

Mälardalen University Press Dissertations
No. 130

SUPPORTING THE DESIGN OF RECONFIGURABLE PRODUCTION SYSTEMS

Carin Rösiö

2012



SCHOOL OF ENGINEERING
JONKÖPING UNIVERSITY

Department of Industrial Engineering and Management



MÄLARDALEN UNIVERSITY
SWEDEN

School of Innovation, Design and Engineering

Copyright © Carin Rösiö, 2012

ISBN 978-91-7485-079-6

ISSN 1651-4238

Printed by Mälardalen University, Västerås, Sweden

Mälardalen University Press Dissertations
No. 130

SUPPORTING THE DESIGN OF RECONFIGURABLE PRODUCTION SYSTEMS

Carin Rösiö

Akademisk avhandling

som för avläggande av teknologie doktorsexamen i innovation och design vid
Akademin för innovation, design och teknik kommer att offentligens försvaras
torsdagen den 11 oktober 2012, 10.00 i Filen, Smedjegatan 37, Eskilstuna.

Fakultetsopponent: docent Erik Sundin, Linköpings universitet



Akademin för innovation, design och teknik

Abstract

To compete, manufacturing companies need production systems that quickly can respond to changes. To handle change drivers such as volume variations or new product variants, reconfigurability is advocated as a competitive means. This implies an ability to add, remove, and/or rearrange the structure of the production system to be ready for future changes. Still, it is not clear how the production system design process can capture and support the design of reconfigurable production systems. Therefore, the objective of this thesis is to increase the knowledge of how to support the design of reconfigurable production systems.

Reconfigurability could be defined by a number of reconfigurability characteristics including convertibility, scalability, automatibility, mobility, modularity, integrability, and diagnosability. In eight case studies, reconfigurability characteristics in production system design were studied in order to investigate reconfigurability needs, knowledge, and practice in manufacturing companies. In three of the case studies reconfigurable production systems were studied to identify the links between change drivers and reconfigurability characteristics. In the remaining five case studies, reconfigurability in the production system design processes was addressed in terms of needs, prerequisites, and consideration.

Based on the literature review and the case studies, support for reconfigurable production system design is suggested including two parts. The first part comprises support for analyzing the need for reconfigurability. Based on relevant change drivers the need for reconfigurability must be identified to enable selection of right type and degree of reconfigurability for each specific case of application. A comprehensive view of the reconfigurability characteristics is presented and links between change drivers and reconfigurability characteristics are described. The characteristics are divided into critical characteristics, that lead to a capacity or functionality change of the production system, and supporting characteristics, that reduce system reconfiguration time but do not necessarily lead to a modification of functionality or capacity of the production system. The second part provides support in how to consider reconfigurability in the production system design process. A holistic perspective is crucial to design reconfigurable production systems and therefore constituent parts of a production system are described. According to their character physical, logical, and human reconfiguration must be considered through the whole production system design process.

Abstract

To compete, manufacturing companies need production systems that quickly can respond to changes. To handle change drivers such as volume variations or new product variants, reconfigurability is advocated as a competitive means. This implies an ability to add, remove, and/or rearrange the structure of the production system to be ready for future changes. Still, it is not clear how the production system design process can capture and support the design of reconfigurable production systems. Therefore, the objective of this thesis is to increase the knowledge of how to support the design of reconfigurable production systems.

Reconfigurability could be defined by a number of reconfigurability characteristics including convertibility, scalability, automatibility, mobility, modularity, integrability, and diagnosability. In eight case studies, reconfigurability characteristics in production system design were studied in order to investigate reconfigurability needs, knowledge, and practice in manufacturing companies. In three of the case studies reconfigurable production systems were studied to identify the links between change drivers and reconfigurability characteristics. In the remaining five case studies, reconfigurability in the production system design processes was addressed in terms of needs, prerequisites, and consideration.

Based on the literature review and the case studies, support for reconfigurable production system design is suggested including two parts. The first part comprises support for analyzing the need for reconfigurability. Based on relevant change drivers the need for reconfigurability must be identified to enable selection of right type and degree of reconfigurability for each specific case of application. A comprehensive view of the reconfigurability characteristics is presented and links between change drivers and reconfigurability characteristics are described. The characteristics are divided into critical characteristics, that lead to a capacity or functionality change of the production system, and supporting characteristics, that reduce system reconfiguration time but do not necessarily lead to a modification of functionality or capacity of the production system. The second part provides support in how to consider reconfigurability in the production system design process. A holistic perspective is crucial to design reconfigurable production systems and therefore constituent parts of a production system are described. According to their character physical, logical, and human reconfiguration must be considered through the whole production system design process.

Sammanfattning

Tillverkande företag måste kunna konkurrera genom produktionssystem som snabbt kan hantera förändringar. För att hantera förändringar i t.ex. volym eller produktvariation har rekonfigurerbarhet förespråkats som ett viktigt konkurrensmedel. Detta innebär en förmåga att enkelt ordna om i produktionssystemets struktur för att vara förberedd på framtida förändringar. Det är dock inte tydligt hur behovet av rekonfigurerbarhet ska identifieras och hur utformningen därefter ska kunna stödjas utifrån detta behov. Därför är syftet med denna avhandling att öka kunskapen kring hur utformningen av rekonfigurerbara produktionssystem ska kunna stödjas.

Rekonfigurerbarhet innefattar många olika förmågor eller karakteristik såsom konverterbarhet, skalbarhet, automatiserbarhet, mobilitet, modularitet, integrerbarhet och diagnoserbarhet.

I åtta fallstudier har kunskap och praktik kring rekonfigurerbarhet studerats under produktionssystemutformning i tillverkande företag. I tre av fallstudierna har rekonfigurerbara produktionssystem studerats med syfte att identifiera och exemplifiera länken mellan behovet av förändring och rekonfigurerbarhetskaraktistik. I de resterande fallstudierna har behov av och förutsättningar för rekonfigurerbarhet studerats samt hur rekonfigurerbarhet beaktas under produktionssystemets utformningsprocess.

Baserat på litteraturgenomgången och resultaten av fallstudierna förslås ett stöd för utformning av rekonfigurerbara produktionssystem. Stödet omfattar två delar. Den första delen innefattar stöd för att specificera behovet av rekonfigurerbarhet vilket bör baseras på behovet av förändring. En heltäckande bild av rekonfigurerbarhet presenteras och länkar mellan rekonfigurerbarhetskaraktistik och behov av förändringar beskrivs. En kategorisering i kritiska och stödjande rekonfigurerbarhetskaraktistik görs. Den andra delen av stödet innefattar stöd för att beakta rekonfigurerbarhet i produktionssystemets utformningsprocess. För att möjliggöra rekonfigurerbarhet måste produktionssystemets alla delar beaktas. Ett holistiskt perspektiv är viktigt och därför beskrivs ingående delar i ett produktionssystem. De olika delarna måste vara förberedda för rekonfigurering och därför måste rekonfigurerbarhet beaktas redan i utformningsprocessen.

Acknowledgements

The process of being a PhD student now comes to its end. It has been a great experience that has included both ups and downs. A lot of people have crossed my path from the start until now. Therefore, there are many people that I would like to take the opportunity to thank.

I am deeply grateful to my supervisors Mats Jackson and Kristina Säfsten. You have had the amazing capability to point out weaknesses and at the same time encourage, inspire, and provide energy. I also owe thanks to Monica Bellgran for your support during my research studies and Magnus Wiktorsson for a well-conducted final review. The feedback and suggestions helped me improve my work.

I would like to express gratitude to former and present colleagues at the Department of Industrial Engineering and Management in Jönköping. The head of the department Ingrid Wadskog for your support in letting me prioritize my research studies, Christer Johansson and Mats Winroth for advice and support leading up to my licentiate thesis. Special thanks to Jenny Bäckstrand who has accompanied me during my entire PhD studies. I appreciate our discussions about small and big things and all the coffee breaks you initiated.

I also owe thanks to my former and present colleagues at the School of Innovation, Design and Engineering in Eskilstuna. Even if my visits were sporadic I always felt very welcome. Especially I would like to express my gratitude to Sofi Elfving. I hope that our Friday e-mail conversations do not end here.

In my research projects, I am grateful that I have had the opportunity to cooperate with such competent persons. Thank you Mikael Hedelind, Andreas Ask, Robin Hedström, Joel Schedin and many, many more...

During my research studies I have had the opportunity to conduct studies at a number of manufacturing companies. I would like to thank the employees at the case study companies. Financial support was provided by ProViking and the Swedish Foundation for Strategic Research as well as Vinnova – the Swedish Agency for Innovation Systems, for which I am very grateful. I would also like to thank the ProViking Research School for financing my research visits to the UK and Germany.

Someone who really deserves a very special thank is Jessica Bruch. You made this much more fun and you have always been willing to discuss all

kinds of problems. Without your company this journey would have been very long. I owe you a lot.

Finally, my deepest gratitude goes to my family. Carl Edvard, who followed the progress of this thesis each day sharing frustrations and joy and always supported me and gave me the time that I needed. Valdemar and Mathilde, for forcing me to switch off the thoughts of my research studies when I came home. All my love to you.

Huskvarna in August, 2012

Carin Rösiö

List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals. The contribution of the authors differed between the papers.

- I** Rösiö, C. and Säfsten, K. Reconfigurable Production System Design – theoretical and practical challenges. *Journal of Manufacturing Technology Management*. Status: Accepted for publication (4 September 2012).

Rösiö initiated the paper and made the literature review, data collection, data analysis and writing. Säfsten reviewed and quality assured the paper.

- II** Rösiö, C. and Jackson, M. (2009), “Enable Changeability in Manufacturing Systems by Adopting a Life Cycle Perspective”, *Proceedings of the 3rd International Conference on Changeable, Agile, Reconfigurable and Virtual Production, October 5-7 2009, Munich, Germany*, pp. 612-620.

Rösiö initiated the paper and did the literature review, the data analysis, and the writing. Jackson reviewed and quality assured the paper.

- III** Rösiö, C. (2011), Considering Reconfigurability Characteristics in Production System Design, *Proceedings of the 4th International Conference on Changeable, Agile, Reconfigurable and Virtual Production, 2-5 October 2011, Montreal, Canada*, pp. 57-62.

- IV Rösio, C. and Hedström, R. (2009), Linking Production Strategy to Production System Specification - a case study, *Proceedings of the 3rd International Swedish Production Symposium, 2-3 December 2009*, Göteborg, Sweden, pp. 12-18.

Rösio and Hedström initiated the paper and made the data collection. Rösio wrote the parts introduction, method, the literature review about production system design and production system specification, case study results about production system development, and the conclusion.

- V Stillström, C. and M. Jackson (2007), "The Concept of Mobile Manufacturing", *Journal of Manufacturing Systems*, Vol. 26 No. 3-4, pp. 188-193.

Rösio (formerly Stillström) initiated the paper and did the literature review, data collection, data analysis, and writing. Jackson reviewed and quality assured the paper.

Additional publications by the author not included in the thesis

Stillström, C. and Johansson, B. (2006), "Mobile Manufacturing System Characteristics", *Proceedings of the 17th Annual Conference of the Production and Operations Management Society "OM in the New World Uncertainties"*, 28 April – 1 May 2006, Boston, MA, USA.

Ask, A. and Stillström, C. (2006), "Mobile Manufacturing System: Market Requirements and Opportunities", *Proceedings of the 2006 IJME – Intertech International Conference, 19-21 October 2006*, New York, NY, USA.

Stillström, C., Ask, A. and Jackson, M. (2007), *An Article Database Research of Mobile Flexible Manufacturing Systems*, Institutionen för innovation, design och produktutveckling, Eskilstuna.

Stillström, C. and Jackson, M. (2007), "The concept of Mobile Manufacturing", *Proceedings of the 2nd International Conference on Changeable, Agile, Reconfigurable and Virtual Production, 22-24 July 2007*, Toronto, Canada, pp. 222-231.

Bäckstrand, J. and Stillström, C. (2007), "Investigating the Interaction Aspect in the Mobile Manufacturing Concept", *Proceedings of the 2007 NOFOMA Conference, 7-8 June 2007*, Reykjavik, Iceland, pp. 179-193.

Stillström, C. and Bäckstrand, J. (2007), "Effects on Supply Chain Relations in Mobile Manufacturing Systems", *Proceedings of the Swedish Production Symposium 2007, 28-30 August 2007*, Göteborg, Sweden.

Stillström, C. (2007), *The Concept of Mobile Manufacturing*, Licentiate Thesis, Department of Product and Production Development, Chalmers University of Technology, Göteborg.

Schedin, J. and Rösiö, C. (2012), *Considering Production Location in Production System Design*, Paper submitted to the 4th International Swedish Production Symposium, 6-8 November 2012, Linköping, Sweden, submitted (18 June 2012).

Contents

CHAPTER 1 - Introduction	1
1.1 Manufacturing challenges	1
1.1.1 The ability to handle change	2
1.2 Reconfigurability	3
1.2.1 Adopting a life-cycle perspective	4
1.2.2 Reconfigurability concepts	4
1.2.3 Prerequisites for designing reconfigurable production systems ...	5
1.3 Objective and research questions	7
1.4 Scope and delimitations	7
1.5 Thesis outline	8
CHAPTER 2 – Frame of reference	11
2.1 Production systems	11
2.1.1 The system approach	11
2.1.2 Regarding production with a system approach	13
2.2 Reconfigurability	16
2.2.1 The RMS concept	18
2.2.2 Change drivers	19
2.2.3 Reconfigurability characteristics	23
2.2.4 Reconfigurability categorization	28
2.3 The production system design process	30
2.3.1 Holistic view in the production system design process	34
2.3.2 Production system design approaches	36
2.3.3 Reconfigurable production system design approaches	37
2.4 Overview/summary of the frame of reference	39
CHAPTER 3 – Research method	41
3.1 Research approach	41
3.2 Literature review	43
3.3 Research design	44
3.3.1 Case study design	44
3.3.2 Real-time or retrospective case studies	45
3.3.3 Case selections	45
3.3.4 Unit of analysis	46
3.4 Data collection	48
3.4.1 The Factory-in-a-Box study	48

3.4.2 The DaxVehicles study	50
3.4.3 The MaxAuto study	51
3.4.4 The VoxVan study	54
3.5 Case study analysis	55
3.6 Reliability and validity	57
3.6.1 Reliability	57
3.6.2 Internal validity	57
3.6.3 External validity	59
CHAPTER 4 – Empirical findings	61
4.1 The Factory-in-a-Box study	61
4.1.1 Demonstrator 1	61
4.1.2 Demonstrator 2	63
4.1.3 Demonstrator 5	65
4.2 The DaxVehicles study	66
4.2.1 Identification of change drivers	67
4.2.2 Considering reconfigurability in the production system design process	68
4.3 The MaxAuto study	71
4.3.1 MaxAuto UK	72
4.3.2 MaxAuto Germany	75
4.3.3 MaxAuto Sweden	78
4.4 The VoxVan study	80
4.4.1 Change drivers	81
4.4.2 Support for reconfigurability in the production system design process	81
CHAPTER 5 – Reconfigurability in production system design	83
5.1 Analysing reconfigurability need and consideration	83
5.2 Change drivers and need for reconfigurability	84
5.2.1 Strategy-related change drivers	85
5.2.2 Product-related change drivers	87
5.2.3 Volume-related change drivers	88
5.2.4 Technology-related change drivers	89
5.3 Consideration of reconfigurability in the production system design process	90
5.3.1 Existing support for reconfigurability in the production system design process	90
5.3.2 Considering reconfigurability in the production system design process	93
CHAPTER 6 – Supporting reconfigurable production system design	97
6.1 Proposing support in two parts	97
6.2 Part 1: Support for analysing the need for reconfigurability	98

6.3 Part 2: Considering reconfigurability need in the production system design process	103
CHAPTER 7 – Discussion and conclusion.....	111
7.1 General discussion.....	111
7.2 Method discussion.....	116
7.3 Conclusion.....	118
7.4 Contribution of the research	120
7.4.1 Academic contribution.....	120
7.4.2 Industrial contribution	120
7.5 Future research	121
References.....	123
Appendix A: Interview guides	135
Appendix B: Scenario formulation Dax Vehicles.....	139

List of Figures

<i>Figure 1.</i> The ability to change permeating all production levels of a manufacturing company based on ElMaraghy and Wiendahl (2009), Löffler et al. (2011b), and Wiendahl and Heger (2004).....	2
<i>Figure 2.</i> System aspects (Seliger <i>et al.</i> , 1987).	12
<i>Figure 3.</i> A hierarchical perspective on the production system (Bellgran and Säfsten, 2010).....	13
<i>Figure 4.</i> Overview of the constituent parts of the production system.	15
<i>Figure 5.</i> Physical, logical, and human reconfiguration.	18
<i>Figure 6.</i> Change drivers affecting production system elements (Schuh <i>et al.</i> , 2003).	22
<i>Figure 7.</i> Enabling change through reconfigurability.....	23
<i>Figure 8.</i> Overview of reconfigurability characteristics.	24
<i>Figure 9.</i> Exemplifying system convertibility.	26
<i>Figure 10.</i> Link between change drivers, critical characteristics, and supporting characteristics.....	30
<i>Figure 11.</i> Typical activities carried out when designing the production system, revised from Bruch (2012).....	33
<i>Figure 12.</i> A proposed general model for considering flexibility and reconfigurability when designing production systems (Jackson, 2000).	38
<i>Figure 13.</i> Overview of the frame of reference.	40
<i>Figure 14.</i> Data collection process.	48
<i>Figure 15.</i> Research design of the Factory-in-a-Box study.	49
<i>Figure 16.</i> Research design of the DaxVehicles study.	50
<i>Figure 17.</i> The production system design process and the researcher’s participation in the process.....	51
<i>Figure 18.</i> Research design of the MaxAuto study.	52
<i>Figure 19.</i> Research design of the VoxVan study.	54
<i>Figure 20.</i> Robots, equipment, and tools, demonstrator 1.....	62
<i>Figure 21.</i> Pipes prepared for welding, demonstrator 2.....	64
<i>Figure 22.</i> Collapsible container including assembly and test, demonstrator 5.....	66
<i>Figure 23.</i> Scenario description, Dax Vehicles.	68
<i>Figure 24.</i> The production system design process, DaxVehicles.	69
<i>Figure 25.</i> Conceptual design of production system, DaxVehicles.....	70
<i>Figure 26.</i> Main phases in the project management model MaxAuto.	72
<i>Figure 27.</i> Two types of mobility, system mobility and module mobility. ..	86

Figure 28. Comparison of the production system design phases between case studies and the frame of reference.....91

Figure 29. Order when specifying reconfigurability need.....99

Figure 30. Support for reconfigurable production system design: Part 2 – Considering reconfigurability need in the production system design process.....104

Figure 31. Support for reconfigurable production system design – phase 0.105

Figure 32. Support for reconfigurable production system design – phase 1.107

Figure 33. Support for reconfigurable production system design – phase 2.109

List of Tables

Table 1. <i>Determinants of changeability</i>	20
Table 2. <i>Types of change drivers</i>	21
Table 3. <i>Analysis of the holistic perspective in production system design literature</i>	35
Table 4. <i>Overview of the research design</i>	47
Table 5. <i>Interviews, the MaxAuto study</i>	53
Table 6. <i>Interviews, the VoxVan study</i>	55
Table 7. <i>Support for reconfigurable production system design: Part I – Identifying prerequisites and need for reconfigurability</i>	101

CHAPTER 1 - Introduction

This chapter introduces the research presented in this thesis on the topic of design of reconfigurable production systems. It describes the background of the research and presents current challenges associated with the topic, which are narrowed down to an objective of the thesis. The objective is thereafter conceptualized in three research questions. In order to set the framework for the research presented, the research area is defined and delimited. Finally an outline for the thesis is presented.

1.1 Manufacturing challenges

Manufacturing companies compete in an age that is characterized by rapidly changing technologies as well as demanding customers with an ever-increasing claim for variety and aggressive international competition (European Commission, 2006). European manufacturing companies have a high standard and a strong position in industrial engineering with innovative and customized product solutions, however, they lose market shares in mass production (Westkämper, 2006). Attractive product solutions are not enough, a successful production activity is also required in order to be competitive. The potential of an effective production system design process is often not prioritized enough in manufacturing companies. However, it must be kept in mind that the success of several new products relates to the skill to integrate production system design into products designed in a balanced way (Bellgran and Säfsten, 2010). The challenge is thus not only to develop products according to customer needs but also to be able to put them on the right market at the right point in time (Koren, 2010). In order to succeed on a global market, manufacturing companies must have the ability to respond to changes. The production system must be ready for change in order to be able to produce changing products.

Already in the rather outdated report from the National Research Council (1998), it was argued that manufacturing companies must effortlessly respond to quickly changing customer needs, quickly changing market opportunities, and developments in process, product, and electronic communication technology. The need for a production activity that is responsive to handling changes has thereafter been highlighted in reports one after another (e.g. Carlsson *et al.*, 2010; European Commission, 2004; Teknikföretagen *et*

al., 2011; Teknisk Framsyn, 2000; The Ad-hoc Industrial Advisory Group, 2010). Still the question is whether manufacturing companies in high-cost countries have the prerequisites for responsiveness to handle change.

1.1.1 The ability to handle change

In the field of changeability it is advocated that the ability to change must be permeated through all production levels of a manufacturing company (ElMaraghy and Wiendahl, 2009; Wiendahl and Heger, 2004). Depending on production level, different capabilities are required to respond to changes, *Figure 1*.

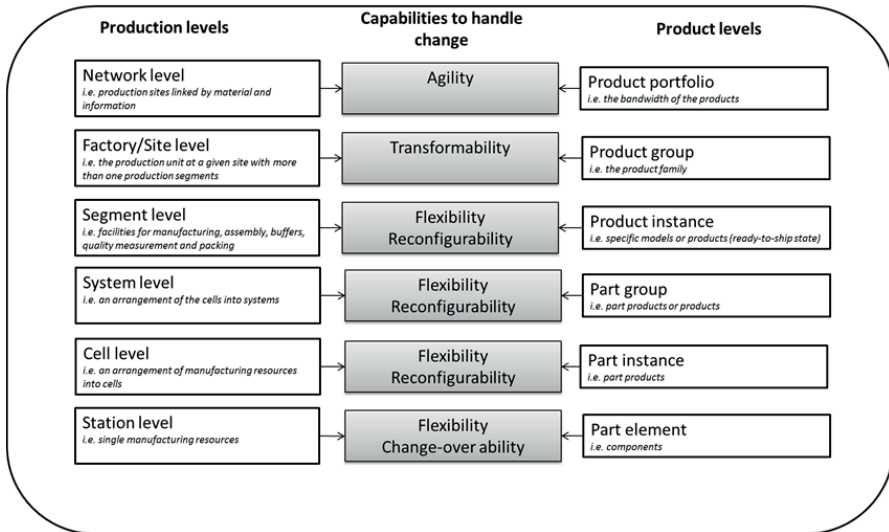


Figure 1. The ability to change permeating all production levels of a manufacturing company based on ElMaraghy and Wiendahl (2009), Löffler et al. (2011b), and Wiendahl and Heger (2004).

At a network level the entire company needs a strategic ability to respond to changing markets by e.g. an ability to easily enter new markets, designing product and service portfolios and building necessary manufacturing capacity. This is described in the field of agile manufacturing (Dove, 1994; Goldman *et al.*, 1995; Gunasekaran and Yusuf, 2002; Yusuf *et al.*, 1999). At a site or factory level the entire factory needs a structure in order to easily switch to different product groups or families. This is described in the field of transformable manufacturing (Nyhuis *et al.*, 2006; Wiendahl and Heger, 2004). At segment, system, and cell levels change is proposed to be dealt with by flexibility and/or reconfigurability (ElMaraghy and Wiendahl, 2009). At a segment level all facilities needed to develop products in ready-to-ship-state, i.e. to put a product on the market, must be prepared for chang-

es including manufacturing, assembly, buffers, quality measurement, and packaging. In this thesis, this refers to the manufacturing system (CIRP, 1990). At system and cell levels, facilities needed to manufacture a product or parts of the product must easily be able to adapt to changes in e.g. product types and volumes. In this thesis this refers to the production system (CIRP, 1990). At the lowest level, the station level, single machines or workstations must have an operative ability to perform particular operations on a known component or subassembly at any desired moment with minimum effort and delay. This is dealt with by flexibility or change-over ability (Wiendahl *et al.*, 2007).

The ability to change is thus governed by different capabilities. This thesis focuses on the ability to change at a system/cell level, which in the thesis is referred to as the production system.

In order to be responsive to change, therefore, the production system must be characterized by flexibility and/or reconfigurability. The division between flexibility and reconfigurability is debated in the literature. Flexibility has been researched extensively in academia (e.g. D'Souza and Williams, 2000; Koste and Malhotra, 1999; Sethi and Sethi, 1990). Generally, flexibility could be defined as “the ability to change or react with little penalty in time, effort, cost, or performance” (Upton, 1995, p. 73). Reconfigurability, on the other hand, calls for an ability to restructure the production system through an ability to add, remove, and/or rearrange the structure of the production system (Abdi and Labib, 2003; Jackson, 2000). Reconfigurability provides manufacturing companies with “the engineering tools that they need to be flexible and respond quickly to market opportunities and changes” (Mehrabi *et al.*, 2000b, p. 407). Consequently, reconfigurability does not contradict flexibility but is in this thesis rather seen as a capability to achieve flexibility.

1.2 Reconfigurability

Reconfigurability has explicitly been pointed out as an important means to be responsive to handling change in additional future reports (Carlsson *et al.*, 2010; National Research Council, 1998; Technology Strategy Board, 2012; The Ad-hoc Industrial Advisory Group, 2010; Thomas *et al.*, 2012). The National Research Council (1998, p. 38) points out that “adaptable, integrated equipment, processes, and systems that can be readily reconfigured for a wide range of customer requirements [...] is a priority ...”. When the Technology Strategy Board (2012, p. 11) lists opportunities for high-value manufacturing, the importance of “flexibility of production and manufacture supporting customised and rapidly reconfigurable manufacturing” is highlighted.

1.2.1 Adopting a life-cycle perspective

Reconfigurability calls for an ability to restructure the production system through rearrangement and reuse and thereby prolong the length of life of the production system (ElMaraghy and Wiendahl, 2009; Koren, 2010). During a product life cycle, changes occur in e.g. volumes or product variants (Schuh *et al.*, 2005). A production system must be developed and changed in accordance with these changes. Consequently, a long-term view is needed when designing the system. While there is increased focus on the need for sustainability, the need for reconfigurability has been even more crucial (Bi, 2011; Garetti and Taisch, 2012). To regard the production system in a life-cycle perspective is accordingly justified. This implies focusing on the manufacturing efficiency over the whole life cycle (Bellgran and Säfsten, 2010). The production system itself could be studied as a whole and the system could be seen as an object that is created, used, and retired over time (Wiktorsson, 2000).

Conventionally, the length of life of the production system is often much longer than the product that the production system was originally designed for, which implies that the production system does not always perfectly fit the product that is produced in the system (Bellgran, 1998). The length of life of a production system could be divided into technical, conceptual, and economic length of life, where the conceptual length of life is longer than both the product length of life and the technical and economic length of life (Bellgran, 1998). By enhancing the ability to reconfigure the production system it could be adapted according to required changes and therefore increase the length of life of the production system and thereby also enable a better fit between the products and the production system.

1.2.2 Reconfigurability concepts

Reconfigurability is mainly described in the literature in the reconfigurable manufacturing system (RMS) field. Over the years, additional concepts have, however, been proposed with similar capabilities. During the 1980s flexible manufacturing systems (FMS) were introduced in order to handle change in e.g. product variations (Browne *et al.*, 1984; Sethi and Sethi, 1990). However, FMS had limited success due to, among other things, the high investment cost required. FMS turned out to be not as cost-efficient as needed in order to compete since often too much flexibility was built into the system (Mehrabi *et al.*, 2000a). In order to handle change, flexibility is useful, but the customer does not want to pay for more flexibility than required. As a reaction to FMS the RMS was introduced during the 1990s in order to cost-effectively respond to changes in production requirements (Koren *et al.*, 1999). RMS is a production system with highly reconfigurable hardware and software. In the RMS field much research effort is devoted to development

of techniques and tools enabling reconfigurable hardware and software (Koren *et al.*, 1999; Mehrabi *et al.*, 2000a), layouts in the form of determination and classification of various configurations (Koren and Shpitalni, 2010), and ways of considering future product variants (Abdi and Labib, 2004; AlGeddawy and ElMaraghy, 2009; Matta *et al.*, 2008).

In the concept of holonic manufacturing system (HMS) the system is made up of building blocks or holons, where the system should be self-reconfigured according to changing needs (Van Brussel *et al.*, 1999; Van Brussel *et al.*, 1998). A production system with biologically inspired ideas such as self-organization, adaption, evolution, and learning is proposed in the bionic manufacturing system (BMS) (Ueda, 2007; Ueda *et al.*, 2001). A similar concept is proposed by Onori *et al.* (2011) in evolvable production systems (EPS). An object-oriented simulation system is proposed by Hibino *et al.* (1999) with similar thoughts as the approach for design for changeability (DFC) proposed by Schuh *et al.* (2009).

The RMS field contributes to a broad knowledge about what a highly reconfigurable production system should look like in terms of technology solutions and layouts (Ateekh-Ur-Rehman and Subash Babu, 2012). Still, there are issues not often treated in the RMS field. A comprehensive picture of the reconfigurability capability is seldom given, neither how to consider reconfigurability in the production system design process.

1.2.3 Prerequisites for designing reconfigurable production systems

Reconfigurability is a broad term, including additional subcapabilities that are needed to achieve reconfigurability, i.e. reconfigurability characteristics. In the RMS field, reconfigurability and the reconfigurability characteristics are described but an overview of reconfigurability capability and how it could deal with different types of changes during the system's life cycle is seldom given. In this thesis, reconfigurability is regarded as a production system capability that could characterize the production system in different ways and to a different extent, depending on the specific need for change during its life cycle. To respond to changes, knowledge about reconfigurability is required in terms of what opportunities it could offer and how the system must be designed for reconfigurability in order to handle the specific need for change. In order to design reconfigurable production systems, the term reconfigurability needs to be clearly defined together with all its characteristics.

In order to respond to changes by reconfigurability, knowledge is needed about all its characteristics and how to deal with different types of change.

In order to achieve a reconfigurable production system the constituent parts of the production system must all be ready for reconfiguration (Koren *et al.*, 1999). A production system is, however, complex comprising not only physical hardware, but also people who manage and operate the hardware and who must communicate information within the production system (Cochran *et al.*, 2002). The production system includes several constituent parts that all must interact to fulfil the purpose of the system (Bi *et al.*, 2008). When designing production systems, the ability to respond to change must be built into the production system (Bennett and Forrester, 1993). To have a clear knowledge of the constituent parts in order to design a reconfigurable production system is thus crucial (Mehrabi *et al.*, 2000b).

To enable reconfigurable production systems, a clear understanding of the constituent parts of the production systems is needed.

The production system must be responsive to handling changes and an active design for reconfigurability is important (Mehrabi *et al.*, 2000b). In the RMS field limited attention is, however, given to how to involve the reconfigurability knowledge in the production system design process. Regarding general production system design literature, on the other hand, there is an abundance of approaches for design of production systems with several designations. There are approaches for production system design (Bellgran and Säfsten, 2010; Bennett and Forrester, 1993; Wu, 1994), for assembly system design (Bellgran, 1998; Nof *et al.*, 1997; Rampersad, 1994), for selecting production layout (Hayes and Wheelwright, 1979; Miltenburg, 2005), and for system evaluation (Säfsten, 2002). Additionally, there are several approaches for designing production systems based on methods such as axiomatic design (Almström, 2005; Bröte, 2002; Cochran *et al.*, 2002; Duda, 2000; Suh, 1990; Suh *et al.*, 1998; Yien, 1998) and system engineering (Blanchard and Fabrycky, 1998; Hitomi, 1996). Reconfigurability is, however, seldom considered in these processes.

There is a lack of knowledge about how to consider reconfigurability in the production system design process.

Even if there are strong indications that reconfigurability is an important production system capability, the prerequisites for considering reconfigurability in the production system design process are still not clearly focused on in the literature. The RMS field contributes to a broad knowledge about what a highly reconfigurable production system should look like in terms of technology solutions and layouts. The field of reconfigurable production systems is not clearly integrated into the production system design field.

1.3 Objective and research questions

The main challenge and problem statement in this thesis is to bridge the gap between the two fields of RMS and production system design and thus how to consider reconfigurability during the production system design process.

Based on this the following objective has been formulated:

The objective of this thesis is to increase the knowledge of how to support the design of reconfigurable production systems.

In order to meet this objective three research questions have been formulated:

(RQ1) What are the constituent parts of a production system and how could they be described?

A holistic perspective on reconfigurable production system design is crucial and therefore a clear understanding of what parts are included in a production system is required. The first research question is posed to investigate how the production system can be defined and described.

(RQ2) What characterizes reconfigurability and a reconfigurable production system?

The literature presents a fragmented picture of reconfigurability and reconfigurable production system design. By answering this question, the meaning of reconfigurability will be analysed to conclude what it implies and by what it is characterized.

(RQ3) How could reconfigurability in the production system design process be considered?

This question will be answered by analysing the need for reconfigurability and how this need can be handled during the production system design process.

1.4 Scope and delimitations

In this thesis, the term reconfigurable production system is used due to the adoption of the term production system as a subpart of the manufacturing system but also in order to make a distinction from the RMS concept.

The objective of this thesis is to increase the knowledge of how to support the design of reconfigurable production systems. Since both the design of production systems and reconfigurability are broad topics, delimitations were required.

This thesis refers to reconfigurability on a production system level/cell level and literature on other levels is not included. Literature about e.g. agility and transformability is thus not taken into account.

Reconfigurability involves production system design as well as product design. Concurrency in all operations is required (National Research Council, 1998) and it is impossible and unjustified to segregate the product and the production system design process since development of new production systems is often made in the context of a product development project. However, research in design of production systems is underexposed compared to that in product design (Ruffini, 1999) and in practice support for designing production systems is vague. Therefore, a need to take a production system design perspective was justified. This thesis consequently deals with design of production systems and not design of products.

Production systems could be designed by production system designers in the manufacturing company or by a system supplier. In some of the empirical studies system suppliers were used. This thesis has, however, taken the perspective of the manufacturing company.

The focus on the production system design process also implies that the realization and start-up phases are not included (Bellgran and Säfsten, 2010). The early phases of the production system design process are essential for the whole production system life cycle (Bellgran, 1998), and the fact that reconfigurability must be considered from the outset when designing production systems (Koren *et al.*, 1999) emphasizes the need to focus on early phases in the production system design process.

Finally, the research has been carried out on a conceptual level to enable a comprehensive picture of the topic. Consequently, detailed solutions to achieve reconfigurability have not been focused on. The thesis does not encompass e.g. technology solutions for reconfigurability.

1.5 Thesis outline

The thesis is composed of two parts, (1) a frame and (2) five appended papers. The frame connects the five papers and summarizes their main points.

Part 1 includes seven chapters. In the introducing chapter the background to the research is described followed by the objective and the research questions. In Chapter 2, the frame of reference is presented, which includes production systems, the design of production systems, and reconfigurability. In Chapter 3 the research method is presented describing the research approach undertaken and the research design comprising case studies combined with a literature review. Thereafter, each case study is described and the method chosen in each of the case studies as well as how the case studies have been analysed. A discussion of validity and reliability of the chosen research method concludes the chapter. In Chapter 4, the empirical findings from

each separate case study are described. In Chapter 5, the empirical findings are analysed based on the frame of reference. An analysis of needs and prerequisites for reconfigurability as well as an analysis of the consideration of reconfigurability in the production system design process is included. The results from the analysis are compiled in Chapter 6 presenting a support for designing reconfigurable production systems in accordance with the objective of the thesis. Finally, a discussion and a conclusion of the results are given in Chapter 7. The applied research methods as well as the academic and industrial contribution are discussed and future research on the topic is proposed.

Part 2 comprises the papers included in the thesis. Paper I justifies the research topic and presents theoretical and practical challenges of the design of reconfigurable production systems. Paper II justifies a life-cycle approach when designing production systems and analyses support for that to enable reconfigurability. Paper III describes the consideration of reconfigurability when designing production systems linked to one of the case studies. Paper IV describes a part of one of the empirical studies and its production system design process. Paper V, finally, analyses mobility in production systems, which is one part of reconfigurability. This paper also summarizes the licentiate thesis.

CHAPTER 2 – Frame of reference

In this chapter the frame of reference is presented in which the research topic will be placed, viewed, and interpreted. First, the theoretical considerations of the production systems will be described. Thereafter, reconfigurability and design of reconfigurable production systems will be described. The chapter ends with a summary of the frame of reference.

2.1 Production systems

Most production systems are very complex and considerable time and efforts are used on their design and implementation. Due to this complexity, the design of a production system is difficult and it is challenging to be able to see the production system as anything else than a black box which can be regarded only in its totality (Bennett and Forrester, 1993). It is, however, of major importance to have a clear view of the parts included to avoid suboptimization (Bellgran, 1998). This requires a system approach. In the following sections this will therefore be described.

2.1.1 The system approach

The main idea in the system approach is that a complex whole may have properties that refer to the whole, by which the whole is not the same as the sum of its parts (Checkland, 1999). This means that contents are not solely in the individual parts but the relations between the parts are important and affect the whole (Arbnor and Bjerke, 1994).

In system theory, three system aspects can be distinguished, see *Figure 2*. First, the functional aspect (A), which describes the behaviour of a given system irrespective of its realization. The system is considered as a black box where inputs are transformed into outputs. Second, the structural aspect (B), which describes the system as a set of elements that are connected by relations (Seliger *et al.*, 1987). Third, the hierarchical aspect (C), which considers the system as a part of a larger system in which a complex whole is divided into a hierarchical system according to organizational, functional, or geographical connections (Langefors, 1970; Seliger *et al.*, 1987).

When designing production systems, there is a challenge not only to have a functional aspect, but to pay regard to the subsystems and elements includ-

ed (Bennett and Forrester, 1993) and also see the system from a structural and hierarchical perspective.

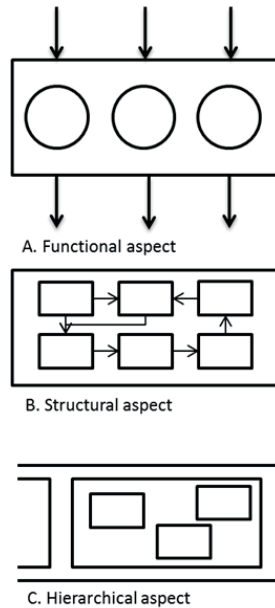


Figure 2. System aspects (Seliger *et al.*, 1987).

When applying a hierarchical perspective, the division starts from the largest function and thereafter the system is divided into smaller systems, subsystems. These are in turn divided into even smaller subsystems and so on, until every subsystem only has a few relevant functions (Arbnor and Bjerke, 1994; Seliger *et al.*, 1987). These constituent parts of a system are described in terms of units (e.g. Hitomi, 1996), components (e.g. Rampersad, 1994), or elements (e.g. Bennett and Forrester, 1993). In this thesis the term element is chosen to describe the constituent parts of a production system.

Describing the system could also be done based on four basic attributes that play a fundamental role characterizing the system (Hitomi, 1996).

- a. Assemblage: A system entails more than one distinct element, which could be physical or conceptual, natural or artificial.
- b. Relationship: Several elements assembled together simply constitute a group. In order to accept this group as a system there must be a relationship or an interaction between the elements.
- c. Goal seeking: A system as a whole performs a function and has one or several specific objectives.
- d. Adaptability to environment: A specific system behaves so as to adapt to the change in its surrounding or external environment. This external environment influences and is influenced by the system.

The influence involves energy and/or information that is mutually transformed.

The system could either be defined based on the first two attributes, where “a system is a collection of recognisable units having relationships among the units” (Hitomi, 1996, p. 27) or on the first three attributes, as “a collection of components [...] which are interrelated in an organized way and work together towards the accomplishment of a certain logical and purposeful end” (Wu, 1994, p 30).

Production systems must be designed in accordance with their environment as previously described. In this thesis the definition based on all four attributes is believed most proper to use for production systems, in accordance with Hitomi (1996, p 27).

*A **system** is a collection of recognizable elements having relationships between the elements, aiming at specified single or multiple objectives subject to their external environment.*

2.1.2 Regarding production with a system approach

The production system is described differently in the literature depending on author and context. Irrespective of what view is adopted, the system should be clearly defined in order to enable transparency.

The production system could be seen as a limited part of the manufacturing system. It denotes all activities and facilities needed to transform raw material into products (CIRP, 1990). This could be compared with the manufacturing system, which denotes all activities needed to put a product on the market. The assembly system and the part production system are regarded as subparts of the production system, *Figure 3*.

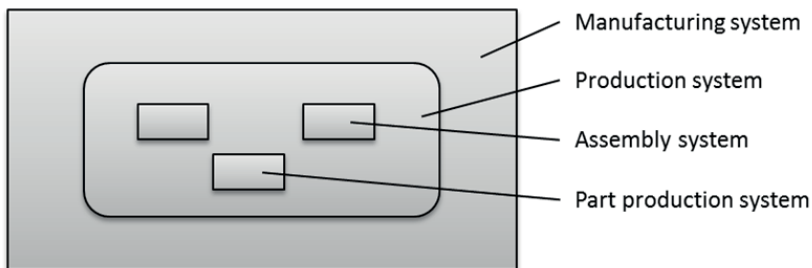


Figure 3. A hierarchical perspective on the production system (Bellgran and Säfsten, 2010).

The production system could include, for example, an individual work cell, consisting of a single production machine and the person who operates

the machine but also a group of machines and workers such as a production line (Groover, 2001). In this thesis, this view is adopted and a production system could comprise an assembly system, a machining system, or a combination of both.

The production system is seen as a limited part of the manufacturing system and denotes activities and facilities needed to transform raw material into products or parts of products.

At a more detailed level the subsystems and elements included are described differently among scholars. The production system and its included parts have been described as

- the arrangement and operation of machines, tools, materials, people, and information that are needed in order to produce a product or part of a product (Cochran *et al.*, 2002; Wu, 1994).
- a transformation process including four subsystems to guide and support the transformation process comprising (1) the human system, including for example operative staff, supervisors, and higher management; (2) the technical system, including for example machines and equipment; (3) the information system, which is used as a storage medium and source of necessary information including elements such as notebooks, information files, and computers; and (4) the management and goal system constituting the execution system, with the purpose of providing coordinated directions of the execution system to achieve a desired end, including for example instructions and data information (Hubka and Eder, 1984).
- a production system including (1) hardware directly linked to the production process, for example production machines, tools, fixtures, and other related hardware; (2) the material handling system including hardware related to loading, positioning, and unloading on to/from the machine as well as transport between stations; (3) the computer system to coordinate and/or control the above components including hardware/software related to, among other things, the functions to communicate instructions to workers, downloading of part programs, material handling system control, production schedules, quality control, and operation management; and (4) the human workers including direct and indirect labour (Groover, 2001).
- a production system including two physical components that convert input to output as labour and physical facilities, the latter including machines, buildings, and equipment. It is the choice of these components together with their organization that determines the system's ability to produce the desired output (Bennett, 1986).

- a production system that is characterized by (1) organization of work, i.e. the way the human resources are organized, and (2) the choice and arrangement of the physical facilities (Bennett and Forrester, 1993).

Accordingly, descriptions of the production system content are slightly different among scholars. However, based on the descriptions listed above, four subsystems could be identified in the literature: (1) the technical system, (2) the material handling system, (3) the computer and information system, and (4) the human system. A few scholars also include a fifth subsystem, buildings and premises. In order to get an overview of the constituent parts, the production system is described in terms of a hierarchy including subsystems and their elements in *Figure 4*. The relationships between the subsystems are described by the arrows. The sum of all elements as well as the relationships among them and with their environment is collectively termed a system (Hubka and Eder, 1984).

The production system is the product of how people utilize the available work organization options, ergonomic options, and technical options to design the system. Influences such as company culture, strategies, and production philosophies affect how people design the production system (Bellgran, 1998).

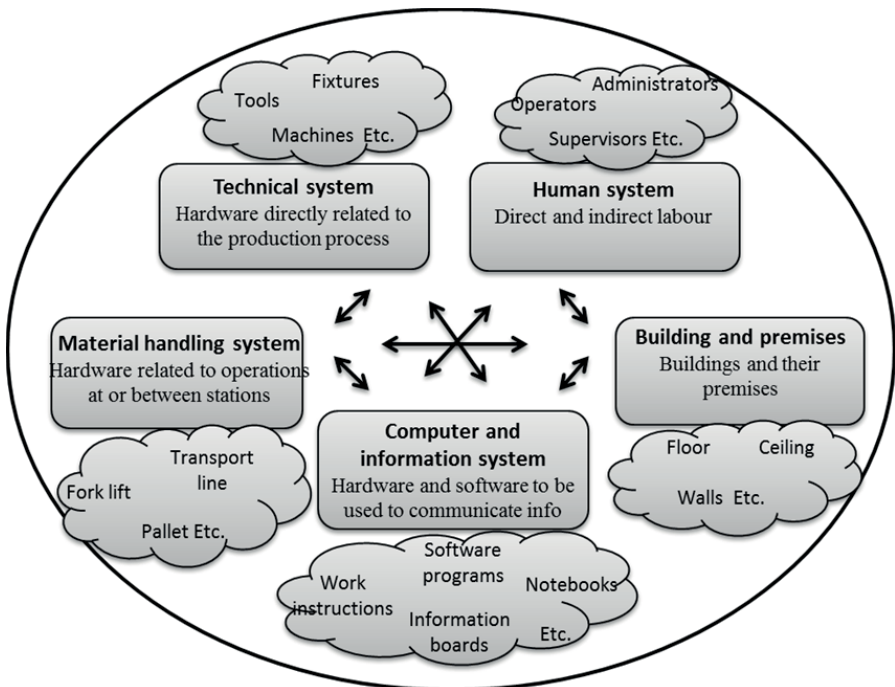


Figure 4. Overview of the constituent parts of the production system.

The core idea of the system approach, as previously described, is holism, i.e. “the theory that certain wholes are to be regarded as greater than the sum of their parts” (The Concise Oxford Dictionary, 1990, p. 562). This signifies that the relations between the parts are important and affect the whole, and contents are thus not solely in the individual parts (Checkland, 1999). To enable the design of production systems, a holistic perspective is needed (Bellgran, 1998; Bennett and Forrester, 1993), and this can be described as

a holistic perspective where all subsystems and elements included as well as the relations between the elements are regarded.

2.2 Reconfigurability

As previously described, reconfigurability is regarded as a capability to achieve flexibility. Reconfigurability could be described as customized flexibility in contrast with general flexibility. The production system should be adapted to the product families to be produced in the system and still be ready to be changed to new product variants or product families (Mehrabi *et al.*, 2000b). A central role of a reconfigurable production system is thus played by its customization (Hu, 2005; Koren, 2007). Consequently, a distinction must be made between a dedicated production system, which is designed for a single product variant, a production system with general flexibility, which is designed for a wide variety of products, and a reconfigurable production system, which is designed for a product family but ready to be reconfigured when a need for change turns up (Koren, 2007).

Even if the idea of reconfigurability as customized flexibility is agreed on among the scholars in the RMS field, the term reconfigurability has been defined in different ways. Reconfigurability defined as “the ability to robustly handle long-term changes quickly and at low cost, effecting and transforming the production system” (Jackson, 2000, p. 96) points out “changes” in the system and makes a distinction between short-term changes when flexibility is needed and long-term changes when the system as such must be deconstructed and reconstructed in accordance with contextual changes. Reconfigurability in terms of “the ability of rearranging and/or changing manufacturing elements aimed at adjusting to environmental and technological changes” (Abdi and Labib, 2003 p. 2274) emphasizes the need to better link market demand to environmental or technological changes and the production system.

What is intended to be rearranged and/or changed within the production system is focused on in a number of definitions. Reconfigurability as “the ability to repeatedly change and rearrange the components of a system in a cost-effective way” (Setchi and Lagos, 2004, p. 529) focuses on the compo-

nents (in this thesis described as elements) in the system, while in the definition by McFarlane and Bussmann (2003, p. 304), “the ability of a function of a manufacturing unit to be simply altered in a timely and cost effective manner”, the functions of the manufacturing units or elements are highlighted. The two definitions above could be combined and include both components and functions when reconfigurability is defined as “the ability to add, remove, and/or rearrange in a timely and cost-effective manner the components and functions of a system, which can result in a desired set of alternative configurations” (Farid, 2008, p. 1276). An even more specified definition is given by Heisel and Meizner (2007, p. 48), who state that “reconfigurations are later conversions and modifications of structure, functionality, capacity and technology by replacing supplementing and removing discrete, autonomously operating components”.

The definitions described in this section are not contradictory but rather focusing on different aspects. In this thesis reconfigurability is seen as a way to handle long-term changes and to deal with external influences and changes as well as internal changes, in accordance with Abdi and Labib (2003) and Jackson (2000). Furthermore, reconfigurability involves the ability to change and/or rearrange production system elements according to the holistic perspective of the production system described in the previous section. All elements, and thereby their function, must be prepared for reconfiguration. According to this, in this thesis,

reconfigurability is defined as the ability to add, remove, and/or rearrange the production system elements in a timely and cost-effective manner which can result in a desired set of alternative configurations.

Depending on what elements will be changed and/or rearranged, the nature of the reconfiguration differs. Reconfiguration can be divided into physical, logical, and human reconfiguration (Deif and ElMaraghy, 2007). Physical reconfiguration includes reconfiguration in for instance machines, workstations, machine tools, or material handling equipment. (ElMaraghy, 2007). Logical reconfiguration includes, among other things, re-programming of machines, re-planning, re-scheduling, and re-routing (Deif and ElMaraghy, 2007). Human configuration implies for example reallocating human resources or reconfiguring the job task. Consequently, depending on the character of the elements, physical, logical, and human reconfiguration must be considered to achieve reconfigurability, *Figure 5*.

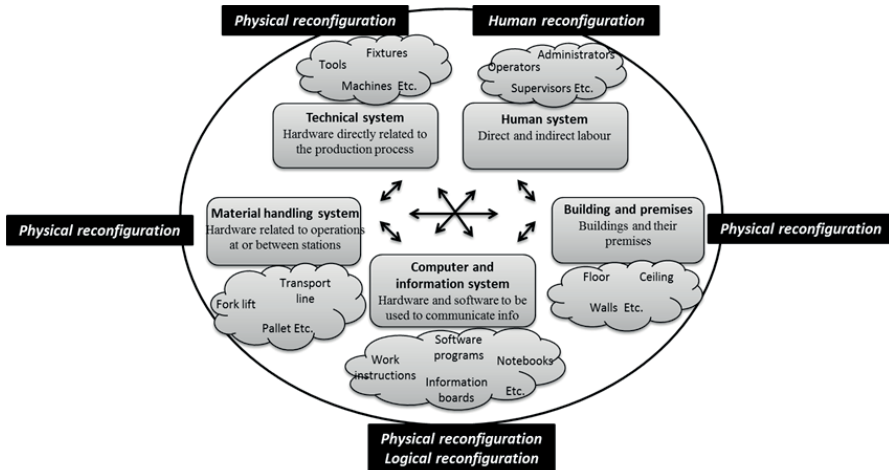


Figure 5. Physical, logical, and human reconfiguration.

2.2.1 The RMS concept

A Reconfigurable Manufacturing System, RMS, is a system “designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements” (Koren *et al.*, 1999, p. 529). The RMS is a system installed with precisely the production capacity and functionality needed and may be upgraded in the future, exactly when needed (Koren *et al.*, 1999).

This concept proposes a fully reconfigurable production system in both hardware and software. The RMS concept is mostly focused on a cell level and is also described as a machining system that can be created by incorporating basic process modules, both hardware and software, that can be rearranged or replaced quickly and reliably (Mehrabi *et al.*, 2000b).

The RMS is a highly automated system, which is motivated by the complexity involved when the system is scaled down or when the product variety gets extensive. In such cases the system complexity could cause human errors and affect system performance and therefore the level of automation must be kept high (Koren and Shpitalni, 2010). In addition, a fully automated system, according to Bi *et al.* (2007), reduces cost due to the reduction of labour, achieves a high and constant quality, meets technology changes since operation of components is too complicated or difficult for the capability of human beings, overcomes labour shortages, and protects workers from poor working conditions.

The RMS concept could be summarized into three principles (Koren, 2010).

1. RMS contains adjustable production resources to respond to unpredictable market changes and system-inherent occurrences, i.e.
 - a. RMS capacity can be rapidly scalable
 - b. RMS functionality can be rapidly adaptable to new products
 - c. RMS inbuilt adjustment capabilities enable rapid response to unexpected equipment failures
2. RMS is designed around a part or a product family with just enough customized flexibility to produce the family
3. The core characteristics (modularity, integrability, customization, scalability, convertibility, diagnosability) should be embedded in the whole production system.

Koren and Shpitalni (2010, p. 238) state that “the more these principles are applicable to a given manufacturing [production] system, the more reconfigurable that system is”.

What is not included in the RMS concepts to any great extent is the link to the production system design literature and how to involve the knowledge of reconfigurability and modularity in a design process. There is a strong focus on methods and techniques on how to achieve reconfigurability, but a comprehensive picture of reconfigurability is seldom given. A common view is not given of what characterizes reconfigurability and a justification for including certain characteristics and not others is seldom given. It is thus not clear when to choose a reconfigurable production system and when to choose different reconfigurability characteristics.

In the following section, the need for reconfigurability and what characterizes reconfigurability will be discussed as well as how the reconfigurability characteristics are linked to each other.

2.2.2 Change drivers

In order to handle a turbulent market, manufacturing companies must understand the main influences that require action. Necessary and appropriate action at the right time is required. Manufacturing companies must be able to handle issues such as an increasing globalization of markets and networked production, increasing individualization of customer demands, fluctuating consumption, permanent pressure on product cost and quality, life-cycle-oriented products and services, increasing demands on the workforce, and greater delivery reliability (Wiendahl and Heger, 2004). Preparedness is required at all production levels and, consequently, the production system must be prepared for reconfiguration according to this market and order situation (Ateekh-Ur-Rehman and Subash Babu, 2012; Löffler *et al.*, 2011b). How and to what extent the manufacturing company is affected by the influences of various issues differs however. To decide how to be prepared for change and to secure the right extent of reconfigurability for each specific

production system is vital (ElMaraghy and Wiendahl, 2009). Main determinants of changeability that are important to identify are proposed by Wiendahl *et al.* (2007) and ElMaraghy and Wiendahl (2009), see Table 1. The determinants are given a general description and are linked to the production system level and reconfigurability.

Table 1. *Determinants of changeability*

Determinants	General description	Production system level
Change drivers	Influences that claim a change	See Table 2
Change object	The object that is affected by the change driver	The production system and its parts and/or the product
Change enablers	The enablers that should characterize the change object in order to handle the change drivers.	Reconfigurability characteristics, see Section 2.2.3
Change extension	To what extent the change object must be characterized by the change enablers	E.g. system or element level
Change strategy	How to deal with the change drivers including change enablers and change extensions	Need for and extent of reconfigurability

It is important to clarify the change drivers and the need for developing a reconfigurable production system (Bi *et al.*, 2007). A change driver is described in a similar way among scholars, i.e. as “the changeability requirement of a production system” (Schuh *et al.*, 2005, p. 442) or “the factors involved whose changes impact the structure of the manufacturing system [production system]” (Park and Choi, 2008, p. 8).

*A **change driver** triggers changes in the structure of the production system. Based on the change driver the need and extent of reconfigurability can be decided.*

What must be kept in mind is that change drivers are characteristic of a specific production system and can hence hardly be generalized. At a high level of aggregation, it is possible to distinguish different types of change drivers (Schuh *et al.*, 2005). The most often mentioned change drivers are uncertainties in production volumes, product design, and process technology (e.g. Park and Choi, 2008; Schuh *et al.*, 2005). ElMaraghy and Wiendahl (2009) also add a new company strategy as a type of change driver including for example a decision to enter a new market. According to the categoriza-

tion of product, volume, technology, and strategy-related change drivers, various change drivers are described and exemplified in Table 2.

Table 2. *Types of change drivers*

Type	Description	Example
Product-related ^{1,2,3,4,5}	Variations in basic models as well as variants within the models ⁴	Geometry changes of certain parts ¹ Dimension, shape, surface form ² New technology solutions in the product ³
Volume-related ^{1,3,4,5}	Volume fluctuations over time ⁴	-
Technology-related ^{1,2,3,6}	Changes in production technology ¹	New joining technique ¹ Machine breakdowns, tool failures ⁶
Strategy-related ^{4,5}	A new company strategy ⁴	A decision to enter a new market ⁴

1: (Schuh *et al.*, 2005) 2: (Park and Choi, 2008) 3: (Löffler *et al.*, 2011b) 4: (ElMaraghy and Wiendahl, 2009) 5: (Wiendahl *et al.*, 2007), 6: (Brucoleri *et al.*, 2003)

The character of the change drivers varies and could be categorized into internal and external change drivers. External change drivers cannot be influenced by the manufacturing company, whereas internal drivers are designed by the manufacturing company itself, driven by the influences of the environment (Löffler *et al.*, 2011a; Löffler *et al.*, 2011b; Park and Choi, 2008). Strategy-related change drivers could for instance be described as internal drivers while volume-related change drivers could be described as external.

The change drivers can be explained along the diverging life cycles of the product and the production system. At the beginning of the life cycle, future market demands and variant mix are often uncertain. Hence a production system needs to be ready to adapt to both changing capacity requests and variant-specific production requirements. After start of production, design improvements often occur and new product variants are introduced. This causes changes to for instance equipment or technology at certain parts of the production system. Finally, the life cycle of the production equipment exceeds the product life cycle. Therefore, reuse of the production resources for the next product generation is often an economic necessity (Schuh *et al.*, 2005).

The change drivers to large extent affect how the reconfigurable production system should be designed. In conventional production systems the production system must be replaced more frequently based on the current change drivers. Instead of starting from scratch every time a new production

system is designed, the designers can use a modular approach to quickly reconfigure the existing system by replacing or modifying a few modules in order to deal with the change drivers (Park and Choi, 2008). In order to reduce changes in the entire production system design, production system elements that tend to change during the production system life cycle need to be combined into modules according to the identified change drivers and the need for and extent of reconfigurability (Schuh *et al.*, 2005). Therefore, production system elements that tend to change at the same time for the same reasons are potentially integrated into one module while production system elements that do not change or change for different reasons are separated (Schuh *et al.*, 2005). Therefore, the initial identification of change drivers is vital.

If the whole production system is designed for reconfigurability, all elements included are ready for reconfiguration. This implies that with a reconfigurable production system ideally only the elements that are affected by the change will be changed and that an individual change driver ideally should only affect one production element (Schuh *et al.*, 2003), *Figure 6*.

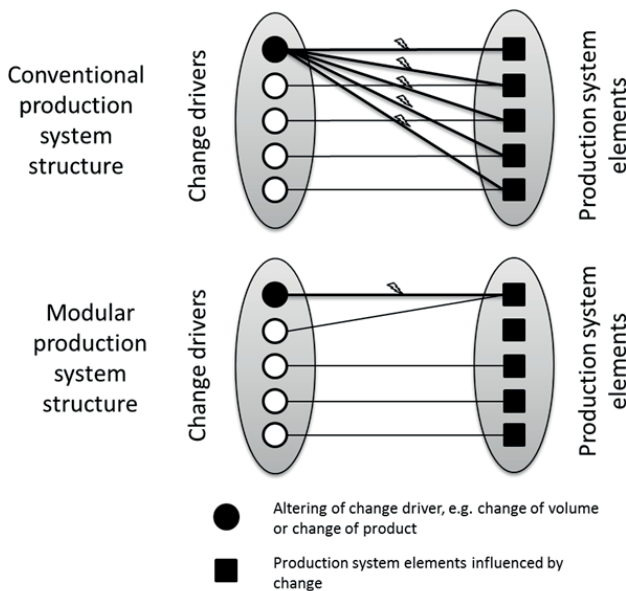


Figure 6. Change drivers affecting production system elements (Schuh *et al.*, 2003).

To summarize, the need for and extent of reconfigurability depends on the change drivers. By first identifying the change drivers, the need for reconfigurability could be specified, *Figure 7*. A maximum degree of reconfigurability is resource consuming and therefore economically suboptimal (Bussmann and McFarlane, 1999; Schuh *et al.*, 2005; Urbani and Negri, 2006).

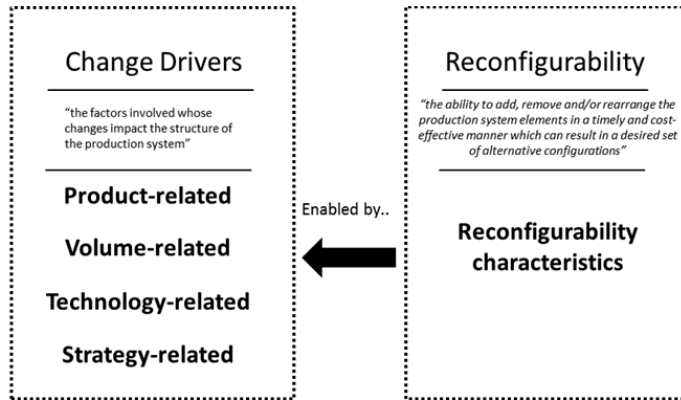


Figure 7. Enabling change through reconfigurability.

It is therefore crucial to specify the need and extent of reconfigurability, and thus reconfigurability will be further described in the following section.

2.2.3 Reconfigurability characteristics

Reconfigurability can be described by a number of capabilities, defined as reconfigurable manufacturing system (RMS) characteristics (Koren *et al.*, 1999), RMS key features (Setchi and Lagos, 2004), reconfigurability characteristics (Koren and Shpitalni, 2010), or reconfigurability enabler (ElMaraghy and Wiendahl, 2009). In this thesis the term reconfigurability characteristics is used.

Reconfigurability characteristics are the capabilities of the production system to enable reconfigurability.

A common view is not given in the literature of reconfigurability characteristics. The incentive to include certain characteristics and not others is seldom given. A summary of the characteristics referred to by scholars is described in Paper III.

In summary, reconfigurability characteristics are defined as automatibility, modularity, integrability, convertibility, diagnosability, scalability, and mobility, see *Figure 8*. In addition, customization is also defined as a reconfigurability characteristic in literature. As previously mentioned, customization plays a crucial role for reconfigurability since it implies that the capability and flexibility of the production system are designed according to products to be produced in the system (Hu, 2005; Koren, 2007). In this thesis customization is therefore not seen as a reconfigurability characteristic but rather as a basis for reconfigurability that distinguishes reconfigurability as customized flexibility from general flexibility.

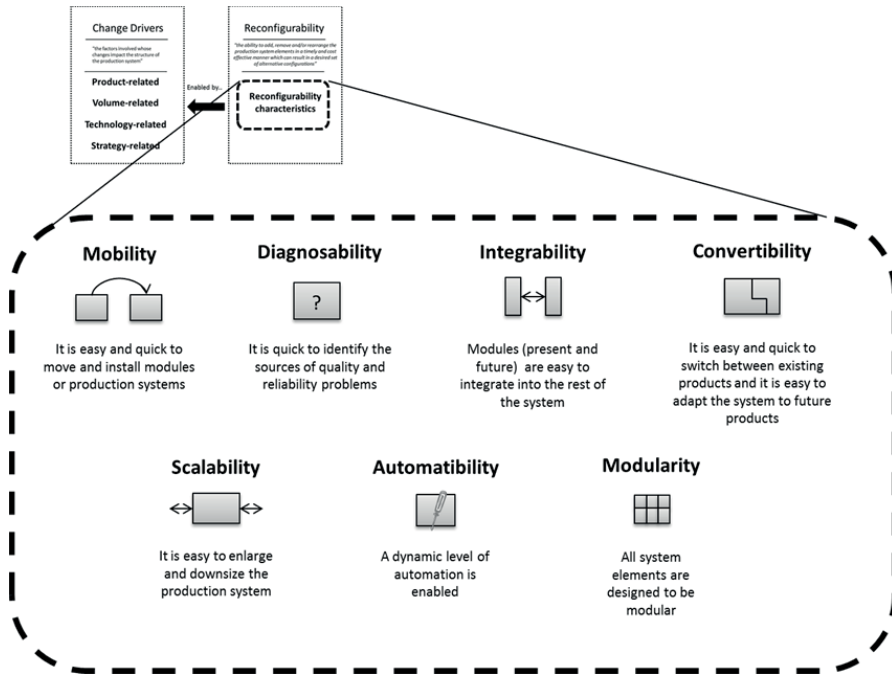


Figure 8. Overview of reconfigurability characteristics.

In the following section the reconfigurability characteristics are briefly described in order to give a comprehensive view of the concept of reconfigurability.

Automatability

One way to enable reconfigurability is to have the ability to change the degree of automation (ElMaraghy and Wiendahl, 2009). Automatability, which has been described as a reconfigurability characteristic, mainly concerning assembly systems, implies “the ability to upgrade and downgrade the degree of automation” (ElMaraghy and Wiendahl, 2009, p. 17). This could be exemplified by changing a manual workstation into a robot cell in order to handle volume increase.

Three basic types of assembly systems concerning automation are (1) manual assembly, (2) assembly systems that include both human operators and automated mechanism and robots, and (3) fully automated assembly systems (Koren and Shpitalni, 2010). A more detailed spectrum of levels of automation is described in the field of dynamic levels of automation, see e.g. Fasth (2012) and Lindström (2008), who make a distinction between mechanical and cognitive levels of automation and thus emphasize that also for instance information handling involves a choice of level of automation.

The question of what level of automation is needed to enable a reconfigurable production system as well as whether a dynamic level of automation is needed, differs among scholars. In the RMS concept a fully automated systems is advocated due to the complexity involved when the system becomes scaled down or when the product variety becomes high (Koren and Shpitalni, 2010). However, in many situations manual assembly systems are the most reconfigurable due to the human capacity to convert and easily adapt to new tasks (Koren and Shpitalni, 2010), and human operators are possibly the most flexible element of a production system (ElMaraghy, 2005). Therefore, reconfigurability is enabled by choosing an optimum level of automation for each situation as well as having the ability to change the level of automation.

Diagnosability

To enable reconfigurability, detecting quality and reliability problems is crucial. In reconfigurable production systems the design is modified more frequently, the ramp-up phases are more frequent and, consequently, diagnosability is important and increases reconfiguration time and effort (Koren *et al.*, 1999).

Diagnosability has been defined in different ways, such as “the ability to automatically read the current state of a system to detect and diagnose the root cause of output product defects, and quickly correct operational defects” (Koren and Shpitalni, 2010, p. 3) or more generally “identify quickly the sources of quality and reliability problems that occur in large systems” (Mehrabi *et al.*, 2000b, p. 407). In this thesis diagnosability is neither delimited to level of automation or to the size of the production system but implies that “it is quick to identify the sources of quality and reliability problems” (ElMaraghy, 2005, p. 265).

Diagnosability involves detecting machine failures and also identifying the causes of unacceptable part quality (Koren, 2007). Achieving diagnosability requires quality control and reliability tools for ramp up (Koren *et al.*, 1999). In fully automated production systems this could imply reconfigurable inspection machines (Koren and Shpitalni, 2010).

Modularity

Modularity is the most apparent of the reconfigurability characteristics (Mehrabi *et al.*, 2000b) and is often described as the key reconfigurability characteristic (e.g. Urbani and Negri, 2006). Modularity means that production system elements are designed to be modular (Bi *et al.*, 2008; Koren *et al.*, 1999), which indicates “a high degree of independence among separate production system elements, excellent general usability and seamless interfacing between the elements” (Tsukune *et al.*, 1993, p. 163). When needed, the modules can be replaced or upgraded instead of maintaining and updat-

ing whole subsystems, and therefore the life cycle cost is kept down (Bi *et al.*, 2008; Heilala *et al.*, 2006; Koren, 2007).

The principle of modularity ensures that only a minimum part of a production system is affected by a change driver and a change could be carried out easily by only changing the affected modules (Schuh *et al.*, 2005). Rapid reconfiguration is enabled when the modification of the system in each reconfiguration is limited. The modules or the elements could work individually through modularity (Tsukune *et al.*, 1993), which facilitates reconfigurability. Increasing modularity thus reduces reconfiguration time and effort (Koren *et al.*, 1999).

Practically, modularity is achieved by e.g. modular interfaces (information, power, mechanical), modular machine tools, plug-and-produce modules and open architecture systems (Koren *et al.*, 1999; Mehrabi *et al.*, 2002).

Convertibility

The ability to quickly change the functionality of the production system to new product types is crucial for reconfigurability. Convertibility is the ability to easily transform the functionality of the existing production system and its included subsystems and elements to meet new production requirements (Koren, 2010). Convertibility is defined as “the capability of a system to rapidly adjust production functionality, or change from one product to another” (Maier-Speredelozzi *et al.*, 2003, p. 367). Convertibility thus expresses the mix flexibility (Koren, 2010), which in turn depends on machine flexibility (Groover, 2001).

Convertibility could be described at a system level as well as a machine level (Maier-Speredelozzi *et al.*, 2003). System convertibility implies how the machines, workstations, and material handling devices are arranged. An example of system convertibility is given in *Figure 9* where the product in a product flow (a) only has one part-flow path through the system while in (b) it has two. If a new product is introduced in (a), the entire line must be shut down, changed over and restarted, while in (b) only 50 % of the machines have to be shut down and reconfigured (Maier-Speredelozzi *et al.*, 2003).

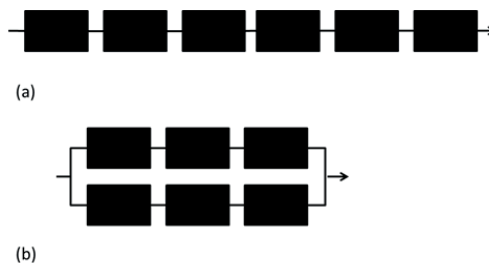


Figure 9. Exemplifying system convertibility.

System convertibility, however, does not only depend on the chosen configuration, but also on machine convertibility (Maier-Speredelozzi *et al.*, 2003). If the machines are equipped with e.g. an automatic tool changer or multihead spindle, machine features increasing machine convertibility are easily reprogrammed with flexible software, modular with flexible hardware components, equipped with flexible fixturing capacity, and equipped with a large capacity tool magazine (Maier-Speredelozzi *et al.*, 2003). Machine convertibility could also be achieved by combining the lean tool Single Minute Exchange of Dies (SMED) with reconfigurability (Deif and ElMaraghy, 2006). Both system and machine convertibility is also attained through training of operators and education of engineers (Mehrabi *et al.*, 2002).

Scalability

If the investment in additional capacity can be suspended until it is really necessary, then this will reduce cost and risk. Scalability means that the production system is scalable in terms of product volume (Koren, 2010) and involves both capacity expansion and reduction (Deif and ElMaraghy, 2007). Scalability characterizes the production system to handle volume variation and volume fluctuations (Bi *et al.*, 2008) and denotes volume flexibility (Koren, 2010).

Scalability implies reconfiguring the production system according to the volume changes in the production system life cycle. When production demand is low, a system can be designed to have fewer stages with highly functional machine tools (e.g. Spicer and Carlo, 2007; Spicer *et al.*, 2002). When the volumes increase it is possible to design a system to have more stages by distributing the tasks thinly across stages (Son *et al.*, 2001). An alternative to increasing the stages is station duplication, where multiple stations in a stage perform identical tasks. In more manual production systems, scalability could be achieved by either adding more resources or extending the working time (Bussmann and McFarlane, 1999).

A distinction could be made between physical and logical scalability. Physical scalability is achieved by a modular structure of the system elements (Deif and ElMaraghy, 2007). Heisel and Meizner (2007) suggest a concept of universal machine modules suited for several customers and therefore scalability could be achieved by selling used models to another customer or leasing modules. Logical scalability implies modern open architecture control techniques (Deif and ElMaraghy, 2007).

The line balancing problem is central for scalable production systems, i.e. the process of allocating tasks to stations in a way that all stations have the same amount of work assigned to them (Thomopoulos, 1967), and it is hard to get a conventional system scalable due to the fact that such systems are optimized for a fixed capacity (Son *et al.*, 2001).

Integrability

A modular production system structure requires a high level of integrability, i.e. “that the system and its components [elements] are designed for both ready integration and future introduction of new technology” (Mehrabi *et al.*, 2000b, p. 407).

Integrability reduces reconfigurability time and effort and implies that machine and control modules are designed with interfaces for integration (Koren *et al.*, 1999).

Integrability refers to both the system level and the machine level. At the system level the machines or workstations have standardized interfaces in terms of mechanics, information, and control to be integrated via the material transport system (Koren, 2010). At a machine level modules or part modules must be easily integrated with each other (Abele and Wörn, 2009). Integrability hence requires standard interfaces that could be classified into mechanical interfaces and functional interfaces (Abele and Wörn, 2009). The mechanical interfaces include transmit forces and torques and perform locking and alignment functions. Functional interfaces transmit data, energy, and auxiliary material.

Mobility

Mobility is discussed in the literature as a reconfigurability characteristic in terms of easiness of moving around and relocating elements and subsystems (Lee, 1997) or movement of manufacturing equipment (ElMaraghy and Wiendahl, 2009; Nyhuis *et al.*, 2006). Mobility could be achieved by placing machines on rollers (ElMaraghy and Wiendahl, 2009; Nyhuis *et al.*, 2006) or by designing machine tools and other production machines with a three-point base that allows them to be readily lifted and moved by a crane or fork-lift truck (Groover, 2001).

2.2.4 Reconfigurability categorization

Reconfigurability is a wide term based on several reconfigurability characteristics giving opportunities to handle the change drivers. However, the nature of the reconfigurability characteristics differs, and in order to bring structure among them and to bring order in what reconfigurability characteristics directly lead to a modification in production capacity or functionality, they could be divided into categories.

The relationship between reconfigurability characteristics and sufficient conditions to achieve reconfigurability has been described in three statements (Koren, 2007):

- I A system that possesses customization and scalability is reconfigurable.

- II A system that possesses customization and convertibility is reconfigurable.
- III A production system that possesses the characteristics of modularity and integrability has the likelihood of being reconfigurable.

This indicates that some reconfigurability characteristics are more critical than others and always imply reconfigurability, i.e. scalability and convertibility. Other reconfigurability characteristics might lead to reconfigurability but it is not sure that the production system is reconfigurable because it possesses these characteristics, i.e. modularity and integrability.

Accordingly, if a reconfigurability characteristic leads to a capacity or functionality change, it could be categorized as an essential reconfiguration characteristic (Koren, 2007; Wiendahl *et al.*, 2007) or critical reconfigurability characteristic (Koren and Shpitalni, 2010). If it is neither, the characteristic could be categorized as a supporting reconfigurability characteristic (Koren, 2007). A supporting characteristic means that it reduces system reconfiguration time and ramp-up time but does not necessarily lead to a modification of functionality or capacity.

In this thesis reconfigurability is categorized according to these two categories:

*A **critical reconfigurability characteristic** leads to a capacity or functionality change of the production system and thus reconfigurability.*

*A **supporting reconfigurability characteristic** reduces system reconfiguration time but does not necessarily lead to a modification of functionality or capacity of the production system and therefore not inevitably reconfigurability.*

The critical reconfigurability characteristics comprise convertibility and scalability, while the supporting reconfigurability characteristics comprise modularity, integrability, and diagnosability (Koren, 2007; Koren and Shpitalni, 2010; Wiendahl *et al.*, 2007).

This categorization, however, does not comprise the reconfigurability characteristics used for a reconfigurable assembly system (Wiendahl *et al.*, 2007), which are comprised as reconfigurability characteristics in this thesis, i.e. mobility and automatibility.

The categorization of critical and supporting characteristics distinguishes the characteristics that result, or do not result, in a change of capacity or functionality. The critical characteristics are the characteristics that lead to a capacity or functionality change and are thus linked to the change drivers.

Based on the categorization in *Figure 8*, the characteristics can be further specified to include the relationship between the characteristics, see *Figure 10*.

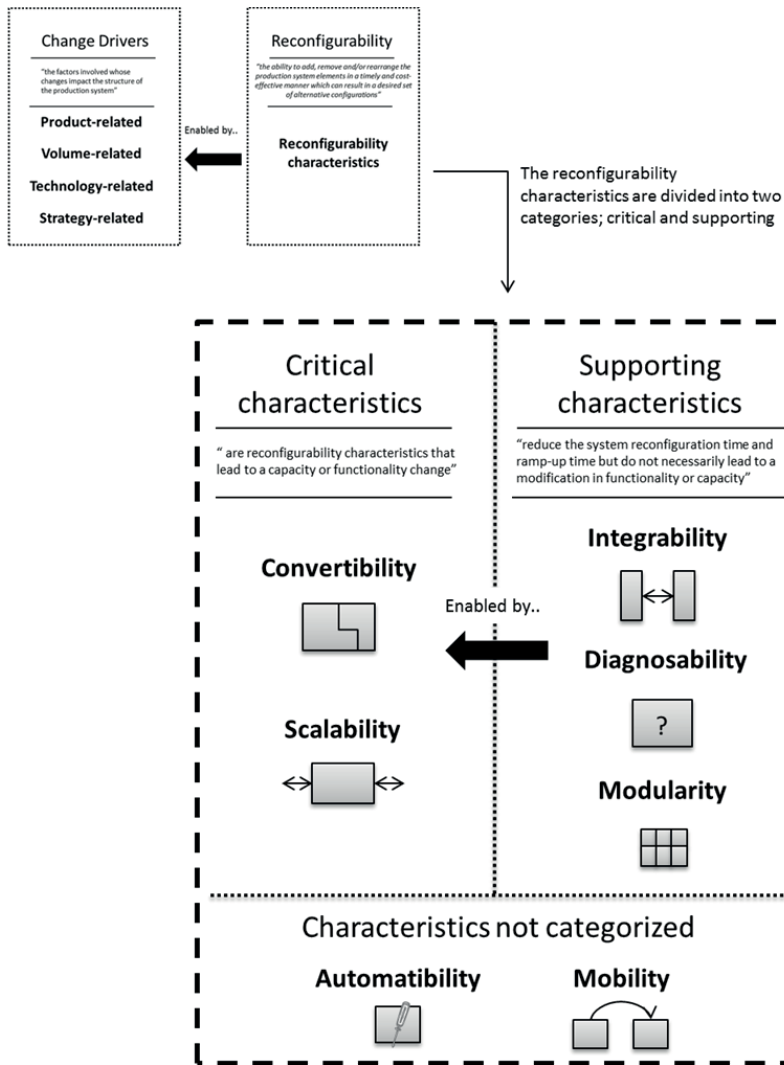


Figure 10. Link between change drivers, critical characteristics, and supporting characteristics

2.3 The production system design process

To design a production system implies generating, evaluating, and proposing a production system. This could be compared to the production system development, which also involves the realization of the production system (Bellgran, 1998).

What was stated already in the early 1990s is that production systems are getting more and more extensive and complex and have an integrative nature

of technology (Bennett and Forrester, 1993). Therefore, it is hard for one system designer to comprehend all details in relation to the overall system (Bennett and Forrester, 1993). To successfully design production systems a structured design process is needed (Bellgran and Säfsten, 2010). In addition, the increasing need for change caused by e.g. more frequent product introductions calls for shorter lead times in the design process as well as greater flexibility, which motivates a structured process even more (Bennett and Forrester, 1993).

In the literature, the production system design process looks similar and originates from product design literature (e.g. Roozenburg and Eekels, 1995; Ulrich and Eppinger, 2003). The term *process* could be defined as “a sequence of interdependent and linked procedures which, at every stage, consume one or more resources (employee time, energy, machines, money) to convert inputs (data, material, parts, etc.) into outputs. These outputs then serve as inputs for the next stage until a known goal or end result is reached” (Business Dictionary, 2012). A process is hence the comprehensive approach when all stages and activities when designing production systems are described. A similar word could be *method*, which could be described as “a prescribed approach which offers the user a guide and the necessary means to implement a new system” (Bennett and Forrester, 1993, p 72).

A design process should tell what should be done and when, what techniques and tools will be needed at each stage, what information needs to be collected, and what the output or result of each stage would be (Love, 1996).

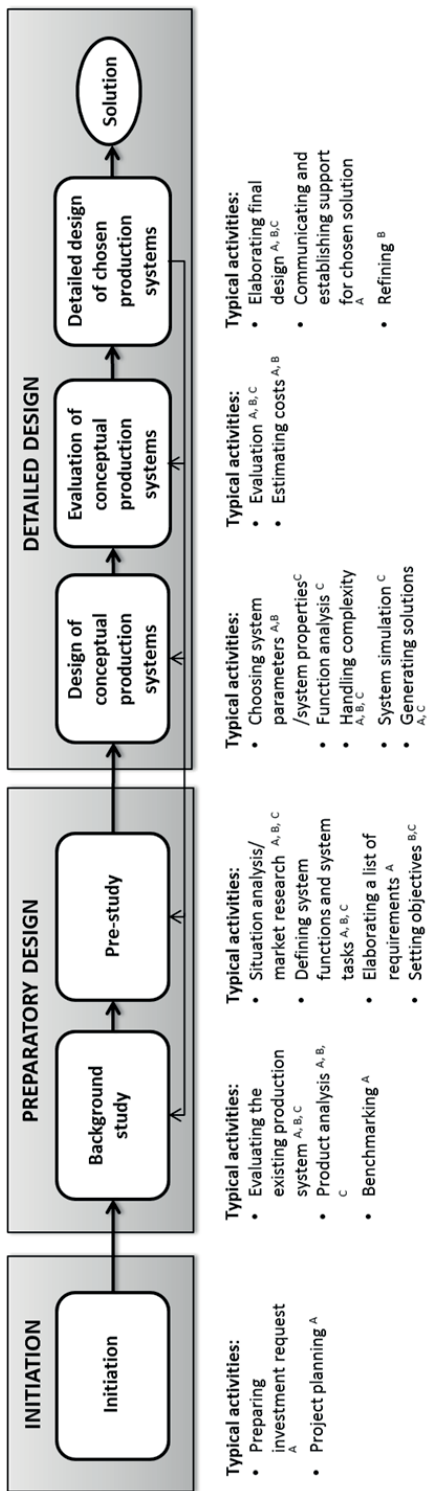
Important features of an ideal production system design process are, among other things, simple to be widely used by engineers, efficient with minimum trial-and-error actions, versatile to be applicable in different situations, and prescriptive instead of descriptive to recommend the solutions (Houshmand and Jamshidnezhad, 2006).

Even if the area of production system design is getting more and more attention in the academic field, there is still no consensus on the approaches to use in industry. In the literature, a limited number of comprehensive production system design processes have been presented that implement some of these features, (e.g. Bellgran and Säfsten, 2010; Bennett and Forrester, 1993; Wu, 1994).

Typical activities that are carried out when designing a production system are summarized in *Figure 11*. The process includes iterations according to the process described by Wu (1994). In a production system design process the problem is normally defined in an initial stage, and the project is initiated and defined in terms of e.g. project leader, budget, and time plan. Thereafter, an analysis of the background including present as well as future production systems and products including market research and environmental requirements is made. Based on this, objectives for the production system are formulated. The detailed design subsequently includes first designing conceptual production system alternatives. The alternatives are thereafter evaluated in

order to choose one final solution. The chosen production system is finally designed in detail.

A study evaluating the usability of the structured production system design process proposed by Bellgran and Säfsten (2010) showed that the usage leads to increased learnability, efficiency, effectiveness, and satisfaction (Arnesson and Bengtsson, 2012). It was shown that this process contributed most in the early phases of the production system design process by putting emphasis on the planning and providing a structure to follow. Even if this was a study concerning one specific model and one company it strengthens the need for structured production system design processes.



A: Bellgran and Säfsten (2010), B: Wu (1994),
 C: Rampersad (1994)

Figure 11. Typical activities carried out when designing the production system, revised from Bruch (2012)

2.3.1 Holistic view in the production system design process

The design of a system is a progression from a defined need to an entity that will perform a useful function in a satisfying manner. The whole system must be addressed with all its elements from a life cycle perspective (Blanchard and Fabrycky, 1998). Therefore it is vital to have a clear view of the production system, its subsystems, and its elements as well as its capabilities. The production system should be designed according to its technical and physical characteristics, its human resource requirements, and organization of work (Bennett, 1986), which is also emphasized by Bellgran (1998).

The system complexity is often highlighted and a holistic perspective is advocated, but support for this in the design process is seldom given in the literature. The thought that a holistic view is needed when designing production systems is however accepted (Bellgran, 1998). On a general level an approach for a holistic design of production systems is to identify all subsystems before entering the stage of defining elements (Blanchard and Fabrycky, 1998). Attention is first directed to the system as a black box that interacts with its environment. Thereafter, attention is focused on how the subsystems (within the black box) should be combined to achieve the system objective. The lowest level of concern is then the individual elements within the subsystems. This could be compared to when one subsystem is focused on and described in great detail before the other subsystems are considered, which leads to suboptimization and increased cost.

However, the approaches presented in the literature to a different extent support a holistic view. The features are implemented to a different extent in the approaches, and when regarding the holistic view there are approaches focusing on single subsystems or on a general level and not down on an element level. Table 2 summarizes the literature in the production system design field based on the overview of the constituent parts of the production system, *Figure 4*. A description is given of what subsystems are considered and to what extent they are focused on. A holistic perspective is taken when all subsystems are considered.

Table 3. Analysis of the holistic perspective in production system design literature

Reference	Human system	Computer & info system	Technical system	Material handling system	Buildings & premises
Almström (2005)	■	■	■	■	■
Bellgran (1998)	■	■	■	■	■
Bellgran and Säfsten (2010)	■	■	■	■	■
Bennett and Forrester (1993)	■	■	■	■	■
Bi <i>et al.</i> (2008)		■	■	■	
Bonney <i>et al.</i> (2000)	■	■	■	■	
Bröte (2002)	■	■	■	■	■
Chryssolouris (2006)	■	■	■	■	■
Cochran <i>et al.</i> (2002)	■	■	■	■	
Duda (2000)	■	■	■	■	
Hibino <i>et al.</i> (1999)		■	■	■	
Jackson (2000)	■	■	■	■	
Kulak <i>et al.</i> (2005)	■	■	■	■	
Love (1996)	■	■	■	■	■
Matt (2008)	■	■	■	■	
Mehrabi <i>et al.</i> (2000b)		■	■	■	
Nof <i>et al.</i> (1997)	■	■	■	■	
Park and Choi (2008)		■	■	■	
Rampersad (1994)	■	■	■	■	■
Rao and Gu (1997)		■	■	■	
Ruffini (1999)	■	■	■	■	■
Schuh <i>et al.</i> (2005)		■	■	■	
Schuh <i>et al.</i> (2009)		■	■	■	
Suh <i>et al.</i> (1998)	■	■	■	■	
Terkaj <i>et al.</i> (2009)		■	■	■	
Tsukune <i>et al.</i> (1993)		■	■	■	
Ueda (2007)	■	■	■	■	
Van Brussel <i>et al.</i> (1998)	■	■	■	■	
Wu (1994; 2001)	■	■	■	■	■
Yien (1998)	■	■	■	■	

■ Mention
 ■ Exemplify
 ■ Describe in detail

Designing within a life cycle context requires immediate responsiveness to customer needs (Blanchard and Fabrycky, 1998) since the needs may change through the life cycle. A holistic view is therefore crucial to enable reconfigurable production systems. Reconfigurability corresponds to the selection and the composition of elements into modules, according to the specification and requirements of the user (Heisel and Meitzner, 2007). The system complexity related to reconfiguration is often discussed as well as the need for a holistic perspective and the importance of determining all system elements and their interaction and of optimizing the system architecture to gain full potential of the system (Bi *et al.*, 2008). The production system subsystems and their elements must be designed from the start of the production system design process to possess the reconfigurability characteristics needed to fulfil the system objective (Koren *et al.*, 1999; Mehrabi *et al.*, 2000b). The problem is to get an understanding of how the production system design process can capture and support the design of reconfigurable production systems with all production subsystems under consideration. In the following two sections the reconfigurability consideration in the production system design process will be described.

The approaches presented in Table 3 could be divided into two groups, approaches within the general production system design field, thus not specifically focused on reconfigurable production systems, and approaches within the RMS field.

2.3.2 Production system design approaches

Additional production system design processes are accordingly presented in the literature. The prerequisites for considering reconfigurability when designing production systems are however not very well covered in literature. A design process that comprises methods to achieve automated systems in order to gain flexibility is described by Rampersad (1994), who focuses on robotic assembly system design, in which the product, the assembly process, and the assembly system are designed simultaneously.

Another example is a process for market-focused production system design (DRAMA) (Bennett and Forrester, 1993). DRAMA includes guiding principles for needs analysis, and the design of production systems is based on identified needs by a number of feasible design options. The DRAMA process is a guide to arrive at the best configuration or option. In the support for choosing layout, variety and volume flexibility are design criteria, but the ability to reconfigure is not. The ease of reconfiguration is considered in the guidelines concerning transportation (by having manual transportation) and concerning physical integration (by not having an integrated design but a segregated one).

A design process including seven steps for production system design is presented by Rao and Gu (1997). It briefly goes through the design process

from requirements of a production system to implementation and finally reconfiguration. It does not, however, describe how to consider the possibility to achieve a reconfigurable production system in the previous six steps.

A process that does not explicitly concern reconfigurability or its characteristics but takes into account related issues such as how to consider flexibility, redesign of jobs, and change of organizational design in the production system design process is presented by Wu (1994; 2001). A comprehensive and holistic production system design process considering the whole production system life cycle is proposed.

A comprehensive method for assembly system design describing the process from initiation to detailed design is suggested by Bellgran (1998). The levels of automation and modularization are discussed as important aspects, but no support for how to consider that is given. The process is further developed to concern all types of production systems and extended to comprise also realization and start-up (Bellgran and Säfsten, 2010).

Approaches for production system design are also presented by scholars using axiomatic design, which focuses on the generation of requirements and the selection of means for achieving them (Cochran *et al.*, 2002; Duda, 2000; Yien, 1998). These approaches are however often described at a low level of detail focusing on the structure of the system rather than on the design process and do not often involve reconfigurability.

To conclude, there are approaches taking a holistic view on production system design and they often include flexibility. Reconfigurability is fragmentarily included.

2.3.3 Reconfigurable production system design approaches

A general production system design process begins with the recognition and identification of a need or the desire for a new capability (Duda, 2000). Such a capability could be reconfigurability. Analysing the need for reconfigurability and involving it in the production system design process is advocated by Jackson (2000), *Figure 12*. First, the need for reconfigurability should be evaluated, thereafter the needs should be analysed, and then a production system should be suggested in accordance with the needs, and finally alternatives should be generated, evaluated, and implemented.

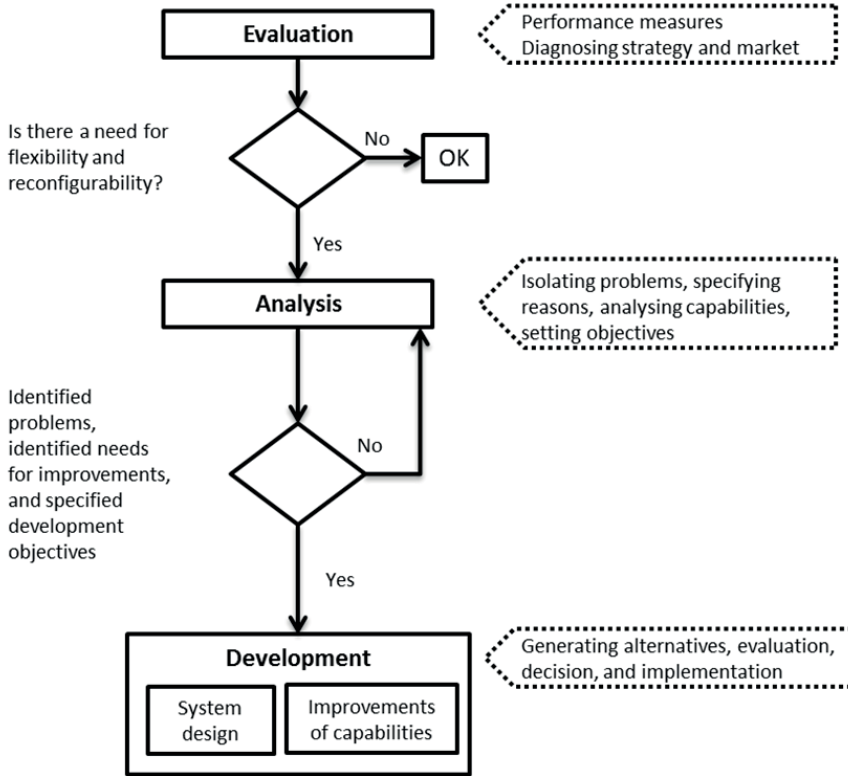


Figure 12. A proposed general model for considering flexibility and reconfigurability when designing production systems (Jackson, 2000).

Although this model highlights the analysis of reconfigurability, it does not go into detail in how to involve the need for reconfigurability in the stages of the production system design process.

With regard to reconfigurability there are several aspects that must be included in the production system design process. Requirements of reconfigurability, usage area, efforts needed, the extent of reconfigurability, and possibilities and limitations of a reconfigurable production system are such aspects (Heisel and Meitzner, 2007). Thereafter the production system must be designed, which according to Heisel and Meizner (2007) includes design of modules, interfaces, machine tools, electrical elements, and test equipment.

The subsystems and their elements must be designed according to the reconfigurability characteristics that are needed (Mehrab *et al.*, 2000b). Mehrabi *et al.* (2000b) propose to first define the part family and then research system-level issues, component-level issues, and ramp-up time reduction issues. System-level issues include, among other things, development of a systematic approach for the reconfigurable production system design at a system level, analysis of the impact of system configuration on reliability, quality, and cost, economic analysis of various system configurations and

their selection, and analysis and design of the process from identifying customer needs through operation selection and system specification.

A similar approach is presented by Deif and ElMaraghy (2006), in which the market demand first is apprehended in order to generate the required capacity and functionality in accordance with customer needs. This will act as input to the second layer, system-level reconfiguration, when different reconfigurations are generated. The most feasible configuration is chosen and taken into the third layer, which deals with physical implementation of the selected configuration (Deif and ElMaraghy, 2006). The model concerns both physical (e.g. add or remove a machine), logical (e.g. reprogram a machine), and human configuration (e.g. reconfigure a job task).

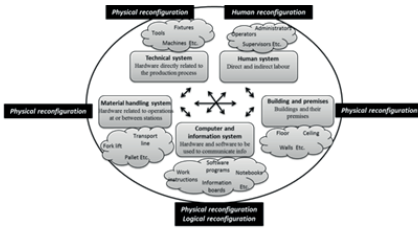
A model to evaluate the production system requirements when designing reconfigurable production systems is proposed by Abdi and Labib (2003; 2004). Five strategic objectives for reconfigurable production system design are defined: responsiveness, product cost, product quality, inventory, and operator skill. A comprehensive reconfigurable production system design process is, however, not described.

Consequently, the reconfigurable production system design literature provides knowledge of how to design for reconfigurability through e.g. analysing the need for reconfigurability and how to prepare subsystems and their elements for reconfigurability. However, it gives limited support in how to bring in the thoughts of reconfigurability into the general production system design process.

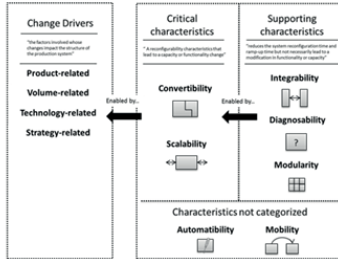
2.4 Overview/summary of the frame of reference

In this chapter an overview of the literature in the areas of production systems, production system design, and reconfigurability has been presented and synthesized in order to give a survey of the reconfigurable production system design field and to create a frame of reference. The need for a holistic perspective when designing reconfigurable production systems was explained. Also, the need for reconfigurability and what characterizes reconfigurability was described. It was identified that there is a lack of literature involving the thoughts of reconfigurability in the production system design process although there is much knowledge in the separate areas.

To design a reconfigurable production system three main parts are emphasized, see *Figure 13*.



A **holistic perspective** is needed to achieve reconfigurable production systems, and both physical, logical, and human reconfiguration must be considered in production system design.



The need for reconfigurability based on identified change drivers must be identified to enable selection of right type and degree of reconfigurability for each specific case of application. Therefore, **knowledge of reconfigurability and its characteristics** and its links to change drivers is required.



A **structured design process involving reconfigurability** in accordance with the identified need is useful to handle the complex activity of designing a reconfigurable production system.

Figure 13. Overview of the frame of reference.

CHAPTER 3 – Research method

This chapter describes how the research presented in this thesis was carried out and why certain research methods were used. First the research approach is described where the research methods are defined followed by a description of the research design. Subsequently, the data collection is presented including an account of the separate case studies that were made. Finally, the validity and reliability related to the research methods are discussed.

3.1 Research approach

Since a holistic view on production systems is taken in this research, it is believed that the design of the production system and the way the production system is defined plays an important role. A holistic view implies that all parts of the production system and the links between the parts should be considered. In production system research it is relevant to consider all parts included and the relation between the parts, since such relations are important and affect the whole (Checkland, 1999).

Depending on maturity and extent of existing knowledge, different approaches might be needed in the knowledge development (Karlsson, 2009). Research should typically explore before being able to describe a field of knowledge and build knowledge of the components before understanding the relations (Karlsson, 2009). Production system design and reconfigurable production systems are separately established literature fields. However, there is limited knowledge in the intersection of the two fields.

Three research questions were formulated in order to reach the specified objective; they built upon each other, which means that the answer to RQ1 (*What are the constituent parts of a production system and how could they be described?*) together with the answer to RQ2 (*What characterizes reconfigurability and a reconfigurable production system?*) formed the basis for RQ3 (*How could reconfigurability in the production system design process be considered?*). Based on the character of the research questions the research methods were chosen (Yin, 2009).

The first research question aimed to describe a production system and its parts and therefore called for a descriptive study, which implied gathering and systematization of data (Wallén, 1996). Since the production system

design field is rather mature, this was thus mainly done by a literature review. A frame of reference was developed that could direct the data collection and a descriptive approach was taken (Scholz and Tietje, 2002) (know-how).

The second research question had an exploratory character and could be answered by several methods such as case study method, survey, or archival analysis (Yin, 2009). An explorative research approach was used to gain insight into the structure of reconfigurable production systems (know-what).

The third research question had an explanatory character and was likely to lead to the use of case studies or experiments (Yin, 2009). At the end, the researcher developed models explaining how elements are related to each other, which enables the researcher to build models and support (Karlsson, 2009) (know-why).

When choosing research method, strengths and weaknesses of the methods were reviewed. In this research contemporary events were studied, i.e. reconfigurability in the production system design process, and the relevant behaviour could not be manipulated. This excluded methods like experiments but instead the case study method was a proper choice (Yin, 2009). The use of the case study method facilitated managing the complexity involved when studying production systems. By using case studies the unit of analysis could be examined in its natural environment, and meaningful and relevant results could be generated from the understanding that was created when the practice was observed (Karlsson, 2009). Therefore, case studies in combination with literature studies were chosen as the most proper research method to use in order to answer the research questions.

The research approach taken depends on the researcher's view of reality and, consequently, also on the researcher's role. In this research study the researcher was involved in production system design projects, however with an explicitly defined role as a researcher, and a distinction was made between the research project and the industrial development project. The level of participation differed in the studies conducted in this research. Wigren and Brundin (2008) describe different levels of interactions depending on what role the researcher adopts in the empirical research process and how the process develops. In this thesis, the researcher had a role as participant observer in some of the studies (Yin, 2009). Then the researcher was not a passive observer but assumed a variety of roles in the situation that was studied and participated in some of the events that were studied. There were both opportunities and critical aspects with regard to participant observations. First, they enabled access to events or groups that otherwise would have been inaccessible to scientific investigations. Another opportunity was the ability to see reality from the viewpoint of someone inside the event, i.e. the industrial development project. The researcher had also the possibility to manipulate minor events, such as calling a meeting (Yin, 2009).

3.2 Literature review

The literature review was divided into three parts, each of which referring to one of the research questions. The three parts were:

1. Specification of the production system (RQ1)
2. Reconfigurability and reconfigurable production systems (RQ2)
3. Reconfigurability in production system design (RQ3)

The first part of the literature review answered the first research question focusing on the specification of production systems; manufacturing system/production system¹ literature was studied. The selection of literature was made on the keywords production system design and manufacturing system design. The literature was mapped in two stages, first a feature map was done (Hart, 2005) answering three questions: (1) *How are the production system and the parts of the production system defined?*, (2) *What parts are included in a production system?*, and (3) *In what detail are the included parts described?* In the second stage the answers were analysed and a compositional characteristic map was set up (Hart, 2005) regarding the questions where the level of detail of the subsystems was described in order to get a holistic view of the production system.

The second part of the literature review, about reconfigurability characteristics, laid the foundation for the second research question and the case studies linked to that question. Literature explicitly considering reconfigurability was chosen, mainly literature in the RMS field. This part was made in two stages, first the literature in the field was studied and characteristics were identified, which resulted in a definition of reconfigurability characteristics. Thereafter the literature was examined once again and three questions were answered concerning each of the characteristics. (1) *How does this characteristic enable or allow reconfigurability?* (2) *Are there other terms similar to this characteristic?* and (3) *How do you achieve this (the characteristic) in practice?* In order to answer the second question a broader literature study was needed and the literature in the field of changeable production systems² was included.

Finally, a literature review was made on reconfiguration in production system design, referring to the third research question. This review laid the foundation for the case studies linked to this question. The review included literature in production system design and manufacturing system design and

¹ Since the terms manufacturing system and production system are defined differently depending on author there is confusion concerning what the authors include in the terms. In this thesis the definition given in Chapter 2 is used and, therefore, irrespective of what term was originally used, this definition is applied in the thesis. However, in a few cases the original definition is kept since the concepts have become established (e.g. RMS, BMS) and explanations given in square brackets.

² The areas FMS, RMS, HMS, BMS, and modular manufacturing were included.

included three questions: (1) *Is reconfigurability considered in the design process and in that case how?*, (2) *At what stage in the process is it considered?*, and (3) *What parts of the production system are considered in these cases when reconfigurability is considered?*

All results were structured and summarized to be used in the case study analysis (Section 3.5).

3.3 Research design

After selecting the case study method the next step was to plan the research in detail. The research design connects the empirical data to the research questions and to the conclusions and is simply a logical plan for getting from the research questions to the conclusions (Yin, 2009). Based on the research questions the number and types of cases were selected, and the units of analysis were specified.

At the outset a number of case studies were specified in order to answer the research questions. When the first two case studies had been carried out, gaps were identified in answering the research questions, and additional case studies were defined to cover those gaps. A strength in case study research is the flexibility to make modifications over time, but the nature of the alterations made must be totally understood. The original theoretical concerns and objectives must be retained while the selection of cases could be changed if the cases do not address the research questions (Yin, 2009).

3.3.1 Case study design

The research started with a multiple-case design including three case studies, which gave a possibility to study reconfigurability in different production systems and compare different cases to get an understanding of what reconfigurability implied in practice.

The next case study that was selected had a single-case design. The strength of single-case studies is that they provide an ability to go into depth and offer possibilities to study something over a period of time (Karlsson, 2009). In this research this gave a deeper understanding of the production system design process as well as how reconfigurability was considered.

At this point it was decided that additional case studies were required in order to answer the research questions. Therefore, a multiple-case study was carried out to study reconfigurability in the production system design process in three cases where a similar production system design model was used.

The total number of case studies is ideally determined when the theoretical dispersion is attained. However, with fewer than four cases it is often hard to generate theory with much complexity, and the empirical basis is

likely to be unconvincing (Eisenhardt, 1989). To get an even broader view of how reconfigurability is considered in the production system design process a final single-case study was conducted.

3.3.2 Real-time or retrospective case studies

A combination of real-time case studies and retrospective case studies was used in this research to enhance its validity (Leonard-Barton, 1990). There are strengths and weaknesses of the two types and therefore a combination was to prefer. In retrospective case studies a main disadvantage is that participants may not recall important events or their recollections might be biased. The interpretation of the events is different from what it would have been at the time (Meredith, 1998; Voss *et al.*, 2002). In real-time case studies this is overcome, but it is often time-consuming since cases run over a longer period of time (Voss *et al.*, 2002). Another risk in real-time studies is that the researcher might lose objectivity and get too involved with the organization, the people, and the process (Leonard-Barton, 1990).

Selection of retrospective case studies could be done in a more controlled manner; it is, for example, possible to select a case that resulted in failure or success (Voss *et al.*, 2002)

3.3.3 Case selections

The selection of cases was done depending on the objective of the case study. All cases were selected for theoretical reasons, not statistical reasons (Eisenhardt, 1989) with the goal to make it possible to extend the emergent theory.

In this thesis two types of cases were studied: (I) those that had an identified need for reconfigurable production systems and aimed to develop such systems, and (II) those that had not explicitly defined a need for reconfigurability, i.e. not consciously designed for reconfigurability.

The sampling criteria for type I was based on an explicit need for reconfigurability. The cases were developed within a research project (the Factory-in-a-Box project) and were selected based on the companies' need for developing and investing in a reconfigurable production system, but also on the researchers' theoretical interest in developing a production system in the production context that the company could offer. It was desirable from the point of view of the research project to have dispersion among the cases in, for example, application area.

The sampling criteria for type II were based on the prerequisites for reconfigurability. Cases in the automotive industry were chosen due to their need for responsiveness in terms of e.g. shrinking product life cycles combined with an increasing number of product variants (Asnafi *et al.*, 2008), which caused a need for reconfigurability. In addition, cases where new pro-

duction systems were designed were chosen since they involved a comprehensive change.

3.3.4 Unit of analysis

In order to answer the research questions by the case study method the cases or the units of analysis must be specified (Yin, 2009).

The first research question (*What are the constituent parts of a production system and how could they be described?*) called for an analysis of the production system. This question was answered by a literature review. The second question (*What characterizes reconfigurability and a reconfigurable production system?*) called for an analysis of reconfigurability in the production system. The third research question (*How could reconfigurability in the production system design process be considered?*) called for an analysis of reconfigurability in the production system design process.

To study the ‘production system design process’ included both the study of process activities and the result of the activities, such as requirement specifications and conceptual solutions. To study ‘reconfigurability’ included studying change drivers, the need for reconfigurability, and reconfigurability characteristics.

Even if the research questions are closely linked to each other and build on each other, all research questions were however not directed at all case studies.

An overview of the research design is presented in Table 4.

Table 4. Overview of the research design

Studies	Included case studies	Real-time or retrospective	Unit of analysis	Embedded unit of analysis	RQ	Paper	Company location	Branch	OEM*/First-tier supplier
Factory-in-a-Box	Demonstrator 1	Real-time	Reconfigurability	-	RQ 2	V	Sweden	Automation technology	OEM
	Demonstrator 2	Real-time	Reconfigurability	-	RQ 2	V	Sweden	Modular facilities	OEM
	Demonstrator 5	Real-time	Reconfigurability	-	RQ 2	V	Sweden	Aircraft and trains	OEM
Max Auto	MaxAuto UK	Real-time	The production system design process	Reconfigurability	RQ 3	I	UK	Automotive industry	First-tier supplier
Dax Vehicles	MaxAuto Germany	Retrospective	The production system design process	Reconfigurability	RQ 3	I	Germany	Automotive industry	First-tier supplier
	MaxAuto Sweden	Retrospective	The production system design process	Reconfigurability	RQ 3	I	Sweden	Automotive industry	First-tier supplier
Dax Vehicles	DaxVehicles	Real-time	The production system design process	Reconfigurability	RQ 2, 3	III, IV	Sweden	Automotive industry	First-tier supplier
VoxVan	VoxVan	Retrospective	The production system design process	Reconfigurability	RQ3	I	Sweden	Automotive industry	OEM

*Original Equipment Manufacturer

3.4 Data collection

In total eight case studies were made in order to answer the research questions. Since the studies had different focus concerning objective and structure, all case studies are presented separately in the following section. First a short summary of the research design in each of the case studies is given and then the data collection is described.

Figure 14 presents an overview of the data collection process in the case studies on a timeline.

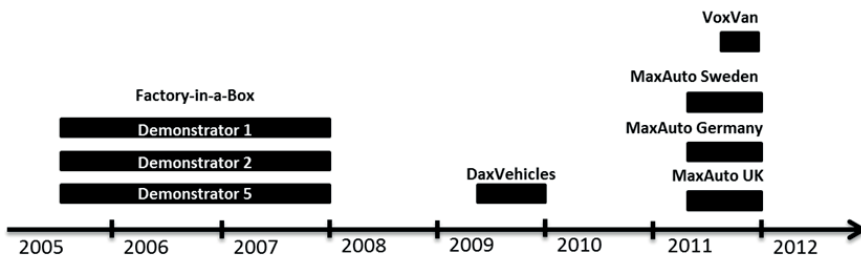


Figure 14. Data collection process.

3.4.1 The Factory-in-a-Box study

The first three case studies were conducted within the research project *Factory-in-a-Box*, which was a joint research project between four universities and eight industrial companies. In the project, three³ production systems (demonstrators) to be characterized by “flexibility, mobility, and speed” were developed in close collaboration between the universities, research institutes, and industrial partners. Flexibility was defined differently in the project compared to this research (see Section 4.1) and could be equated with reconfigurability as it is defined in this thesis.

The Factory-in-a-Box study had a holistic multiple-case design (Yin, 2009) and included three case studies, each representing a demonstrator which in two of the case studies consisted of a realized production system and in the third case study a conceptual production system. The reconfigurability in the demonstrators was studied in all of the three case studies. This included studying the change drivers, the reconfigurability characteristics of the production system, and how the reconfigurability characteristics were realized. The multiple-case design is described in Figure 15.

³ The project originally comprised five demonstrators but only three were accomplished to conceptual design and therefore included in this study.

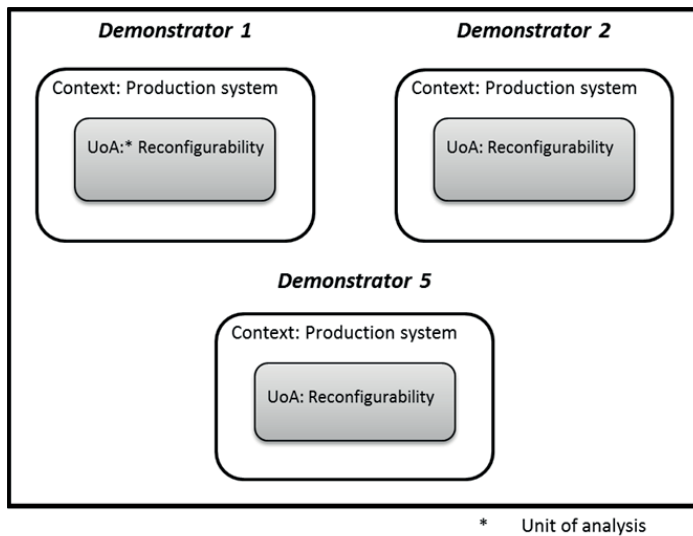


Figure 15. Research design of the Factory-in-a-Box study.

In demonstrators 1 and 2, data were collected by performing direct observations of the production systems (under development). Regular visits were made at the company in order to follow the development and realization.

Unstructured interviews were performed with industrial engineers, production managers, and other manufacturing staff, as well as with researchers working with the design of production systems. Both natural conversations and open-ended interviews were carried out (Gillham, 2000). The interviews were held both at project meetings and during visits at the company where the production system was developed. They were not recorded.

In demonstrator 5, data were collected through participant observations, which meant that the researcher was “in” the setting in an active sense (Gillham, 2000). The researcher spent approximately one day a week to follow the work and participate at project meetings. Project meetings were held once a month, with a project group composed of the operative project leader, the operations manager, the sales manager, the manufacturing engineering manager, and the quality manager. Unstructured interviews were performed with industrial parties. Natural conversations and open-ended interviews (Gillham, 2000) were carried out with industrial engineers, production managers, and other manufacturing staff. The interviews were not recorded. The interviews were carried out at project meetings and at the company where the production system was developed.

Documents such as work instructions and archival records such as bills of materials were also examined in case study demonstrator 5.

In all three demonstrators documents such as pre-study reports, master theses (Bengtsson and Eriksson, 2007; Muriz and Mesinovic, 2006;

Ramström and Gustafsson, 2006; Zaman, 2007), and presentations of the development were studied.

3.4.2 The DaxVehicles study

The DaxVehicles study was carried out from March to December 2009 at a Swedish manufacturing company providing products to the automotive industry, and its Swedish production site.

The empirical data were collected by means of a case study with an embedded design (Yin, 2009), where the consideration of reconfigurability in the production system design process was studied. The study included identifying change drivers, as well as studying how reconfigurability was considered in the phases in the production system design process and the reconfigurability characteristics of the conceptual solution.

A summary of the case study design for the DaxVehicles study is given in *Figure 16*.

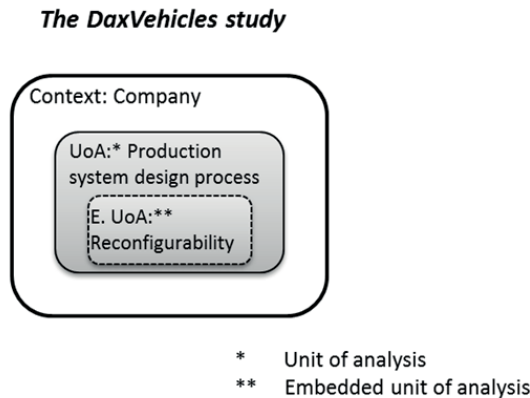


Figure 16. Research design of the DaxVehicles study.

In the case study the production system was designed by a project group consisting of an operative production manager, a consultant production system designer, and a mechanical engineer.

Through the design process, data were gathered differently. In the previous phases data were gathered with the project group through participant observations (Yin, 2009). In the later phases the researcher had a passive role as an observer and did not participate. The process and the participation are described in *Figure 17*.

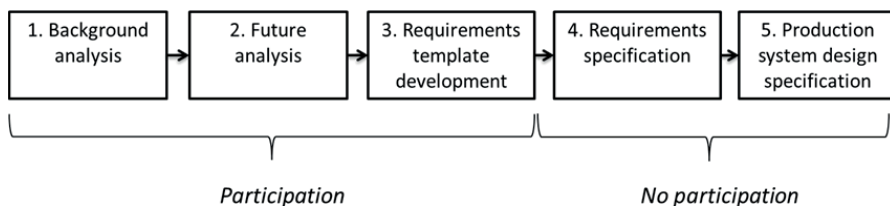


Figure 17. The production system design process and the researcher’s participation in the process.

The first three phases culminated in a template for specifying requirements. In the last two phases, the production system was designed based on this template. The requirement template was developed in order to create a support for design of the production system from a holistic perspective and developed by the researcher and the project group in cooperation. The requirements template was based on a literature study on production system specifications as well as collection of documents and the project group’s knowledge. The documents included management models, technical requirement manuals, and manufacturing philosophy.

The fact that the researcher’s participation was greater at the beginning of the project than in the later phase implied that the researcher laid a basis for the design process (in form of a requirements template) and also got an understanding of, among other things, the products, the production process, and the organization. The design itself of the production system was, however, performed by the project group and could be studied without participation.

Physical meetings were held at the company once a month during one day, telephone meetings were held every two weeks, and e-mail and telephone contacts were maintained between the meetings. There was also participation at the steering group meetings once a month, which were held as telephone meetings. At those meetings the work done during the month was presented by the project group as well as the researcher. Feedback and comments were given and general outlines were drawn up for the next month.

In the later phases of the project, data were gathered through a study of documents produced by the project group and less formal observations (Yin, 2009).

Notes were taken during the case study, but no formal case study minutes were kept. After the case study had finished a case study report was written.

3.4.3 The MaxAuto study

The MaxAuto study included three case studies identified in a manufacturing company, here called MaxAuto, providing products to the automotive industry, and its sites in the UK, Germany, and Sweden. The study was carried out from May to December 2011.

The study had a multiple-case design (Yin, 2009), including three case studies on production system design processes. The study had an embedded design (Yin, 2009), where the units of analysis were the production system design process and reconfigurability, see *Figure 18*. The case study included investigating the support for reconfigurability in the production system design process, change drivers, and the activities carried out in the production system design process with a focus on how reconfigurability was considered.

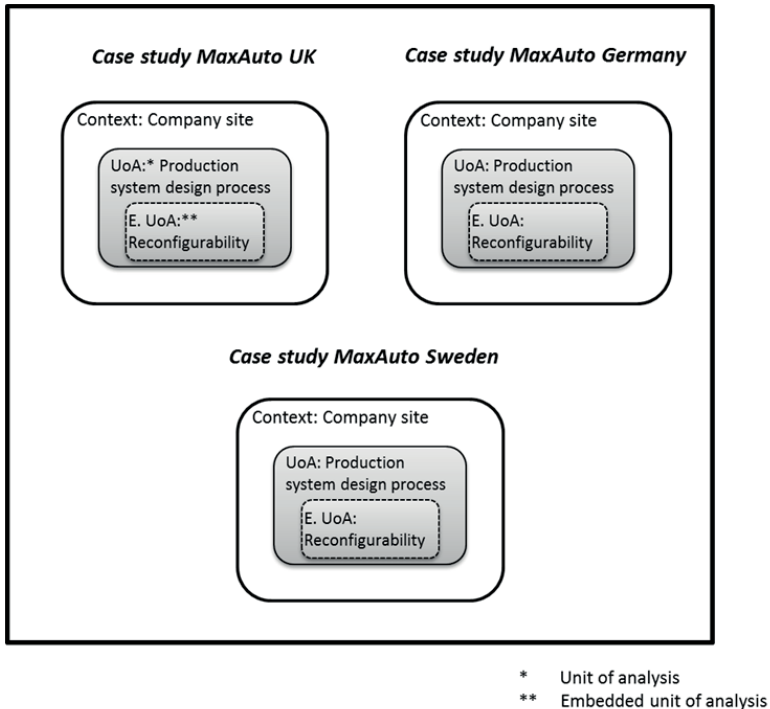


Figure 18. Research design of the MaxAuto study.

Before the study started the research design was carefully described and discussed with the representatives of the company. The role of the researcher varied due to the combination of real-time and retrospective studies. In case study MaxAuto UK the researcher was present at the site during two months to follow the production system design project. Observations were made at production system design meetings and daily contact was maintained with the production system design team. Before and after the visit at the site, contact was kept with key persons in the production system design team.

The case studies MaxAuto Germany and MaxAuto Sweden involved already closed production system design projects and consequently a different approach was required.

As an initial activity in the case studies, semi-structured interviews were carried out based on an interview guide, Appendix A, which was sent to the respondents beforehand. Each interview lasted approximately one hour. Respondents involved in the production system design projects were identified at different levels in the organization, such as vice president R&D, strategic operations managers, operations managers, project managers, industrial engineers, and production engineers. In the case studies MaxAuto UK and MaxAuto Germany one interviewer performed the interviews and in case study MaxAuto Sweden there were two interviewers.

Before an interview started, the terminology used was presented to the respondents (production system, reconfigurability, the different reconfigurability characteristics) in order to avoid misunderstandings. All initial interviews were recorded and transcribed. Details about the interviews are given in Table 5.

Table 5. *Interviews, the MaxAuto study*

Interviews	No. (single/group)	Duration [minutes]	Types of data collected
MaxAuto UK			
Face-to-face interviews	7 (7/0)	45-107	See Appendix A Respondents: Senior vice president, Global strategic operations and supply chain manager, Technical director, Electronic design engineer, Project manager, Project design engineer, Engineering manager
Telephone interviews	1 (0/1)	72	See Appendix A Respondents: Quality engineer, Production engineer
MaxAuto Germany			
Face-to-face interviews	6 (6/0)	46-85	See Appendix A Respondents: R&D engineer, Technical director, Product manager, Process engineer, Operations manager
MaxAuto Sweden			
Face-to-face interviews	3 (2/1)	65-88	See Appendix A Respondents: Production engineering manager, Production manager, Vice president R&D, Project manager

After the interviews were conducted relevant documentation was collected, such as project management models, production system design support, support for requirement specifications, and checklists and support used by

individuals, all of which were made fully available. In all three case studies an ongoing dialogue was held with key persons involved until rich descriptions of the cases were achieved (Yin, 2009).

Observations were carried out in two of the case studies. In case study MaxAuto UK the existing production system (which at the time was moved to the site in Germany) was studied. Passive observations were performed at project meetings as well as at one meeting with the system supplier. In case study MaxAuto Germany the existing production system was studied.

Field notes were carefully written through the whole case study (Yin, 2009), by which all activities were documented concerning what activity was done, how it was done, when it was done, and what people were involved.

3.4.4 The VoxVan study

The VoxVan study was carried out between August and November 2012 at a manufacturing company in the automotive industry.

The study was a single-case study with an embedded design (Yin, 2009), where the units of analysis were the production system design process and reconfigurability, *Figure 19*.

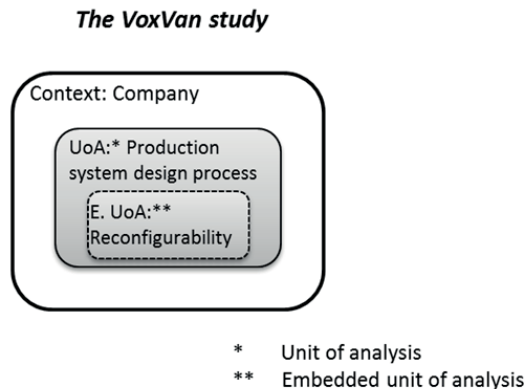


Figure 19. Research design of the VoxVan study.

The case study included semi-structured interviews, study of documents, and observations. Before the interviews were carried out, an interview guide was written, Appendix A, and sent to the respondents beforehand. One group interview including three respondents and one single interview were carried out. The people who were interviewed were the production manager and two industrialization project leaders. Both interviews were performed by two interviewers, carried out face to face, and were recorded and transcribed. Details about the interviews are given in Table 6.

The documents that were studied were documented production system design processes and individual checklists and supports that were used when designing the production system. Main documents were available.

Observations were also made of the existing production system.

Table 6. *Interviews, the VoxVan study*

Interviews	No. (single/group)	Duration	Types of data collected
Face-to-face interviews	2 (1/1)	65-76	See Appendix A Respondents: Industrialization project manager, Senior industrialization project manager, Production engineer, Industrialization manager

3.5 Case study analysis

The data collection was carried out over a long period of time. Concerning the Factory-in-a-Box study the data were analysed in two steps. First, the data were analysed concerning the mobility within the demonstrators. This resulted in a licentiate thesis (Stillström, 2007), which is also summarized in Paper IV. However, since the demonstrators were designed for reconfigurability it was appropriate to make a broader study of the collected data in order to get a more complete view of their reconfigurability. A review of the data was therefore made.

The data collected in the case studies, including the review of the data collected in the Factory-in-a-Box study, were analysed in five phases (Yin, 2011):

1. **Compiling:** The data were put in a certain order, e.g. in a database
2. **Disassembling:** The data were broken down into fragments
3. **Reassembling:** The data were reorganized into different groupings
4. **Interpreting:** The reassembled data were used to create a new narrative
5. **Concluding:** Conclusions were drawn from the study

The analysis process had, however, not this linear fashion, which is also not advocated by Yin (2011), but an iterative fashion. The phases are however presented one after another in this section.

In the first phase, the data were reduced by selecting, focusing, simplifying, abstracting, and transforming the data that had been collected (Miles and Huberman, 1994; Yin, 2011). This included gathering and compiling data from each case study consisting of both electronic and physical material in a systematic fashion.

In the second phase, the data were broken down according to the topics that were studied.

- The Factory-in-a-Box study included data concerning the need for reconfigurability, the reconfigurability characteristics of the production system, and how these were realized.
- The DaxVehicles study included data concerning the need for reconfigurability and how it was considered in the production system design process.
- The MaxAuto study included data concerning the support for reconfigurability in the production system design process, the need for reconfigurability, and how it was considered in the phases of the production system design process.
- The VoxVan study included data concerning the need for reconfigurability and the support for it in the production system design process.

In the third phase the data were reassembled in order to answer the research questions and interpreted based on the theoretical frame. The data were analysed in two main steps: analysis within case data, and secondly searching for cross-case patterns (Eisenhardt, 1989). Therefore, an analysis was first made within each case study. This was done in order to become familiar with each of the case studies and identify patterns unique for each case (Eisenhardt, 1989).

When each case had been analysed as a stand-alone entity it was time to move on to the cross-case analysis. Case studies having the same unit of analysis were compared and analysed (Leonard-Barton, 1990). In the Factory-in-a-Box study the link between the reconfigurability need and the reconfigurability characteristics as well as how reconfigurability was realized was analysed. In the MaxAuto study the support for reconfigurability and how it was considered in the production system design process in accordance with the specified need was analysed and compared between the case studies.

In the fourth phase data were interpreted and a comprehensive picture was given. Interpreting data does not mainly include interpreting the separate data but aims at a comprehensive interpretation of the whole study (Yin, 2011).

Finally, *in the fifth phase* conclusions were drawn which lay beyond the interpretations previously made. The findings were raised to a higher conceptual level. The interpretations made were compared and related to existing theory concerning what this is similar to, what it contradicts, and why (Eisenhardt, 1989).

3.6 Reliability and validity

In order to judge the quality of the research its reliability and validity should be tested. Reliability could be expressed as the extent to which a procedure yields the same answers however and whenever it is carried out. Validity is the extent to which it gives the correct answers (Kirk and Miller, 1987).

3.6.1 Reliability

Reliability depends on how accurately and explicitly the research procedures are described (Kirk and Miller, 1987). The more the whole research process is documented, the better reliability (Flick, 2006). In case study research, reliability implies that the reader should be able to follow the description of the case study, understand the chain of logic, and come to the same conclusion or at least understand how it was reached (Karlsson, 2009).

To what extent the case studies in this research have been documented has differed. In the early studies, i.e. the Factory-in-a-Box study and the DaxVehicles study, no formal case study minutes were taken but field notes were made concerning the major activities. During the interviews notes were taken and to some extent written out directly after the interviews. All collected data were put into a case study database.

In the latter studies, the MaxAuto study and the VoxVan study, detailed case study minutes and field notes were written where all activities conducted in the case study were noted. The collected data were put into the case study database after the case study was finished. All interviews were carried out based on an interview guide (Appendix A) and were recorded and transcribed.

3.6.2 Internal validity

Internal validity refers to the “true value” of the research (Miles and Huberman, 1994, p. 278), if the research measures what is intended to be measured (Saunders *et al.*, 2007). There are several ways to enhance the internal validity when creating the research design.

First of all, the research study must be carefully designed. The research questions must be clear and the features of the study design must be congruent with them (Miles and Huberman, 1994). In this thesis, the case studies were designed and the units of analysis specified based on the research questions. This implies that reconfigurability in production systems as well as production system design processes has been studied in accordance with the research questions. Two real-time studies were combined with two retrospective studies (Leonard-Barton, 1990). Through real-time studies post-rationalization was avoided, which enhances the internal validity. In retrospective case studies there is a risk that the picture is seen through the lenses

of the respondent, the observed person, or the author of a document. This implies that the researcher may take the story as told, without questioning interpretations (Leonard-Barton, 1990). Therefore, it was important to triangulate the data. Method triangulation was made, which implied that multiple sources of evidence were used including interviews, documents, and observations (Johnson, 1997). Also data triangulation was made to enhance the internal validity (Johnson, 1997). The interviews were made with several people with different organizational positions and functions. Triangulating among complementary methods and data sources generally resulted in converging conclusions (Mathison, 1988).

The interviews were carried out differently between the case studies. During the interviews in the MaxAuto and VoxVan studies, central terms such as reconfigurability and its characteristics, and production system design were described in order to avoid misunderstandings and to establish a common meaning of the terms. It was also clarified whether other terms were used by the respondents with the same meaning, (e.g. reconfigurability and upgradability). The interviews were mainly performed with one respondent at a time. This reduced the risk that the respondents got influenced by each other. The same interview guide was used in these case studies. In the Factory-in-a-Box study the interviews were not recorded but notes were taken. The notes were read after each interview.

There was an ambition to give context-rich and meaningful descriptions of the case studies (Miles and Huberman, 1994). In all case studies reports were written and key informants reviewed the case study reports (Anfara *et al.*, 2002). In addition, findings in each case study were presented and discussed with the respondents or the staff involved at the companies concerned.

Also the literature review was carefully designed based on the research questions. The literature review went on continuously and the data gathered in the case studies were continuously based on and compared with existing theory.

The case study method is often criticized for biases and the risk of losing objectivity. In the case studies where participant observations were made, as in demonstrator 5 and the DaxVehicles study, the criticism become even stronger. There is a risk that the researcher may be perceived as, and may in fact become, an advocate rather than an observer (Leonard-Barton, 1990). The potential bias depends on the fact that the researcher has less ability to work as an external observer and may have to assume positions contrary to the interest of a good scientific practitioner (Yin, 2009). Another problem might be that the participant role may simply require too much attention relative to the observer role, which is another argument for defining the different roles early in the case study. To avoid this, the researcher's role was clearly defined before the case studies were carried out.

3.6.3 External validity

External validity defines the domain to which the findings could be generalized and is also known as generalizability (Meredith, 1998). The case study method is often criticized for its lack of generalization (Yin, 2009). However, theory generated from case studies is applicable to other similar situations and since the situation is as complex as the reality, the external validity might be even higher than in other methods like e.g. simulation modelling (Meredith, 1998).

Retrospective studies give a more controlled case selection and thus enhance external validity (Voss *et al.*, 2002).

In single-case studies, theory plays an extra important role. The case studies in this research study were initiated by a literature review and also analysed by a model based on a literature review. Single-case studies are generalizable to theoretical propositions with the goal to expand and generalize theories, i.e. analytic generalization (Yin, 2009).

In multiple-case studies the use of replication logic must be carefully considered in order to secure external validity. In this thesis, theoretical replication logic has been used, which implies that the cases were chosen for theoretical, not statistical reasons (Eisenhardt, 1989).

In this thesis, it is also suggested how the findings could be tested further in future research (Miles and Huberman, 1994)

To help the reader to know when to generalize the results, certain information needs to be given, i.e. the number and kinds of people in the study, information about the participants, how they were selected, contextual descriptions, the researcher's relationship to the participants, methods of data collection, and methods of data analysis (Johnson, 1997). Detailed case descriptions or case study reports enable the readers to draw their own conclusions. Therefore, efforts were made to provide all this information.

CHAPTER 4 – Empirical findings

In this chapter the findings from each of the eight case studies will be presented. Reconfigurability in production systems as well as the consideration of reconfigurability in the production system design process has been studied.

4.1 The Factory-in-a-Box study

The Factory-in-a-Box study was carried out at three different manufacturing companies between January 2005 and December 2007. In each of the companies reconfigurable production systems, called demonstrators, were studied. The demonstrators were consciously designed for reconfigurability and were to various extent and type characterized by reconfigurability depending on the companies' specific needs, the change drivers.

The objective of the study was to examine reconfigurability in production systems, which included

- studying the change drivers,
- identifying the reconfigurability characteristics of the production system, and
- analysing how the reconfigurability characteristics were realized.

In the following sections the findings from each demonstrator will be described. The study is also described in Paper V.

4.1.1 Demonstrator 1

Demonstrator 1 was designed and fully realized at a large industrial company in Sweden that provides industrial robot solutions.

Demonstrator 1 was intended to be a part of the assembly line of the robot controller cabinets and included the operations of sealing and folding of cabinet doors, as well as folding of a power supply system.

Due to changing customer demands the company needed to handle changes in their production system to stay competitive. Therefore, demonstrator 1 needed to be moved within the site, between different production lines, and it needed to handle different product variants as well as variations in volume.

This was enabled by a reconfigurable production system. The reconfigurability characteristics were realized differently in the subsystems.

The *technical system* included robots, equipment, and fixtures. All major equipment was mounted on independent/stand-alone base plates placed on air cushions to enable fast and smooth transport. The base plates had standardized interfaces for electricity, data, and air compression. Accordingly, the technical system was characterized by integrability and modularity in order to meet the need of moving the whole demonstrator between places quickly and easily.

The production system could also handle volume variations due to the base plates since additional equipment, e.g. a robot, could be easily added. The focus was mainly on how to handle volume increase while downsizing the system was not as prioritized.

The robots could easily be replaced by manual workstations and thus change the level of automation.

The technical system also comprised equipment to automatically supervise the performance and avoid disturbances in the production as well as random controls, i.e. to secure diagnosability. When a decrease in equipment performance was identified, the equipment could be overhauled or replaced before failure in a proactive manner. The automatic supervision, however, did not comprise all equipment, and therefore manual maintenance was required to some extent.

Each workstation had well-defined operations and the equipment could be moved and rearranged in a preferred configuration to enable changes in product variants.



Figure 20. Robots, equipment, and tools, demonstrator 1.

Even if demonstrator 1 was designed for a high level of automation, staff were needed for supervising the production cell as well as maintaining the

equipment. The *human system*, including the staff members, needed competence in managing the advanced technical solutions and their reconfigurability.

An input of material and components in batches was required due to the robot handling and the *material handling system*, comprising buffer solutions of material and components to enable the robot to easily identify its position. The components were transported within the cell by transfer line/conveyor, gates, and rotary tables. The material handling system had a modular structure with standardized interfaces to be able to handle volume variations, product variations, and the need to move the demonstrator.

The *computer and information system* included a superior control system that linked the different software solutions/programs to each other. The linking of software programs was a prerequisite to enable the high level of automation required. The computer and information system also comprised software for automatic configuration of new product types to be manufactured in the production system and identified the system requirements and limitations.

Additional elements in the computer and information system were simulation and programming software in order to analyse performance as well as software for cell calibration and coordination of robots.

To handle volume variations the *building and premises* needed to be designed to fit the production system in terms of e.g. required size and weight.

To sum up, demonstrator 1 was studied in order to examine change drivers and the reconfigurability characteristics of the production system and exemplify how the reconfigurability characteristics could be realized. The main findings can be summarized as follows:

- *The identified change drivers in demonstrator 1 were volume variations and product variations. It also needed to be moved within the site.*
- *To handle the change drivers the production system was characterized by integrability (standardized interfaces), modularity (base plates), mobility (air cushions), and diagnosability (automatic supervision of performance).*

4.1.2 Demonstrator 2

Demonstrator 2 was designed, realized, and implemented at an industrial company supplying modular facilities to the off-shore, telecom, and pharmaceutical industries.

Demonstrator 2 was used for cutting, bevelling, and welding of carbon steel pipes, see *Figure 21*.

The demonstrator needed to handle changes in product variations in terms of variations in pipe components and pipe dimensions. These variations re-

quired a configuration in the production system in terms of scale and change of welding method.

Demonstrator 2 also needed to be moved between the company's sites in order to work as an additional production resource when e.g. volume peaks appeared. In order to enable this, the production subsystems were characterized by reconfigurability in different ways.

The *technical system* included fixtures, welding equipment, equipment for cutting and bevelling, equipment for quality control, and safety equipment. The equipment parts were semi-automatic and not linked to each other. No heavy equipment was used. Consequently the technical system could easily be packed up in order to quickly and easily be moved between sites.

The equipment was placed on a base plate with standardized interfaces concerning air, data, and electricity to quickly and easily integrate the production system with a major system. The *material handling system* included equipment for handling and fixturing of the pipe components and lifting equipment.

The *human system* comprised operators with a competence to handle both semi-automatic and manual welding as well as to perform quality control.

The *computer and information system* included a computer terminal to run and control the system including, among other things, work instructions to enable fast production start-up when changing production sites.

Since the system needed to be moved between sites, special requirements were formulated for the *building and premises*. The production system would be placed in a modified standard container to be moved easily between sites, and emissions and temperatures could be regulated according to the surrounding climate.

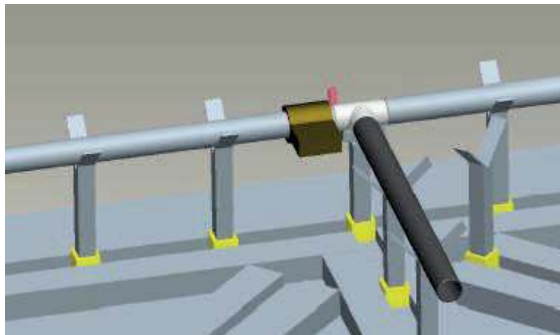


Figure 21. Pipes prepared for welding, demonstrator 2.

In demonstrator 2 change drivers and the reconfigurability characteristics were studied. Examples of how the reconfigurability characteristics could be realized were also studied. The main findings can be summarized as follows:

- *The identified change drivers in demonstrator 2 included product variations and the ability to be moved between sites.*
- *To handle product variations the production system was characterized by integrability (standardized interfaces), modularity (independent equipment), mobility (avoid heavy equipment), and diagnosability (software for quality control).*
- *To handle change in production location the production system was characterized by mobility (avoiding heavy equipment, mobile building) and integrability (standardized interfaces).*

4.1.3 Demonstrator 5

In demonstrator 5, a conceptual production system was studied which was directed towards a global company that manufactures trains and their site in Sweden. The production system would be used for manual assembly and testing of high-voltage boxes that were a part of the propulsion system.

Many of the company's customers had strong wishes to place some part of an import order within the borders of their own country. By sending a mobile production system, the company could meet this production relocation demand while at the same time retaining control of the production. Instead of building factories that would be abandoned as soon as the order had been processed, the idea was a mobile unit. The aim of the demonstrator was to develop a mobile production system that could be relocated as soon as the production of an order was finished. The demonstrator, therefore, needed to be prepared for movement between geographically different places. To enable this, all its subsystems needed to be ready for mobility. The *technical system* included tools for assembling and product tests and working tables. The equipment parts were manual and not linked to each other (independent) to enable modularity. No heavy equipment was used to enable mobility.

The *material handling system* included equipment for packaging, lifting equipment due to the weight of the finished products, and material carriers. In the same way as the technical system, the material handling system was characterized by modularity and mobility.

The *building and premises* included a collapsible container that could be transported as a standard container and easily be unfolded to provide a space that is three times as large as that of a standard container, *Figure 22*.

The *human system* would comprise operators that would be employed locally. The *information system* included a training solution for local labour and a methodology for how to move, install, and put the mobile production system into work.

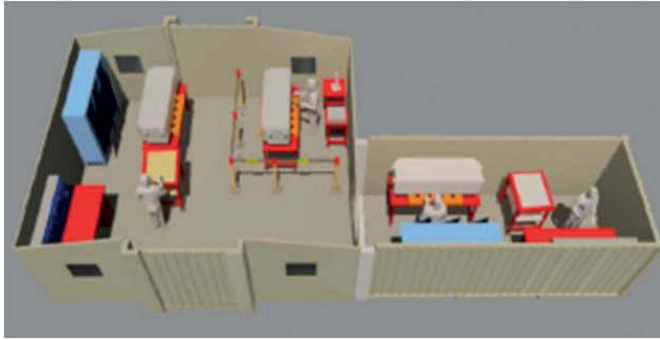


Figure 22. Collapsible container including assembly and test, demonstrator 5.

Demonstrator 5 was analysed in order to identify links between change drivers as well as reconfigurability characteristics of the production system, and also exemplify how the reconfigurability characteristics were realized. The main findings can be summarized as follows:

- *The identified change drivers in demonstrator 5 included the ability to be moved between locations.*
- *To handle change in production location the production system was characterized by mobility (avoiding heavy equipment), modularity (modular building, independent equipment), and integrability (standardized interfaces).*

4.2 The DaxVehicles study

The DaxVehicles study was carried out from March to December 2009 at a Swedish industrial company here called DaxVehicles providing products to the automotive industry and their Swedish production site.

DaxVehicles was on their way to expanding their production since they had a strong market position and a broad global customer base, which most likely would require global production. In order to investigate what a future production system would look like and where it should be located, an industrial development project called *Manufacturing Footprint* was carried out at the company. The Manufacturing Footprint project included defining a production system in the form of a hub.⁴ The production system would be designed for an existing product and the upcoming generation of the product and involved assembly and test.

In the DaxVehicles study reconfigurability in the production system design process was studied.

⁴ A hub can be described as a production site that is linked to a master plant.

- The objective of the case study was
- to identify change drivers,
 - to study how reconfigurability was considered in the phases in the production system design process,
 - to identify the reconfigurability characteristics of the conceptual production system design,
 - and to study how the reconfigurability characteristics were realized in the conceptual system design.

4.2.1 Identification of change drivers

At an early stage in the project a future analysis was made concerning future market, production situation, products, and organization. Factors to describe future scenarios were specified and gathered in a matrix, *Figure 23*.

Three future scenarios were developed by brainstorming technique:

- A stable scenario: a scenario characterized by stability including the factors described in the right-hand column
- A complex scenario: a scenario characterized by complexity including the factors described in the left-hand column
- A probable scenario: the scenario that was most probable according to the scenario formulation group; the factors were rated between 1 and 10

For more details of how the scenario formulation were carried out, see Appendix B.

		Estimating a probable scenario										
		Complex scenario										Stable scenario
Market	Complex	1	9	8	7	6	5	4	3	2	1	Stable
Customers	Existing/new (50/50%)											Existing (100%)
Competitors' new technology	High											None
Competitors' similar technology	High											None
Regulations	Several/tough											Few/easy
Markets	Several											Few
Production	Complex											Stable
Volume size (volume/years)	High											Average
Volume variations	High											Stable
Planning	Short-term											Long-term
Fluctuations (time intervals)	Irregular											None
Product	Complex											Stable
Generation	Mix of existing and new											New
Product variations	High											Low
New technologies	Several											None
New branches/applications	Several											None
Product range expansions	Several											None
Organization	Complex											Stable
Competence	Hard to find											Easy to find
Management involvement	High											Low
Growth of organization	High											Low
Production sites	Several											Single

Figure 23. Scenario description, Dax Vehicles.

In the probable scenario that was estimated, a mix of existing and new customers was expected, each of which with specific demands. New customers were expected at new markets, which implied an increased number of product types and also product variations. Also, the volumes were expected to increase, however with large fluctuations. The planning horizon was also expected to decrease.

Customization was important, i.e. only an investment into the capacity and flexibility required could be justified and therefore it was concluded in the project group that reconfigurability was needed in order to better adapt to the probable scenario and the complex scenario.

The link between change drivers and production system design is also described in Paper IV.

4.2.2 Considering reconfigurability in the production system design process

A project group was initially set up including an operative production manager, a consultant production system designer, and a mechanical engineer. (The author was part of the project group in the first three phases as described in Section 3.5.2.)

DaxVehicles did not have any documented production system design process or support and previous production systems were mainly designed

based on the skills of the staff. As a first activity in this project, phases in the project were therefore specified including background analysis, future analysis, and design of the conceptual production system. While the project was running, the phases were modified and finally five phases were included, *Figure 24*.

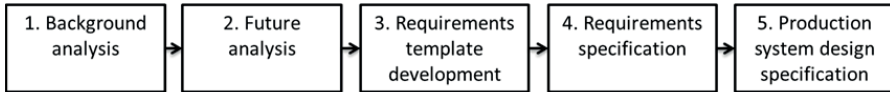


Figure 24. The production system design process, DaxVehicles.⁵

In the first phase, the background analysis, information was gathered to give a common view of the current situation including existing products and production systems. The current production system was not characterized by reconfigurability.

In the second phase, a future analysis was made, which was presented in the previous section.

In a third phase, a template for a list of requirements was defined based on first a literature study⁶ and thereafter further developed based on the project group's knowledge.

The list of requirements consisted of six categories that in turn included a number of subcategories, which all together gave prerequisites for a holistic picture of a production system: production processes, machines and equipment, material handling and logistics, workplace design, factory and premises, and information system. In order to be able to formulate requirements relevant for the future, the need for reconfigurability identified in the previous phase was kept in mind when the list of requirements was formulated.

The reconfigurability characteristics focused on the two categories production process and machines and equipment. Subcategories that could be linked to the need for reconfigurability were

- *modularization*, which was explicitly formulated,
- *mix flexibility*, which was formulated and defined as 'the easiness to quickly switch between orders, maximum set-up time'.
- *volume flexibility*,
- *mobility*, and
- *level of automation*.

In the fourth phase the list of requirements was specified based on the subcategories described in the previous phase.

Requirements were formulated about modularity, for instance that at least each workstation should be one separate module. The requirements concerning convertibility and scalability were formulated. Requirements about diag-

⁵ The process phases are named slightly differently in Paper IV, but the content is the same.

⁶ The study resulted in a first draft of a list of requirements based on Bellgran (1998) and Johansson and Nord (1999).

nosability were described in detail by for example poka yoke and control plans. Requirements on mobility and automatibility were also formulated.

In the sixth phase a conceptual production system was proposed. The conceptual production system was divided into two parts, a technical solution and a solution linked to organization, information, and logistics. The technical solution, *Figure 25*, was characterized by modularity. The workstations were designed according to a standard module with standardized interfaces for mechanical docking, electricity, compressed air, and data. Solutions for reduced set-up time increased the convertibility, for example cassettes with fixtures that would be set up and be prepared off line, and could be installed inline quickly.

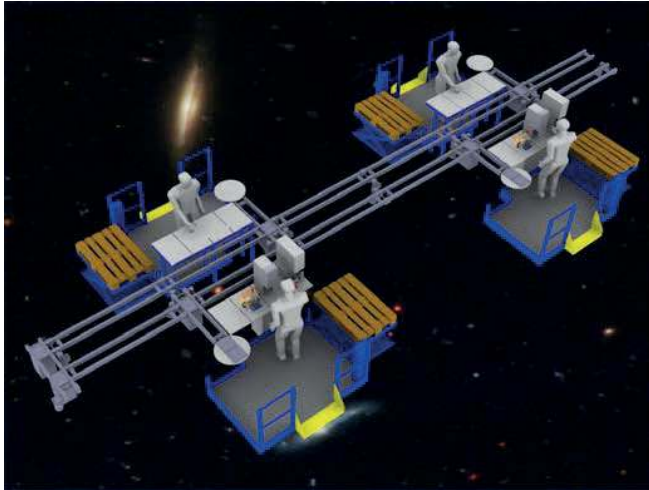


Figure 25. Conceptual design of production system, DaxVehicles.

In the conceptual design solution the need for mobility was considered and the modular design of the system facilitated relocation of the system if needed.

System expansion could be achieved by means of introducing more than one workstation for one particular operation and planning the workspace for that. Mechanical and cognitive levels of automation were also considered, however they were not considered as dynamic.

The second stage of the production system design was on the other hand not characterized by reconfigurability to the same extent as the first stage. Factors like standardization of information and a small team-based-organization with a broad competence among staff would enable reconfigurability.

To sum up, in the DaxVehicles study the change drivers were identified as well as how reconfigurability was considered in the phases in the production system design process; the study also examined the reconfigurability

characteristics of the conceptual production system and how they were realized. The main findings can be summarized as follows:

- *Based on a scenario description the change drivers were identified and included volume variations, product variations as well as the ability to be moved between places.*
- *Reconfigurability was in this case study partially considered in the production system design process. A requirement template would support the holistic perspective and thereby reconfigurability. The formulated requirements mainly involved the technical system.*
- *The conceptual production system design was characterized by convertibility and scalability, which was enabled by modularity (stations, equipment, fixtures), integrability (standard interfaces), and mobility (no heavy equipment).*

4.3 The MaxAuto study

A multiple-case study was conducted at a company called MaxAuto, which is a global manufacturing company in the automotive industry.

The MaxAuto study included three case studies that were carried out from May to December 2011 at different sites in the company and in different production system design projects focusing on various product segments with very low interference from the other sites.

The MaxAuto study was intended to examine the production system design process and how reconfigurability was considered in the process.

The objective of the case study was

- to study the support for reconfigurability in the production system design process,
- to identify the change drivers,
- to study the activities carried out in the production system design process with a focus on how reconfigurability was considered.

A project management model (stage-gate model), *Figure 26*, was used at all the MaxAuto sites studied to support the design of products as well as production systems. The model mainly included product design activities and only a few activities related to the design of production systems. The phases and the gates were carefully followed in the production system design process according to all respondents. The model, however, did not consider reconfigurability.



Figure 26. Main phases in the project management model MaxAuto.

4.3.1 MaxAuto UK

In the case study a production system design process was studied. The process was intended to result in a production system including a production line for assembly and test. The production system was designed for a new product including five variants.

Support for reconfigurability in the production system design process

Except for the project management model, *Figure 26*, the production system design team did not use any additional supporting documentation specifically for design of production systems. This implied that the design of production systems was mainly based on the skills of the project team.

Until a few years ago the site had its own production facilities but recently the production was moved from the UK site to other production sites in the company as well as external suppliers. The UK site, however, kept responsibility for the design of the production systems. The removal of the production from the site resulted in a decrease in staff assigned the task of designing production systems. At the time when the case was studied the site had two persons assigned for production system design as well as maintenance of the production lines that had previously been moved from the site, a production engineer and a quality engineer. In the middle of the case study the quality engineer left the company. The production engineer was supported by product engineers and the project manager who had competence in both product design and production system design. This group constituted the production system design project team.

Since MaxAuto UK had limited staff resources in production system design, they used a system supplier that designed the production system in collaboration with the project team. The project team directed and coordinated the production system design process.

Change drivers

When the case study was initiated, the project team did not express an explicit need for reconfigurability. During the initial interviews it was shown that reconfigurability was a term that was not often used. The project team used terms such as “flexibility”, “upgradability”, and “ability to change” but not reconfigurability.

The project team and the additional respondents found it hard to anticipate the need for change in the future even if they thought that easily upgradable production systems would be necessary in the future.

Concerning their view of the future, they found it hard to think in product generations since the length of life of the product was long. Consequently, they would not plan for the next production system if they did not know that it was coming. This implied that the production system was customized and aimed at the specific product and its life cycle and was prepared to be changed according to the planned volume increase and a few product variants.

However, when the production system was designed it was strongly inspired by the previous production system concerning concept and technology solutions. The project team tried to stay with known processes and use reinvention as far as possible. The previous production system was not initially designed for reuse.

In the current project the context differed since the production system would be moved to the company's production site in China. The production system was developed in the UK and would be installed and ramped up at the UK site. During this time Chinese staff were supposed to be trained at the UK site. After ramp-up the production system would be packed and moved to the Chinese site.

Reconfigurability in the production system design process

In the production system design process reconfigurability was partially considered.

In phase zero, the initiation phase, the project started based on the marketing need. It was decided that the production system was to be developed at the UK site, resources needed for the production system were specified, and an idea of what the production system was going to look like was decided on. This constituted a first rough production plan. The product that was going to be made in the production system was based on a previous product and therefore the production system was also planned to be based on the previous production system.

The cost of the project was estimated in a rough budget. Based on this, a cost suggestion was sent to alternative system suppliers. Then they firmed up the costs. The project team found it possible to do this at such an early stage since they had a great deal of knowledge from previous similar projects.

In addition, the discussion about where the production system was going to be located started, which was much earlier than normal for MaxAuto UK.

The need for reconfigurability was not analysed in this phase, nor was it consciously considered in the rough production plan or the budget.

In phase one, the definition phase, the project team was specified but since there were only two persons assigned to production system design at that time it was not a choice; both of them were involved in all projects carried out at the site. The project team started to discuss the choice of system supplier linked to location.

The project team continued with the production plan, which had been started in the previous phase. The discussion of location alternatives continued in more detail. Assumptions were made about, among other things, the production equipment that was needed.

At the end of this phase the choice of the UK system supplier was made. The system supplier that was chosen was the same as they had used in previous projects and according to several respondents the personal contact with the supplier played a central role in the choice. The choice was not based on specific skills that were needed in this specific project. The interface between the production system design team and the system supplier was not explicitly specified. This implied that the production system was designed in dialogue with the system supplier through the production system design process. The system supplier was involved from phase one and thereafter through the design and development until realization and ramp-up.

At this point in the project the project team also defined, among other things, tact time, test criteria, output, quality, and repeatability. The level of automation was decided to be low based on the business case. This meant that the equipment parts were not strongly linked to each other. This, together with the absence of heavy machines or equipment, resulted in a rather high level of mobility, which was required in order to enable the transfer from the UK site. It was decided to turn out one product at one line; the line was then going to be duplicated across different sites if the market increased.

In phase two, the concept design phase, the project team started to define the external material flow including type of transport needed, choice of suppliers, and purchase of components, and a risk analysis was made by the production engineer including, among other things, the process, costs, time, competence, and material.

Based on discussions between the project team and the system supplier, a preliminary concept was suggested by the system supplier. The concept was based on a previous production system that had also been designed by the system supplier. The project team finally carried out an initial concept review together with the system supplier. This comprised a review of included manufacturing processes and assembly methods including a preliminary sequence of events that would be used for manufacturing and how the manufacture and assembly modules would operate. The preliminary concept was not designed according to any formulated need for reconfigurability or ability to change. The concept was characterized by modularity on a station level but not concerning fixtures and equipment, which were specific for all products. The modularity also implied an easiness of integrating new stations.

In phase three, the detailed design phase, the activities were done in collaboration with the system suppliers to a large extent. The collaboration consisted of discussions and not much documentation was made. For example, requirements regarding the workplace design and ergonomics (work position, noise, light, lifting weight, and vibrations) were discussed according to

the project team but not documented. Also, design rules and requirements applied to the production equipment (such as height of the equipment, ability to stop machines, ability to detect process variation, poka yoke, and visual flow) were considered in discussions with the system supplier but not documented.

A floor plan was sent to the plant where the production system was going to be located. Finding a suitable location for the new production system was thereafter the responsibility of the production plant (such as analysing the height of ceiling required, floor/base, access to materials deliveries, possible barriers for the material transport way, access to electricity, gas, and water). The system supplier proposed the concept, drawings, layout, fixture, and tooling, which was reviewed by the project team and agreed on.

A process failure mode and effects analysis (FMEA) was made on the part of the production system, but not for all stations due to lack of resources. In addition, a draft of a process flowchart was made and maintenance requirements specified.

The project was studied until the middle of phase three.

Summary case study MaxAuto UK

In case study MaxAuto UK the production system design process was studied in order to identify the consideration of reconfigurability. The main findings could be summarized as follows:

- *A majority of the respondents thought that reconfigurability was important (e.g. in terms of “easily upgradable systems”).*
- *They found it hard to anticipate the need for change in future. However, there was a need for change in production location.*
- *There was no support for considering reconfigurability in the production system design process. Furthermore there was a lack of skilled production system designers in the company.*
- *Change drivers were not analysed in the process and reconfigurability was not consciously considered in the actual process.*
- *The change in production location would be handled by modularity (manual equipment parts that were independent from each other were chosen) and mobility (heavy equipment was not chosen).*

4.3.2 MaxAuto Germany

At MaxAuto Germany reconfigurability in the production system design process for a production system including a semi-automatic assembly and testing line was studied. The production system was designed for a new product comprising three variants.

Support for reconfigurability in the production system design process

Also in this case study reconfigurability was a term normally not used and the respondents rather discussed “flexibility” than reconfigurability.

In addition to the project management model, *Figure 26*, several individual checklists, including things to remember throughout the design process, were used by the production engineers. Reconfigurability, or any of its characteristics, was not explicitly considered in the supporting documentation. Several of the design activities were undertaken based on the engineers’ skills.

At MaxAuto Germany there were two production engineers employed when the case study was conducted. The production system design was performed by a production engineer with support from a project leader. At MaxAuto Germany a system supplier was used to support the design of production systems. The system supplier was selected on the criteria of experience and contact and was involved from an early stage and throughout the project.

Change drivers

The respondents did not see reconfigurability as a requirement since volume fluctuations were not expected, neither was a change in production location. The company had its production facilities at its own site where they tried to keep as much as possible of the manufacturing of the products they designed, according to the respondents.

The respondents described a need to change the production system according to product variants and highlighted the need for flexibility, which implied that the production system was primarily designed to handle a certain number of variants.

None of the respondents thought they had a long-term view of production system generations. However, when a new production system was designed they retained many of the old ideas such as production processes (layout, concept) and based the new production system on the previous generations. Since the product variants had a long length of life, six to ten years, new technology solutions were required.

Reconfigurability in the production system design process

The production system design activities carried out followed the phases described in the project management model.

In phase zero, initiation phase, the project was set in motion. The need for reconfigurability was not analysed.

In phase one, a responsible production engineer was chosen to run the production system design project. The production engineer formulated a project plan including a time plan and defined a budget for the project including necessary investments such as equipment, tooling, IT hardware,

software licences, and new staff. If new investments were not required they were not included in the budget (e.g. reuse of equipment, staff already in-house). Production volumes were also reviewed. Performance objectives were determined as well as productivity measures such as cycle time, lead times for placing orders, procuring of components, and assembly operations. The level of automation was specified depending on the required cycle time. It was not considered to easily change the level of automation. Reconfigurability was not explicitly considered in this phase.

In phase two, a preliminary concept for the new production system including, among other things, manufacturing processes, layout, material flow, capacity, and machine utilization was developed. The volumes through the product life cycle were reviewed as well as how the system would be scaled up by adding test equipment stations and extending and adapting the transfer system.

In phase three, the conceptual production system was specified. The design was mainly based on discussions between the project team and the system suppliers and few documentations were made. Packaging and material supply, design rules, and workplace design including, among other things, work position, noise, light, lifting weight, and vibrations were discussed but not written down.

In this phase it was also determined how the new production system would fit into the production site. A process flow and a test plan describing how, for example, the test rig would work was made. Possible bottlenecks were reviewed. Some environmental requirements were specified in this phase such as length of life of the production equipment, list of preferred materials used, and the fact that assembly can only be done in a correct way.

The conceptual production system was thereafter designed by the system supplier. The choice of the final conceptual solution was made in the project team and was, according to a production engineer, not a very formal decision.

Since requirements were not documented, the consideration of reconfigurability was hard to analyse. According to the respondents, reconfigurability was not explicitly considered.

The conceptual design was done to be modular both in stations, fixtures, and tooling in order to handle product variations. It had, for instance, a ground plate in the fixtures with clamps while the fixture as such was specific for each variant. The tables were standard ones. New stations could easily be integrated into the system due to standard interfaces. Poka yoke solutions were designed in all operations. The production system was thus designed for convertibility that was enabled by modularity, integrability, and diagnosability.

In the following phase, *phase four*, the detailed design was made. Checkpoints related to requirements for change (e.g. *does the manufacturing equipment have sufficient capacity to handle forecast production and service*

volumes?) were established. Requirement specifications for test equipment were formulated concerning the performance required as well as documentation, service, and training for operators, but not involving reconfigurability. This included, among other things, order and install equipment as well as a pre-acceptance test. When the equipment was installed, the training of operators was prepared and performed and instructions were written.

Summary of case study MaxAuto Germany

In case study MaxAuto Germany, the production system design process was analysed in order to identify the consideration of reconfigurability. The main findings could be summarized as follows:

- *The respondents thought that the need for reconfigurability was unimportant except for the ability to handle new product variants.*
- *Support for production system design was used but it did not consider reconfigurability. The production system was designed by the production system designers together with a system supplier.*
- *Change drivers were not analysed in the production system design process.*
- *The production was designed to be convertible and was enabled by modularity in stations, fixtures, and tooling, integrability, and diagnosability.*

4.3.3 MaxAuto Sweden

At MaxAuto Sweden reconfigurability in a production system design process was studied in a project aimed to design a semi-automatic assembly and testing line for a new product type.

Support for reconfigurability in the production system design process

To support the design of production systems, the company had developed an extended version of the product management model, *Figure 26*, including more activities related to the design of production systems, even if it still mainly comprised product design activities. Besides this model additional support for requirement specifications was used.

Change drivers

The ability to change the production system according to fluctuating demand was very important according to all respondents, mainly due to potential new variants but also to handling volume variations. The product length of life was expected to be more than 10 years and volume changes could be estimated during the product life cycle according to the contract with the customer. Additional variants were expected and therefore the production sys-

tem should be ready to be changed according to introductions of new variants.

According to the respondents, mobility was also getting increasingly important since several rearrangements at the production site had been made during the last few years. Within eight months all machine tools and assembly stations had been moved at least once, according to the respondents.

Reconfigurability in the production system design process

The consideration of reconfigurability was studied in three activities and these were pre-study, formulation of requirements, and detailed production system design.

In the conceptual design phase *a pre-study* was conducted in order to specify what the request for quotation would contain. It was specified that alternative conceptual solutions would be suggested including e.g. process flow and balancing and positioning of parts, space requirements, expected investment cost, ergonomics, and material handling. It was specified that the production system had to be characterized by traceability, be modular, easy to move, easy to run in an effective way with a varying number of operators, have information boards at all stations, be ready for variations in product types, and have poka yoke solutions at all stations. Reconfigurability was thus considered in terms of explicit requirements for modularity and implicit requirements for mobility and diagnosability.

In the detailed design phase *a requirement specification* was formulated based on a standard document for the production system, taking a holistic view. The documentation included requirements concerning the usage of the assembly system, performance and quality, concept and material handling, control, environment, safety, ergonomics, IT/IS, machinery and equipment, manual information flow, and maintenance.

In the list of requirements, diagnosability requirements were formulated: "All operations that are performed at manual assembly stations must be designed so that the assembly only can be done in one single way and one order (poka yoke)." In addition, requirements about modularity were included: "The IT/IS system must be modular. The system must be designed to handle future expansions of the assembly equipment." Overall, the documentation did not give much support to consider reconfigurability. Requirements about diagnosability were implicitly described in terms of traceability, information boards, and poka yoke solutions at all stations.

The *detailed production system design* complied with the list of requirements. The production system was designed to be modular with stations that were decoupled from the line, which enabled adding or removing stations. The pallets were designed to be modular in order to fit the product types that were planned to be produced. The modularity enabled some extent of scalability. Due to the cycle time the production system was not designed to be

very scalable and consequently designed for a maximum volume. To scale down was deemed much easier because then operators could be removed.

Consequently, the production system was not designed to be easily changed when volumes increased more than the planned maximum volume or when new variants appeared. In an early phase, when the pre-study was formulated, the production system had been planned to be able to handle different volumes and variants in the future, as previously described. However, investing in such flexibility could not be justified. The system was therefore designed to be flexible to a certain volume and a certain number of variants.

Mobility was required in the pre-study but when the final production system solution was subsequently chosen it was not included.

Summary of case study MaxAuto Sweden

In case study MaxAuto Sweden parts of the production system design process were analysed in order to identify the consideration of reconfigurability. The main findings could be summarized as follows:

- *The project indicated a need to handle the introduction of new variants and volume variations in the production system.*
- *Documented support for designing production systems existed and it did partially consider reconfigurability.*
- *In the pre-study requirements for modularity, mobility, and diagnosability were formulated.*
- *In the requirements specification reconfigurability was not considered.*
- *In the detailed design the production was designed for modularity.*

4.4 The VoxVan study

The VoxVan study was conducted at VoxVan, a global manufacturing company in the automotive industry at their site in Sweden. A production system design process was studied included machining and semi-automated assembly. The machining had a cellular layout and several product types were made in the production system. The production system design implied a modification of machining in the existing production system but also design of a pre-assembly station intended for the product.

In the VoxVan case study the consideration of reconfigurability in the production system design process was studied.

The objective of the case study was

- to identify the change drivers,

- to study the production system design process with a focus on the consideration of reconfigurability.

4.4.1 Change drivers

VoxVan had recently started to work with a more long-term view and a mindset for product generations, and the ability to change the production systems was becoming increasingly important. However, it was a balance between cost and ability to change. Management did not want the production system to be limited to one product type but could not justify investments that were not required at the moment. The respondents thought that it would be increasingly more important to quickly react and be able to change in production system design. They described the need for “change flexibility” in the production system design.

A very high level of automation was avoided since it made it more difficult to change the system. The company therefore had a rather flexible production system in the sense that it could make different variants. When a new equipment or technique was needed for a new product variant they were, however, slow to adapt the system to this change. The machines and equipment were not designed to easily switch to new product types. General flexibility was rather built into the systems than designing for convertibility.

Mobility was important in order to enable rearrangements in the production system and had been considered to some extent, but the system was not designed to be mobile since machine tools are hard to get mobile while still maintaining quality, due to instability. Moreover, the cells were not designed to enable movement of equipment.

4.4.2 Support for reconfigurability in the production system design process

A project management model (stage-gate model) was used, including the stages of pre-study, concept study, detailed development, final development, industrialization and commercialization, and follow-up. It was considered to include both product and production system design according to the respondents but it mainly included product design activities and to some extent production system design activities.

The stage-gate model was not very detailed and did not take reconfigurability into account. An extensive checklist was used as a supplement to the stage-gate model, but this document did not regard reconfigurability.

In case study VoxVan the production system design process was analysed in order to identify the consideration of reconfigurability. The main findings could be summarized as follows:

- *There was a need to handle product variations.*
- *The consideration of reconfigurability was not included in the documented production system design process.*

CHAPTER 5 – Reconfigurability in production system design

In the present chapter the empirical findings will be analysed. First, reconfigurability comprising change drivers and needed reconfigurability characteristics in the case studies will be analysed. Thereafter the consideration of and the support for reconfigurability in the production system design process will be described.

5.1 Analysing reconfigurability need and consideration

In the previous section the findings from each of the case studies were described separately. In the Factory-in-a-Box study, reconfigurability was studied including the change drivers, the reconfigurability characteristics of the production system, and how those characteristics were realized in production systems. In the DaxVehicles study change drivers were identified in a scenario analysis and reconfigurability in the production system design process was studied. In the MaxAuto and the VoxVan studies change drivers and the consideration of reconfigurability in the production system design process were studied. In this chapter the case studies will be compared with each other and related to the frame of reference.

In the frame of reference, summarized in *Figure 13*, it was concluded that change drivers should be identified to enable specification of the need for reconfigurability for each specific case of application (Bussmann and McFarlane, 1999; ElMaraghy and Wiendahl, 2009; Schuh *et al.*, 2005; Urbani and Negri, 2006). Therefore, knowledge of reconfigurability, its characteristics, and its links to change drivers is required.

In order to investigate existing change drivers and need for reconfigurability characteristics in manufacturing companies compared to the frame of reference, the case studies will first be analysed.

It was concluded in the frame of reference that a holistic perspective is needed in order to achieve reconfigurable production systems and physical, logical, and human reconfiguration should be considered in the production system design process. A structured design process involving reconfigurabil-

ity in accordance with the identified need would be useful when managing the complex activity of designing a reconfigurable production system (Bellgran and Säfsten, 2010; Bennett and Forrester, 1993; Wu, 2001).

In order to investigate prerequisites for designing reconfigurable production systems the consideration of reconfigurability in the production system design processes has been investigated in the case studies. This will be analysed in the second section of this chapter.

5.2 Change drivers and need for reconfigurability

In the frame of reference it was described that the change drivers trigger a change in the structure of the production system. The change drivers were described as enabled by critical and supporting reconfigurability characteristics. When deciding what reconfigurability characteristics are required, the manufacturing company should therefore start identifying change drivers and formulate the need for reconfigurability based on that.

In all case studies the ability to handle change drivers was considered highly important. However, it was not clear that reconfigurability was a potential way to deal with the change drivers. In the DaxVehicles, MaxAuto, and VoxVan studies reconfigurability was not a common term and the respondents rather used terms such as “flexibility”, “upgradeability”, and “ability to change”. It was concluded among the respondents that the ability to change was getting more and more important mainly in accordance with changes in product variants and changes in volume. None of the respondents had a comprehensive knowledge of what characteristics were included in the reconfigurability term. A clear gap between academic knowledge and industrial knowledge was shown.

Handling change drivers was considered highly important in the case studies. Still, reconfigurability and reconfigurability characteristics were not well-known terms among the respondents.

The fact that reconfigurability was not a regularly used term did, however, not necessarily mean that reconfigurability as such was not required. What distinguishes reconfigurability is that the production system is adapted to the product families to be produced in the system but is still ready to be changed when new product types or product families appear (Mehrabi *et al.*, 2000b). A difference was made between dedicated production systems, production systems characterized by general flexibility, and production systems characterized by customized flexibility. The production systems that were studied in the Factory-in-a-Box study and the production systems to be de-

signed in the other studies were positioned according to the product range that would be manufactured in the production systems. In the case studies most of the production systems were intended to be customized for a specific product family and only an investment into the equipment and tooling that was necessary for the moment could be justified. The production system in the VoxVan study was more characterized by general flexibility than the other ones.

The respondents found it hard to predict the future, even if they had an idea of what product variants would require changes and what product variants were likely to fluctuate in volume. The combination of a need for handling long-term changes in the future, an inability to exactly predict the required future changes, and an inability to invest in too much flexibility indicates that reconfigurability was a proper way to deal with the change drivers. Reconfigurability is, however, not always needed and if needed it could be expressed in different ways all depending on the change drivers. When initially designing the production system the possible change drivers should therefore be identified to achieve a proper type and degree of reconfigurability (Bussmann and McFarlane, 1999; Schuh *et al.*, 2005; Urbani and Negri, 2006).

A production system could be characterized by reconfigurability at both a system level and an element level (Koren, 2010; Maier-Sperdelozzi *et al.*, 2003), and at what level reconfigurability is needed depends on the change drivers. What must initially be identified is hence the change drivers, and thereafter the need for reconfigurability must be specified.

5.2.1 Strategy-related change drivers

Strategy-related change drivers are internal change drivers that refer to the company's own manufacturing strategy (ElMaraghy and Wiendahl, 2009). In the Factory-in-a-Box study reconfigurable production systems were designed in order to handle the change in production location. In all the Factory-in-a-Box case studies reconfigurability was considered needed in order to enable the change in production location quickly and easily. The need for change in production location could thus be regarded as a strategy-related change driver. That was an in-company decision and related to strategy rather than to an external requirement.

Mobility was previously described in the sense of mobility of single modules to enable rearrangement of the modules. What has been shown in the Factory-in-a-Box study and also pointed out by ElMaraghy and Wiendahl (2009), is that mobility also involves moving the whole production system to new locations.

A distinction could be made between

- *module mobility – the ability to move modules, i.e. groups of elements within or between systems, and*
- *system mobility – the ability to move whole production systems to new locations.*

In this thesis module mobility is what was previously referred to as “mobility” (ElMaraghy and Wiendahl, 2009; Nyhuis *et al.*, 2006). In all the case studies in the Factory-in-a-Box study, module mobility characterized the modules in order to enable rearrangement. Module mobility does not lead to a change in functionality or capacity as such but rather affects the reconfiguration time by enabling quick movement of the modules. Module mobility is thus suggested to be defined as a supporting characteristic based on the categorizations previously made.

System mobility, on the other hand, implies that the production system is easy and quick to move and install. In the Factory-in-a-Box study it was shown that reconfigurability could enable this. System mobility was enabled by e.g. module mobility, modularity, and integrability for the system to easily and quickly be reassembled and moved. After removal it could easily and quickly be assembled. System mobility enabled the change driver and in these cases led to a change of location. Therefore, there are suggestions that it should be categorized as a critical characteristic. The two types of mobility are described in *Figure 27*. Mobility is described in more detail in Paper V.

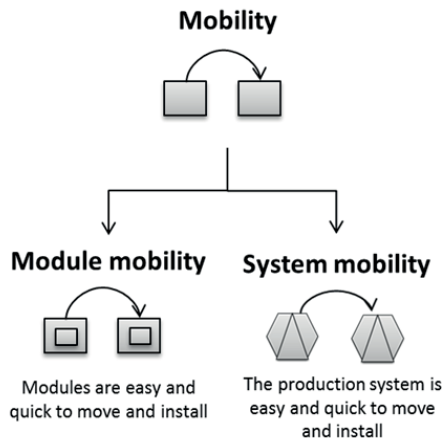


Figure 27. Two types of mobility, system mobility and module mobility.

The need to change the production location was also considered as a change driver in MaxAuto UK and DaxVehicles. In these case studies the production systems were designed to be moved to another production site in order to reach a new market. The production systems were designed to easily

be packed, transported, and unpacked and also to easily and quickly be ramped up to full production. To enable this, the whole production system was designed to be prepared for system mobility, however, to different extents between the three case studies. The ambition was for the production systems to be kept “as simple as possible” (as described by a respondent in the MaxAuto UK case study). Even if the aim was to reach new markets, this implied a move to low-wage countries and therefore a high level of automation was not justified. Manual or semi-automatic equipment parts were used or planned to be used that were independent from each other. Heavy equipment was avoided in order to achieve module mobility.

Also the material handling system was planned to be manual or semi-automatic. The information system would be prepared for the differences in culture as well as language according to the respondents. In e.g. the DaxVehicle study there were plans to develop multilingual instructions.

5.2.2 Product-related change drivers

In several case studies product variations were identified as an important change driver. This mainly implied that the number of product variants increased during the product life cycle due to specific customer demands. When the production systems were designed, the respondents knew that new variants of particular product types would appear but not exactly when they would be introduced and what they would look like.

To deal with future product variants the production systems were characterized by reconfigurability to different extents and in different ways. In the MaxAuto Sweden study and the DaxVehicles study the production systems were designed to be modular to enable rearrangement. The easiness to quickly switch between orders was considered highly important and modularity was the reconfigurability characteristic that would primarily enable this. In e.g. MaxAuto Germany the production system was designed to be modular in stations, fixtures, as well as tooling in order to handle new product types. In MaxAuto Sweden the production system was designed to be modular with pallets that were also designed to be modular in order to fit the product types that were planned. Also the stations were decoupled from the line that enabled adding or removing of stations. Modularity was consequently the reconfigurability characteristic mainly considered.

Modularity is often regarded as a key reconfigurability characteristic and as the most apparent characteristic (Mehrabi *et al.*, 2000b). Modularity was, however, previously categorized as a supporting characteristic.

The supporting characteristics, especially modularity, were more explicitly focused on in the case studies than were the identified critical characteristics.

Modular manufacturing could be seen as a precursor to the field of reconfigurable production systems (Tsukune *et al.*, 1993). However, modularity as such does not necessarily lead to a change in product variations but it must be in combination with the other supporting characteristics. In the case studies the focus on modularity is consequently not sufficient to design a production system to be reconfigured according to new product variants. To enable reconfigurability the modules must be easily integrated with each other and be characterized by diagnosability (Koren, 2010). These characteristics may have been embedded in the modularity requirement, but this was not shown in the case studies.

In the frame of reference the critical reconfigurability characteristic that explicitly deals with product variations is convertibility, which implies the ability to easily transform the functionality of the existing production system and its including subsystems and elements to suit new production requirements (Koren, 2010).

Demonstrators 1 and 2 were explicitly designed for convertibility that was enabled by standardized interfaces (integrability), modular base plates and independent equipment (modularity), equipment on air cushions or avoiding heavy equipment (module mobility), and automatic supervision of performance/software for quality control (diagnosability).

In addition, demonstrator 1 was prepared for change of level of automation to enable making a new product type requiring e.g. more manual production equipment.

In the frame of reference automatibility was not categorized as a critical or supporting characteristic. In case study demonstrator 1 automatibility was used to handle new product types. In that case study it could, therefore be regarded as a critical characteristic.

Consequently, these demonstrators were designed in accordance with the critical and supporting reconfigurability characteristics and a comprehensive perspective of reconfigurability. The change drivers were enabled by convertibility and automatibility, which in turn were enabled by the supporting characteristics.

5.2.3 Volume-related change drivers

Volume variations were expected in most of the cases. The volume variations were either unpredictable (demonstrator 1, DaxVehicles, and MaxAuto Sweden) or predicted to change along a stable curve through the product life cycle (MaxAuto UK and MaxAuto Germany). In these cases where volume changes were predictable, the production systems were designed for an expected maximum volume and scaled up during their life cycle mainly by adding test stations.

Modularity was emphasized as an important characteristic also when handling volume variations (in the same way as it was an important characteristic to deal with product variations, which was concluded in the previous section).

In the frame of reference scalability was defined as a critical reconfigurability characteristic enabling volume variations and volume fluctuations (Bi *et al.*, 2008). It was argued that it is hard to get a conventional system scalable due to the fact that such systems are optimized for a fixed capacity (Son *et al.*, 2001). Physical scalability is closely connected with line balancing. The balancing problem involved when scaling up and down was highlighted in MaxAuto Sweden. The modularity enabled some extent of scalability, but due to the cycle time the production system was not designed to be very scalable and consequently designed for a maximum volume. To scale down was deemed much easier because then operators could be removed.

Demonstrators 1 and 2 were deliberately designed for scalability to handle volume variations, which implied using equipment with standardized interfaces (integrability), modular base plates (modularity), equipment on air cushions (module mobility), and automatic supervision of performance (diagnosability). These characteristics were the same as the ones enabling product variations, but the detailed options of the supporting characteristics to enable scalability compared to e.g. convertibility differ.

Handling volume variations could be enabled by changing the level of automation, which was exemplified in demonstrator 1. When the volumes increased a manual workstation could be exchanged for a more automatic one.

A distinction could be made between physical and logical scalability, where physical scalability is achieved by a modular structure of the system elements while logical scalability implies modern open architecture control techniques (Deif and ElMaraghy, 2007). Logical scalability was exemplified in demonstrator 1, where a superior control system was installed that linked the different software solutions/programs to each other. In the rest of the case studies scalability referred to physical scalability since the case studies involved semi-automatic and manual production systems.

5.2.4 Technology-related change drivers

Several technology-related change drivers were identified in the literature concerning uncertainties in production technology along the product life cycle (Löffler *et al.*, 2011b; Park and Choi, 2008; Schuh *et al.*, 2005), for example replacing manual resources with automatic resources, and substituting slow tooling by fast tooling.

In the case studies production technology was not identified as a change driver. The respondents in the MaxAuto study tried to stay with known processes and did not have many resources to perform e.g. benchmarking activi-

ties of new production technology. Nor was there an expected future external requirement from customers or legislation to change production technology.

To conclude, this section aimed to analyse the general need for reconfigurability and each change driver linked to the reconfigurability characteristics. The main conclusions of the analysis in this section can be summarized as follows:

- *To handle changes in production location, the production system was characterized by mobility. A distinction could however be made between system mobility and module mobility.*
- *Handling change drivers was considered highly important, but reconfigurability and the reconfigurability characteristics were not well-known terms among the respondents.*
- *The supporting characteristics, especially modularity, were more explicitly focused on in the case studies than the critical characteristics.*

5.3 Consideration of reconfigurability in the production system design process

In five of the case studies, production system design processes were studied with a focus on the consideration of reconfigurability. This included how the change drivers were analysed in the actual process and subsequently considered throughout the design process. It also included to what extent the production system design support involved reconfigurability.

5.3.1 Existing support for reconfigurability in the production system design process

Due to the complexity involved when designing production systems it is hard to consciously design the production system from a holistic perspective. It is hard for one system designer to fully grasp all details in relation to the overall system (Bellgran and Säfsten, 2010; Bennett and Forrester, 1993). When designing reconfigurable production systems there are several dimensions to consider since all subsystems must be ready for reconfigurability and reconfigurability is a term comprising several characteristics. (This is also described in Paper III.) Furthermore, when designing reconfigurable production systems, reconfigurability must be considered from the outset (Koren *et al.*, 1999) and the need for reconfigurability should be analysed before the production system design is started (Jackson, 2000). To handle the complexity involved when designing reconfigurable production systems a structured production system design process is desirable and reconfigurability should be included in such a process. A design process should say what

should be done and when, what techniques and tools will be needed at each stage, what information needs to be collected, and what the output or result of each stage would be (Love, 1996).

In the DaxVehicles, MaxAuto, and VoxVan studies, the production systems were designed according to structured processes. The models used in the MaxAuto and the VoxVan studies were mainly focused on product design but did also include a few activities related to the design of production systems. The processes were divided into similar phases to the ones described in the frame of reference, *Figure 28*. None of the processes in the cases studied in detail described the activities that needed to be carried out.

The processes in the case studies to a larger extent comprised stages and activities in the latter phases of the process. This contradicts the need to put as much effort as possible into earlier activities since in the early phases the decision space is often large while the cost for changes is low (Blanchard and Fabrycky, 1998).

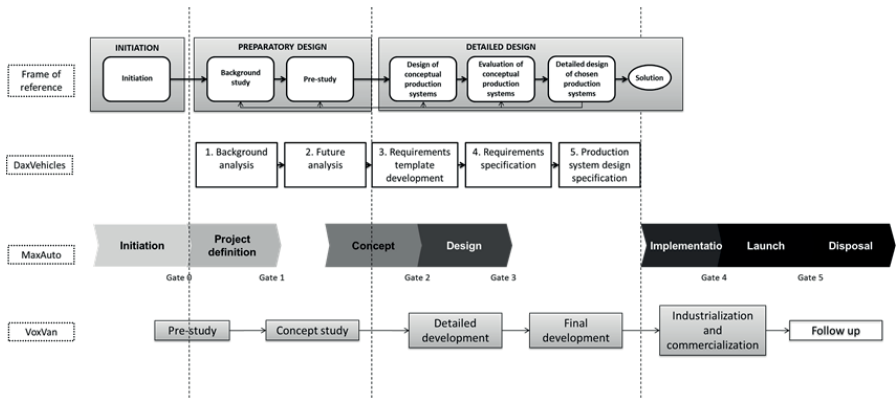


Figure 28. Comparison of the production system design phases between case studies and the frame of reference

Additional support for designing production systems in terms of checklists and templates for requirement specifications was used. However, in none of the case studies a structured production system design process (as defined by Love (1996)) was used. The support that existed for designing production systems considered reconfigurability to a very small extent, by briefly paying regard to single reconfigurability characteristics, for example in MaxAuto Sweden.

The case studies indicated that there was a lack of structured production system design support and that the support that existed only occasionally involved reconfigurability.

According to previous research studies (Chryssolouris, 2006; Duda, 2000), the design of production systems in practice often evolves ad hoc and is not based on a long-term plan, which was also shown in these case studies. Production system design is founded on past experience and judgement based on experience (Yien, 1998).

Several case studies had a lack of in-house competence in design of production systems, i.e. there were few production engineers or industrial engineers. In MaxAuto UK only one person was assigned for production system design and in MaxAuto Germany there were two. To strengthen production system competence, external production system suppliers were used. The external system suppliers were, however, only involved until the installation of the production system and thereafter their assignment was terminated. In addition, the system suppliers focused on one single project and had no comprehensive picture of the activities in the company.

In the MaxAuto case study the design of the production system was performed in discussion with the system supplier and very few requirements were documented. Even if the stage-gate model was followed carefully, it gave limited support for designing production systems, as previously mentioned. Similarly, in the DaxVehicles study production systems were mainly designed based on the staff's existing skills. This is alarming since ad hoc approaches require numerous iterations and correction stages (Wu, 2001) and thus carry a risk of losing responsiveness to change.

The case studies showed that the production system was designed according to existing skills but in several case studies there was a lack of in-house competence in designing production systems.

In those case studies where there was a lack of both structured production system design support and in-house competence in the production system design field the prerequisites for a structured production system design process adopting a long-term view were inadequate.

The lack of in-house competence could also denote a risk of being less responsive when a need for a change in the system occurred since the external production system designers were only involved until installation of the production system and did thereafter not provide any support.

To summarize, the lack of staff skilled in production system design and the lack of support for designing production systems as well as inadequate consideration of reconfigurability in the production system design support that existed implied that the prerequisites for considering reconfigurability when designing the production system in the case studies were scant.

5.3.2 Considering reconfigurability in the production system design process

The actual consideration of reconfigurability when designing production systems could be divided into two parts, first the identification of change drivers and the specification of the need for reconfigurability, and thereafter the consideration of reconfigurability in the production system design process (Jackson, 2000).

It was shown in the case studies that change drivers were not considered in the early phases of the production system design processes. Instead alternatives for the production system design were discussed very early in the process without considering for the need for reconfigurability. Subsequently, throughout the process reconfigurability was fragmentarily considered.

In MaxAuto UK an idea of what the production system was going to look like was agreed on already in phase 0 and it was decided that the production would be designed based on a previous production system. In the following phase tact time, test criteria, output, quality, repeatability, and level of automation were decided. The production system was prepared to be changed according to the planned volume increase and a few product variants. In MaxAuto Germany the production volumes and level of automation were specified in phase 1. A plan for necessary equipment, tooling, IT hardware, software licences, and new staff was also made in this phase. Accordingly, there was a focus on the goals of the production system instead of on the means, which would have been important to focus on in such an early phase of the production system design process (Bellgran, 1998).

In MaxAuto Sweden the reconfigurability characteristics were in focus at an early stage. First, a specification of requirements was made in an early phase including traceability, modularity, easiness of moving, easiness of running in an effective way with a varying number of operators, having information boards at all stations, and being ready for variations in product types. However, investing in such reconfigurability could not be justified at the management level. The production system was therefore designed for a certain volume and a certain number of variants. In this case study, therefore, reconfigurability was considered in the early phases but not in relation to identified change drivers.

In all case studies, there were prerequisites for analysing the need for reconfigurability due to the available information in the early phases. All projects had a plan for the volumes throughout the life cycle and at least a brief view of what product types were going to be introduced. A market analysis was done in an early stage and it was also considered whether the production system should be produced at the site, be relocated, or a mix of both.

In the case studies, change drivers were not analysed in a structured way before production system alternatives were generated, which was often done in a very early phase of the production system design process.

A holistic perspective in the production system design process has been advocated. When designing for reconfigurability a holistic perspective is crucial since all elements must be ready for reconfiguration. In the case studies the focus was, however, mainly on the technical systems.

In the DaxVehicle study it was shown that taking a holistic perspective was challenging. Since the researcher had a participant role in this project in the earlier phases there were opportunities to discuss the holistic perspective in the project team. All team members in an early phase agreed on the importance of a holistic perspective. However, when the requirement template was to be developed later on it was not obvious that the “headings for requirements” about e.g. the work environment and security would be formulated. The project team advocated “headings for requirements” that would result in a quantitative requirement, e.g. cycle time or set-up time. Specifications for qualitative requirements were seen more or less unnecessary by the project team. However, both types of headings were formulated. Later on in the process, in the phase when the research had a passive role, the requirements were formulated concerning the technical system. In order to follow the template the project team subsequently specified requirements concerning the human system, the material handling system, and the information system. A similar attitude was also noticed in the MaxAuto Germany and the MaxAuto UK studies.

A holistic perspective was initially proposed among the respondents but when the production system was designed the technical system was prioritized.

In order to focus on the manufacturing efficiency over the whole product life cycle when designing the production system it was necessary to have a long-term view (Bellgran and Säfsten, 2010). However, because of the changing needs it was perceived hard to have a long-term view, which was shown in several of the case studies. In the MaxAuto study the production systems were planned for the product variants that they knew were coming but they had designed the production systems for the existing product variants. They did not have a mindset in production system generations. Volume variations in the product life cycle and different product variants were considered to various extents. This was, however, according to the planned volume and product variations and not ready to be reconfigured according to possible future product types and volume variations.

The lack of a long-term view was combined with a tendency to stay with old ideas. In the MaxAuto, Dax Vehicle, and VoxVan studies the production systems were designed according to previous production concepts. In other words, the conceptual length of life was much longer than both the product length of life and the technical and economic length of life. This has also been shown in previous research (Bellgran, 1998).

Since the production system concept has a long life it is, however, crucial how the production system is initially designed. In the case studies the pre-conditions, such as the need for reconfigurability, had changed compared to previous product generations. When the production system concepts were reused, there was hence a risk that they were not totally adapted to the present conditions. In MaxAuto UK the previous production system was designed for production in the UK, which implied, among other things, a closeness to product development with an in-house knowledge about the product and how it was produced. The current production system on the other hand would be used at a site far from the UK site, and the product development had different conditions due to its location in China. This was considered to a certain extent a very low level of automation to keep the production system as simple as possible, but the concepts as such were the same as the previous ones.

The respondents advocated retaining good things from previous production systems, getting experience from lessons learned, and staying with known processes that had been successful. However, to carefully consider what will or might be needed in the future must also be considered.

The respondents found it hard to have a long-term view and designed their system according to today's products. The production system concepts were strongly influenced by previous production systems.

The life-cycle perspective when designing production systems is also described in Paper II.

The point of a reconfigurable production system is that it is designed for the current product family but possible to change to future products when that is needed. Therefore, by designing a reconfigurable system it is possible to be prepared for a future that the designer for the moment only has a vague notion of without making unnecessary investments. In the case studies this became slightly paradoxical since the investment into reconfigurability could not be justified since it was not certain that reconfigurability would be necessary in the future.

This section aimed to analyse the supports for reconfigurability in the production system design process that were used in the case studies and how reconfigurability was considered in the actual production system design pro-

cesses. The main conclusions of the analysis could be summarized as follows:

- *The companies had a lack of structured production system design support and the support that existed did not involve reconfigurability.*
- *The production systems were designed according to current knowledge in combination with a lack of in-house competence in designing production systems in several case studies.*
- *Change drivers were not analysed in a structured way before production system solutions were generated, which was often done in a very early phase of the production system design process.*
- *The respondents found it hard to have a long-term view and designed their system according to today's products. The production system concepts were strongly influenced by previous production systems.*

CHAPTER 6 – Supporting reconfigurable production system design

In this chapter, support for designing reconfigurable production systems is proposed based on the results presented in this thesis. First, support to identify change drivers and to specify the reconfigurability need is suggested. Thereafter support to consider reconfigurability in the production system design process is presented.

6.1 Proposing support in two parts

Several challenges were identified in the case studies described in the previous section in order to successfully consider reconfigurability in the production system design process. It was argued that change drivers were not analysed in a structured way before alternatives were generated. Therefore the actual need for reconfigurability was not identified. It was also argued that there was a lack of a structured production system design support in the case studies and that the support that existed did not involve reconfigurability. This was also concluded in Paper I.

This thesis aims at increasing knowledge of reconfigurability and will therefore discuss what support is needed to consider reconfigurability in a structured way to be used as a complement in an existing production system design process used at manufacturing companies.

In existing support for designing reconfigurable production systems presented in the RMS field Deif and ElMaraghy (2006) presented an approach in which market demand is first captured in order to generate the required capacity and functionality in accordance with customer needs. This will act as an input to the second layer, system-level reconfiguration, when different reconfigurations are generated. The best feasible configuration is chosen and taken into the third layer, which deals with physical implementation of the selected configuration (Deif and ElMaraghy, 2006). Also Heisel and Meitzner (2007) and Jackson (2000) emphasises that it is vital to first identify the need for reconfigurability and thereafter design the production system in accordance with that need. The proposed support will therefore be described in two parts. First, support needed to analyse the change drivers and the actual need for reconfigurability will be described. Thereafter, support to

consider reconfigurability in the production system design process will be described.

6.2 Part 1: Support for analysing the need for reconfigurability

A problem in production system design practice in manufacturing companies, which was described in the previous chapter, is the mix between goals and means or, in other words, the fact that alternatives are often generated before the requirements are specified. In the case studies it was shown that supporting reconfigurability characteristics were often considered even if the change drivers had not been carefully analysed.

By first identifying the change drivers and the actual need for reconfigurability rather than generating solutions, a movement towards reconfigurability could more easily be justified. In two of the case studies, reconfigurability was considered but the actual need for reconfigurability was not specified, which could have been one reason why the management level could not justify such a movement.

A logical order based on what has been presented in this thesis is to first identify change drivers that form the basis for the need for reconfigurability. When the change drivers are identified, relevant critical and supporting reconfigurability characteristics could be decided, *Figure 29*.

However, in this categorization described in the frame of reference the characteristics mobility and automatibility were not included. Based on the analysis made of the case studies in the previous chapter, a categorization of mobility and automatibility was suggested. However, in order to definitely categorize the two characteristics further research is required.

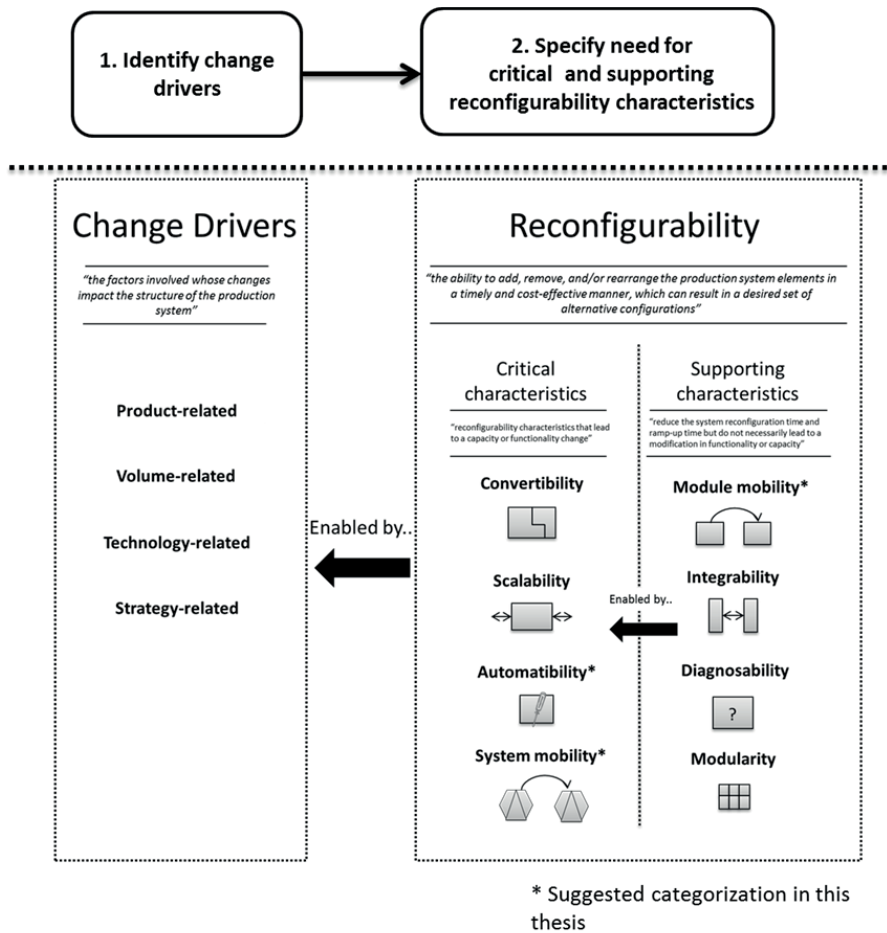


Figure 29. Order when specifying reconfigurability need.

Since all production system design projects are unique, there is no universal manual on how to achieve reconfigurability. Reconfigurability might not be needed in all production systems, nor are there prerequisites for reconfigurability in all production systems. But in order to prepare for the future, the need for reconfigurability should always be considered early in the production system design process. The need for reconfigurability should be analysed in each such process in order not to be deprived of an effective way of managing change.

A proposal is presented in Table 7 suggesting questions to pose to identify prerequisites and the need for reconfigurability based on the findings in this thesis. The table has two sections, first general questions to pose in order to decide the prerequisites for reconfigurability in the actual case and thereafter questions focusing on the change drivers linked to the critical reconfigurability characteristics.

Prerequisites for reconfigurable production systems depend both on the production system design process and the product to be manufactured (Table 7, section 1).

Factors identified in this research are first having skilled staff and a knowledge of reconfigurability (1A in Table 7). This implies, among other things,

- the need to understand the importance of comprising all production sub-systems from the beginning of the production system design process to avoid suboptimization (by for instance forming a cross-functional production system design team),
- utilizing efforts of previous phases in which the decision space is large while the cost of changes is low,
- beginning to generate requirements before designing solutions,
- staying updated in e.g. new technology solutions and not necessarily persisting with known processes,
- being aware of the reconfigurability characteristics and how they can be realized in a holistic manner.

Second, a design according to a structured production system design process is useful in order to handle the complexity involved (1B). A stage-gate model is often used to coordinate the product development project including the design of production systems (which was shown in the case studies). The process is, however, seldom seen as a means to design the ultimate production system and does not specify activities in detail and is hence not the support that it has the potential to be. A support should say what should be done and when, what techniques and tools will be needed at each stage, what information needs to be collected, and what the output or result of each stage would be (Love, 1996).

Reconfigurability was described as a customized flexibility, and consequently a prerequisite for reconfigurability is customization. This implies that the production system is designed for a specific product family (1C).

The ability to reconfigure the production system according to change drivers requires a long-term view of the production system. All investments in the production system life cycle are not made from the beginning but only the capacity that is needed for the moment is invested in. This requires a long-term view in terms of investment (1D).

Reconfigurability also requires a readiness to have a life-cycle perspective of the production system and to be ready to change the production system during its life cycle (1E).

When prerequisites for reconfigurability have been analysed, the change drivers need to be identified (Table 7, section 2). If the volumes are predicted to vary or fluctuate (2 A-B), either a scalable production system is justified or a system that could easily be changed in level of automation. If several new product types are going to be introduced, convertibility or automatability is justified (2C). If new production technology needs to be added,

reconfigurability is justified (2D) (e.g. Bruccoleri *et al.*, 2003). However, due to the fact that this change driver was not identified in the case studies no links could be suggested. If the production location needs to be changed, system mobility is required (2E). Reconfigurability could also be needed as a part of the business case, i.e. to attract new customers (2F).

Table 7. *Support for reconfigurable production system design: Part I – Identifying prerequisites and need for reconfigurability*

1 Questions to analyse prerequisites for reconfigurability	Alternatives	Prerequisites for reconfigurability
<p>A Are staff skilled in production system design and reconfigurability available?</p> <ul style="list-style-type: none"> • <i>The need to understand the importance of comprising all production subsystems from the beginning of the production system design process to avoid suboptimization (by for instance forming a cross-functional production system design team.).</i> • <i>Utilizing efforts of previous phases in which the decision space is large while the cost of changes is low.</i> • <i>Starting listing requirements before designing solutions.</i> • <i>Staying updated in e.g. new technology solutions and not necessarily persisting with known processes.</i> • <i>Being aware of the reconfigurability characteristics and how they can be realized in a holistic manner.</i> 	<p>Yes No</p>	<p>√</p>
<p>B Are the production systems designed according to a structured production system design process? <i>This includes a process that says</i></p> <ul style="list-style-type: none"> • <i>what should be done and when</i> • <i>what techniques and tools will be needed at each stage</i> • <i>what information needs to be collected</i> • <i>what the output of the result of each stage would be</i> 	<p>Yes No</p>	<p>√</p>
<p>C Is the production system customized for a specific product family?</p>	<p>Yes No</p>	<p>√</p>
<p>D Is there a readiness to have a long-term view in investment in production capacity?</p>	<p>Yes No</p>	<p>√</p>
<p>E Is there a readiness to have a life-cycle perspective of the production system?</p>	<p>Yes No</p>	<p>√</p>

2 Questions to analyse the need for reconfigurability		Alternatives	Scalability	Convertibility	System mobility	Automatability
Volume-related						
A	Is the product volume going to vary? Are there volume variations expected through the product life cycle and in future product generations?	Yes	√*			√
		No				
		Don't know	√			√
B	Is the product volume going to fluctuate? Will the volume vary fast and often?	Yes	√			√
		No				
		Don't know	√			√
Product-related						
C	Number of product variants to be introduced? Were the products initially designed in several variants?	A few				
		Many		√		√
Technology-related						
D	Is new production technology required in the product life cycle? Does new production technology need to be added?	Yes				
		No				
		Don't know				Reconfigurability needed**
Strategy-related						
E	Is the production location going to change through the product life cycle? Will production be moved between several sites depending on e.g. the position in the life cycle?	Yes				√
		No				
		Don't know				√
F	Are there any requirements or constraints concerning reconfiguration? Is some reconfigurability characteristic required for some other strategic reason?	Yes	√	√	√	√
		No				

*The symbol (√) indicates what critical reconfigurability characteristics are linked to the question and are relevant to consider.

** No links have been identified in the case studies or in the literature review.

Based on the above the detailed need for reconfigurability should be specified including both critical and supporting reconfigurability characteristics. This involves what level of reconfigurability is required and therefore specifies the need on an element level and/or system level.

If the questions in Table 7 are posed in an early phase, the need for reconfigurability can be considered throughout the whole production system design process.

6.3 Part 2: Considering reconfigurability need in the production system design process

Previously, a production system design process including typical work activities was presented (*Figure 11*), which was also compared to the processes carried out in the case studies (*Figure 28*). It was shown that the processes in the case studies were divided into phases similar to these processes and similar activities were performed, but with a lack of documentation and formulation of requirements. Neither in the process presented in the literature nor in the case study has reconfigurability been comprehensively considered in the production system design process.

Therefore, the second part of the support for designing reconfigurable production systems suggested in this thesis will be described in this section. Activities identified in the case studies as well as in the literature are considered. The activities have a character of “reminders” in order to increase the awareness of consciously designing reconfigurable production systems from a holistic perspective. In detail, the activities must be described in each specific case.

In phase 0 the production system design process is initiated. At this stage the market analysis is normally initiated and the project is formulated including investment request and project planning. In the case studies this phase also involved a first market analysis, mainly to justify the project at a management level.

A first gathering of data for analysing the need for reconfigurability (which was presented in the previous section and Table 7) is suggested to be made in this phase. Hence, the data that need to be gathered are

- available skills for designing production systems and reconfigurability
- available structured production system design process
- customized production system
- preparedness for long-term view and a life-cycle perspective
- predicted product volume and its variations and fluctuations
- predicted number of future product types
- future production technology requirements
- production location and need to change location
- constraints linked to reconfigurability

The data should be structured and documented when gathered.

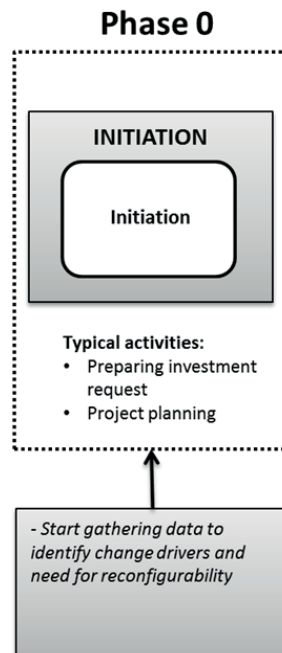


Figure 31. Support for reconfigurable production system design – phase 0.

In phase 1, the preparatory design, the gathering of data is suggested to continue in order to give opportunities for analysing the need for reconfigurability. In the background analysis the present production system and products are analysed which could give input to the reconfigurability needs analysis.

In the pre-study the market analysis is finished, which implies that enough data have often been gathered in order to analyse and identify the need for reconfigurability.

When all data have been gathered as early as possible, this analysis should be conducted according to Table 7 in the previous section. By identifying the need for reconfigurability at an early stage, opportunities for considering the needed reconfigurability in the following production system design process are given e.g. when specifying system functions and system tasks, and the first list of requirements is developed.

The human resources that should be involved in the production system design project, e.g. system suppliers, are often selected at this stage. The reconfigurability aspect should be considered since special competence might be needed to enable reconfigurability. A certain reconfigurability knowledge might be a requirement when selecting a system supplier.

If the need for reconfigurability is carefully analysed in the pre-study, additional investments into reconfigurability could also be justified. The analysis could be used as a decision support at a management level.

Also, if needed, additional benchmarking activities due to reconfigurability are suggested to be made at this stage.

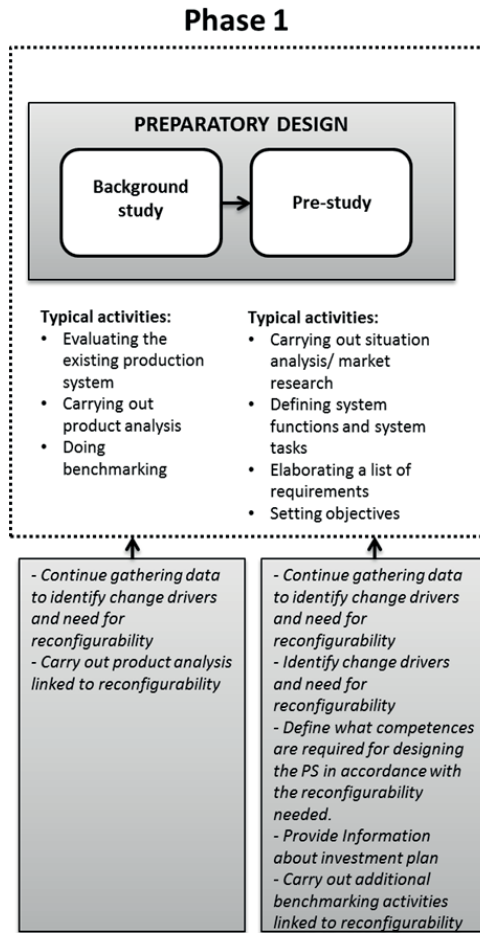


Figure 32. Support for reconfigurable production system design – phase 1.

In phase 2 the conceptual production system is designed. At this point the project team should have a clear view of what critical and supporting reconfigurability characteristics are needed as well as a general knowledge of how to achieve them. In this phase reconfigurability should be considered in all activities, first in terms of requirements for the production system and then in terms of alternative production system design options.

Activities that could be performed at this stage (identified in the case studies) are formulating a project plan including e.g. a time plan for procuring equipment, prototype building, education, and a time-phased list of activities; reviewing patents, legislations, and ISO certification; doing a risk analysis; and going through performance objectives. In all these activities reconfigurability should be considered in order to formulate proper requirements for the alternative production system design options.

Subsequently, based on the formulated requirements the preliminary concept for the new production system could be specified (in the case studies this included e.g. time plan, budget, manufacturing processes, layout, material flow, capacity, and machine utilization as well as overall production layout of the machines, flow of materials, and flow and process charts). At this point alternatives for reconfigurability are suggested to be designed. The basis for success in the conceptual system design is laid since reconfigurability has been considered from the start of the design process, in which knowledge has been gathered and specific requirements have been formulated linked to reconfigurability.

In the conceptual system design, physical, logical, and human reconfiguration is proposed to be considered, based on the need for reconfigurability initially formulated.

In the detailed production system design the conceptual production system is specified. Factors considered in this phase (identified in the case studies) are e.g. quality parameters, workplace design, design rules, packaging, material supply, work content, training, IS/IT, health and safety, environmental requirements, material feeding, storage, and maintenance. When analysing and specifying all these factors, reconfigurability should be considered since all elements of the production system must be ready for reconfigurability.

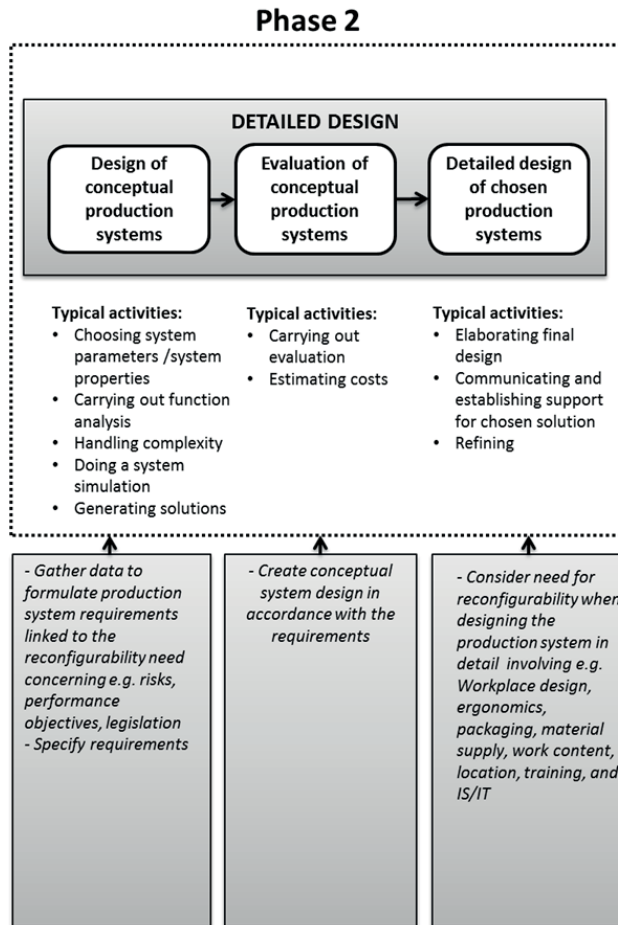


Figure 33. Support for reconfigurable production system design – phase 2.

CHAPTER 7 – Discussion and conclusion

In this chapter the results of the thesis are discussed and concluded. First a general discussion about the research is presented. The chosen method is thereafter discussed. Conclusions are made where the research questions are briefly answered. Thereafter the academic and industrial contribution of this thesis is described. Finally future research on the topic is proposed.

7.1 General discussion

In this thesis reconfigurability has been pointed out as a possible way to handle responsiveness to changes in the production system. This positioning was based on several future reports explicitly denouncing reconfigurability as an important future capability (Carlsson *et al.*, 2010; National Research Council, 1998; Technology Strategy Board, 2012; The Ad-hoc Industrial Advisory Group, 2010; Thomas *et al.*, 2012).

The first research question aimed at identifying and describing constituent parts of a production system. A holistic perspective was justified when designing reconfigurable production systems (Bi *et al.*, 2008) and an overview of the constituent parts of the production system was presented in *Figure 4*. The overview was based on system theory and included subsystems most often described in production system design literature. Based on this overview the holistic approach taken in production system design literature could be studied and the constituent parts were explicitly described. However, the overview did not capture the thought that the system as a whole has properties that refer to the whole, where the whole is not the same as the sum of its parts (Checkland, 1999). The fact that the production system is the effect of how people utilize the available work organization options, ergonomic options, and technical options to design the system (Bellgran, 1998) was not captured in the overview.

It was found that RMS literature seldom adopts a holistic perspective but focuses on single subsystems. Since a holistic approach was rarely taken in any of the case studies, the need to support a holistic perspective when designing reconfigurable production systems was further emphasized.

The second research question regarded describing what characterizes reconfigurability and a reconfigurable production system.

In production system design literature reconfigurability has seldom been considered. Flexibility has been considered, however, to a limited extent. In e.g. the DRAMA process (Bennett and Forrester, 1993) variety and volume flexibility were expressed as design criteria, and in the process proposed by Wu (1994; 2001) flexibility was included. By considering reconfigurability as a way to achieve flexibility and regarding reconfigurability characteristics as design criteria, as proposed in this thesis, more concrete ways to handle change drivers could be offered. Reconfigurability and flexibility are related terms. For example, scalability expresses volume flexibility and convertibility expresses mix flexibility (Koren, 2010). The reconfigurability characteristics could thus be seen as a palette of design criteria.

The need for a comprehensive view of reconfigurability was supported by the case studies. The interest among the case study companies regarding reconfigurability was strong. It became clear that the field of reconfigurable production systems is still mainly active in academia and that the knowledge of the topic in manufacturing companies was limited. However, since the need for handling change was urgent in several of the companies studied, the thoughts and ideas of realizing reconfigurability met with a favourable reception by most of the respondents.

Four types of change drivers were described and explicit change drivers were listed. The types of change drivers included both change drivers that cannot be influenced by the manufacturing company and change drivers that were designed by the manufacturing company itself, driven by influences from the environment (Löffler *et al.*, 2011a; Löffler *et al.*, 2011b).

Technology-related change drivers differed from the other types of change drivers. Technology-related change drivers could be linked to the previously mentioned change drivers since a change in technology could be triggered by a new product type or by a change in volume.

Based on the RMS field a compilation of reconfigurability characteristics was presented (Paper III). Characteristics linked to both reconfigurable production systems and reconfigurable assembly systems were included since this thesis includes assembly systems in the production system term.

To bring order among the reconfigurability characteristics a categorization was made into the characteristics that lead to a change in capacity and functionality and those characteristics that do not necessarily lead to that but rather reduce the reconfiguration time (Koren, 2007; Koren and Shpitalni, 2010). This categorization was chosen since it clarified whether there were any reconfigurability characteristics that were more essential for reconfigurability than others. This categorization, however, only comprised the reconfigurability characteristics that these authors included as such characteristics. Among these characteristics, mobility and automatibility were not included. These have been defined as reconfigurability characteristics by other scholars (ElMaraghy and Wiendahl, 2009; Nyhuis *et al.*, 2006). Therefore, a categorization of the reconfigurability characteristics mobility and automatibility

was suggested based on the case studies. Mobility was divided into system mobility and module mobility. System mobility was suggested as a critical change driver since it dealt with the strategy-related change drivers to change production location. Whether reconfigurability is needed to change production location could, however, be discussed. In the case studies, it was shown that a change in production location was often needed. Moreover, the change needed to be made quickly and easily. Therefore, the system needed to be easily packed, moved, and unpacked. In order to manage that, it is argued that the system must be reconfigurable i.e. have a modular structure to be easily reassembled and also easily integrated and started up. However, if there is no need to make the change in location quickly and easily, reconfigurability might not be required.

Module mobility on the other hand has a different character compared to system mobility. It was shown that it was needed for system mobility but also to enable e.g. scalability and convertibility. To reconfigure a production system, equipment needs to be moved easily and quickly. Since this reduces reconfiguration time, it was suggested to be categorized as a supporting characteristic. In the VoxVan study it was argued that it is hard to make machining equipment mobile due to, for example, instability. However, in order to easily rearrange the equipment it was desirable.

Automatibility was the other characteristic not previously categorized. It was shown in demonstrator 1 that by changing the level of automation, the change drivers to manage volume variations and product variations could be dealt with. Therefore it was suggested as a critical characteristic. To regard automatibility as a design criterion and an enabler to deal with change has been advocated by Hedelind *et al.* (2007). Previous research also shows that automatibility is relevant to consider in order to, for instance, increase flexibility (Winroth *et al.*, 2006).

This categorization should be regarded as a suggestion with the purpose of providing support when defining the need for reconfigurability. It must also be pointed out that categorizations could be made in different ways. One categorization was made in Paper III, where the characteristics were categorized based on the nature of the reconfigurability characteristics, where some of them describe the structure of the production system and how production system elements/modules are arranged while others describe the functionality of the system and its elements.

The categorization into critical and supporting characteristics was, however, chosen. Another choice was made not to describe a more detailed pattern of how the characteristics are linked to each other. As previously described, change drivers are characteristic of a specific production system and can hence hardly be generalized (Schuh *et al.*, 2005). This justifies not giving a detailed plan how to deal with the change drivers through reconfigurability characteristics.

To carefully analyse potential change drivers and adopt a life-cycle perspective on the production system is important (Bi, 2011; Garetti and Taisch, 2012). The concept of reconfigurable production systems gives new perspectives on the production system life cycle. Previously it was described that the life cycle perspective implies that the production system itself could be studied as a whole and the system could be seen as an object that is created, used, and retired over time (Wiktorsson, 2000). By reconfigurable production systems the retirement is avoided and instead the production system is reconfigured and reused.

A challenge identified in the case studies was that the respondents found it hard to have a long-term view and often designed their system according to current products. Meanwhile, the production system concepts were strongly influenced by previous production system developments. The point of a reconfigurable production system is that it should be designed for a current product family and the current situation but be reconfigured when it is necessary. Accordingly, this is a way to handle the unpredictable future. To justify reconfigurability and to be able to design the production system in accordance with specific reconfigurability needs, a long-term view is required. However, it is rather a question of how unpredictable the future is than predicting what will happen. For instance, if a company knows that the volumes will follow a stable curve through the life cycle and not vary to any great extent, a reconfigurable production system might not be needed. But if the volumes are impossible to predict, and there is a probability that the volumes will fluctuate, reconfigurability can be justified.

The third research question addressed how to consider reconfigurability in the production system design process. Support divided into two parts was suggested. The first part aims to support the analysis of the need for reconfigurability and the second part aims to support the consideration of reconfigurability in the production system design process.

In the first part, prerequisites for reconfigurability and the need for reconfigurability should be analysed. The list of questions presented in the support is based on what has been identified in this thesis; however, there could be additional factors that affect the prerequisites and the need. What is important is to consciously analyse the prerequisites and the need for reconfigurability. The first part aims to support this analysis even if modifications might be needed depending on each specific case. The second part of the support aims to support the consideration of reconfigurability in the production system design process. The key point is that reconfigurability should be considered in all activities to prepare for physical, logical, and human reconfiguration.

In the RMS literature, approaches for designing reconfigurable production systems have been suggested (Deif and ElMaraghy, 2006; Mehrabi *et al.*, 2000b). However, these models were not linked to a general production sys-

tem design process and the general production system design literature (e.g. Wu, 1994).

The suggested support should be used as a supplement to existing production system design support by the production system designers, e.g. production engineers or industrialization engineers. In the case studies stage-gate models were used to support the production system design. These were similar to the production system design processes described by Wu (1994) and Bellgran and Säfsten (2010), even if the level of detail was lower. Therefore, the suggested support is based on the same phases. Depending on what the current production system design process looks like at each manufacturing company, the support must be adapted to fit the phases. A dilemma is, however, if the production system design process is poor and does not take a holistic perspective. In the case studies it was shown that there is a lack of production system design support and production systems are designed based on the production system designers' existing skills. This is in accordance with previous studies, which show that production system design is typically based on past experience and judgement based on experience (Yien, 1998). In practice, the production system design process is not regarded as a means to design the ultimate production system (Bellgran and Säfsten, 2010). The ad hoc approaches adopted require numerous iterations and correction stages (Wu, 2001). The case studies indicate that design of production systems is still not as prioritized an area as product design is (Bruch, 2012). Therefore, existing production system design processes presented in the literature must be transferred to the manufacturing companies.

The support proposed in this thesis has not yet been verified but is developed together with the case study companies. The support needs to be further tested and verified.

The objective has been to present a balanced picture of reconfigurability with an idea of encouraging the application of the reconfigurability thoughts and to involve reconfigurability in the actual production system design process. Reconfigurable production systems do not necessarily imply highly automated production systems, which are almost self-reconfiguring, as described in much of the RMS literature. In addition, it is not certain that reconfigurability is always needed. However, it is advocated that change drivers should always be analysed and the need for reconfigurability should always be considered.

7.2 Method discussion

The three research questions initially posed in order to fulfil the formulated objective have been answered. What must still be kept in mind is that the chosen research method and the research design influence the conclusions that can be drawn from the research.

Reconfigurability was studied on a conceptual level. A comprehensive view on reconfigurability and on the production system was taken. It has not been possible to both go into depth and be broad since the topic as such touches several theoretical fields. Therefore, the choice was made to include literature in the production system design field and the RMS field (including related concepts). However, what must be kept in mind is that the result of the research could have differed if another theoretical approach had been taken.

Besides the literature review the case study method was chosen to properly deal with the type of questions formulated. Several strengths of the case study method were highlighted, such as the ability to deal with a full variety of evidence and a flexibility to make modifications if the cases do not turn out to fit the research questions (Yin, 2009). Reconfigurability and reconfigurable production systems are still not very common terms in manufacturing companies and therefore the case study method was preferred to surveys. Case study research is appropriate in early stages of research on a topic (Eisenhardt, 1989), and even if reconfigurability and production system design are well established fields, the combination of the two is not. By using the case study method, data could be gathered by making interviews, studying documents, and making observations, which enabled a comprehensive picture of the topic (Yin, 2009).

In this thesis, two types of cases were studied: (I) companies that had an identified need for reconfigurable production systems and aimed to develop such systems and (II) companies that had not explicitly defined a need for reconfigurability, i.e. not consciously designed for reconfigurability. By studying reconfigurability in the first type of case studies, opportunities for reconfigurability were proposed and examples how to achieve reconfigurability could be studied. The second type of case studies, on the other hand, allowed studying the application and consideration of the thought of reconfigurability in conventional production system design processes.

Modifications were made throughout the process, however, mainly by adding case studies in order to get a broader picture. The number of case studies finally conducted gave an opportunity to gather knowledge about reconfigurable production systems and reconfigurability characteristics (the Factory-in-a-Box study) and to get a picture of how reconfigurability is considered in the production system design process (The Dax Vehicle, MaxAuto, and VoxVan studies).

One of the drawbacks often mentioned from case studies is the limited possibilities of generalizing (Yin, 2009). In this thesis, the ability to generalize is enabled through cross-case analysis in multiple-case studies (Leonard-Barton, 1990) and analytical generalizations (Yin, 2009) in single-case studies. In the Factory-in-a-Box study the demonstrators were compared to each other to get a general picture of change drivers linked to reconfigurability characteristics. In case study MaxAuto the case studies were compared to get

a general picture of how the production system design process supported reconfigurability. Still, it must be kept in mind that the conclusions are only valid for the cases that were studied.

The data collection in the Factory-in-a-Box study was made very early in the research process. The data were thereafter reviewed at a later stage in which all reconfigurability characteristics were studied. This could have affected the result since the data were initially gathered in order to study mobility. However, this risk is considered very small since an extensive amount of documentation was developed and gathered in the Factory-in-a-Box project and the demonstrators were studied in detail.

A disadvantage of using retrospective case studies is that the participants may not recall important events or their recollections might be biased. In MaxAuto Germany, for instance, the production system design process was studied retrospectively. Since there was a lack of documentation, the results were to a great extent based on the interviews that were conducted and thus dependent on the respondents' ability to correctly recall the process. The interpretations of the events could be different from what they would originally have been at the time (Meredith, 1998; Voss *et al.*, 2002). However, by using multiple sources of evidence, i.e. the little documentation made as well as respondents from different levels, this was tried to be avoided.

In the real-time case studies the problem of not recalling data was overcome, but this was more time-consuming (Voss *et al.*, 2002). In MaxAuto UK a project was followed through the early phases and this offered possibilities to get a comprehensive view, but it would have been too time-consuming to follow the project through all its phases.

Another risk in the real-time studies was that the researcher might lose objectivity and get too involved with the organization, the people, and the process (Leonard-Barton, 1990). To avoid this, interviews were carried out as the very first activity in e.g. MaxAuto UK and therefore unbiased data could be gathered. In demonstrator 5 and the DaxVehicles study this was not done.

Participant observations were used to different extents in the case studies (Yin, 2009). The participant observations gave several opportunities. In the DaxVehicles study it enabled the change drivers to be identified in a group including a variety of competences. Thereafter a template for a requirement specification for the production system could be formulated based on a holistic perspective. With the researcher assuming a passive role in the latter phases, the consideration of the identified change drivers and the usage of the template could be studied. The applied approach led to a close collaboration with people at the companies where the case studies were conducted. Therefore it was possible to get access to relevant data and get an understanding of the difference between what was said and what was done, to distinguish between rhetoric and practice. In demonstrator 5 as well as case studies DaxVehicle and MaxAuto UK, the author was situated at the compa-

ny for a period of time, which offered the possibility to get access to data that would otherwise not have been available.

7.3 Conclusion

The objective of this thesis was to develop knowledge of how to support the design of reconfigurable production systems. This objective was met by answering three research questions.

The first research question aimed to identify and describe the constituent parts of a production system. This question was first posed since a holistic perspective is crucial when designing reconfigurable production systems and therefore a clear view of what parts a production system includes is required.

A literature review provided a summary of the production subsystems including technical system, human system, material handling system, computer and information system, and buildings and premises. Examples of elements were given in the production system subsystems. Physical, logical, and human reconfiguration was relevant to consider according to the character of the elements.

It was shown that the literature in the RMS field seldom takes a holistic perspective but focuses on the technical system and the computer and information system. Reconfigurable production systems are often highly automated and human reconfiguration is therefore seldom described. In the Factory-in-a-Box study, where reconfigurable production systems were examined, reconfigurability involved physical reconfiguration, logical reconfiguration, and human reconfiguration.

The second research question implied describing what characterizes reconfigurability and a reconfigurable production system. In order to support the design of reconfigurable production systems an awareness of the reconfigurability characteristics is needed and how they can be realized in a holistic manner.

Reconfigurability is a broad term and could be defined by a number of reconfigurability characteristics. The critical reconfigurability characteristics including convertibility and scalability are characteristics that lead to a capacity or functionality change of the production system and reconfigurability. The supporting reconfigurability characteristics including modularity, integrability, and diagnosability are characteristics that reduce system reconfiguration time, but do not necessarily lead to a modification of functionality or capacity of the production system and not necessarily reconfigurability. In addition, automatibility and mobility are two reconfigurability characteristics not previously categorized.

In the Factory-in-a-Box case study it was shown that the need to handle change in production location was addressed by mobility at both a system level and a module level. A distinction was therefore suggested between

system mobility and module mobility. System mobility could be needed to handle change in production location and was suggested to be categorized as a critical characteristic. Module mobility, on the other hand, is needed to enable several types of change drivers, and was suggested to be categorized as a supporting characteristic.

Based on one case study, automatibility was suggested as a critical characteristic.

The third research question included describing how to consider reconfigurability in the production system design process. The literature review revealed that the general production system design literature described structured production system design processes but did not include reconfigurability to any great extent. The RMS literature, on the other hand, provided knowledge about how to achieve reconfigurable production systems but only to a small extent how it could be involved in the production system design process.

In five case studies the production system design process was studied and it was shown that a structured production system design process was used but there was not much support for designing production systems on a detailed level. The design of production systems was mainly done based on the production system designers' skills. The production system design support fragmentarily considered reconfigurability. No support for analysing the need for reconfigurability was given in the case studies and the need for reconfigurability was not analysed.

Based on the results, support for reconfigurable production system design was proposed. It includes two parts. The need for reconfigurability should be analysed in an early phase of the production system design process. This should be done by first identifying the change drivers and thereafter the critical reconfigurability characteristics. Based on the need for reconfigurability, the production system should thereafter be designed. The second part of the support included how to consider reconfigurability in the different phases of the design process. Based on the production system design literature, a process was described including typical production system design activities. This process was in line with the actual processes investigated in the case studies. How to involve reconfigurability in the different activities was described.

Altogether, the objective of developing knowledge of how to support the design of reconfigurable production systems was fulfilled.

7.4 Contribution of the research

In this section the academic as well as the industrial contribution of the research is described.

7.4.1 Academic contribution

Reconfigurable production systems are a topic mainly discussed in the RMS literature synonymous with highly automated production systems, highly reconfigurable in hardware and software. In this thesis reconfigurability has been pictured as a capability that could be considered in different ways, due to the reconfigurability characteristics, as well as to different extents depending on the manufacturing company's specific needs. Although there is an extensive knowledge of reconfigurability in the RMS field, how to transfer it into the production system design process is seldom described. On the contrary, the knowledge of designing production systems is strong in the general production system design literature but reconfigurability is seldom considered.

The main academic contribution of this thesis is argued to be the combination and synthesis of the general production system design field and the RMS field. It has been proposed in this thesis how to carefully analyse the need for reconfigurability and how to consider that need in the production system design process. Therefore the knowledge of reconfigurability from the RMS field is applied in the general production system literature field, and the production system design perspective, taken from the general production system design literature, is applied in the RMS field.

7.4.2 Industrial contribution

To regard the production system design as a competitive means has been advocated in this thesis. There is great potential to increase competitiveness by improving the production system design activities. This thesis argues for the importance of adopting a holistic perspective when designing production systems and of using a structured production system design process. The empirical findings show that there is still a lack of structured support for designing production systems in manufacturing companies.

A need to handle change drivers has been identified in the case studies but also limited skill in designing reconfigurable production systems according to the identified change drivers. Therefore, this thesis proposes a support for reconfigurable production system design including both how to analyse the need for reconfigurability and how to design production systems to satisfy that need.

This thesis proposes to consider reconfigurability in conventional production systems and in the existing production system design process and therefore tries to provide a broader understanding of the opportunities that reconfigurability could offer.

7.5 Future research

As concluded, the existing knowledge on reconfigurability and reconfigurable production systems was limited on the companies involved. Therefore, a challenge that still remains is to increase the knowledge of reconfigurability in manufacturing companies. The suggested support needs to be verified and tested at additional companies in order to clarify the need for modifications in its design. This would give opportunities for development of a more detailed support concerning how to specify the reconfigurability need and the linkage between change drivers, critical characteristics, and supporting characteristics. It would also give opportunities to further study how to consider reconfigurability in the production system design process. Testing and verification of the support should be done both in the automotive industry, where the main part of the case studies were carried out, and in other sectors in the manufacturing industry. The effect of using the support needs to be followed up based on the conclusion that further development should be made.

The thesis comprises production system design and not the realization and start-up phases. Therefore a next step could be to also include how to consider reconfigurability in realization and start-up phases.

Case studies at large companies were carried out and a future activity could also be to study reconfigurability needs and prerequisites at small- and medium-sized companies (SMEs). Their circumstances differ and the applicability of the suggested support in SMEs would therefore be an interesting research activity.

It was shown that structured production system design processes were seldom used to give detailed support for production system design. Therefore, future research is needed in order to analyse the deficiencies of the support presented in the literature and the reasons why structured production system design support is not used on a larger scale.

To successfully handle change drivers, products as well as production systems must be ready for reconfiguration. Product design was not included in this thesis. A future research activity would therefore also be to study how reconfigurability should be considered in the product design process and be combined with current research.

Mobility has been identified as a characteristic attracting increasing interest from manufacturing companies. The need to effectively move production systems between places has generated strong interest. Additional knowledge and research activities on this topic are encouraged.

This research was based on RMS literature and general production system design literature. Since a holistic perspective was seldom adopted in neither RMS literature nor the case studies, there is a risk that e.g. human reconfiguration was not much of a centre of interest in this thesis. A future research activity would therefore be to put greater focus on human reconfiguration.

References

- Abdi, M.R. and Labib, A.W. (2003), "A design strategy for reconfigurable manufacturing systems (RMSs) using analytical hierarchical process (AHP): A case study", *International Journal of Production Research*, Vol. 41, No. 10, pp. 2273-2299.
- Abdi, M.R. and Labib, A.W. (2004), "Grouping and selecting products: the design key of Reconfigurable Manufacturing Systems (RMSs)", *International Journal of Production Research*, Vol. 42, No. 3, pp. 521-546.
- Abele, E. and Wörn, A. (2009), "Reconfigurable Machine Tools and Equipment", in ElMaraghy, H.A. (Ed.) *Changeable and Reconfigurable Manufacturing Systems*, Springer Verlag, London, UK, pp. 111-125.
- AlGeddawy, T. and ElMaraghy, H.A. (2009), "Changeability Effect on Manufacturing Systems Design", in ElMaraghy, H.A. (Ed.) *Changeable and Reconfigurable Manufacturing Systems*, Springer Verlag, London, UK, pp. 267-284.
- Almström, P. (2005), *Development of Manufacturing systems: A Methodology Based on System Engineering and Design Theory*, Doctoral thesis, Department of Materials and Manufacturing Technology, Chalmers University of Technology, Göteborg.
- Anfara, Jr., V.A., Brown, K.M. and Mangione, T.L. (2002), "Qualitative Analysis on Stage: Making the Research Process More Public", *Educational Researcher*, Vol. 31, No. 7, pp. 28-38.
- Arbnor, I. and Bjerke, B. (1994), *Företagsekonomisk metodlära* [in Swedish], Studentlitteratur, Lund.
- Arnesson, F. and Bengtsson, J. (2012), *Usability Evaluation of a Production System Development Framework*, Master thesis, School of Engineering Jönköping University, Jönköping, Sweden.
- Asnafi, N., Hjelm, S., Holmgren, B., Malmsköld, L., Granström, M., Svenningstorp, J. and Mellgren, H. (2008). *2015 Sustainable Manufacturing Systems Capable of Producing Innovative Environmentally Friendly and Safe Products*. R&D program proposal to secure competitive vehicle and powertrain production in Sweden.
- Ateekh-Ur-Rehman and Subash Babu, A. (2012), "Reconfigurations of manufacturing systems – an empirical study on concepts, research, and applications". *International Journal of Advanced Manufacturing Technology*, Published online: 30 June 2012. <http://dx.doi.org/10.1007/s00170-012-4311-1>.

- Bellgran, M. (1998), *Systematic Design of Assembly Systems: Preconditions and Design Process Planning*, Doctoral thesis, Department of Mechanical Engineering, Linköping University, Linköping.
- Bellgran, B. and Säfsten, K. (2010), *Production Development: Design and Operation of Production Systems*, Springer-Verlag, London, UK.
- Bengtsson, M. and Eriksson, J. (2007), *Funktionsförsäljning av produktion* [in Swedish], Master thesis, Institutionen för Tillämpad fysik, Maskin- och materialteknik, Luleå University, Luleå.
- Bennett, D.J. (1986), *Production System Design*, Butterworths & Co, London, UK.
- Bennett, D.J. and Forrester, P.L. (1993), *Market-Focused Production Systems: Design and Implementation*, Prentice Hall International, Hemel Hempstead, UK.
- Bi, Z.M. (2011), "Revisiting System Paradigms from the Viewpoint of Manufacturing Sustainability", *Sustainability*, Vol. 3, No. 9, pp. 1323-1340.
- Bi, Z.M., Wang, L. and Lang, S.Y.T. (2007), "Current status of reconfigurable assembly systems", *International Journal of Manufacturing Research*, Vol. 2, No. 3, pp. 303-328.
- Bi, Z.M., Lang, S.Y.T., Shen, W. and Wang, L. (2008), "Reconfigurable manufacturing systems: the state of the art", *International Journal of Production Research*, Vol. 46, No. 4, pp. 967-992.
- Blanchard, B.S. and Fabrycky, W.J. (1998), *Systems Engineering and Analysis*, Prentice-Hall, Inc, Upper Saddle River, NJ.
- Bonney, M., Head, M., Ratchev, S. and Moualek, I. (2000), "A manufacturing system design framework for computer aided industrial engineering", *International Journal of Production Research*, Vol. 38, No. 17, pp. 4317-4327.
- Browne, J., Dubois, D., Rathmill, K., Sethi, S.P. and Stecke, K.E. (1984), "Classification of flexible manufacturing systems", *The FMS Magazine*, Vol. 2, No. 2, pp. 114-117.
- Bruccoleri, M., Amico, M. and Perrone, G. (2003), "Distributed intelligent control of exceptions in reconfigurable manufacturing systems", *International Journal of Production Research*, Vol. 41, No. 7, pp. 1393-1412.
- Bruch, J. (2012), *Management of Design Information in the Production System Design Process*, Doctoral thesis, School of Innovation, Design and Engineering, Mälardalen University, Västerås.
- Bröte, S. (2002), *Towards Market Driven Manufacturing Systems Design*, Doctoral thesis, Department of Mechanical Engineering, Linköping University, Linköping.
- Business Dictionary (2012). Retrieved 10 August 2012 from <http://www.businessdictionary.com/definition/process.html>.
- Bussmann, S. and McFarlane, D.C. (1999), "Rationales for Holonic Manufacturing Control", *The Second International Workshop on Intelligent Manufacturing Systems*, 22-24 September 1999, Leuven, Belgium, pp.177-184.

- Carlsson, A., Hjelm, S., Holmgren, B., Malmsköld, L., Granström, M., Svenningstorp, J. and Wik, A. (2010). *2020 Sustainable Manufacturing Systems Capable of Producing Innovative Environmentally Friendly and Safe Products*. R&D program proposal to secure competitive vehicle and powertrain production in Sweden.
- Checkland, P. (1999), *Systems Thinking, Systems Practice*, John Wiley & Sons Ltd, Chichester, UK.
- Chryssolouris, G. (2006), *Manufacturing Systems: Theory and Practice*, Springer-Verlag, New York, NY.
- CIRP (1990), "Nomenclature and Definitions for Manufacturing Systems (English Language Version)", *Annals of the CIRP*, Vol. 39, No. 2, pp. 735-742.
- Cochran, D.S., Arinez, J.F., Duda, J.W. and Linck, J. (2002), "A decomposition approach for manufacturing system design", *Journal of Manufacturing Systems*, Vol. 20, No. 6, pp. 371-389.
- D'Souza, D.E. and Williams, F.P. (2000), "Toward a taxonomy of manufacturing flexibility dimensions", *Journal of Operations Management*, Vol. 18, No. 5, pp. 577-593.
- Deif, A. and ElMaraghy, W. (2006), "A Systematic Design Approach for Reconfigurable Manufacturing Systems", in ElMaraghy, H.A. and ElMaraghy, W.H. (Eds.), *Advances in Design*, Springer-Verlag, London, UK, pp. 219-228.
- Deif, A.M. and ElMaraghy, W. (2007), "Investigating optimal capacity scalability scheduling in a reconfigurable manufacturing system", *International Journal of Advanced Manufacturing Technology*, Vol. 32, Nos. 5-6, pp. 557-562.
- Dove, R. (1994), "The meaning of life & the meaning of agile", *Production Magazine*, Vol. 106, No. 11, pp. 14-15.
- Duda, J.W. (2000), *A Decomposition-Based Approach to Linking Strategy, Performance Measurement, and Manufacturing System Design*, Doctoral thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA.
- Eisenhardt, K.M. (1989), "Building Theories from Case Study Research", *Academy of Management Review*, Vol. 14, No. 4, pp. 532-550.
- ElMaraghy, H.A. (2005), "Flexible and reconfigurable manufacturing systems paradigms", *International Journal of Flexible Manufacturing Systems*, Vol. 17, No. 4, pp. 261-276.
- ElMaraghy, H.A. (2007), "Enabling change in manufacturing systems", *International Journal of Flexible Manufacturing Systems*, Vol. 19, No. 3, pp. 125-127.
- ElMaraghy, H. and Wiendahl, H.-P. (2009), "Changeability – An Introduction", in ElMaraghy, H.A. (Ed.) *Changeable and Reconfigurable Manufacturing Systems*, Springer-Verlag, London, UK, pp. 3-24.

- European Commission (2004). *Manufacture: A Vision for 2020. Assuring the Future of Manufacturing in Europe. Report of the High-Level Group, November 2004*. Office for Official Publications of the European Communities, Luxembourg.
- European Commission (2006). *Manufacture: Strategic Research Agenda. Report of the High-Level Group, September 2006*. Belgium.
- Farid, A.M. (2008), "Facilitating ease of system reconfiguration through measures of manufacturing modularity", in *Proceedings of the The Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol. 222, No. 2, pp. 1275-1288.
- Fasth, Å. (2012), *Quantifying Levels of Automation – to enable competitive assembly systems*, Doctoral thesis, Department of Product and Production Development, Chalmers University of Technology, Göteborg, Sweden.
- Flick, U. (2006), *An Introduction to Qualitative Research*, SAGE Publications, London, UK.
- Garetti, M. and Taisch, M. (2012), "Sustainable manufacturing: trends and research challenges", *Production Planning & Control: The Management of Operations*, Vol. 23, Nos. 2-3, pp. 83-104.
- Gillham, B. (2000), *Case Study Research Methods*, Continuum, London, UK.
- Goldman, S.L., Nagel, R.N. and Preiss, K. (1995), *Agile Competitors and Virtual Organizations: Strategies for Enriching the Customer*, Van Nostrand Reinhold, New York, NY.
- Groover, M.P. (2001), *Automation, Production Systems and Computer-Integrated Manufacturing*, Prentice-Hall, Upper Saddle River, NJ.
- Gunasekaran, A. and Yusuf, Y.Y. (2002), "Agile manufacturing: A taxonomy of strategic and technological imperatives", *International Journal of Production Research*, Vol. 40, No. 6, pp. 1357-1385.
- Hart, C. (2005), *Doing a Literature Review: Releasing the Social Science Research Imagination*, SAGE Publications, London, UK.
- Hayes, R.H. and Wheelwright, S.C. (1979), "Link Manufacturing Process and Product Life Cycle", *Harvard Business Review*, Vol. 57, No. 1, pp. 133-140.
- Hedelind, M., Jackson, M., Funk, P., Stahre, J., Söderberg, R., Carlsson, J., Björkman, M. and Winroth, M. (2007), "Factory-in-a-Box – solutions for availability and mobility of flexible production capacity", in *Proceedings of the 1st Swedish Production Symposium 2007*, 28-30 August 2007, Göteborg, Sweden.
- Heilala, J., Helin, K., Montonen, J. and Väätäinen, O. (2006), "Life Cycle and Cost Analysis for Modular Re-Configurable Final Assembly Systems", in *Precision Assembly Technologies for Mini and Micro Products*, International Federation for Information Processing, Vol. 198, pp. 277-286.
- Heisel, U. and Meitzner, M. (2007), "Progress in Reconfigurable Manufacturing Systems", in Dashchenko, A.I. (Ed.) *Reconfigurable*

- Manufacturing Systems and Transformable Factories*, Springer Verlag, Berlin, Heidelberg, pp. 45-60.
- Hibino, H., Fukuda, Y., Fujii, S., Kojima, F., Mitsuyuki, K. and Yura, Y. (1999), "The development of an object-oriented simulation system based on the thought process of the manufacturing system design", *International Journal of Production Economics*, Vols. 60-61, pp. 343-351.
- Hitomi, K. (1996), *Manufacturing Systems Engineering: A unified approach to manufacturing technology, production management, and industrial economics*, Taylor & Francis, London, UK.
- Houshmand, M. and Jamshidnezhad, B. (2006), "An extended model of design process of lean production systems by means of process variables", *Robotics and Computer-Integrated Manufacturing*, Vol. 22, No. 1, pp. 1-16.
- Hu, S.J. (2005), "Paradigms of manufacturing – a panel discussion", in *Proceedings of the 3rd Conference on Reconfigurable Manufacturing*, 10-12 May 2005, Ann Arbor, MI.
- Hubka, V. and Eder, W.E. (1984), *Theory of Technical Systems: A Total Concept Theory for Engineering Design*, Springer-Verlag, Heidelberg.
- Jackson, M. (2000), *An Analysis of Flexible and Reconfigurable Production Systems: An Approach to a Holistic Method for the Development of Flexibility and Reconfigurability*, Doctoral thesis, Department of Mechanical Engineering, Linköping University, Linköping.
- Johansson, B. and Nord, C. (1999), *Nyanskaffning av produktionssystemer än bara inköp* [In Swedish], Institutet för verkstadsteknik forskning och LCP Consultants, Surte.
- Johnson, R.B. (1997), "Examining the Validity Structure of Qualitative Research", *Education*, Vol. 118, No. 2, pp. 282-292.
- Karlsson, C. (2009), "Researching Operations Management", in Karlsson, C. (Ed.) *Researching Operations Management*, Routledge, New York, NY, pp. 6-41.
- Kirk, J. and Miller, M.L. (1987), *Reliability and Validity in Qualitative Research*, Sage Publications, Beverly Hills, CA.
- Koren, Y. (2007), "General RMS Characteristics. Comparison with Dedicated and Flexible Systems", in Dashchenko, A.I. (Ed.) *Reconfigurable Manufacturing Systems and Transformable Factories*, Springer-Verlag, Berlin, Heidelberg, pp. 27-46.
- Koren, Y. (2010), *The Global Manufacturing Revolution: Product-Process-Business Integration and Reconfigurable Systems*, John Wiley & Sons, Hoboken, NJ.
- Koren, Y. and Shpitalni, M. (2010), "Design of reconfigurable manufacturing systems", *Journal of Manufacturing Systems*, Vol. 29, No. 4, pp. 130-141.
- Koren, Y., Heisel, U., Jovane, F., Moriwaki, T., Pritschow, G., Ulsoy, G. and Van Brussel, H. (1999), "Reconfigurable manufacturing systems",

- CIRP Annals – Manufacturing Technology*, Vol. 48, No. 2, pp. 527-540.
- Koste, L.L. and Malhotra, M.K. (1999), "A theoretical framework for analyzing the dimensions of manufacturing flexibility", *Journal of Operations Management*, Vol. 18, No. 1, pp. 75-93.
- Kulak, O., Durmusoglu, M.B. and Tufekci, S. (2005), "A complete cellular manufacturing system design methodology based on axiomatic design principles", *Computers and Industrial Engineering*, Vol. 48, No. 4, pp. 765-787.
- Langefors, B. (1970), *System för företagsstyrning* [in Swedish], Studentlitteratur, Lund.
- Lee, G.H. (1997), "Reconfigurability consideration design of components and manufacturing systems", *International Journal of Advanced Manufacturing Technology*, Vol. 13, No. 5, pp. 376-386.
- Leonard-Barton, D. (1990), "A Dual Methodology for Case Studies: Synergistic Use of a Longitudinal Single Site with Replicated Multiple Sites", *Organization Science*, Vol. 1, No. 3, pp. 248-266.
- Lindström, V. (2008), *Formulation of Automation Strategy in Manufacturing Systems: Developing a Methodology for Analysing and Choosing Levels of Automation*, Doctoral thesis, Department of Product and Production Development, Chalmers University of Technology, Göteborg.
- Love, D. (1996), "The design of manufacturing systems", in Warner, M. (Ed.) *International Encyclopedia of Business and Management*, International Thomson Business Press, London, UK, pp. 3154-3174
- Löffler, C., Westkämper, E. and Unger, K. (2011a), "Change Drivers and Adaptation of Automotive Manufacturing", in *New Worlds of Manufacturing: Proceedings of the 44th CIRP International Conference on Manufacturing Systems 2011*, 1-3 June, 2011, Madison, WI.
- Löffler, C., Westkämper, E. and Unger, K. (2011b), "Method for analysis and dynamism of factory structure in automotive manufacturing", *Robotics and Computer-Integrated Manufacturing*, Vol. 27, No. 4, pp. 741-745.
- Maier-Sperdelozzi, V., Koren, Y. and Hu, S.J. (2003), "Convertibility Measures for Manufacturing Systems", *Annals of the CIRP – Manufacturing Technology*, Vol. 52, No. 1, pp. 367-370.
- Mathison, S. (1988), "Why Triangulate?", *Educational Researcher*, Vol. 17, No. 2, pp. 13-17.
- Matt, D.T. (2008), "Template based production system design", *Journal of Manufacturing Technology Management*, Vol. 19, No. 7, pp. 783-797.
- Matta, A., Tomasella, M., Clerici, M. and Sacconi, S. (2008), "Optimal reconfiguration policy to react to product changes", *International Journal of Production Research*, Vol. 46, No. 10, pp. 2651-2673.
- McFarlane, D.C. and Bussmann, S. (2003), "Holonc Manufacturing Control: Rationales, Developments and Open Issues", in Deen, S.M.

- (Ed.) *Agent-Based Manufacturing: Advances in the Holonic Approach*, Springer-Verlag, Heidelberg, pp. 303-330.
- Mehrabi, M.G., Ulsoy, A.G. and Koren, Y. (2000a), "Reconfigurable manufacturing systems and their enabling technologies", *International Journal of Manufacturing Technology and Management*, Vol. 1, No. 1, pp. 114-131.
- Mehrabi, M.G., Ulsoy, A.G. and Koren, Y. (2000b), "Reconfigurable manufacturing systems: Key to future manufacturing", *Journal of Intelligent Manufacturing*, Vol. 11, No. 4, pp. 403-419.
- Mehrabi, M.G., Ulsoy, A.G., Koren, Y. and Heytler, P. (2002), "Trends and perspectives in flexible and reconfigurable manufacturing systems", *Journal of Intelligent Manufacturing*, Vol. 13, No. 2, pp. 135-146.
- Meredith, J. (1998), "Building operations management theory through case and field research", *Journal of Operations Management*, Vol. 16, No. 4, pp. 441-454.
- Miles, M.B. and Huberman, A.M. (1994), *Qualitative Data Analysis*, SAGE Publications, Thousand Oaks, CA.
- Miltenburg, J. (2005), *Manufacturing Strategy: How to Formulate and Implement a Winning Plan*, Productivity Press, New York, NY.
- Muriz, L., and Mesinovic, B. (2006), *Analys av konceptutvecklingen inom Factory-in-a-Box-projektet* [in Swedish], Master thesis, Department of Product and Production Development, Chalmers University, Göteborg.
- National Research Council (1998), *Visionary Manufacturing Challenges for 2020*, National Academy Press, Washington, D.C.
- Nof, S.Y., Wilhelm, W.E. and Warnecke, H. (1997), *Industrial Assembly*, Chapman & Hall, London, UK.
- Nyhuis, P., Kolakowski, M. and Heger, C. (2006), "Evaluation of Factory Transformability – a Systematic Approach", *Production Engineering*, Vol. 13, No. 1, pp. 147-152.
- Onori, M., Semere, D. and Lindberg, B. (2011), "Evolvable systems: an approach to self-X production", *International Journal of Computer Integrated Manufacturing*, Vol. 24, No. 5, pp. 506-516.
- Park, H. and Choi, H. (2008), "Development of a Modular Structure-based Changeable Manufacturing System with High Adaptability", *International Journal of Precision Engineering and Manufacturing*, Vol. 9, No. 3, pp. 7-12.
- Rampersad, H.K. (1994), *Integrated and Simultaneous Design for Robotic Assembly*, John Wiley & Sons, New York, NY.
- Ramström, A. and Gustafsson, H. (2006), *Factory-in-a-Box: Projecting of Mobile Production Facilities for Assembly Production*, Master thesis, Department of Product and Production Development, Chalmers University of Technology, Göteborg.
- Rao, H.A. and Gu, P. (1997), "Design methodology and integrated approach for design of manufacturing systems", *Integrated Manufacturing Systems*, Vol. 8, No. 3, pp. 159-172.

- Roozenburg, N.F.M. and Eekels, J. (1995), *Product Design: Fundamentals and Method*, John Wiley & Sons, Chichester, UK.
- Ruffini, F.A.J. (1999), *Production System Design: From Practice to Theory*, Doctoral thesis, Institute for Business Engineering and Technology Application, University of Twente, Enschede, The Netherlands.
- Saunders, M., Lewis, P. and Thornhill, A. (2007), *Research Methods for Business Students*, Pearson Education Limited, Harlow, UK.
- Scholz, R.W. and Tietje, O. (2002), *Embedded Case Study Methods: Integrating Quantitative and Qualitative Knowledge*, Sage Publications, Inc., Thousand Oaks, CA.
- Schuh, G., Harre, J. and Gottschalk, S. (2005), "Design for Changeability (DFC) in Product-Oriented Production", *CIRP Journal of Manufacturing Systems*, Vol. 34, No. 5, pp. 439-445.
- Schuh, G., Lenders, M., Nussbaum, C. and Kupke, D. (2009), "Design for Changeability", in ElMaraghy, H.A. (Ed.) *Changeable and Reconfigurable Manufacturing Systems*, Springer-Verlag, London, UK, pp. 251-266.
- Schuh, G., Van Brussel, H., Boër, P., Valckenaers, M., Sacco, M., Bergholz, M. and Harre, J. (2003), "A Model-Based Approach to Design Modular Plant Architectures", in *Proceedings of the 36th CIRP International Seminar on Manufacturing Systems*, pp. 3-5 June 2003, Saarbrücken, Germany, pp. 369-373.
- Seliger, G., Viehweger, B. and Wieneke, B. (1987), "Decision support in design and optimization of flexible automated manufacturing and assembly", *Robotics and Computer - Integrated Manufacturing*, Vol. 3, No. 2, pp. 221-227.
- Setchi, R.M. and Lagos, N. (2004), "Reconfigurability and reconfigurable manufacturing systems: state-of-the-art review", in *Proceedings of the 2nd IEEE International Conference on Industrial Informatics*, 24-26 June, Berlin, pp. 529 - 535.
- Sethi, A.K. and Sethi, S.P. (1990), "Flexibility in manufacturing: A survey", *International Journal of Flexible Manufacturing Systems*, Vol. 2, No. 4, pp. 289-328.
- Son, S.-Y., Olsen, T.L. and Yip-Hoi, D. (2001), "An approach to scalability and line balancing for reconfigurable manufacturing systems", *Integrated Manufacturing Systems*, Vol. 12, No. 7, pp. 500-511.
- Spicer, P. and Carlo, H.J. (2007), "Integrating Reconfiguration Cost Into the Design of Multi-Period Scalable Reconfigurable Manufacturing Systems", *Journal of Manufacturing Science and Engineering, Transactions of the ASME*, Vol. 129, No. 1, pp. 202-210.
- Spicer, P., Koren, Y., Shpitalni, M. and Yip-Hoi, D. (2002), "Design Principles for Machining System Configurations", *CIRP Annals - Manufacturing Technology*, Vol. 51, No. 1, pp. 275-280.
- Stillström, C. (2007), *The Concept of Mobile Manufacturing*, Licentiate thesis, Department of Product and Production Development, Chalmers University of Technology, Göteborg.

- Suh, N.P. (1990), *The Principles of Design*, Oxford University Press, New York, NY.
- Suh, N.P., Cochran, D.S. and Lima, P.C. (1998), "Manufacturing System Design", *CIRP Annals – Manufacturing Technology*, Vol. 47, No. 2, pp. 627-639.
- Säfsten, K. (2002), *Evaluation of assembly systems: An exploratory study of evaluation*, Doctoral thesis, Department of Mechanical Engineering, Linköping University, Linköping.
- Technology Strategy Board (2012) *High Value Manufacturing: Strategy 2012-2015* Swindon, UK.
- Teknikföretagen, Swerea and Svenska ProduktionsAkademien (2011). *Svensk Produktion 2025: Strategisk forsknings- och innovationsagenda för att möta de globala utmaningarna* [in Swedish].
- Teknisk Framsyn (2000), *Teknisk framsyn - Produktionssystem* [in Swedish], Typoform, Stockholm.
- Terkaj, W., Tolio, T. and Valente, A. (2009), "Designing Manufacturing Flexibility in Dynamic Production Contexts", in Tolio, T. (Ed.) *Design of Flexible Production Systems – Methodologies and Tools*, Springer-Verlag, Heidelberg, pp. 1-18.
- The Ad-hoc Industrial Advisory Group (2010). *Factories of the Future PPP: Strategic Multi- Annual Roadmap*. European Commission Brussels.
- The Concise Oxford Dictionary (1990) Oxford University Press, New York, NY
- Thomas, A.J., Byard, P. and Evans, R. (2012), "Identifying the UK's manufacturing challenges as a benchmark for future growth", *Journal of Manufacturing Technology Management*, Vol. 23, No. 2, pp. 142-156.
- Thomopoulos, N.T. (1967), "Line Balancing-Sequencing for Mixed-Model Assembly", *Management Science*, Vol. 14, No. 2, pp. B59-B75.
- Tsukune, H., Tsukamoto, M., Matsushita, T., Tomita, F., Okada, K., Ogasawara, T., Takase, K. and Yuba, T. (1993), "Modular manufacturing", *Journal of Intelligent Manufacturing*, Vol. 4, No. 2, pp. 163-181.
- Ueda, K. (2007), "Emergent Synthesis Approaches To Biological Manufacturing Systems", in Cunha, P.F. and Maropoulos, P.G. (Eds.), *Digital Enterprise Technology: Perspectives and Future Challenges*, Springer-Verlag, New York, NY.
- Ueda, K., Markus, A., Monostori, L., Kals, H.J.J. and Arai, T. (2001), "Emergent Synthesis Methodologies for Manufacturing", *CIRP Annals – Manufacturing Technology*, Vol. 50, No. 2, pp. 535-551.
- Ulrich, K. and Eppinger, S. (2003), *Product Design and Development*, McGraw-Hill, New York, NY.
- Upton, D.M. (1995), "Flexibility as process mobility: The management of plant capabilities for quick response manufacturing", *Journal of Operations Management*, Vol. 12, Nos. 3-4, pp. 205-224.

- Urbani, A. and Negri, S.P. (2006), "Production System Modelling for the Evaluation of the Degree of Reconfigurability", in Dashchenko, A.I. (Ed.) *Reconfigurable Manufacturing Systems and Transformable Factories*, Springer Verlag, Heidelberg, pp. 239-258.
- Wallén, G. (1996), *Vetenskapsteori och forskningsmetodik* [in Swedish], Studentlitteratur, Lund.
- Van Brussel, H., Bongaerts, L., Wyns, J., Valckenaers, P. and Van Ginderachter, T. (1999), "A conceptual framework for holonic manufacturing: Identification of manufacturing holons", *Journal of Manufacturing Systems*, Vol. 18, No. 1, pp. 35-52.
- Van Brussel, H., Wyns, J., Valckenaers, P., Bongaerts, L. and Peeters, P. (1998), "Reference architecture for holonic manufacturing systems: PROSA", *Computers in Industry*, Vol. 37, No. 3, pp. 255-274.
- Westkämper, E. (2006), "New Trends in Production", in Dashchenko, A.I. (Ed.) *Reconfigurable Manufacturing Systems and Transformable Factories*, Springer Verlag, Heidelberg, Germany, pp. 15-26.
- Wiendahl, H.-P. and Heger, C.L. (2004), "Justifying Changeability: A Methodical Approach to Achieving Cost Effectiveness", *International Journal for Manufacturing Science and Production*, Vol. 6, No. 1-2, pp. 33-39.
- Wiendahl, H.-P., ElMaraghy, H.A., Nyhuis, P., Zäh, M.F., Wiendahl, H.-H., Duffie, N. and Brieke, M. (2007), "Changeable Manufacturing – Classification, Design and Operation", *Annals of the CIRP*, Vol. 56, No. 2, pp. 783-809.
- Wigren, C. and Brundin, E. (2008), "Interaktiv fältforskning – möjligheter och omöjligheter", in Johannisson, B., Gunnarsson, E. and Stjernberg, T. (Eds.), *Gemensamt kunskapande: den interaktiva forskningens praktik* [in Swedish], Växjö University Press, Växjö, pp. 95-114.
- Wiktorsson, M. (2000), *Performance Assessment of Assembly Systems*, Doctoral thesis, Department of Manufacturing Systems, Royal Institute of Technology, Stockholm.
- Winroth, M., Säfsten, K. and Stahre, J. (2006), "Automation Strategies: Requirements on the Strategy Process", *Paper presented at the 39th CIRP International Seminar on Manufacturing Systems*, 7-9 June 2006, Ljubljana, Slovenia.
- Voss, C., Tsikriktis, N. and Frohlich, M. (2002), "Case Research in Operations Management", *International Journal of Operations & Production Management*, Vol. 22, No. 2, pp. 195-219.
- Wu, B. (1994), *Manufacturing Systems Design and Analysis: Context and Techniques*, Chapman & Hall, London, UK.
- Wu, B. (2001), "Strategy analysis and system design within an overall framework of manufacturing system management", *International Journal of Computer Integrated Manufacturing*, Vol. 14, No. 3, pp. 319-341.

- Yien, T.S. (1998), *Manufacturing System Design Methodology*, Doctoral thesis, Hong Kong University of Science and Technology, Hong Kong.
- Yin, R.K. (2009), *Case Study Research: Design and Methods*, SAGE, Thousands Oaks, CA.
- Yin, R.K. (2011), *Qualitative Research from Start to Finish*, Guilford Press, New York, NY.
- Yusuf, Y.Y., Sarhadi, M. and Gunasekaran, A. (1999), "Agile manufacturing: The drivers, concepts and attributes", *International Journal of Production Economics*, Vol. 62, Nos. 1-2, pp. 33-43.
- Zaman, A. (2007), *FinaBox - Emergence of New Paradigm*, Master's thesis, Department of Innovation, Design and Product Development, Mälardalen University, Eskilstuna.

Appendix A: Interview guides

Interview guide MaxAuto UK and MaxAuto Germany

1.x	Can you generally describe how a product development process is carried out?	
a-b	What stages are included?	In what sequence?
c-d	Describe the functions involved and your role.	Describe in what stages you are involved.
2.x	Is there any documented product development process?	<input type="checkbox"/> Yes <input type="checkbox"/> No <input type="checkbox"/> Don't know <i>Comments Why/why not? Complete/change.</i>
	If No, go to question 3.x . If Yes, describe what this documented process includes and if, how and when it is used? <i>Ask for written documentation if available</i>	
a-b	(Extent of the document, what is included?)	Does it work/is it useful? Why/ Why not?
c-d	When/ In what situations have you used this documentation?	Is there something that is missing in the documentation?
e	Does the documented product development process include both product design and production system design	<input type="checkbox"/> Yes <input type="checkbox"/> No <input type="checkbox"/> Don't know <i>Comment, Why/why not.</i>
f	What is the largest difference between the documented process and the actual process?	
	Is the fact that the production system can be reconfigured considered in the product design process?	
	Do you have a long term view and thinking in product generations? How? To what extent?	
4.x	Is there a documented process specifically for the production system design?	
a	If No, go to question 7.c. If Yes, describe what this documented process includes and if, how and when it is used? <i>Ask for written documentation if available</i>	
b-c	Extent of the document, what is included? (What subsystems and elements are considered?)	Does it work/is it useful? Why/ Why not?
d-e	When/ In what situations have/will <u>you</u> use this documentation in the project?	Is there something that is missing in the documentation?
f-g	For whom is the process available?	Is it available for production development?
h-i	Who has developed the documented process?	What are the routines for update and usage? Who? When?
5.x	How do the actual production system design process differ compared to the documented process?	

a- b	How is the documented process followed? What parts of the documented process are followed? (Compared to the actual process)	Who follows the documented process? (Compared to the actual process)
c- d	How could the actual process be described?	What stages are included? In what sequence?
6.x	Are reconfigurability characteristics considered in the production system development process? (Documented and actual process)	
	<i>Characteristics of the production system</i> Is this considered? In The actual process? In the documented process? How? When? Why?	
a	Mobility (E.g. machines and equipment could easily be moved to another location. Personnel could easily be educated. Information system is adapted for changes in location.)	
b	Automatibility (E.g. the level of automation of machines, equipment, information handling, and material handling could easily be changed according to the conditions.)	
c	Modularity (E.g. modular machines, equipment with standardized interfaces; modular material handling equipment with standardized interfaces)	
d	Convertibility (E.g. machines and equipment are could easily be converted between product types or easily be adapted to new product updates; personnel have the competence to easily switch between product types and new products, information system could easily handle several product types and be adapted to new product types)	
e	Integrability (E.g. Easiness to integrate machines, equipment, material handling equipment in the rest of the system; easy to educate personnel; easy to implement new/extend information handling systems)	
f	Diagnosability (E.g. quality and reliability problems could easily be identified about machines, equipment, material handling, personnel, and in the information system.)	
g	Customization (E.g. capacity of machines and equipment are based on the products that are produced; the competence is in line with the products that are produced; the material handling system and information system are based on the products that are produced.)	
h	Scalability (E.g. it is easy to enlarge and downsize the system concerning number of machines, material handling system, the information system, number of employees.)	

Interview guide MaxAuto Sweden and VoxVan

1	Describe the type of product (in the specific project)	
a- b	How many products are you producing and how many variants? (Approximate number)	How large volumes, volume variations and volume fluctuations do you have?
c- d	How long is your planning horizon? Do you have a good view of what the upcoming product generations will look like and how the product design will change?	
2	Describe type of production system	
a- b	Type of layout	Are your production systems designed for a specific product family?
c	What type of skills is required in the production and what does the providing of skills look like?	
3	What is your role in the industrialization process?	
a- b	Your responsibilities?	In what stages/activities are you involved?

4	Is there any documented industrialization process?	<input type="checkbox"/> Yes <input type="checkbox"/> No <input type="checkbox"/> Don't know	<i>Comments, why/why not?</i>
If no, go to question x. If yes, ask for the documentation if possible?			
a-b	Extent of the documentation, what is included?	Does it work? Is it useful? (Why/Why not?)	
c-d	What is the difference compared to the actual process?	How are the activities spread? At what point in time in the product development do you start considering what the production system is going to look like?	
5	Is it important for you to develop production systems that are easy to change due to changing requirements?	<input type="checkbox"/> Yes <input type="checkbox"/> No <input type="checkbox"/> Don't know	<i>Comments Why/why not? Complete/change.</i>
6	Do you develop production systems that are easy to change	<input type="checkbox"/> Yes <input type="checkbox"/> No <input type="checkbox"/> Don't know	<i>Comments Why/why not? Complete/change.</i>
7	When you design a new production system (or making larger changes in existing), to what extent do you base it on the previous production system concerning..		
a-b	Production processes (e.g. type, flow, level of automation)	Machines and equipment (hardware and its function)	
c-d	Material handling solutions and logistics (choice of transport between the stations, packaging, material handling equipment)	Work place design (staff, work organisation, work environment)	
e-f	Information (software, information flow)	Building and premises (internal and external layout)	
8	When you design new production systems (or major changes in existing ones), do you then consider..		
		Yes/No, When in the design process, how?	
a	That machines and equipment could easily be moved , that personnel easily could be educated, that the information system easily could be adjusted to new environments		
b	The level of automation of machines, equipment, material handling, information system		
c	That machines and equipment are modular and have standardized interfaces		
d	That machines, equipment, and information system easily could be converted or changed between different product types and easily could be adapted based on the product updates		
e	That it is easy to integrate new machines, equipment, software in the rest of the system, easy to train new personnel.		

f	Is it easy to identify problems in quality and reliability of machines, equipment, material handling, personnel and in information system.	
h	That it is easy to scale up and down the production system according to volume variations.	
13	The recent years the global manufacturing footprint has changed and several manufacturing companies have global production. In what way has this affected the production system design process?	
a-b	Do you have production in several places in the world?	Is the production carried out at different places depending on your position in the product life cycle?

Appendix B: Scenario formulation Dax Vehicles

The scenario formulation activity was intended to determine future scenarios for DaxVehicles and was carried out in two steps. In the first step potential future events, i.e. things that could happen in the future, were generated in a brainstorming session. The events together formed different scenarios. This was done in two parallel sessions using the following procedure:

1. During 10 minutes write down on post-it notes possible future events for the company! This is done individually with no discussions among the session participants. Think problems/events and not solutions.
2. Thereafter, put up the post-it notes and tell the rest of the session participants about the event. Nobody is allowed to comment.
3. When all post-it notes have been introduced all ideas that pop up are presented. This is done in a discussion among the session participants. Also these ideas are written down on post-it notes by the session chair. Do this until all ideas have been recorded. Nobody is allowed to give critique.
4. The post-it notes are clustered into groups based on topics. At this point in time the ideas are discussed, sorted out, and critiqued.
5. Based on the topics and the notes included distinguish different scenarios.

In the second step, all participants were gathered. The results from the separate brainstorming sessions were discussed once again and finally summarized. The participants are presented in Table B1.

Table B1. *Participants, scenario formulation DaxVehicles*

Session 1	Session 2
Session chair	Session chair
Purchasing /Planning manager	Mechanical engineer
Customer project coordinator	Consultant production system designer
Customer project coordinator	Mechanical engineer
Operative production manager	

