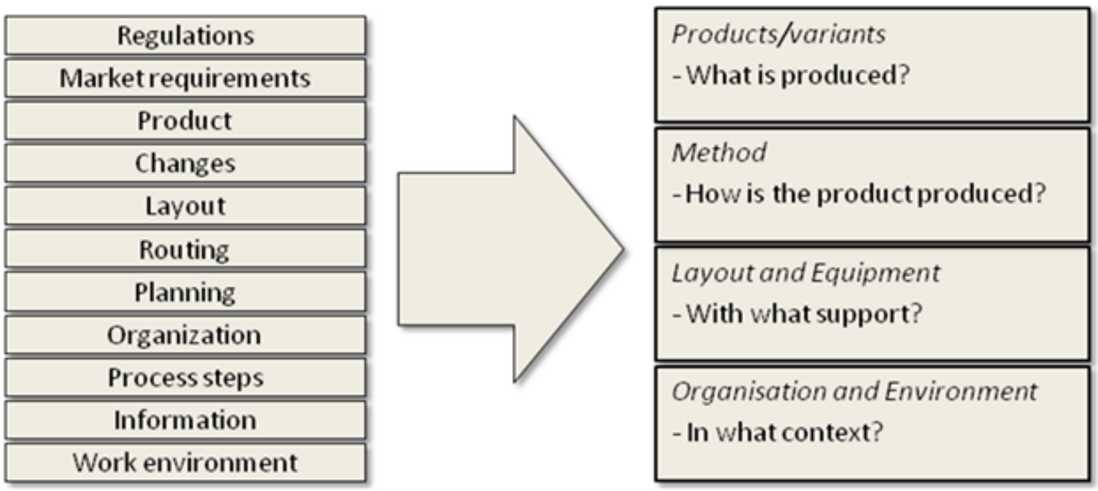


Figure 3: Complexity parameters

The implication of each parameter will differ between the different roles, required to evaluate a station. As an example, product/variant for internal logistics includes consideration about; How does the products and number of variants affect storage, package (repackaging) and the information system used? How does the change in volume/deviations affect the packaging, organization, support systems used for internal and external communication? How does this effect the sequence regulations?

While for a production personnel, the same parameter includes consideration about; how do the products and number of variants affect information handling i.e. work instruction and method of working? How does the change in volume/deviations affect control, time pressure and metal workload? How does this affect maintenance?

4.2 Manual

For each of the parameters a manual, similar as for RI, stating what criteria should be considered when judging the degree of complexity was made. The manual should be read "To what extent is the line complex in terms of the *Parameter*?" see Table 2, specifically considering the *Main question* and the *Aspects* connected to is.

Table 2: Manual for Complexity Index

Parameter	**Main question**	**Aspects to consider**
Product and variants	What is produced?	Number of products, models, variants, variance between variants, frequency of same parts, frequency of changes etc
Method	How is the product produced?	Information support, number of work instructions, type of instructions, information system for both machine and humans, number of components to pick, similarities/differences between components, pick to handle, type of assembly, number of methods
Layout and Equipment	With what support?	Layout, equipment, tools, fixtures, number of programs, material facade,
Organisation and Environment	In what context?	Organisation, man-hour planning, communication, leadership, rules, time pressure, competence, ergonomics, different work tasks, improvement work

5. DISCUSSION

Existing methods together with data from an industrial case show that there is a need for methods that can include more production aspects than analysis methods, which are based on the product and components. Methods identified in the literature study have disadvantages of being hard to understand and use, as well as not being sufficiently holistic. The entropy model is hard to understand by shop floor people [2, 11] but is good since it discusses both static and dynamic complexity. This can be connected to structural complexity as well as dynamic complexity, which have been used for modeling complexity [1-3]. However the model does not consider subjective complexity, which also was considered important [4, 6]. The information diversity model was also seen hard to use and considers dynamic complexity. It was seen that the entropy and MFC model complimented one another and focuses on different kinds of complexity [8]. The MFC model was based on subjective complexity (Ibid.). Nevertheless the methods provide a guide for choosing measurable parameters, relations and the conceptual models should be included in a holistic complexity model.

We propose that users should assess complexity subjectively using the parameters for defining production complexity. In this way, we can include the relevant parameters and ideas that generate complexity.

The parameters chosen for complexity consider static, dynamic and subjective parameters. The main parameters are *Product/variants* which covers the dynamical changes also seen in the entropy and information diversity model and *Method* which covers the process and instruction process similar to the task complexity in Li & Wieringa's conceptual framework [4]. *Layout and Equipment* is similar to the systems technical complexity seen in the same framework and perceived complexity (also from Li &Wieringa) is connected to the last parameter *Organisation and Environment*. The second parameter *Method* is also connected to the MFC model and content seen in the information model is seen in the last parameter *Organisation and Environment.*

At VCC a method RI has had an implementation process of 3 years and is now part of normal working procedure. Many of the evaluation criteria used are highly relevant for a complexity method, and the procedure has the advantage of being established. However, it is made from a product perspective and does not include enough production or logistics relevant parameters. It can also be understood that it was difficult to gather people from different units at the same time.

Since one of the demands for the method was that the method should be easy to use a CXI was formed using the same principle as RI. One of the improvement suggestions for RI, that the scale should also consider 5, was suggested for CXI. Also, instead of having a group of people sitting together for several days, the CXI-method is designed for one person at the time (for different roles). This could be more efficient in a production setting, but could also have its disadvantages since two or three people with different roles could have very different views of the complexity. Also if the roles in the company are not well defined it could be hard to find a person with a specific role for example internal logistics. The method, its parameters and manual need empirical testing to reduce such problems.

The Swedish project has focused on qualitative parameters in terms of subjective or perceived complexity in order to bring many aspects together. Since the Belgian project has focused on objective parameters they should act as a complement to one another.

5.1 Future work

The method suggested will be part of an iterative in-depth study made at VCC. First stations or lines, good for both internal logistics and production technicians to study will be chosen together with the company. Second, the method and manual will be tested and commented separately by key people at VCC, without consideration of a specific line or station. Third, the stations and the revised method will be tested for validation.

6. CONCLUSIONS

Gullander et al. [5] and Fässberg et al. [6] stated that a more perceptive view of complexity, especially connected to a role perspective is needed to define production complexity. In reaching this, existing methods, parameters for complexity and company requirements were investigated, in order to give a first draft of the method and to prepare for an in-depth study at VCC. A complexity method, CXI, was based on a literature review, an analysis of parameters found in previous case studies and the RI used by VCC. In comparison the CXI was developed to act as a continuous tool at a station level. This method should act as a compliment to the Belgian complexity method and will be tested further to develop a practical and useful guide for companies to calculate the degree of production complexity.

7. ACKNOWLEDGEMENTS

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Paper III

Testing complexity index – a method for measuring perceived production complexity

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Testing Complexity Index – a Method for Measuring Perceived Production Complexity

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Abstract

CompleXity Index (CXI) is a method developed to help manufacturing companies to describe complexity as experienced and to assist in reducing the effects it has on operator performance. The method is targeting the perceived complexity and was tested at Volvo Cars Corporation. Reproducibility of the method could be seen between respondents and was considered a valuable tool for visualizing problem-areas at the stations. It is suggested that objective data could be one way to identify which stations should be tested in-depth with the CXI method, and that CXI could be used for suggesting improvements or appropriate support tools.

Keywords: Production complexity; perceived complexity; case study; improvement suggestions; problem areas

1. Introduction

Manufacturing companies face challenges in handling dynamic customer demands, fluctuating material needs and requirements on sustainability regarding economical, environmental and social aspects. These challenges result in increasingly complex production and process systems, especially regarding assembly systems. If these effects on production complexity could be measured, work on reducing complexity would be greatly supported, thus creating advantages for companies working with flexible and complex production lines.

1.1. Perceived complexity governs performance

The ultimate goal of measuring and managing complexity is to improve the end users´ performance – in this context – the operator's performance, i.e. to decrease process errors, achieve high quality, good working conditions, fast processes/work and quick change-overs.

The performance depends on the situation and on individual aspects. For example, an operator without sufficient training or experience can perceive a workstation as highly complex although it generally is seen as a station with low complexity. The level of experience is one of many factors; the behaviour of an operator may vary depending on stress level, specific situation, personality and so on. A high workload can induce stress for an operator that might usually not perceive the station as a difficult matter. In order to achieve a practical and applicable measure of complexity, a definition and measure is required that incorporate individual aspects.

1.2. CompleXity Index

In Gullander et al., [1] a framework was proposed showing different aspects of complexity, including static, dynamic and objective complexity. This

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framework emphasizes the subjective or perceived perspective of the system to ensure that the individual experience is considered. The framework was used as a basis for conducting empirical studies and was further developed in Fässberg et al., [2].

The Complexity Index (CXI) method, presented in Mattsson et al., [3], suggest a complexity index based on perceived production complexity and the problem areas included in the framework. In this paper, the problem areas are further developed and the CXI method is tested in a case study.

1.3. Purpose and scope

The aim of this paper is to investigate the usefulness of the CXI method. This is done through answering the following research questions from the operators' perspective:

- What problem areas could be used to describe and measure perceived production complexity at a station level? *(RQ1)*
- How can CXI be useful in handling and reducing the perceived complexity? *(RQ2)*

This is done at a station level. To visualize complexity at a higher level, e.g. a line, several stations can be measured separately and aggregated.

2. Frame of reference

2.1. Modeling perceived complexity

Many research efforts have been made to model complexity: separating it into static and dynamic [4, 5], elaborating on causes [6, 7] and looking at entropy measures. However, only few complexity models explicitly include individual subjective aspects, e.g. [1, 8-10]. Furthermore, most work concern complexity models, and not the implementation of models into measuring methods. Four frameworks and models are presented:

Li and Wieringa presented a framework for perceived complexity that proposes that perceived complexity depends on the human-machine system complexity, task complexity, personal factors, operation and management strategy [11]. The perceived complexity is indirectly affected via the human-machine system through task complexity, processes, and control system. The personal factors include job training and knowledge, type/personality, intelligence, cultural background, and motivation to work (willingness). The operation and management strategy is based on experience, by the operator or for the operator. A similar model is presented by Guimaraes et al., who propose that there is a basic complexity associated with the system and the tasks [12]. They state that perceived complexity is a moderation of the basic complexity, where the moderation variables are: operator training and man/machine interface.

Some models include information aspects. For instance Urbanic and ElMaraghy put forward a complexity model for products, process, and operations where three elements affect the complexity: the diversity (measuring uniqueness of a task), content of information (measuring effort needed), and the quantity (information needed for a task) [13]. The parameter of information content includes effort needed and difficulty of task. Meyer and Foley Curley [14] defined a framework and method for measuring complexity, targeting management and decisions within software development processes. The model focuses on the knowledge and information needed to make decisions, including estimation of the breadth and depth of knowledge, as well as how much the knowledge has changed.

The presented descriptions can be synthesized in a common model, see Figure 1. In addition to research that explicitly focuses on the concept of *System complexity*, specific relations and areas that affect the perceived complexity are the *Human-machine system, Task complexity* and *Personal Factors*. Human-machine systems affect the way the situation, system, and tasks are perceived by the operator (and thus the perceived complexity) [15].

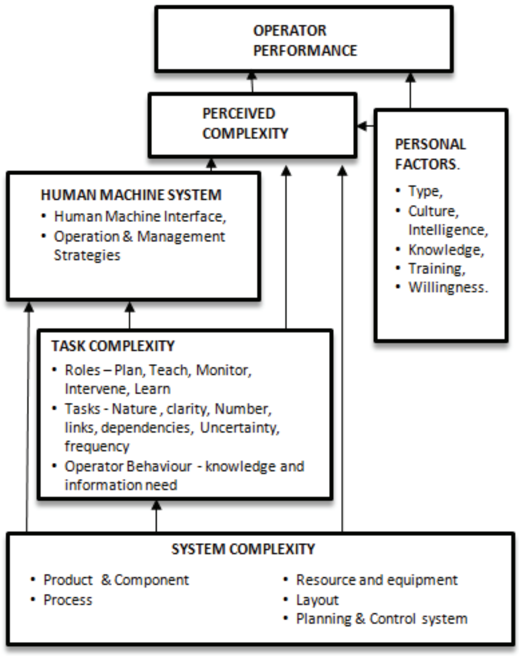

Fig. 1. A common model of perceived complexity, synthesis of models presented in [11] [12] [14].

Also affecting the complexity are the different task roles that operators have during their work (programming tasks, teaching, monitoring process, intervening, learning) [16], which is related to the level of automation of the system [17]. The importance of roles was also stressed in Gullander et al., [1]. Another important factor is research on what types of behaviour the operator have when performing the tasks, i.e. skilled, rule or knowledge based behaviour [18]. Related to this are studies on information support and training needs appropriate for executing tasks, thus reducing the perceived complexity. Each of these areas may provide knowledge into areas that have a major affect on the *Operator performance*, and the perceived complexity.

The common model of perceived complexity gives an understanding of what effects perceived complexity in a complex working environment.

2.2. Production complexity problem areas

The framework proposed in Fässberg et al., [2] includes the identification of problem areas (called causes of complexity in Fässberg et al.). The problem areas were: Regulations, Market requirements, Product, Changes, Layout, Routing, Planning, Organization, Process steps, Information and work environment. In Mattsson et al., [3] a further development was done suggesting the following areas: *Product and variants, Method, Layout and equipment* and *Organization and environment*. As part of the practical application of the method the problem areas will be further developed (*RQ1*).

3. Methodology

As a further development of the CXI the problem areas were re-evaluated. The following problem areas are suggested:

- Product variants (Area i)
- Work content (Area ii)
- Layout & Tools (Area iii)
- Support tools & Work instructions (Area iv)
- General (Area v)

The re-evaluation was due to that the previous version presented in Mattsson et al., were used as a spreadsheet with an accommodating manual; which meant that they had a bigger descriptive part. The problem areas were re-arranged so that they would match operators, logistical personnel as well as production technicians (see Mattsson et al., [3] for details regarding the development of the method). The fifth area was included to include what the respondents think of the station as a whole.

The new version of CXI is questionnaire with 23 statements. The respondents rated Likert-type scaled statements on each area. A Liker-type scale is an attitude statement [19] ranging from one to five where one was *I do not agree at all* and five was *I fully agree*. Respondents could also answer *I don't know/Not relevant*. The questionnaire included 23 statements (21 closed and 2 open-ended). Most of the questions were stated so that the answer five would mean that the station was complex. Some of the questions were reversed to reduce possibilities of bias.

The problem areas were not ranked, instead they are thought to have the same impact on complexity. If an impact variation is found the calculation of CXI could be changed; differences may be seen for different companies.

3.1. Analysis

The usefulness of the method is tested by looking its reproducibility and then by using objective data to move towards validating the method. Reproducibility means to test the degree of agreement between measurements or observations on more than one respondent [20]. A disagreement could be due to experiment bias, which is the tendency to answer questions according to the researcher's expectation, or that the respondent can have preferences for certain numbers. The reproducibility was determined using Pearson's product-moment correlation coefficient.

Validation of subjective measurement with few samples is very difficult. A first indication of validity will be tested comparing CXI to objective data. The objective data used was the number of variants and components on the station.

4. Case study at VCC

CXI have been developed as part of a current state analysis, which could be used before moving into in-depth studies. The current state analysis gives an overview of the problem by selecting an area of interest *A1*, identifying and measuring complexity *A2* and by visualizing complexity *A3*. The current state analysis will be used to understand how CXI practically can be used in industry (*RQ2*).

An operator and a team leader were chosen from each of the eight team areas. The team leaders at VCC coordinate and plan the work that should be done by the team. They have however no managerial responsibilities and do approximately 50% assembly work at the station. The 16 respondents themselves filled out the questionnaire, when the production schedule allowed them to work with it. The response rate of the questionnaire addressing the perceived complexity was 100%.

4.1. Selecting an area of interest A1

In this case study, eight stations, from eight team areas were chosen, Station A-H. The selection was made in cooperation with the company so that a range of layout and characteristics of VCC could be represented and that some stations that were believed to be complex and some not complex were chosen. Four were pre-assembly stations.

4.2. Identifying and measuring complexity A2

CXI was calculated, station-by-station, by taking the total median of the statements and adding the highest median value for the problem areas divided by a factor, see Formula 1. The highest median is added to the station in order to make sure high scores on statements, i.e. individual differences, will be represented by CXI.

$$CXI_{(per\ station)} = total\ median_{(per\ station)} + (highest\ median_{(per\ problem\ area)} / 4) \quad (1)$$

The score was divided into three categories: *Green, Yellow and Red*, which would visualize the complexity index, the limit scores for *Yellow* was > 2 and *Red* >3. The CXI calculation is seen in Table 1 where stations A, C, E-F and H show *Red* values *(R)*. Stations D and G show *Yellow (Y)* and station B *Green (G)* values. The highest score is seen for station E (The median N = 6.3).

Table 1. CXI on stations

STATION	A	B	C	D	E	F	G	H
CXI	3	1.3	3	2.3	6.3	4.3	2.8	3.8
	R	*G*	*R*	*Y*	*R*	*R*	*Y*	*R*

The analysis of reproducibility between the two respondents for each of the stations A-B and E-H is presented in Table 2. There was a strong positive correlation between the two respondents, for stations B and G, $r > 0.82, p<0.05$. Stations A and F had a low correlation, $r < 0.60$ while for stations E and H the correlation was stronger, $r > 0.60$. Stations C and D did not show significant values for the correlation.

Table 2. Pearson product-moment correlation coefficient for stations A-B and E-H

STATION	A	B	E	F	G	H
Pearson's coefficient *r*	0.54	0.94	0.62	0.57	0.82	0.60

As a first step of validating the method CXI was compared to the objective data, number of variants and components. A new coefficient was defined, *VarComp*, which was calculated as the average of *Var*iants and *Comp*onents for each station. CXI correlated with the coefficient, some differences are noted for stations A, E and G that have a higher CXI than *VarComp* and station H that have a lower CXI than *VarComp* see Figure 2.

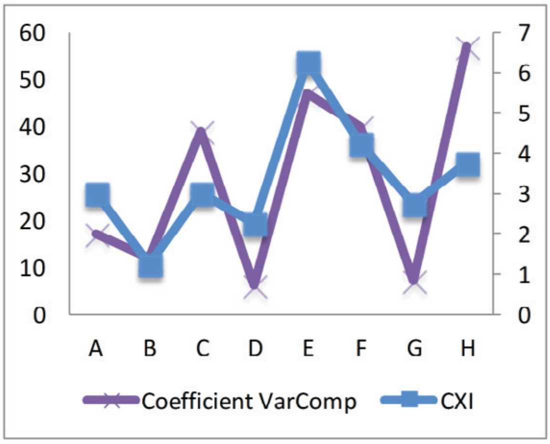

Fig. 2: Graph over the variant and component coefficient and CXI

4.3. A3 Visualizing complexity

In this step the medians for the problem areas are presented in Table 3. The CXI is visualized in Fig 3 with a colour-carpet. A majority of *Red* values were seen for Product/variants (N = 4), Area i. Then came Work content (N =3), Area ii, Support tools & Work instructions (Area iv) and General (Area v) and lastly Layout & tools (Area iii). Looking at the stations, station E and F show the highest values (N = 3 *Red* values). Stations A, D and H, have two *Red* values and station C and G (N = 1 *Red* values) while station B had no *Red* values.

Table 3: The medians on stations

STATION	A	B	C	D	E	F	G	H
Area i	4	1	4	1	5	5	5	5
Area ii	1	1	1	5	5	3	1	1
Area iii	2	1	1	1	2	2	2	3
Area iv	3	1	2	1	1	3	1	1
Area v	2	1	2	3	5	2	1,5	2.5

STATIONS	A	B	C	D	E	F	G	H
Area i	*R*	*G*	*R*	*G*	*R*	*R*	*R*	*R*
Area ii	*G*	*G*	*G*	*R*	*R*	*R*	*G*	*G*
Area iii	*Y*	*G*	*G*	*G*	*Y*	*Y*	*Y*	*R*
Area iv	*R*	*G*	*Y*	*G*	*G*	*R*	*G*	*G*
Area v	*Y*	*G*	*Y*	*R*	*R*	*Y*	*G*	*Y*

Fig. 3: Colour-carpet showing the medians on stations A-H

5. Discussion

As conceived in the common model of perceived complexity, Figure 1, there are a lot of parameters that affects the perceived complexity of a system. Especially the personal factors have a variety, which introduces an individual filter to all parameters. Hence, the approach of asking the operators of their view could thus be an efficient way to comprehend all aspects, including the personal issues. Using CXI as a way to measure the perceived complexity is a way to move closer on what effects operator performance in a complex work environment. Although it does not give the full view of what effects a complex environment the problem areas suggested were valuable for stating why a station was Green, Yellow or Red. Load/ergonomic issues were not part of the statements and could be included in future versions. It was also seen that future studies is needed in order to state the relevance of problem areas and if they should be weighted.

Testing the CXI included reproducibility, to some extent validation and visualization. It was seen that the reproducibility between respondents was high for two stations, and above average for three stations (two stations did not give significant values). Also the comparison between the objective data and CXI showed similar trends, pointing towards that the method gives valid data. It was suggested that objective data, at this company, could be used to state on which personnel the CXI should be given to.

5.1. Using CXI in industry

Since objective data is easy to measure and can sometimes be generated automatically it can be used to practically state which stations that should be further investigated with CXI. The colour-carpets could be used, as an in-depth tool to understand which areas needs urgent changes (A1 from current state analysis). Stating for instance that a *Red* area needs urgent change, *Yellow* needs change and that *Green* would mean that no change is needed (A2 identifying and measuring complexity). This way the perceived complexity can be understood and handled. The team leader could use the colour-carpet together (Figure 3) with the operator in order to discuss what support tools could be used and to prioritize problem area solutions (A3 Visualizing complexity).

5.2. Method implication and future work

The CXI will be developed further to incorporate additional roles when analysing the station. This is due to that different roles perceive stations in different ways according to their specific work tasks and problems.

One of the questions (Question 19: I often (daily) using the work instructions at this station) was removed according to the risk of bias. Question 24: Comments (for instance possibilities for improvements, changes of the station, work content, support or etcetera), was used to further state why high CXI values was given at a station. Four comments were given regarding load/ergonomic issues, which indicates that a statement regarding this could be included.

Furthermore, in the current version of the questionnaire statements about the respondents' background are lacking.

6. Conclusions

The aim of this paper was to investigate how perceived complexity can be measured and in addition how such a method can be tested and used in industry. This paper presents the CXI questionnaire method, as a further development of the conceptual CXI method developed in Mattsson et al. [3]. Results from the examination indicate that CXI can measure perceived production and results confirm the usability and usefulness of the method in terms of visualizing and finding problem areas, where the common model (Figure 1) could be used to understand what is measured. The measurements from CXI correlated with data collected. This represents the systems objective complexity (number of products and variants) and it is suggested that data could be used, to state which stations should be analysed further with CXI.

In summary CXI can help to point out problem areas at a station, which could help companies to pragmatically reduce and handle production complexity at a station level. Also, the visualization of problem areas could be a valuable tool for continuous improvements to handle re-balancing or man-hour planning and to suggest appropriate information support.

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Paper IV

Validation of the complexity index method at three manufacturing companies

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Validation of the complexity index method at three manufacturing companies

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Abstract. In order to manage increasing numbers of product variants, tools that can reduce or manage production complexity are vital. The paper describes CompleXity Index (CXI), an index-based method and tool that assess the complexity and difficulty of work at an industrial workstation. CXI was validated at three Swedish manufacturing companies studying the correctness of the calculation, usage as a prediction tool and the view of different roles. In all three cases, CXI was seen as a useful tool to evaluate the operator-perceived complexity of a workstation.
Keywords: Production complexity; station work; continuous improvements; production planning; industrial competitiveness.

1 Complexity Index

Today increased complexity is still one of the biggest challenges in manufacturing [1]. Manufacturing industry experience an increasing number of product variants, components, product mix, and frequent changes in volume, process, product, and organisation. In order to manage these challenges, it is vital for industry to be able to reduce or manage production complexity. People working with production engineering, operation, or introducing changes need to better understand and visualize what level of *production complexity* they experience. Further, industry needs to have tools to identify what type of improvements that can be made to reduce complexity.

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To meet the apparent need to measure production complexity, a CompleXity Index (CXI) was developed within the project COMPLEX. CXI is a questionnaire-based method and complexity assessment tool that includes 23 statements addressing the following identified problem areas: *Product variants, Work content, Layout, Tools and support tools, Work instructions* and *General* (general view of the station). The problem areas are based on empirical work by Fässberg et al., [2] and Gullander et al., [3] (the development of CXI is further explained in Mattsson et al., [4]) The questionnaire statements in CXI are of Likert-type, and evaluated as part of a formula (see Mattsson et al., [4]). The output of the formula is a complexity index that establishes a measurement for the complexity of a station (see score boundaries in Table 1).

The objective of CXI is to assess whether a station has a low, middle, or high complexity (green, yellow or red) focusing on the perceived view of complexity. Scores are given for separate problem areas and presented in a colour-carpet, which indicate the urgency of action (see scores for CXI in Table 1). This can be used in several ways e.g. to improve stations and plan production.

Table 1. Score boundaries for CXI

CXI	Complexity	Colour	Action
<2	Low	g (Green)	No action needed
2 and <3	Middle	**y** (Yellow)	Need change
≥3	High	R (Red)	Need urgent change

The aim of this paper is to investigate the usefulness of CXI and to test its validity.

2 Validation through triangulation

In this paper an applied research methodology is used, which means that empirical data from industrial case studies are a major part of the research results. To validate the proposed CXI method, a triangulation approach [5] was used. In this paper investigator and data triangulation was used suggested Deniz [6] (Deniz also suggested two other types of triangulations). The validation of CXI includes three cases where the feasibility and outcome of the method is tested and investigated. The case study contained semi-structured interviews and discussions with affected personnel regarding the outcome of CXI (both the measurement index and visualization using the colour-carpet). In all cases, the respondents completed their questionnaire in their own time. Afterwards, to be able to evaluate the CXI usage, their opinion was captured in an interview.

Investigator triangulation means that several researchers gather and/or analyses the same type of data. In the presented studies, multiple researchers and in some cases master students, were involved in collecting the data and the information (see Table 2). Investigator triangulation was used to reduce experiment bias, i.e. data-collection dependency on individual researchers' views and interests.

Table 2. Types of users in the investigator triangulation

Company	Gathering CXI questionnaires	Performing analysis
A	Novice users	Expert users
B	Novice users	Expert users
C	Novice users	Users

Data triangulation is the use of multiple sources, i.e. different participants are asked the same thing. In these studies different types of data sources were used: operators, logistical personnel, trainers, a production supervisor, the head of competence-assurance and higher official and heads (see Table 3). In this table the types of companies, Company A-C, are also presented.

Table 3. Data sources: the respondents and personnel part of discussing the results of CXI

Company	Type of company	Respondents	Part of analysing results
A	Large automotive company	4 operators (2 stations)	4 operators and 1 production supervisor separately
B	Large automotive company	12 operators and 3 trainers (3 stations)	Head of competence-assurance
C	Medium sized company making electronic components	4 kit operators and 10 logistics personnel (11 stations)	An operator representative, higher officials and department heads.

3 Correctness of calculation, usage as a prediction tool and the view of different roles

The validation was made at three manufacturing Companies A-C with different study focuses: *Correctness of the calculation, usage as a prediction tool* and *the view of different roles*. In this chapter the result and discussion is presented.

Whether the CXI *calculation was performed correctly* or not was investigated at Company A, by interviewing the respondents. Two specific stations were chosen for CXI testing at Company A, based on an previous assessment of CXI indicating that the stations had high complexity (see stations F and H in Mattsson et al., [7]). In the new assessment, the stations were rated as complex due to two problem areas: *Product variants* and *Layout.* The respondents stated that the station should be given a red complexity index. Although the operators thought that the station was acceptable to work at, they said that a new person would have difficulty to learn the work and other stations were more difficult for them. The production supervisor also believed the CXI calculation was correct. He however stated that the measurement did not give him new information (in addition he was not given resources to perform any big changes). Instead, he thought the method could be useful on a higher management level.

At Company B, the CXI tool was used to *predict problems* in future stations by studying similar already existing stations. 26 respondents assessed three stations and the main problem area, indicated by CXI, was *Production variants.* Almost all personnel perceived the tools and support tools to be green, but some improvement suggestions were given. Improvement suggestions included work instructions (station 1), sequencing, pre-work and handling of material (station 2), lifting and narrow work place (station 3). The results were considered useful to the company, since it reflected previously unknown facts.

The *view of different roles* was investigated at both Company B and Company C by studying differences between operators and trainers and the views of kit assembly personnel and logistics personnel respectively. The trainers' role at Company B was to teach new trainers how to educate their personnel on the lines i.e. had deeper knowledge of the station but had not worked there for some years. Results indicate that trainers rated the stations as more complex than the actual operators did. However, stations A and C had values close to red values (CXI_A=2.96 and CXI_C= 2.90, see score boundaries in Table 1), see Fig. 1. The difference could however be due to that they had not worked on the station for some time. In order to further understand the problems identified, a discussion with the associated operators is needed. CXI was considered useful as a first step in that discussion.

	Station A		Station B		Station C	
Problem area	Trainers	Operators	Trainers	Operators	Trainers	Operators
Product variants	R	R	R	y	R	y
Work content	y	g	g	y	y	g
Layout	y	y	y	y	R	y
Tools and support tools	g	g	g	g	y	g
Work instructions	g	y	g	y	y	y
General	y	y	g	y	y	y
CXI	R 3.58	y 2.96	y 2.63	R 3.38	R 3.67	y 2.90

Fig. 1. Colour-carpet for trainers and operators at Company B

At Company C, eleven stations were assessed. Studies were made in order to reduce and understand time and work carried out that was not included in the balance, i.e. unbalanced time at the stations. Both operators and logistics personnel were included in the study to get a more holistic view of the stations. Three types of stations were studied: a kitting station, the assembly train, and four assembly stations. It was indicated that perceived complexity was proportional to the unbalanced work and the stations were mainly complex in the following problem areas: *Product variants, Work content* and *Layout*. The station that had the highest index had unbalanced work ranging from 56-61% [8] and the common unbalanced work was listed as: rework, repeated movement of the operators from station to material rack, and waiting time. Results were presented to Company C's operator representative, higher officials, and department heads who thought that the results were useful, since it gave detailed insight on where there are problems with unbalanced work. In addition the colour-carpet was seen as a good basis for discussion since it helped their view of how to improve the process and quality of the system and how to prioritize future actions. The index also coincided with their perceived view of the station.

4 Conclusions

The method, CompleXity Index (CXI), was in all industrial cases seen as a useful tool for evaluating perceived production complexity at a station. It was found that CXI measures what it was intended to measure. Furthermore, the CXI questions, grouping of problem areas and calculation were considered correct. In addition, the use of CXI as a prediction tools and the view of different roles was supported. The method was seen as useful in the context of three Swedish manufacturing companies:

- At Company A the operators were satisfied with the assessment and its usefulness, but that the production supervisor did not have the resources to perform changes according to the known problem areas.
- At Company B, CXI provided a view of complexity that could be used for continuous improvements.
- At Company C a correlation between unbalanced work and complexity was found.

In addition it was seen that the results from different roles should be interpreted together with the personnel. The results cannot be generalized, since three different types of cases were used. However, results indicate if the method measures what it is intended to. Future work includes further studying the benefits of using the method.

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Paper V

Comparing quantifiable methods to manage assembly complexity

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Comparing quantifiable methods to manage assembly complexity

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ABSTRACT

In order to manage complexity and stay competitive manufacturing companies need to be able to quantify production complexity. For that reason two methods from two research projects have been developed: the Belgian Complexity Calculator, CXC, measures objective complexity and the Swedish Complexity index, CXI, focuses on subjective complexity, as experienced by operators in the stations. This paper presents a comparison between the methods, both by comparing them to seven existing quantitative methods and by studying results from case studies. It was seen that the two methods can be used as a compliment to one another where CXC can be used for scanning data automatically can CXI can be used for in-depth studies. In addition the comparison of existing methods could be used to manage complexity depending on need and scope.

Keywords: production complexity, flexibility, manufacturing, assembly, workstation, product variants, components, method comparison, method, operator

1 INTRODUCTION

1.1 Industrial problem

Mass customization increases the number of product models and variants, shortens product cycles, and frequently results in increasingly complex production systems (MacDuffie et al., 1996). Also, there is a trend towards increasing number of components, and increased complexity in processes and products. Future production systems thus need to be extremely flexible and still remain and excel their efficiency.

Today increased complexity is one of the biggest challenges in manufacturing (ElMaraghy et al., 2012). Complexity affects quality, throughput time and reliability (Urbanic and ElMaraghy, 2006) which can have effects on the company turn-over. Although complex systems are unreliable, it is possible to find strategies that can manage complexity i.e. reduce risk, handle uncertainty and catch benefits of having such a system (ElMaraghy et al., 2012). In a study including 14 Italian companies it was seen that the performance of the company was connected to the way they managed their complexity (Perona and Miragliotta, 2004). In order to manage and consider a complex system Chryssolouris et al. stated that the system needs to be quantifiable (Chryssolouris et al., 2013). Although numerous models and methods and studies have been executed in order to understand and optimize production complexity the models and methods engineers use today are unable to deal with the seen challenges (ElMaraghy et al., 2012).

1.2 Background

Against this background, two research projects were initiated. In Sweden a Vinnova-funded National project COMPLEX "Support for Operation and Man-hour Planning in Complex Production", conducted from 2010 until 2013. The overall focus was to reduce complexity by developing generic models and methods to support strategies, planning, management, and optimization of complex production. Parallel to this, in Belgium, a research project, funded by the national Flander's Drive, was running (also with the acronym COMPLEX) "Management and control in a complex manufacturing environment". The concurrent research and development work in the two projects has been regularly coordinated for mutual benefit. As part of the work, from the Swedish project the Complexity Index (CXI) was developed, and from the Belgian project came the Complexity Index Calculator (CXC).

This article is a revised and expanded version of a paper entitled "Comparing two methods to measure assembly complexity from an operator perspective" (Gullander et al., 2012) presented at the Swedish Production Symposium in Linköping, Sweden, the 6-8th of November 2012.

1.3 Scope

The aim of this paper is to suggest ways to manage complexity in order to make manufacturing companies more competitive. The research groups identified the need for comparing the two methods with each other and with other methods found in literature. The groups also wanted to examine the potential benefits of combining the methods into a common methodology. The scope of this paper is to present the two methods briefly, to compare the methods in different aspects, and to evaluate whether a combined methodology could be beneficial. In addition the methods are compared to existing methods. This may increase the understanding of complexity and help manufacturing companies to choose which type of method that is applicable with a specific set of resources.

2 METHOD

The method comprises (1) a detailed comparison of the two measurement methods developed in parallel by the authors, and (2) a broader, less detailed comparison with other available methods.

The detailed comparison is made as a joint work between the two research groups behind the methods. First the methods are described (the two COMPLEX methods are seen in Section 3 and the existing quantitative methods in section 4) and then compared (Section 5). Following is a comparison of the two methods with other complexity measurements (Section 6). In this paper the two methods within the COMPLEX project are described regarding their purpose, overall description of the method, and the model/formula used for calculation. Also presented are results from industrial case studies where the methods were used. The detailed comparison between CXC and CXI is made regarding:

- Purpose of method,
- Contents of the method (what aspects / parameters are covered),
- Intended usage,
- Methods for calculation and for visualising the results,
- Methods' validity,
- Added value the method is expected to give the users
- Prospects for future development.

Succeeding this, a broader, less detailed comparison with seven other methods. The chosen methods have a manufacturing connection, focusing on a subsystem (i.e. not complexity seen on a whole systems level) and have been seen relevant in managing assembly complexity. They are also methods developed i.e. not models, and have been used to quantify complexity.

For this comparison, the methods were further classified to enable a comparison with other methods and assess their usability. The criteria used were inspired by Calinescu et al. who presented a comparison between the entropy method (Frizelle and Suhov, 2001) and the Meyer Foley Curley (MFC) method (Meyer and Curley, 1993) (studying information and technology complexity) where the following criteria were used to compare the methods: investigation method, purpose and domain, information required, duration, measurement cost and results (Calinescu, 1998). The aim of our comparison is to evaluate how usable the methods are in respect to work needed to apply them and the results and knowledge gained, with perspective of a company using the methods. It is important to differ between *dynamic and static complexity*, where static complexity deals with the structure of the product or production processes that are time-independent. Dynamic complexity is time-dependent and includes the uncertainties and the behaviour of the operations in the system (ElMaraghy et al., 2012). In case studies the importance of capturing both objective and subjective data was seen (Gullander et al., 2011). Regarding *objective production complexity*, measurable parameters can capture both *dynamic and static aspects of complexity*. The *static complexity* of a system can be modelled measuring parameters such as number of stations, work tasks, parts, etc. The *dynamic complexity* is modelled to include time and dynamics, like deviations from plans, and uncertainty. In addition the detail level of the *results* (detailed or holistic), how *adaptive* the methods are (low in adaptation or high) and what *strengths and weaknesses* there are were compared. The following criteria were used to classify the methods:

- Purpose of method
- Type of complexity (static or dynamic complexity)
- Type of measures (objective or subjective)
- Results (detailed or holistic)
- Adaptation for use (high or low)
- Strengths and weaknesses (+ or -)

3 THE COMPLEXITY INDEX AND THE COMPLEXITY CALCULATOR

3.1 The CompleXity Index (CXI)

CompleXity Index (CXI) is a method developed to help manufacturing companies to describe the complexity of production system as the people working within the system experience it. The opinions of the workers are captured through Likert-type scales. A Likert-type scale (Dyer, 1995) is used to grade the attitude ranging from one to five, where one is *I do not agree at all* and five is *I fully agree*. Respondents can also answer *I don't know/Not relevant*. The questionnaire includes 26 statements (24 closed and 2 open-ended). The questionnaire is filled out individually (self-administered), which takes approximately 10-15 minutes. The questions are grouped into six problem areas (based on empirical data (Fässberg et al., 2011)):

- Product/variants (problem area i): the number of product variants that can be found on the station. The operator are asked if there are less frequent variants, if the product variants have similar components and for instance if they are different in the assembly.
- Work content (problem area ii) regards if there are many work tasks except for the final assembly, if the operator knows what to do when they come to the station and if they are part of changing or planning work on the station.
- Layout regards the layout of the station regarding if the material handling, material façade and ergonomics is well designed (problem area iii).
- Tools and support tools regards what type of tools they have on the station and if they help the operators in their assembly work (problem area iv).
- Work instructions (this area is especially focused at the operator) regards if the instructions are used everyday and if they help the operator in their daily work (problem area v).
- General view of the station regards what the operator in general think about the station and here it is possible to comment to suggest improvements (problem area vi).

CXI is calculated by calculating the median of the statements in each area; see first part of the formula 1 (in order to capture the median for several respondent the average of the medians for statements are used). Then, the median of the problem area medians is calculated. The second part of the formula concerns making sure that high values of problem areas are captured i.e. individual differences, will be captured in the station CXI. Here the highest median for all problem areas (the maximum median) is taken and is divided by a four (the highest median can be 5 (because the statements are rated from 1-5) which means that if a five is the highest median the second factor will be 1.25).

$$CXI_{station} = \text{median}(M_i, M_{ii}, M_{iii}, M_{iv}, M_v) + \frac{\max(M_i, M_{ii}, M_{iii}, M_{iv}, M_v)}{4}$$

Where $(M_i, M_{ii}, M_{iii}, M_{iv}, M_v)$ is the median of answers for all statements in area *i, ii, iii, iv, v* among responents belonging to the station.

(1)

To visualize the complexity index, the scores from the statements are divided into three categories: *Green (●), Yellow (▲) and Red (◆).* Stating that a *Red* area needs urgent change, *Yellow* needs change and that *Green* would mean that no change is needed. The limits for these categories are: Green for CXI < 2, Yellow for 2 ≤ CXI < 3, and Red for CXI ≥ 3. As an example data from Volvo Car Corporation can be seen in Table 1. The results showed that stations that were not believed to be complex were perceived as complex by the operators and team leaders: only stations C, E and F were considered complex by intuition, but it was seen that also stations A, E, F and H were perceived as complex. By studying the problem areas, see colour-carpet in Table 2, and the comment field (open-ended) question the reasons for why the stations were perceived as complex could be found (e.g. due to product variants for station A and H, and due to lot of time for opening boxes for station D).

Table: 1 CXI on stations at VCC

STATION	A	B	C	D	E	F	G	H
CXI	◆ 3	● 1,3	◆ 3	▲ 2,3	◆ 6,3	◆ 4,3	▲ 2,8	◆ 3,8

Table 2: Colour-carpet showing the medians of the questionnaire answers, indicating complexity for each station and each problem area

	Station / Problem area	A	B	C	D	E	F	G	H
i	Product / variants	◆ 4	● 1	◆ 4	● 1	◆ 5	◆ 5	◆ 5	◆ 5
ii	Work content	● 1	● 1	● 1	◆ 5	◆ 5	◆ 3	● 1	● 1
iii	Layout	▲ 2	● 1	● 1	● 1	▲ 2	▲ 2	▲ 2	◆ 3
iv	Tools / support tools	◆ 3	● 1	▲ 2	● 1	● 1	◆ 3	● 1	● 1
v	Work instructions	▲ 2	● 1	▲ 2	◆ 3	◆ 5	▲ 2	● 1,5	▲ 2,5

Over 70 respondents on 38 stations, mostly from the automotive industry, have used CXI in which the usefulness of the method has been validated by triangulating case study data (e.g. objective data and interviews). The validation showed that operators thought that the assessment was correct, that CXI is a useful tool when building or re-designing stations and that the CXI was a good visualization tool (Mattsson et al., 2013). After the method was validated, CXI was used at three companies as a current state analysis tool, which provided useful information in order to quickly identify problem areas and the characteristics of selected stations (results from two of the cases is presented in (Karlsson et al., 2013)).

3.2 The CompleXity Calculator (CXC)

Within the Belgian Complex project, a complexity measurement method has been developed, Complexity Calculator CXC (Zeltzer et al, 2013). The focus and purpose of the method are to characterize the complexity of manual operator workstations. The intended usage is different from CXI. In CXC objective data is collected from engineering data systems and an algorithm then calculates a complexity measure for all stations, and statistically classifies it as either of High or Low complexity. The operators are thus not involved and the method can easily cover many stations. The list of complexity-driving variables is presented in Table 3 together with a concise explanation of each variable.

A complexity measurement was developed based on a weighted sum of the 11 variables. This measure determines if workstations have a low or high complexity according to equations 2 and 3:

$$\text{basic complexity}(w) = \sum_{i=1}^{n} \frac{\text{score(i)*weight(i)}}{\sum_{i=1}^{n} weight(i)} \tag{2}$$

$$\text{complexity(w)} = \frac{\text{basic complexity(w)} - \sum_{i=1}^{n} \text{min i}}{\sum_{i=1}^{n} \text{max i} - \sum_{i=1}^{n} \text{min i}} * 10 \tag{3}$$

where:

- Basic complexity(w) is the complexity score of a workstation *w*,
- Score(i) is the value of the variable *i* according to the Likert scale,
- Weight(i) is the weight of the variable *i*.
- Max i is the maximum possible score value for variable i,
- Min i is the minimum possible score value for variable i,
- Complexity(w) is the complexity score of a workstation normalized into a scale from 0 to 10.

The 11 variables were: picking technology, number of bulk/sequence/kit, number of packaging types, number of tools per workstation, number of machines per workstation, number of work methods, distance to parts, number of variants of same model, number of variants in this workstation, number of different parts in workstation and number of assembly directions (see (Zeltzer et al., 2012) for a further description).

Figure 1 shows some results from the CXC model. 76 workstations were classified using a Logistical statistical model (LOGIT Classifier), calculating the probability that their complexity was actually HIGH. For these workstations we calculated the CXC score (CXC model) with all weights equal to 1. The figure shows a clear correlation between both models, providing a first validation of this model.

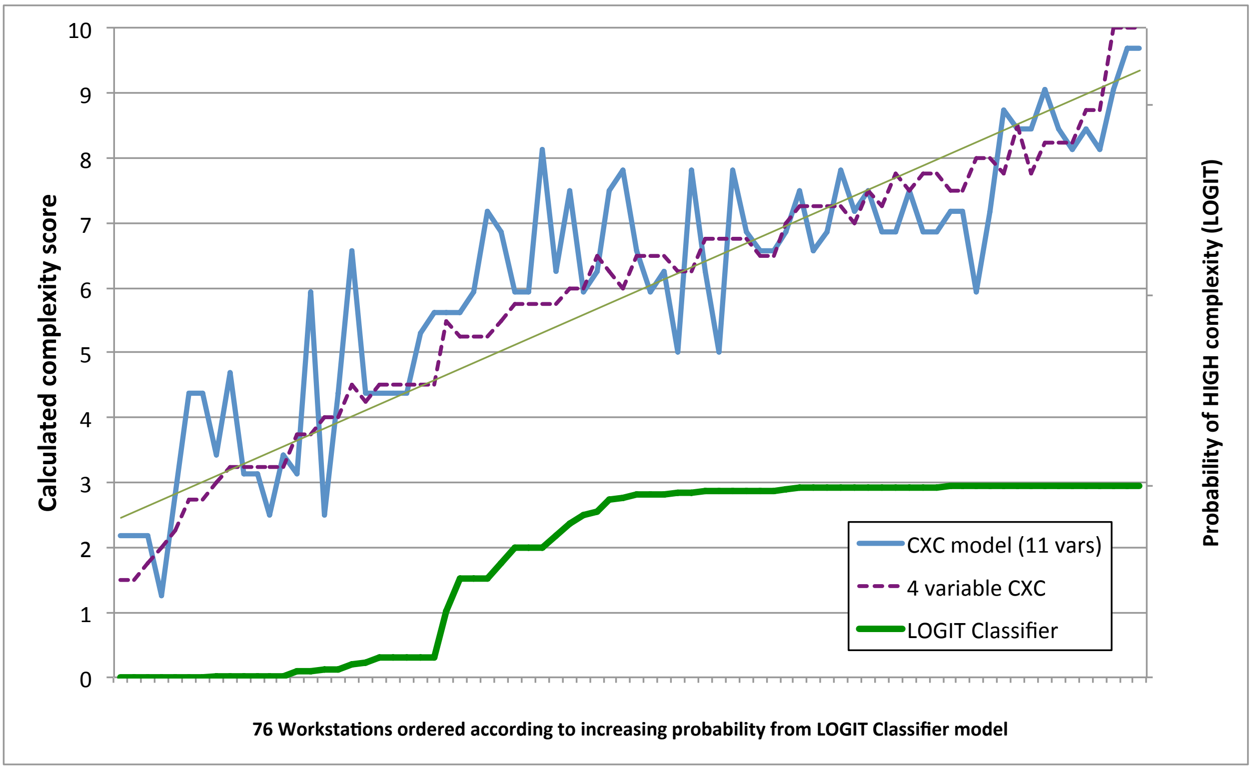

Figure 1: CXC calculation results on 76 assembly workstations (from Zeltzer et al, 2013)

In the same study (Zeltzer et al, 2013) a reduced CXC scoring model, with only 4 variables, was found to perform equally good, with less variability. This was primarily due to the fact that many of the 11 variables proved to be highly correlated. Table 3 gives the variables and weights used in the reduced 4-variable CXC model.

Table 3: Variables, description and weights in the reduced CXC model

Variable	Description	Weigths
# Packaging types	The total number of different packaging types, a type having a specific layout. So, two identical boxes with different inserts are two different types.	2
# Assembly directions	The number of different positions the operator must take to complete his workstation cycle, including repositioning's of the upper body or the feet, but not small repositioning's of the hands.	3
# Different parts in workstation	Total number of unique part references that are assembled in this workstation, including all variants and models that typically occur in one year.	5
# Work methods	Every unique set of work methods the operator must master in this workstation. A method contains several small steps.	

#Tools per workstation	The number of tools that the operator(s) need to handle to perform all possible assembly variants in this station, automatic tools (servants)	1

4 QUANTITATIVE COMPLEXITY METHODS

Below, the seven quantitative methods are briefly presented.

4.1 Operational complexity (Sivadasan et al., 2006)

To measure complexity Sivadasan et al., presented a method focusing on monitoring and mapping the information flow (Sivadasan et al., 2006). The aim is to monitor and manage information and material flows. A measure is provided of the dynamic complexity based on the amount of information required to describe a state: according to flow variations, products, reasons and variation states. Data is gathered by observation during a time interval.

4.2 Entropic measurement (Frizelle and Suhov, 2001)

Another frequently adopted approach to model and measure complexity is based on "entropy" which measures the uncertainty and randomness of a variable in the system. Entropy shows the rate of variety among possible next states, as a system changes state (Frizelle and Suhov, 2001). The entropy of a certain state in a machine is calculated based on the probability of that state to occur. This probability can then be associated with a number of possible states. The more states that are possible, the higher the entropy gets. This entropy is then multiplied by the probability of that state (as a weighing factor for that state's entropy). The entropy of the station is the sum of all these weighed state entropies. The stations entropy may be summed up to obtain the entropy of the line. Applied to production, the entropy of a production system can be applied to states of a station, the tasks/choices in station, or the line/system. The entropy of an operation reflects how uncertain it is that the operation is the next operation in a station.

4.3 Manufacturing complexity index (Urbanic and ElMaraghy, 2006)

Urbanic et al. have put forward a model of complexity of products, process, and operations, calculated based on three elements: the information content, quantity, and diversity (Urbanic and ElMaraghy, 2006). First diversity, measuring uniqueness or a diversity ratio between the specific information needed for the task, to the total information (value between 0-1). Secondly, content, a relative measure of the effort needed (e.g. number of stages or tools) to perform the task (between 0-1). Methodology to calculate this is developed. Thirdly, quantity, absolute quantity of information needed using entropy measurement. A measure of product complexity is calculated by multiplying the product's information quantity with the sum of its diversity and its content. Complexity of each process step is calculated by multiplying its information quantity (entropy) with the sum of diversity ratio and the relative complexity coefficient (content). The relative complexity of a process step is calculated based on both cognitive and physical effort. The complexity of the whole process is the sum of the product's complexity and the sum of the complexity of all the process steps.

4.4 Operator choice complexity (Zhu et al., 2008)

Focusing also on probability Zhu et al., presented a method that calculate the average uncertainty and risk in a choice for right tool, fixture, parts and procedure for variant (Zhu et al., 2008). They use operator choice complexity as their complexity measure and base it on information entropy of the average randomness in a choice process. They state a way to mathematically calculate station complexity that includes product variant, which results in part choice, fixture choice, tool choice, and procedure choice. When accumulating the measurements into line and system complexity the propagation of the variety is included for each station. Their calculations have been used for better understanding the manufacturing system complexity on performance as well as guideline for system design.

4.5 Knowledge and technology complexity (Meyer and Curley, 1993)

Another view was investigated by Meyer and Curley who studied the knowledge and technology complexity (Meyer and Curley, 1993).Their aim was to manage software development and was done by studying subjective complexity. The method uses two concepts: knowledge complexity, which is the domain specific knowledge and decision-making complexity, and the technology complexity, which is the underlying computer technology for developing the application. Knowledge complexity is assessed regarding decision maker's knowledge, information at hand, and the interpretation of these to make decisions. Based on interviews and questionnaires, seven variables are given scores, e.g. breadth, depth, rate of change of decision-making domain.

4.6 Robustness index (RI) (described in (Mattsson et al., 2011))

The method comparison also includes Robustness Index that was developed in-house at Volvo Car Corporation and served as a basis for the development of CXI. The method is based on FMEA methodology and is used in early development phases. The purpose of RI is to secure the produce ability of a part (system) of the product and to evaluate if the new product has a more or less robust system. The robustness is evaluated by every part for one product and then summarized. The aim of RI is to evaluated risks and problem areas on a management/team leader level.

4.7 Complexity index (CXB) (Falck and Rosenqvist, 2012)

It includes also another method developed at Chalmers called CXB that is also an index for measuring complexity in an automotive setting (Falck and Rosenqvist, 2012). In the method stations are judged as having a HIGH or LOW complexity due to several criteria. The aim of CXB is to support product preparation to increase productivity and decrease costs.

5 COMPARISON AND DISCUSSION

The comparison between the Swedish and Belgian complexity method is first presented. Then a comparison between them and their relation to other existing models/methods follows.

5.1 The CXI and CXC method

The CXI and CXC have different approaches which is coupled to the *purposes* of the methods where the Belgian approach focuses on objective data, striving for automatic capturing and calculations and the Swedish focus on capturing the subjective complexity perceived by the operators. For a number of problem areas both the CXI and CXC have similar contents, but different means of measuring the parameter (*contents of the method*) where both methods capture product variants, assembly work methods, machine tools and to some extent layout. A few aspects are covered in the CXI but are not included in the CXC (which is a natural effect of using objective approach e.g. work instructions, work content and general view of the station.

CXI is a self-administered questionnaire that requires the operators at the stations to fill out the questionnaire, the goal is to make it as easy as possible to reduce time needed for this (*intended* *use*). However, this is still a problem since operator time is difficult to get, being required to take part in the assembly. The CXC is intended to capture the data needed from different data systems. An analyst is needed to study systems and capturing the data. The goal is to be able to easily collect and thus scan the complexity level in all stations in the plant.

For *calculating and visualizing* the results both methods capture the complexity for a number of parameters/areas using Likert-scales. The result is for CXI visualised using the "colour-carpet" matrix to provide understanding of complex stations and/or complex areas. Similar visualisation of the results would be possible also for CXC. Both CXC and CXI provide a similar complexity measure for each station. CXC calculate a weighted mean while CXI use the median of scores with a weighted influence of the highest score, in order to better capture high score areas (high complexity) in the station score.

A *validation* of both CXI and CXC has been carried out, with positive results, by applying and using the methods in real cases, with positive feedback. However it is difficult to validate the methods and models with certainty. Hard facts of station complexity, like number of variants or components, can be an indication of complexity level. Since high objective complexity in stations generally will lead to high subjective complexity, objective complexity should on a general level correlate with subjective complexity. However, individual differences due to personal type, experience, education, etc. means that the correlation is necessarily not true on an individual basis.

The research groups see that there are advantages with both methods (*added value*). CXC makes it possible to quickly gather complexity data from the whole plant, and CXI that provides more detailed information on complexity situation and causes regarding specific stations.

We suggest that the methods be used in conjunction (*future development*):

- regular scan using CXC to see trends, problematic stations, on an holistic perspective.
- event-based study using CXI to investigate further the problematic stations, or stations that are in focus of a future change (equipment, variants, layout, variants, etc.)

5.2 Comparison with other methods

Comparisons of nine methods that were seen relevant in a production system context are presented in Table 4 (see full comparison in table in Appendix).

Table 4: Comparison of nine methods for quantifying complexity, regarding five major criteria

Type of complexity (static or dynamic)	**Type of measure/-s (objective or subjective)**	**Data gathering**	**Results (detailed or holistic)**	**Adaptation for use (High or low)**
Static: (Zhu et al., 2008)	*Objective*: (Sivadasan et al., 2006; Frizelle and Suhov, 2001; Urbanic, 2006; Zhu et al., 2008; Falck and Rosenqvist, 2012 and CXC)	*Observation/data logs:* (Sivadasan et al., 2006; Frizelle and Suhov, 2001; Urbanic, 2006; Zhu et al., 2008; Falck and Rosenqvist, 2012 and CXC)	*Detailed*: (Frizelle and Suhov, 2001) and RI)	*High*: (Sivadasan et al., 2006; Frizelle and Suhov, 2001; Falck and Rosenqvist, 2012) and RI
Dynamic: (Sivadasan et al., 2006; Urbanic and ElMaraghy, 2006; Meyer and Curley, 1993), RI and CXI	*Subjective*: (Meyer and Curley, 1993), RI and CXI	*Questionnaire*: (Meyer and Curley, 1993) and CXI (Meyer et al., also used interviews) Specialist discussion: (RI)	*Holistic*: (Urbanic, 2006; Zhu et al., 2008; Meyer and Curley, 1993; Falck and Rosenqvist, 2012)	*Low*: (Zhu et al., 2008; Meyer and Curley, 1993, CXC and CXI)
Both: (Frizelle and Suhov, 2001; Falck and Rosenqvist, 2012) and CXC	-	-	*Flexible*: (Sivadasan et al., 2006), CXC and CXI	(Urbanic and ElMaraghy, 2006)

It was seen that five methods capture dynamic complexity (e.g. (Sivadasan et al., 2006; Urbanic and ElMaraghy, 2006; Meyer and Curley, 1993), RI and CXI) whereas three of the methods capture both static and dynamic complexity (e.g. (Frizelle and Suhov, 2001; Falck and Rosenqvist, 2012) and CXC). Only one method captures only static complexity (e.g. (Zhu et al., 2008)). Only three methods include subjective measures (e.g. (Meyer and Curley, 1993), RI and CXI). In these methods data is captured by questionnaires (Meyer and Curley also used interviews). Most of the data is however captured by observation or extracted from systems. This could be a fast way to gather data, but relies on the premise that the production company does in fact gather that data and that the data is reliable. In addition the observation should in many cases be carried out by a team leader or for instance a controller and does not rely on the knowledge of the people working with the system every day. And most of the methods are carried out by a manager or are intended for the development of systems or for product preparation.

Two methods were seen as capturing a detailed result (e.g. (Frizelle and Suhov, 2001) and RI) whereas Sivadasan and CXC were seen as generating a more broad view of the data of unlimited number of stations (depending on the scope of the study). CXI is holistic since it captures several problem areas but is detailed in the sense that its output is a detailed description (in-depth) of what problem areas can be found on a station level. The other measures have a more holistic view of complexity. As for adaptation before using the methods, four of the methods was considered as having a high need for adaptation (e.g. (Sivadasan et al., 2006; Frizelle and Suhov, 2001; Falck and Rosenqvist, 2012) and RI) while four was considered to be low (Zhu et al., 2008; Meyer and Curley, 1993), CXC and CXI). One method was considered as both high and low in adaptation e.g. (Urbanic and ElMaraghy, 2006). Calinescu (1998) compared Frizelle and Suhov's entropy and the Meyer Foley Curley (MFC) method (Meyer and Curley, 1993), concluding that the methods complement each other since they differ regarding what types of complexity they show, requirements, and methodology. The entropic method, was much more time consuming and data requiring, but provided more information of the system. However, the MFC method provided more information of the decision-making process, and was faster and easier to use.

In general the methods have different aims and could be used for different purposes i.e. they could be used in conjunction to complement one another (see Appendix for a more detailed table). In order to manage production complexity from a company perspective it is important that the adaptation level is low (not much specific knowledge is needed and that the calculation is easy). Methods having low adaptation were (Zhu et al., 2008; Meyer and Curley, 1993), CXC and CXI, where two are objective and two subjective. However the method suggested by Meyer and Curley was developed to manage software development and could be time consuming due to doing interviews.

6 CONCLUSION

The scope of the paper has been to suggest ways to manage production complexity by comparing nine quantitative methods. Especially two developed methods for measuring production complexity were compared in detail suggesting that a combined use of the methods would give possibility for overall scan of plant's stations, and in-depth analysis of specific stations.

As a result of comparing the nine quantitative methods, we see a lack in subjective methods and many of the methods require gathering data from data logs. This could be done automatically, which is fast if all data is logged in for example a larger company, but could take a lot of time if it has to be gathered by observation. The comparison table, Table 6, could be used to suggest ways to manage complexity depending on what type of measurements that is needed: static or dynamic, objective or subjective, what data logs are available and also in what detail the results are needed. To manage complexity, the personnel working closest to the complexity should do the analysis. This indicate that the methods should be low in adaptation, which was seen for CXI, CXC as well as the methods developed by Zhu et al. (2008) and Meyer and Curley (1993).

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APPENDIX

Method	Aim	Type of complexity (Static or dynamic)	Types of measure/-s (objective/subjective)	Data gathering	Results (detailed or holistic)	Adaptation for use (High or low)	Strengths and weaknesses (+ or -)
Operational complexity (Sivadasan et al., 2006)	To monitor and manage information and material flows	Dynamic	Objective: Amount of information required to describe a state: according to flow variations, products, reasons and variation states.	Observed by a controller in a supplier-customer system during a specific time interval	Dependent on scope of study	High: Needs understanding of measures, process knowledge needed	+ Detailed quantitative answers to specific questions. Set boundary's needed
Entropic measurement (Frizelle and Suhov, 2001)	To measure the rate of variety	Static and dynamic complexity (comparison off)	Objective: Probability of a state to occur according to different time measures.	Production data or measurements in factory	Detailed information on the system	High: process knowledge needed	+ Objective data, Valuable for simple systems and line managers - Takes a long time to assess dynamic complexity
Manufacturing complexity index (Urbanic and ElMaraghy, 2006)	To evaluate alternatives and risk with respect to product, process or operation task in a design stage	Dynamic complexity	Objective: Quantity, diversity and content information in the process	Assessments of elements in system	Holistic	Low: can be understood by people from different backgrounds. High: Process information needed	+ Used by people from different background - Understanding of calculation needed (process vs product index)
Operator choice complexity (Zhu et al., 2008)	To find causes, plan assembly sequences and design mixed-model assembly lines	Static complexity	Objective: Average uncertainty and risk in a choice for right tool, fixture, parts and procedure for variant	Observations or from data systems	Holistic	Low	+ Simple measurement, many possible applications - Not detailed, could require logged data
Knowledge and technology complexity (Meyer and Curley, 1993)	To manage software development	Dynamic complexity	Subjective: Assessment of knowledge and technology complexity	Questionnaires/interviews	Holistic	Low	+ Easy to apply, low cost. Could be used for predictions - Limited to knowledge and technology
Complexity index (CXB) (Falck and	To support product preparation to	Static and dynamic	Objective: Criteria for low/high assembly	Logged data from company databases and assessments of area.	Holistic	High: Process information	+ Low/high complexity on index on

Rosenqvist, 2012)	increase productivity and decrease costs	complexity	complexity	Assembly errors from team-leaders		and expert knowledge needed regarding ergonomics, geometry assessment	stations - Requires data gathering from expert
Robustness index (RI) (Paper II)	To evaluated risks and problem areas on a management/team leader level	Dynamic complexity	Subjective: Robustness score regarding material, method, machine and environment	Several specialists gathered, discussed and agreed on index	Detailed (each part evaluated)	High: Experts on products and its parts are needed.	+ Detailed knowledge about parts gathered by experts - Time-consuming and part specific
CompleXity Calculator (CXC) (Zeltzer et al., 2012, 2013)	To automatically assess the complexity of stations	Static and dynamic complexity	Objective: Probability that the workstation's complexity is high or low	Capture data automatically from systems	Flexible depending on scope	Low: Assessment based on Likert scale	+ Gives a high/low complexity index on stations implying direct and in-direct costs - Requires logged data
CompleXity Index (CXI)	To find problem areas at a station level	Dynamic complexity	Subjective: Assessment of product/variants, work content, layout, tools and view of station	Questionnaire made by operators and personnel close to production	Holistic since it is regarding several parameters but detailed on station level	Low: no prior knowledge needed, analysis in Excel	+ Holistic and quick view that visualizes problem areas. Comments can be included - Language dependent, requires operator time