Identify - Quantify - Obtain Qualifications for Virtual Commissioning

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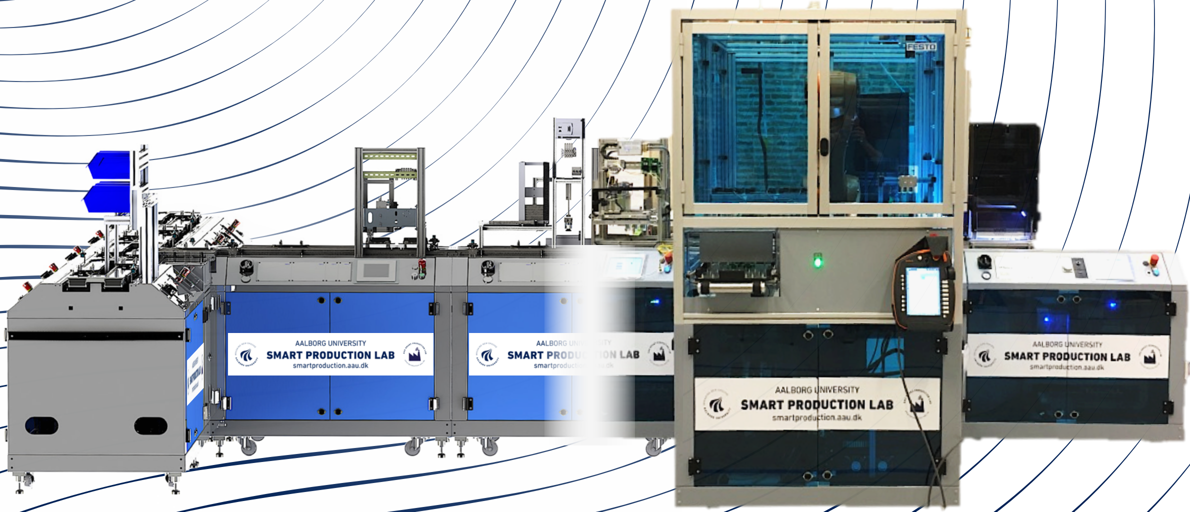

IDENTIFY – QUANTIFY – OBTAIN

QUALIFICATIONS FOR VIRTUAL COMMISSIONING

BY
STEFFEN TRAM MORTENSEN

DISSERTATION SUBMITTED 2019

AALBORG UNIVERSITY
DENMARK

Identify — Quantify — Obtain

Qualifications for Virtual Commissioning

PhD Dissertation

Steffen Tram Mortensen

Dissertation submitted June 2019

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Curriculum Vitae

Steffen Tram Mortensen

Steffen T. Mortensen was an educated welder and sheet metal worker before entering the academic world. Steffen received his M.Sc in Engineering (Manufacturing Technologies) from Aalborg University, Denmark in 2015. He worked as a research assistant prior to his PhD study start in November 2015 with the Robotics and Automation group at the Department of Material and Production, Aalborg University. During the PhD studies, he stayed abroad for a three-month research stay at the Department at Electronic Systems at Chalmers University of Technology, Sweden. Steffen has been involved in lecturing and supervision of undergraduate and graduate students in various topics including Industry 4.0, virtual commissioning, product development and digital manufacturing. During the PhD, he also contributed with insights of his research at the Center for Industrial Production within the nationally funded project Labour 4.0. In addition, he has created two spin-out companies based on his research in his PhD study. Steffen's main research interests lie within how manufacturers can obtain new technologies and working protocols to stay competitive.

Abstract

The global competition and oscillating demand, force manufacturing to be flexible and efficient at the same time. Several initiatives have been launched to address these challenges. National and international initiatives, such as the German initiative Industry 4.0 have been launched to start the digital transformation of manufacturers towards the fourth industrial revolution. Changeable manufacturing systems enable manufacturers to cope with the fluctuating demand and frequently alteration of product variants. However, the frequent change and reconfiguration lead to time-consuming, costly, and in some cases, unstructured commissioning phases mainly due to software errors. One way to overcome this obstacle is to use virtual commissioning. Virtual commissioning enables faster and cheaper commissioning by testing the software in a virtual environment before the physical commissioning. Despite the benefits, virtual commissioning is not widely used in the industry because of the lack of robust methods and technical qualifications.

This doctoral dissertation firstly examined how education programs and industry can gain awareness about Industry 4.0 employing a serious learning game. The learning game utilised the established learning factory at Aalborg University, AAU Smart Production Lab. The learning factory facilitates learning in an industrial-like environment incorporating the challenges and needs of a real manufacturing process of an electronic device. The developed Industry 4.0 awareness game teach the participants about the driving technologies within Industry 4.0, coupled with their impact on the organisation and requirement of new qualifications.

The second part of this thesis tackles one the main impediments of virtual commissioning; Need for virtual commissioning experts to adequately perform a designated task. An exploration of virtual commissioning aspects facilitated with the identification and mapping of the required virtual commissioning skills and knowledge. The skills and knowledge are quantified through a Delphi study within virtual commissioning users. The study reveals that intermediate qualification levels are needed to perform virtual commissioning. A preliminary study shows that an interdisciplinary team consisting of undergraduate students from technical backgrounds can cooperate to solve a virtual commissioning case.

The last part of the thesis presents a method for supporting the reconfiguration process in-between two configurations of a changeable manufacturing system. The method utilises a presented categorisation of the level of complexity and novelty and a division in reconfiguration elementary abilities. The method provides operational guidance towards: hardware and software reconfiguration, virtual recommissioning and the physical recommissioning phases.

Resumé

Den globale konkurrence og vekslende efterspørgsel tvinger producenter til at være fleksible og effektive på samme tid. Flere initiativer er blevet lanceret for at løse disse udfordringer. Nationale og internationale initiativer, såsom det tyske initiativ Industri 4.0, er blevet lanceret for at starte den digitale transformation af producenter i retning af den fjerde industrielle revolution. Omskiftelige produktionssystemer gør det muligt for producenterne at håndtere den vekslende efterspørgsel hyppige ændringer af produktvarianter. Den hyppige ændring og rekonfiguration fører dog til tidskrævende, dyre og i nogle tilfælde ustrukturerede idriftsættelsesfaser, primært som følge af softwarefejl. En måde at overvinde denne hindring på er at bruge virtuel idriftsættelse. Virtual idriftsættelse muliggør hurtigere og billigere idriftsættelse ved at teste softwaren i et virtuelt miljø før den fysiske idriftsættelse. På trods af fordelene er virtuel idriftsættelse ikke udbredt i industrien på grund af manglen på robuste metoder og tekniske kvalifikationer.

Denne ph.d.-afhandling undersøger for det første hvordan uddannelsesprogrammer og industrien kan få bevidsthed om Industri 4.0 ved hjælp af et seriøst læringsspil, der her udnytter den etablerede læringsfabrik på Aalborg Universitet, AAU Smart Production Lab. Læringsfabrikken gør det lettere at lære i et industrielt lignende miljø, der omfatter udfordringer og behov i en reel fremstillingsproces af en elektronisk enhed. Det udviklede Industri 4.0 awareness game lærer deltagerne om de drivende teknologierne i Industri 4.0, kombineret med deres indvirkning på organisationen og kravet om nye kvalifikationer.

Den anden del af denne afhandling tager fat på de vigtigste hindringer for virtuel idriftsættelse: Behovet for virtuelle idriftsættelseseksperter for tilstrækkeligt at kunne udføre en virtual idriftsættelse opgave. En udforskning af virtuelle idriftsættelsesaspekter kombineret med identifikation og kortlægning af de nødvendige virtuelle idriftsættelsesfærdigheder og viden. Færdighederne og viden kvantificeres gennem et Delphi-studie inden for virtuelle idriftsættelsesbrugere. Undersøgelsen viser, at mellem-kvalifikationsniveauer er nødvendige for at udføre virtuel idriftsættelse. Derudover viser en foreløbig undersøgelse, at et tværfagligt team bestående af bachelorstuderende med en teknisk baggrund er i stand til at løse en virtuel idriftsættelse opgave ved at samarbejde.

Den sidste del af afhandlingen præsenterer en metode til understøttelse af rekonfigureringsprocessen mellem to konfigurationer af et omskifteligt produktionssystem. Metoden anvender en præsenteret kategorisering af kompleksitetsniveauet og nyhedsværdien, samt en opdeling i rekonfiguration elementære egenskaber. Metoden giver operationel vejledning i forhold til: Hardware og software rekonfiguration, virtuel genidriftsættelse og de fysiske genidriftsættelsesfaser.

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Thesis Details

Thesis Title: Identify — Quantify — Obtain
Qualifications for Virtual Commissioning
PhD Student: Steffen Tram Mortensen
Supervisor: Professor Ole Madsen, Aalborg University

The thesis consists of an extended thesis summary
and the following peer-reviewed papers:

A Steffen Tram Mortensen, Dimitrios Chrysostomou, and Ole Madsen, "A Novel Framework for Virtual Recommissioning in Reconfigurable Manufacturing Systems," *2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, 2017.

B Steffen Tram Mortensen and Ole Madsen, "A Virtual Commissioning Learning Platform", *Advanced Engineering Education & Training for Manufacturing Innovation, 8th CIRP Sponsored Conference on Learning Factories (CLF 2018)*, 2018.

C Steffen Tram Mortensen and Ole Madsen, "Operational Classification and Method for Reconfiguration & Recommissioning of Changeable Manufacturing Systems on System Level", *CIRP Proceeding of Changeable, Agile, Reconfigurable and Virtual Production (CARV-2018)*, 2018.

D Steffen Tram Mortensen, Kelvin Koldsø Nygaard and Ole Madsen, "Outline of an Industry 4.0 Awareness Game", *CIRP Sponsored: Research. Experience. Education. 9th Conference on Learning Factories 2019 (CLF 2019)*, 2019.

In addition to the main papers, the following publications have also been made during the PhD study:

E Thomas Ditlev Brunoe, Steffen Tram Mortensen, Ann-Louise Andersen and Kjeld Nielsen, "Learning Factory with Product Configurator for Teaching Product Family Modelling and Systems Integration", *CIRP Proceeding of Changeable, Agile, Reconfigurable and Virtual Production (CARV-2018)*, 2018.

The following technical reports have also been made during the PhD study:

i Steffen Tram Mortensen "Classification of AAU Smart Production Lab", technical report for documentation of the classification.

ii Steffen Tram Mortensen "Evaluation of Industry 4.0 Awareness Game", technical report with the full statics report.

iii Steffen Tram Mortensen "Structured Literature Survey - Virtual Commissioning Qualifications", technical report with the full structured literature method.

This thesis has been submitted for assessment in partial fulfilment of the PhD degree. The thesis is based on the extended summary and the published peer-reviewed scientific papers as well as technical reports which are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty.

Preface

This thesis has been submitted to the Faculty of Engineering and Science at Aalborg University in partial fulfilment of the requirements for the degree of Doctor of Philosophy. The research presented in this thesis has been carried out from November 2015 to May 2019 at the Department of Materials and Production at Aalborg University under the supervision of Professor Ole Madsen. The thesis is constructed as an extended summary (containing a number of unpublished results) and a collection of peer-reviewed papers. This thesis contains studies within, qualifications, virtual commissioning, and changeable manufacturing systems. The research performed in this PhD project has increased the accessibility for larger application of virtual commissioning and changeable manufacturing systems in the industry. This has resulted in studies in qualifications and new workflows in the cross-field between two or more of the subjects. The PhD project leading to this thesis has been funded by Aalborg University – AAU Smart Production project.

Acknowledgements

I would like to thank my supervisor Professor Ole Madsen for giving me the opportunity for a PhD with the founding through the Smart Production project. In addition, I would like to thank him for his constructive and encouraging supervision in this PhD study.

Thanks for their assistance and support also goes to Professor Poul H. K. Hansen, Professor Herman Vermaak, and Associate Professor Petter Falkman as part of the assessment committee.

I had the pleasure of three months at Chalmers University of Technology in Gothenburg at the automation group. I would like to thank the group for the kind and pleasant hospitality and their input to my research.

I have had the pleasure of collaborating with many researchers and practitioners from both academia and industry. I would like to extend my sincere thanks to everyone who in one way or the other has contributed to the work leading to this thesis. Especially, I would like to thank the research group around AAU Smart Production for their collaboration and inputs. Also, thanks to Bent Aksel Jørgensen, from Xcelgo, with sparring and aid of construction virtual devices.

I would like to thank my colleagues in the Robotics and Automation Group at the Department of Materials and Productions at Aalborg University for great collaboration, fruitful discussions, and always inspiring and motivating working environment. Especial thanks to Dimitrios Chrysostomou for support and guidance in the writing process of papers and the thesis.

I would also like to thank my family for their huge support. Last and definitely not least, I want to thank the most important people in my life. I want to express my deepest gratitude to my beautiful wife Linda and my amazing son Oscar for their moral support, unconditional love and endless patience all these years. This thesis would not have been realised without them and, therefore, is dedicated to them.

Steffen Tram Mortensen
Aalborg University, June 3, 2019

Part I

Introduction

Chapter 1

Project Motivation

The ever more fluctuating market and demand, caused by the request from customers for customised products, together with the increased competition from low-wage countries challenge traditional manufacturing companies and require new strategies [ELMaraghy, 2009]. Manufacturing companies should not only be flexible, but they also need to be flexible and efficient at the same time. Hence, there is a need for manufacturing strategies and manufacturing systems that may solve the task of being flexible and efficient at the same time.

In the early nineties, the dominant manufacturing strategy was to outsource the production to low wage countries, but during the last decade, there has been a great consensus in the western world to halt and even reverse the deindustrialisation. Industrial production in the home country maintains high value-adding sectors such as product and process design, sales, and marketing in the home country [Roland Berger Strategy Consultants, 2014]. Consequently, many governments have launched initiatives that support the development and transition of their local industry, many of them focusing on digitisation. To name a few: Denmark: MADE, USA: Advanced Manufacturing, European Union: Horizon 2020, Germany: Industrie 4.0 (Industry 4.0), China: 中国制造2025 (Made in China 2025). [Center for Strategic and International Studies, 2016; Davies, 2015; European Commission, 2014; Holdren et al., 2011; Manufacturing Academy of Denmark, 2012; Roland Berger Strategy Consultants, 2014]. The most common term used in Europe and Denmark is Industry 4.0, and will also be used in this thesis.

1.1 Manufacturing Paradigms

As mentioned above there is a great need for a flexible and efficient manufacturing system and a strategy to cope with the fluctuating demand. *Figure* 1.1 illustrates three different manufacturing strategies in relation to product variety and volume. In the following, a short presentation of the various manufacturing strategies is made, for a more detailed description of the different manufacturing strategies, please visit [ElMaraghy et al., 2013].

Craft production is one-of-a-kind production is characterised by high variants but low volume, an example of craft production is the strategy used by a local blacksmith. On the other hand high volume but low variants characterise mass production. An often used example of mass production is the production of the Model T from Ford. Mass customisation is a manufacturing strategy with relative high product variants and volume, the variants are often introduced in the production process as late as possible. An example of mass customisation is the current production of cars where customers may configure their own car by selection among a large number of predefined choices resulting in millions of variants.

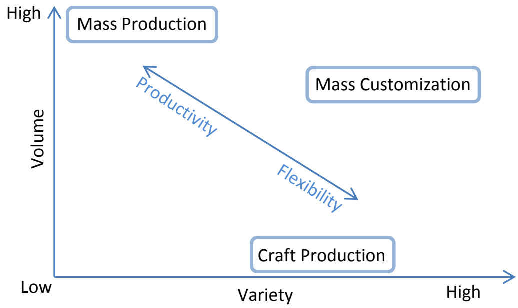


Fig. 1.1: Illustration of three different manufacturing strategies in relation to their production volume and flexibility. Modified from [ElMaraghy et al., 2013].

Mass customisation is a manufacturing strategy that gives a good trade-off between production volume and variety and therefore can be the strategy for dealing with the fluctuating market and demand [ElMaraghy et al., 2013]. In additional mass customisation also have a great potential for Small and Medium-sized Enterprises (SMEs) as most SMEs produce with high variant and low volume [Taps et al., 2016].

Changeable manufacturing setups may enable mass customization through their ability to change the scope of flexibility and capacitive [Ditlev et al., 2016; ElMaraghy et al., 2013; Joergensen et al., 2010; Korena et al., 1999; Wiendahl et al., 2007]. Changeable manufacturing is designed for rapid change in structures, both hardware and software components, to adjust the functionality and capacity of the production. *Figure* 1.2 illustrates how changes can be obtained by a reconfiguration between two states which change the scope of functionality. Hereby, the changeable manufacturing setup can address different product(s) compared to the original configuration, e.g., a new product family. The reconfiguration of manufacturing system is obtained by the use of standardised modules with standardised interfaces, both software and hardware, establish integrability of the manufacturing system. The use of modules, with a defined scope of functionality, ensure the ability to change the manufacturing system economically according to the demand, e.g., changes in capacity or product variety. In an Industry 4.0 contexts the modules are mechatronic modules consisting of control, electrical, mechanical, and software systems in one unit.

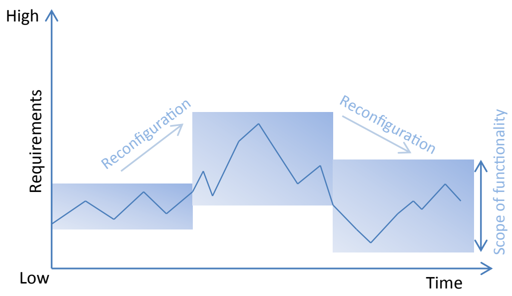


Fig. 1.2: Illustration of how reconfiguration change the scope of functionality to cope with the fluctuating requirement. The scope of functionality is defined in the customization of the modules. Modified from [Nyhius et al., 2008].

1.2 Commissioning

Changing the manufacturing system in any way will introduce a new commissioning phase as the same in a traditional manufacturing line. *Figure* 1.3 illustrates a life cycle for a dedicated manufacturing system which produces product A. It consists firstly of an engineering and design phase followed by commissioning and lastly a manufacturing phase. The traditional dedicated manufacturing system is phased off with the product.

Traditional commissioning is very time-consuming and often associated with uncertainty resulting in high costs and delays. Traditional commissioning begins with the assembly of the manufacturing line, making the physical assembly of the different components. Afterwards, the logic is tested, e.g., recovery after an emergency stop, an empty sequence of the line. Lastly, the manufacturing system is tested towards its ability to reach the target in quality and output rate. Errors in the commissioning phases can extend the commissioning time up to 900% where 70% of the error handling is used in software debugging, e.g., control of logic in Programmable logic controllers (PLCs) and robots [Reinhart and Wünsch, 2007].

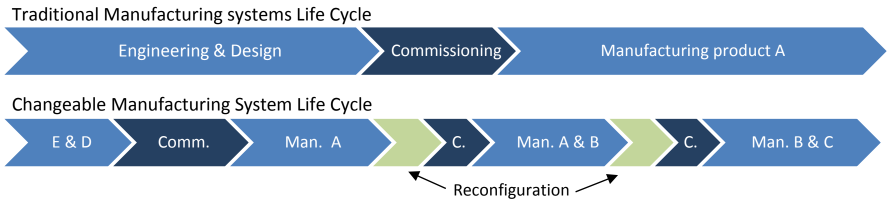


Fig. 1.3: Traditional manufacturing line life cycle compared to a changeable manufacturing life cycle. Modified from [Korena et al., 1999].

Changeable manufacturing is reconfigured and commissioned several times in its life cycle with the result of several commissioning phase in illustrated in *Figure* 1.3. An example of this could be changes in the market occur requires the production of a new product B while at the same time producing product A. This requires reconfiguration and new commissioning of the manufacturing system. Even for changeable manufacturing with the use of standard interfaces and modules traditional commissioning will be expensive both in time and cost. In addition SMEs will have a higher need for reconfiguring more frequently compared to larger companies due to a lower production volume of the higher product variants. Thus, the commissioning phase is even more critical to be reduced [Ditlev et al., 2016]. Hence, there is a need for a tool that can lower the commissioning time, particularly finding software errors.

1.2.1 Virtual Commissioning

A tool to lower the commissioning time is virtual commissioning. Virtual commissioning enables verification of the manufacturing system by the use of a virtual model and real controllers, generally PLC controller. With the utilisation of the physical controller to execute the control program virtual commissioning is also known under the name as "Hardware-in-the-loop" and "Emulation". The virtual commissioning identifies design and control faults before the real commissioning and thereby shorting the implementation time in the real factory [Hoffmann et al., 2010; Lee and Park, 2014a; Reinhart and Wünsch, 2007; Wöhlke and Schiller, 2005]. Virtual commissioning (based on the definition in the German standard VDI 4499 [Verein Deutscher Ingenieure, 2008]) begins after the detailed engineering phase and before the physical commissioning as illustrated with the grey arrow in the detailed view of the life cycle of a manufacturing system in *Figure* 1.4. Studies have shown that virtual commissioning may lower the commissioning time by 75% [Reinhart and Wünsch, 2007]. The reason for this great time saving is that 90% of the delays in the commissioning phase results from commissioning of control of hard- and software [Reinhart and Wünsch, 2007].

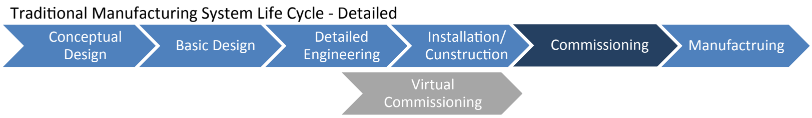


Fig. 1.4: Detailed illustration of a manufacturing line life cycles together with illustration of virtual commissioning. Based on [Oppelt and Urbas, 2014a].

Virtual commissioning software tools reflect the physical environment and physical devices. Common for the virtual commissioning software tools are the main focus on testing the logic and performance of the control program. In addition, some of the virtual commissioning software tools include conditions as forces, gravity, collisions etc.

Despite its large potential virtual commissioning has not yet the same success as other simulation tools, specifically SMEs do not use virtual commissioning [Drath et al., 2008; Hoffmann et al., 2010; Onosato and Iwata, 1993a]. The missing success for virtual commissioning is the classical themes: cost, time consumption, and the demand for high level skills [Wöhlke and Schiller, 2005].

1.3 Digital Qualifications

With the introduction of digitalisation in the manufacturing industry, the demand for new qualifications emerges [European Commission, 2018]. The digitalisation of manufacturing, such as introduction of Industry 4.0, will challenge the human labour force in the manufacturing, especially low-skills jobs will be automated or eliminated but also to some extend high-skills jobs will be automated [Bonekamp and Sure, 2015]. However, new jobs will also emerge with the digital revolution in the manufacturing industry [Wellener et al., 2018]. It is believed, that with training and education the working force may obtain the needed qualifications for the fourth digital transformation [Gehrke et al., 2015]. Especially the Danish industry has a higher opportunity, compared to other European countries, based on the general high digitalised society [Faeste et al., 2016].

Two basic approaches are presented in the literature for exploring new qualifications related to the digitalisation. The first approach is the use of technology-islands and the second approach is the use of lab-manufacturing. The technology-islands are small isolated laboratory experimental set-ups only testing one of the digital technologies, e.g. autonomous robots, Cyber-Physical systems, big data or wireless communication. The drawbacks of the technology-islands are the lack of system integration to a larger manufacturing system, e.g.,how to use Cyber-Physical system combined with RFID technology and training of operator. The lab-manufacturing is centred about the integration of the different technologies by producing a fictive product, e.g. dummy phone at Aalborg University Smart Production Lab [Madsen and Møller, 2017]. The lab-manufacturing do treat not only the technologies but also the workers' qualifications in the use of the key enabling technologies. These laboratories/training facilities are also known as Learning Factories.

1.4 Summary

Several challenges and opportunities have been highlighted in the previous sections.

- Manufacturing systems need to be flexible and efficient at the same time.
- The concept of changeable manufacturing may be the respond to be flexible and efficient at the same time.
- Commissioning time is a major show-stopper for more rapid and frequent change in changeable manufacturing systems.
- Virtual commissioning may lower the commissioning time but is not yet suitable for changeable manufacturing systems and require expert qualifications.
- Acquisition of digital qualifications of key technologies are essential to maintain locally manufacturing.
- Learning Factories enable a platform for teaching, dissemination, and research in digital qualifications.

1.5 Initiating Research Problem

This lead to the initial problem presented as followed:

Initiating research problem
How may we obtain the digital qualifications needed to use virtual commission, enabling the realisation of changeable manufacturing?

The three subjects; Digital Qualifications, Changeable Manufacturing, and Virtual Commissioning, provide the setting of this thesis as *Figure* 1.5 illustrate. In addition, the position of the presented papers is shown.

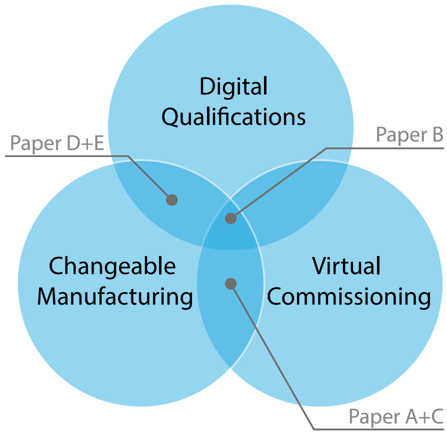


Fig. 1.5: The three subjects which frame the scope of the performed work together with the position of the presentation papers.

Chapter 2

Related Research

This chapter gives a state-of-the-art introduction, description of advantage, and elucidate challenges concerning changeable manufacturing, traditional commissioning, and virtual commissioning. In addition, related research in the cross field of changeable manufacturing and virtual commissioning is enlightened. Lastly, a presentation of the state-of-the-art within learning factory, a mean to obtain new digital qualifications in manufacturing industry, is conducted.

2.1 Changeable Manufacturing

Several manufacturing strategies and systems that all aim for easier adjusting the manufacturing setup as a response to changes have been proposed in the last two decades, such as: Reconfigurable Manufacturing Systems [Koren et al., 1999] (RMS), Reconfigurable Assembly Systems (RAS)[ElMaraghy, 2006], Adaptive Production Planning and Control (APPC) [Wiendahl, 2009], Agile Manufacturing (AM) [Yusuf et al., 1999], Reconfigurable Process Planning (RPP) [ElMaraghy, 2007], and Modular Manufacturing Systems (MMS) [Joergensen et al., 2012].

The research environment with professor H.-P. Wiendahl at Leibniz University Hannover, Germany, and professor H.A. ElMaraghy at University of Windsor, Canada, in the lead, formulated a broad umbrella to embrace the manufacturing strategy and systems in relation to changeable manufacturing. In the following, a presentation of changeable manufacturing, based on this work is performed.

> *Changeable manufacturing is defined as the ability of a manufacturing system to economically accomplish early and foresighted adjustments of the factory's structures and processes on all levels in response to change impulses. It is closely related to "flexible" and "reconfigurable" manufacturing which apply to the manufacturing equipment and systems on the shop floor respectively – the difference being the level, degree, and scope of change.*
>
> [ElMaraghy and Wiendahl, 2016]

Changeable manufacturing is developed to accommodate changes in product variant and volume and minimise the impact on the manufacturing setup. The foundation of changeability can be illustrated as shown in *Figure* 2.1 by [Andersen, 2017] revised and combined of version from [ElMaraghy and Wiendahl, 2009; Wiendahl et al., 2007]. In the following text, the components of *Figure* 2.1 will be explained, the components are highlighted in the text. The change in the production may be triggered by **External**, **Internal** Change Drivers or a mixture of both. The **Change Drivers** are commonly related to changes in volume, technology, strategy, etc. A firm that wants to enter a new market or a market demand change are examples of Internal and External Change Drivers. The change may have an impact on External Change Objectives and/or Internal Change Objectives, from the manufacturing point of view. The **External Change Objectives** are related to changes considering to the manufactured product(s), like product mix and volume. The **Internal Change Objectives** are related to changes in the manufacturing setup achieved by Change Enablers.

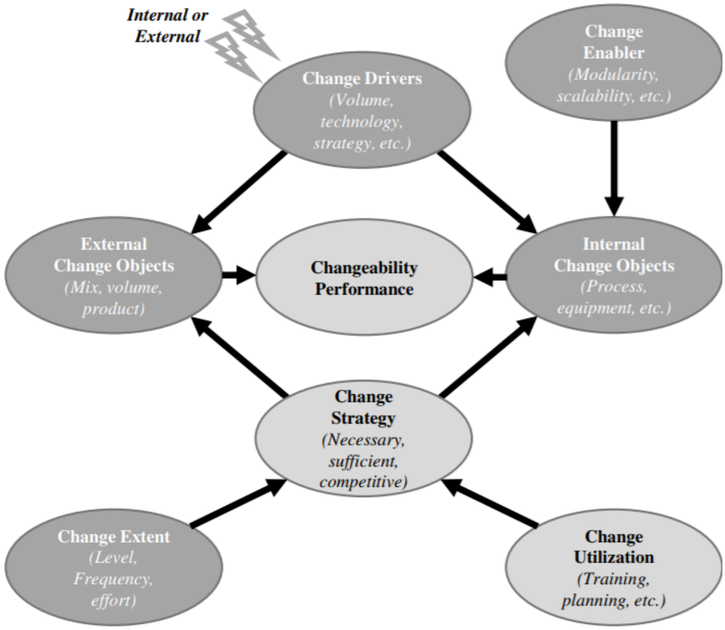


Fig. 2.1: The foundation of changeability. [Andersen, 2017]

Change Enablers are the physically and logically design properties that enable a quicker, cheaper, and less time and effort demanding reconfiguration in changeable manufacturing setup compared to reconfiguration in traditional manufacturing systems [ElMaraghy and Wiendahl, 2009]. The use of Change

Enablers is context specific and influenced by the implementation level and type [Andersen et al., 2017a]. Wiendahl et al. [2015] arguing that even though many Change Enablers exist it can be simplified to the five Change Enables as illustrated in *Figure* 2.2.

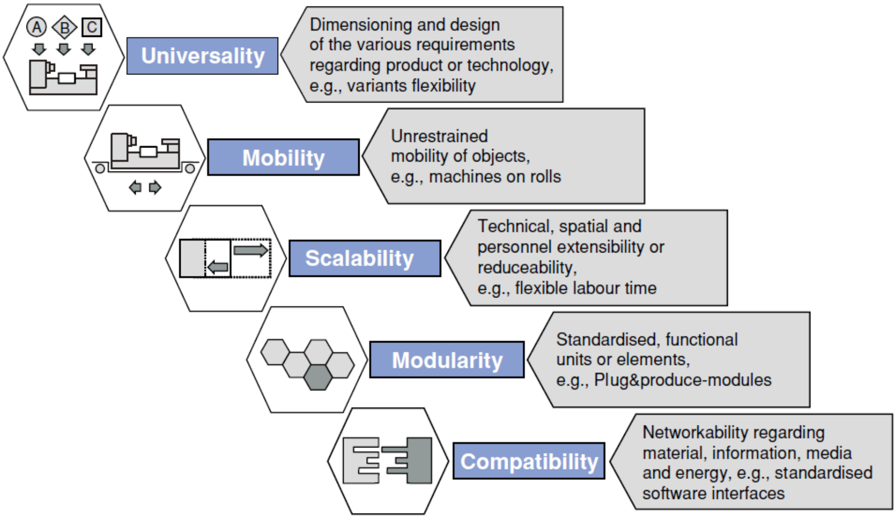


Fig. 2.2: Change Enablers. [Wiendahl et al., 2015]

Both the External and Internal Change Objectives have an impact on Changeability Performance. The **Changeability Performance** compare key performance indicates (KPIs), typically delivery time, due-date performance, turn around rate, and inventory, days of supply and overhead cost before and after the change as a measurement for how successful the changes have been [ElMaraghy and Wiendahl, 2009]. The **Change Strategy** is also input to the External and Internal Change Objectives, e.g., should the change be a here-and-now-solution, or should it be a more generic solution taking near-future product families into account. Moreover, the Change Strategy is based on the Change Extent and Change Utilization.

Needed changes to accommodate new manufacturing demands, called **Change Extend**, may be on different levels and have different effort, time, and frequency. It is therefore desirable to make a segmentation of the Change Extend. Wiendahl et al. [2007] divided production levels into six layers and later related it to the changeability classes and product level presented by El-Maraghy [2006]. The combined view of production view, changeability classes, and production view was presented in ElMaraghy and Wiendahl [2009] as illustrated in *Figure* 2.3. In the following description, the typical changes and time frames/frequency is adapted from Wiendahl et al. [2007].

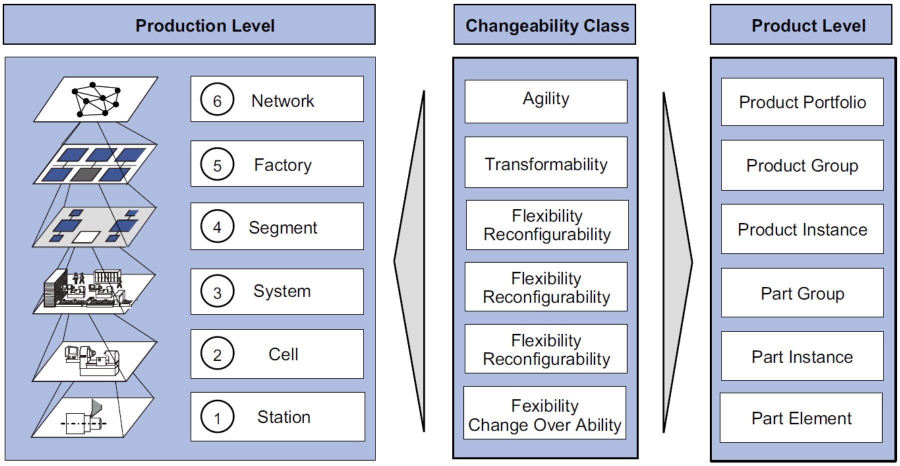


Fig. 2.3: Hierarchies of production level related to changeability classes and example of manufactured product level. ElMaraghy and Wiendahl [2009]

The highest changeability class is Agility on a network level and product portfolio. A network level can be seen as different geographically production factories interconnected by material and information flow. Agility means the ability to enter new markets by constructing new products and services with the typical time frame/frequent from months to years. The next level is the factory level which is related to the changeability class Transformability. Changes in this level occur with a typical time frame/frequent of weeks to months. Transformability is the ability to shift a factory scope of production from one product family to another, including changes in the layout and organisation. A factory may be divided into segments which have the changeability class Flexibility/Reconfigurability. Changes in the segment level could be department layout design with the time frame/frequent days to weeks.

Flexibility may have a different interpretation depending on the context, as illustrated with the ten types of manufacturing flexibility described in ElMaraghy [2006]. However, as described in ElMaraghy and Wiendahl [2009], Flexibility in relation to changeable manufacturing refers to the ability to change an entire production and logistics area to a new, but similar, family of components. Reconfiguration is the ability to add or remove functional elements to produce a familiar product [Koren et al., 1999].

The Flexibility/Reconfigurability changeability classes are also used on the system and cell level. However, with different time frames/ frequency. The system level (also known as line level) is a production system consisting of multiple cells, enabling the system to produce, e.g., a part group, whereas the cells are focused on a part instance. Changes at system and cell level are typically introduced within the time frame/frequent of hours to days.

The last production level is station level with the changeability class Flexibility and Changeover-ability. The Changeover-ability means the ability to quickly and effortless changes tool or machinery with the time frame/frequent of minutes to hours.

Lastly, in relation to *Figure* 2.1, **Change Utilization** is how to ensure fast implementation, e.g., with training and planning.

2.1.1 Challenges of Changeable Manufacturing

Considering the extensive research in changeable manufacturing in the last two decades it is unambiguous that the description, definition, and interpretation of changeable manufacturing is well defined in the academic world [Bortolini et al., 2018]. However, Change Utilization, part of the foundation of changeable manufacturing, is still not well covered in the literature. The Change Utilization is introduced in ElMaraghy and Wiendahl [2009] contained no description of the change utilisation beyond the text in the figure are present. A literature search for the "Change Utilization" and review of Andersen [2017], who also presented the figure, revealed that the change utilisation is not well covered in the literature.

Spena et al. [2016] mapped the extensive potential and need for changeable manufacturing in the industry. However, a misalignment between the potential/need and the actual implementation of changeable manufacturing prevail in the industry [Andersen et al., 2018a; Maganha et al., 2018].
The missing industrial implementation may be caused by several barriers. [Malhotra et al., 2012] identifies twelve barriers for changeable manufacturing, concludes that the impact of different barrier in the design and implementation may differ from case to case. However, [Malhotra et al., 2012] highlighted a general lack of awareness and knowledge about changeable manufacturing in the industry. Correspondingly, Andersen et al. [2018b] conducted an industrial survey with 60 Danish companies also concluded that knowledge and skills are the major barrier towards changeable manufacturing.

Even with a higher level of awareness, knowledge, and skill level the industry still phases critical challenges in the reconfiguration are commissioning phase partly due to insufficient reconfiguration planning [Kurniadi et al., 2018] and/or unforeseen event/obstacles [Andersen et al., 2018c; Pellicciari et al., 2012a]. Koren et al. [1999] and later Ali-Qureshi and ElMaraghy [2014] identifies that short commissioning and ramp-up times are critical to a successful reconfiguration. In addition, as Singh et al. [2017] and Spena et al. [2016] emphasise no research has been conducted in the multi-dimensional and complex nature of reconfigurability.

2.2 Commissioning

This section will explain traditional commissioning and related standard verification and validation tests. Further the challenges of traditional commissioning are presented.

Commissioning is to bring something new, such as a new manufacturing system, into a working condition. Traditional commissioning is often based on standards and guidelines in the industry founded on best practices in the industry, e.g., GAMP (Good Automation Manufacturing Practice)[International Society for Pharmaceutical Engineering, 2008], GAAP (Gode Automations Projekt Processer(Good Automation Project Processes))[SESAM World A/S, 2016] and standards like the IEC 62381:2012 from the International Electrotechnical Commissioning [2012].

Figure 2.4 illustrates the typical lifecycle of a manufacturing system. The construction/manufacturing of the manufacturing system is commonly handled by suppliers as machine builders/original equipment manufacturers (OEMs). The partial deliveries are traditionally tested towards equipment functionality to ensure the solution meets the specification. The partial deliveries are tested at the suppliers' facility by the supplier and examined by the customer and users before shipped to the customer. This test is also called the Factory Acceptance Test (FAT) [Hedberg, 2006] and defined in the IEC 62381:2012 [International Electrotechnical Commissioning, 2012].

The installation and establishment of the equipment on-site may begin afterwards, followed by an I/O test, sometimes called a Hardware Acceptance Test (HAT). The I/O test verifies that the installation of cables, electric connection and supply connection (e.g., power and air), are properly connected to ensure the further focus on the test of the functionality. The commissioning phase contains a number of tests of the functionality with a special focus on the horizontal and vertical interfaces. The horizontal interfaces could be between different partial equipment deliveries and their controllers (PLC) ensuring mechanical and logical interfaces. The vertical interfaces could be the logical and information interface to higher level systems such as MES and ERP. The commissioning also includes functionality test without the product and/or a dummy product followed by tests with the real product. The supplier runs a series of tests with the manufacturing equipment observed by the customer and

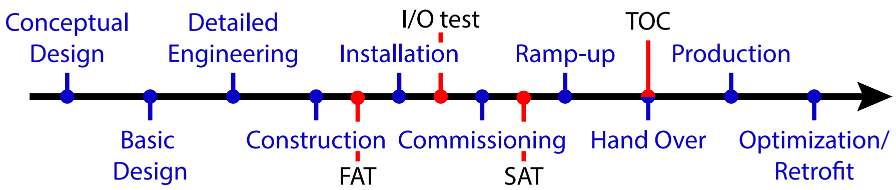


Fig. 2.4: The lifecycle of a manufacturing system with a focus on the commissioning phase and surrounding phases and tests. Drawn with inspiration from [Oppelt and Urbas, 2014b; SESAM World A/S, 2016].

system-end-users. This test is called the Site Acceptance Test (SAT), similar to the FAT [International Electrotechnical Commissioning, 2012].

The commissioning phases end with a ramp-up phase where the production capacity is slowly scaled up to the intended capacity, and the intended production quality is reached. When full production capacity and quality are obtained the supplier officially and legally hand over the manufacturing equipment to the customer also called Take Over Certificate (TOC). The last phase in the lifecycle of the manufacturing system is optimisation and/or retrofitting of newer machines.

2.2.1 Challenges of Traditional Commissioning

Several challenges exist in the use of traditional commissioning. Reinhart and Wünsch [2007] showed that 15% to 25% of the total project time is used in the commissioning phase where 90% of the time-use is concerning commissioning delays and activities in electric and control devices while 70% of the time delay was associated with control software errors. Kiefer [2007] highlights that the effort for error handling is increased when the error is discovered in the process later, e.g., software errors found in the SAT are more expensive in terms of cost and resources to fix than the ones found earlier in the process.. Auinger et al. [1999] also state that "*control programs are often implemented and finished right on the spot during the plant startup phase, which is not only expensive but also risky and error-prone.*" In addition, Reinhart and Wünsch [2007] also point out that companies are not only focused on the cost but also on faster time-to-market. **It is therefore essential to lower the cost and time of traditional commissioning.**

2.3 Virtual Commissioning

To respond to the long commissioning time and cost due to control software errors, virtual commissioning was proposed [Lee and Park, 2014b; Onosato and Iwata, 1993b; Reinhart and Wünsch, 2007]. Auinger et al. [1999] define soft-commissioning, later named hardware-in-the-loop-simulation or virtual commissioning, as "... *coupling the real control system with a simulation model of the plant* ... " for a full verification of the control software, illustrated in *Figure* 2.5.

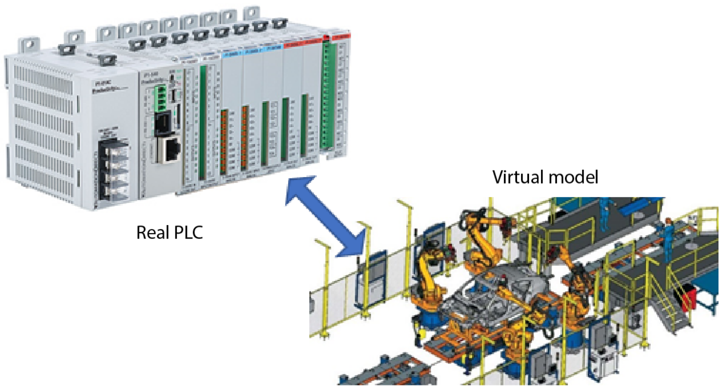


Fig. 2.5: Illustration of virtual commissioning with the real controller communicate with a virtual plant.

Reinhart and Wünsch [2007] later conducted an experiment concluding that use of virtual commissioning may save up to 75% of the commissioning time and reduce the time-to-market with 15%. Shahim and Moller [2017] adds that in addition to saving time the control software quality also improves, due to the intensive testing. Lee and Park [2014b] literature survey of virtual commissioning emphasise that the full verification of the manufacturing system require the plant model to fully describe the actuator and sensor level. Virtual commissioning is mostly applied at a station, cell, and system level [Lee and Park, 2014b; Reinhart and Wünsch, 2007]. Multiple studies have confirmed, with small examples, that virtual commissioning is feasible in different commercial software frameworks e.g., Delmia (Dassault Systemes) [Vermaak and Niemann, 2017], Tecnomatix (Siemens) [Eguti and Trabasso, 2018], or Experior (Xcelgo) [Longo and Fantuzzi, 2018].

2.3.1 Challenges of Virtual Commissioning

One could believe that based on the great benefits and accessibility, virtual commissioning would be widely used in the industry. However, this is not the cases due to several barriers [Lee and Park, 2014b; Oppelt et al., 2015; Wöhlke and Schiller, 2005]. Oppelt et al. [2015] have conducted a survey among 221 responses, including 198 companies, to discover the barriers of virtual commissioning. They identify eight actions or focus points to improve the use of virtual commissioning, four technical and four non-technical focus points are listed in *Table* 2.1.

Technical	Non-technical
Model Reuse	Acceptance
Model Efficiency	Workflows
Integration	Collaboration
Usability	Education

Table 2.1: Virtual Commissioning focus points to improve the use of virtual commissioning. [Oppelt et al., 2015]

Technical Focus Points

The modelling task of the virtual plant and sub-components are troublesome, time-consuming, and require expert skills [Park and Chang, 2012; Zäh et al., 2004]. A number of suggestion has been made to lower the complexity at the modelling task

Oppelt et al. [2015] suggests that model efficiency will improve with automated model generation in addition to the reuse of models from previous steps in the workflow, e.g., reuse from the detailed engineering phase. *Figure* 2.6 illustrates the position of automated generation of factory models from existing data (the green arrow in *Figure* 2.6), e.g., described in Oppelt et al. [2014] or Barth and Fay [2013], in relation to traditional virtual commissioning. Establishment of a model exchange standard, like AutomationML [Lüder et al., 2015], will enable standard model catalogues which also will lower the barriers. Oppelt et al. [2015] also suggests that a higher integration and collaboration with the preceded phase will extend the use of virtual commissioning, an example is provided in Oppelt and Urbas [2014a] or Dahl et al. [2016] and illustrated as the red arrow in *Figure* 2.6. Bausa and Dünnebier [2006] also propose the reuse or extent of the virtual commissioning models too, e.g., operator training, maintenance, supervision, or sale materials illustrated with the purple arrow in *Figure* 2.6. Lastly, of the technical focus points, Oppelt et al. [2015] concludes that the usability of virtual commissioning needs to improve so a non-expert can use the tool.

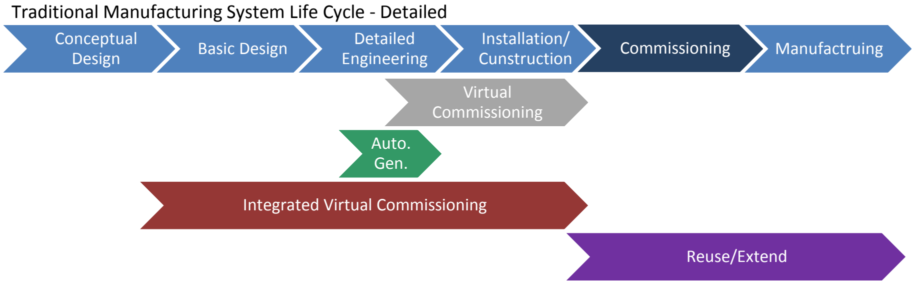


Fig. 2.6: Detailed illustration of a manufacturing line lifecycles together with an illustration of different approaches for virtual commissioning. Based on [Oppelt and Urbas, 2014a].

Non-technical Focus Points

Some of the non-technical focus points have already been touched in the presentation of the technical focus point as the workflow and collaboration between domain experts. Oppelt et al. [2015] argue that acceptance/awareness and training of virtual commissioning knowledge is essential both in the education system but also in the management of the companies. Makris et al. [2012]; Neumeyer et al. [2017]; Reinhart and Wünsch [2007] and Wöhlke and Schiller [2005] also list the need for virtual commissioning experts as one of the show stoppers of virtual commissioning.

2.3.2 Virtual commissioning in Changeable Manufacturing

The multiple reconfigurations of changeable manufacturing setups will also introduce multiple commissioning phases in the lifecycle. Besids, the cost and time saving, virtual commissioning can have a great potential in changeable manufacturing setups. However, only scant literature exists on the subject as presented next.

Robert Harrison and his team at Loughborough University have performed significant research on virtual commissioning in a changeable manufacturing environment in the period from 2009 to 2016. In the early publications, [Jain et al., 2010; Vera et al., 2009], presented a research software tool for virtual commissioning and compared it to an existing commercial virtual commissioning tools. The software uses a component-based architecture of core component that allows virtual models being built easier by use of libraries of sub-models. The use of libraries enables modelled components to be reused and reconfigured. The papers' main focus is on the engineering phase of reconfigurable manufacturing systems. Kong et al. [2011] adds an open-data model in AutomationML

format to the framework to incorporate virtual devices in a neutral data format. Harrison et al. [2016b] expand the software to ensure a common data model extending across all lifecycle phases. Lastly presented in [Harrison et al., 2016a] automated generation of the low-level control is added to the software framework. The reconfiguration and followed commissioning of the new setup is not treated in the papers.
Andrisano et al. [2011] and Pellicciari et al. [2012b] also utilise the use of standard modules to faster build a new virtual model configuration of the changeable manufacturing setup, however, also highlight the need for easy customisation of new modules.

As presented, an enabler of virtual commissioning in changeable manufacturing is the use of modules that permit a faster construction of the virtual plant. **However, literature does not cover the knowledge and work procedure within the use of virtual commissioning in a changeable manufacturing context when: the virtual models are made, the first real commissioning is done, and the systems facing a reconfiguration.**

2.4 Digital Qualifications

This section will firstly describe the drivers behind the need for new digital qualifications in manufacturing companies. Secondly, a review and establishment of a common understanding of the concept of qualifications and how to work within different disciplinary workflows are presented. Lastly, learning factories as a mean for learning new digital qualifications are presented.

2.4.1 Digital Transformation of Manufacturing Companies

The digital transformation of manufacturing companies may have various names in relation geographical affiliation, profession, and manufacturing department, as mention in Chapter 1, such as Industry 4.0 However, a consensus in the literature exists that the digital transformation will effect the current labour market Schumacher et al. [2016]. Bonekamp and Sure [2015] highlight that a general need for new qualifications both for low-skilled and high-skilled workers will arise with the introduction of the digital transformation. Bauer et al. [2015] adds that the digital transformation not only will affect the workers' qualifications but also the organisation and workflows.

The digital transformation is partly driven by technologies such as cheaper and faster micro-controller and with high inspiration from consumer electronics like smartphones, smart TVs, etc. [Kagermann et al., 2013; Liere-Netheler et al., 2018; Schmidt et al., 2015]. Multiple views of which key technologies that will drive Industry 4.0 have been constructed, such as [Helmrich, 2019; Russmann et al., 2015]. The key technologies are not novel technologies respectively, e.g., RFID tags, virtual environments, and collaborative robots. However, the merging of the technologies are revolutionary. Lu [2017] argue that the use of data and the connectivity of technologies will have a high impact on the factory of tomorrow. This may challenge companies concerning digital thinking, new working procedures, and discovery of new needed qualification of employees Schröder [2016].

Technical qualifications	**Personal qualifications**
State-of-the-art knowledge	Flexibility
Technical skills	Ambiguity tolerance
Process understanding	Motivation to learn
Media skills	Ability to work under pressure
Coding skills	Sustainable mindset
Understanding IT security	Compliance
Social qualifications	**Methodological qualifications**
Intercultural skills	Creativity
Language skills	Entrepreneurial thinking
Communication skills	Problem solving
Networking skills	Conflict solving
Ability to work in a team	Decision making
Ability to be compromising and cooperative	Analytical skills
Ability to transfer knowledge	Research skills
Leadership skills	Efficiency orientation

Table 2.2: Illustration of some of the required new qualifications for the digital transformation. Hecklau et al. [2016]

Companies need to gain knowledge and skills both in the technologies and awareness of the context [Sommer, 2015]. Wolter et al. [2015] describe how the new labour demand (demand from the industry) requires a change in the labour supply (education of labour). Hecklau et al. [2016] has performed a literature review for classifying some of the new qualifications, see *Table* 2.2. Hecklau et al. [2016] decompose the needed qualifications in four groups: Technical, Personal, Social, and Methodological. The technical qualifications may vary from domain and task to task, whereas the personal, social, and methodological qualification may be generic for the labour of the future [Hecklau et al., 2016]. Sommer [2015] highlight that SME might be the first victims of Industry 4.0, because of their vulnerable positions as suppliers to larger companies. Sommer [2015] adds "*SMEs have to be supported separately as they are less capable of coping with the financial, technological and staffing challenges than large enterprises*". Madsen et al. [2016] and Wolter et al. [2015] both illustrate how higher qualifications are needed to handle the increased complexity of tasks and how the complex task is moving downwards e.g., an employee with a Bachelor's degree can nowadays solve tasks that previously required the special training that comes with a master's degree and at the same time employees with vocational skills can solve tasks that previously required workers with a college degree.

It is evident that the digital transformation will alter the landscape of qualifications. The requirements for new technical qualifications are a result of the introduction and use of new technologies. The requirements for new personal and social qualifications is based in the need for teamwork to solve the more complex tasks and skill development. Lastly, the requirements for new methodological qualifications rooted in the need for solving increasingly complex tasks.

2.4.2 Definition of Qualifications

In addition with the discussion in the previous Section 2.4.1, about the need of new qualifications for accommodating the digital transformation, an establishment of what qualification really means is important. Hence, this section will establish a definition of the concept of qualifications.

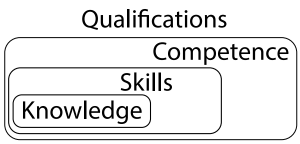


Fig. 2.7: Qualifications in relation to knowledge, skills, and competence. Inspired by Westera [2001].

Qualification is the set of knowledge, skills, and/or competence that qualify a person, group or organisation to perform an assignment, task, function, mission, etc. [European Center for the Development of Vocational Traning, 2017; Ministry of High Education And Science, 2018]. In the majority of the literature, qualifications are divided into three subcategories: knowledge, skills, and competence [European Center for the Development of Vocational Traning, 2017; Le Deist and Winterton, 2005]. *Figure* 2.7 illustrates how knowledge is incorporated in the skills and skills in the competences to build the qualifications.

Even though there is a broad acceptance of the use of knowledge, skills, competence, the interpretation and definition diverge. The interpretation and definition differ between nations, culture, language, profession, and even workplaces [Westera, 2001]. There have been several attempts to standardize the definition of knowledge, skills, and competence through the years [Le Deist and Winterton, 2005; Winterton et al., 2006]. The European Qualifications Framework for lifelong learning (EQF) is a European framework for comparison of 43 different national qualification frameworks [European Ministers of Education, 1999; Lourtie, 2001]. In this thesis, the definition from the Danish National Qualification Framework for Lifelong learning (DK-NQF) is used, illustrated in *Table* 2.3.

Knowledge	Knowledge indicates knowledge of a subject as well as understanding. Knowledge includes the following aspects: **1)** What kind of knowledge is it about: knowledge of theory or knowledge of practice; knowledge in a subject, within a field of study or within a profession. **2)** How complex this knowledge is: the degree of complexity, and how different and unpredictable situations this knowledge is mastered in . **3)** Understanding: The ability to put their knowledge in context. Understanding comes, for example expressed when explaining something to others.
Skills	Skills indicate what a person can do or perform. Skills contain the following aspects: **1)** What kind of skill are these e.g., practical, cognitive, creative, or communicative skills. **2)** How complex the task solution is: what task solution will be used for and the complexity of this task. **3)** Communication: which communication is required, the complexity of the message, the target groups and the means.
Competence	Competences are about responsibility and independence and indicate the ability to apply knowledge and skills in a work situation or in a study context. Competences contain the following aspects: **1)** The scope of action: in what types of work and/or study context knowledge and skills are brought into play, as well as the degree of unpredictability and changeability in these contexts. **2)** Collaboration and responsibility: the ability to take responsibility for own and others' work, as well as how complex collaborative situations can be included. **3)** Learning: The ability to take responsibility for self and others' learning

Table 2.3: The Danish National Qualification Framework (DK-NQF) definition of knowledge, skills and competence [Ministry of High Education And Science, 2018].

2.4.3 Disciplinary Concepts

With the increasing focus on work within teams, a clarification of different work procedures is presented.

Figure 2.8 serves as a base for a understanding of the concept of Disciplinary, Multidisciplinary, and Interdisciplinary. The following is based on [Refsum Jensenius, 2012; Stember, 1991; Tress et al., 2006]. The traditional way of solving a task or achieving a goal has been to work inside one discipline solving tasks in separated knowledge bodies, also known under the word intradisciplinary or the phrase "work in isolated silos" illustrated in the left of *Figure* 2.8. A knowledge body is the knowledge foundation of the individual/team which may contain one or more disciplines, e.g., education background or experience. A multidisciplinary approach uses several disciplines and the integration between them within the knowledge body to solve the task illustrated centre in *Figure* 2.8. In the interdisciplinary approach, two or more individuals/teams work together to solve a common task. Each individual/team solve only part of the task in relation to their knowledge body and one disciple (intradisciplinary approach). However, the individuals/teams collaborate to achieve the common task, e.g., sharing information and knowledge, illustrated right in *Figure* 2.8. In many cases when solving a complex task, a shift or combination of disciplinary approaches is used, e.g., the use of a multidisciplinary approach inside each of the interdisciplinary individuals/teams.

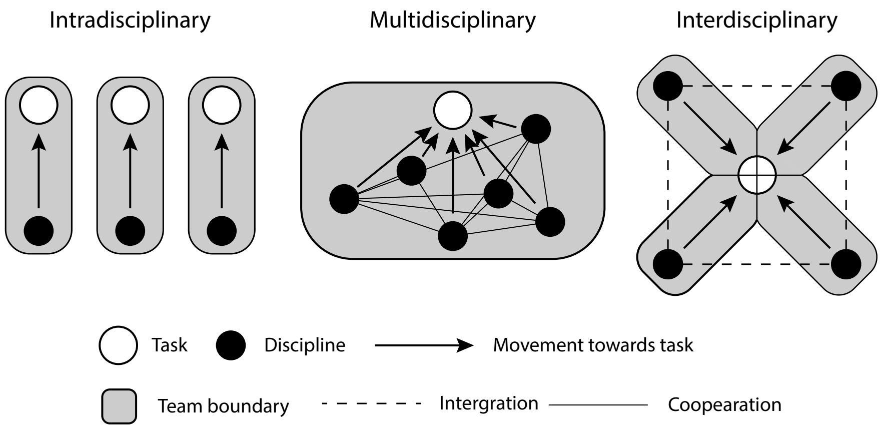


Fig. 2.8: Definition of intradisciplinary, multidisciplinary, and interdisciplinary. Drawn with inspiration from [Refsum Jensenius, 2012; Stember, 1991; Tress et al., 2006]

2.4.4 Learning Factories

This thesis will investigate one of the means to achieve the digital qualification for industrial manufacturing, namely; learning factories.

Learning factories are widely used to facilitate a learning environment for education, training, and research [Abele et al., 2017a]. Learning factories varies in several ways as illustrated with the 31 examples of learning factories in Abele et al. [2018]. Tısch et al. [2015] present a leaning factory morphology with seven parts; *Operating Model*, e.g., operators and trainers, *Purpose and targets* e.g., main purpose and target groups for education & training, *Process* e.g., life cycles and degree of automation, *Setting* e.g., change enablers and changeability dimension, *Product* e.g., variance and materiality type, *Didactics* e.g., learning method and evaluations levels, and lastly, *Metrics* e.g., size of the learning factory and number of participants a year.

The learning factories differ from traditional teaching with its training in realistically manufacturing environments and close work with industrial practice and problems. Furthermore, the learning factory also facilitates as a platform where the industry can gain new knowledge about new technologies and train new strategies in a controlled environment. Abele et al. [2015b] has collected the major researchers and together define the concepts of learning factories. Learning factories can be categorized in two groups; "narrow sense" and "broader sense", [Abele et al., 2015b].
The narrow sense of learning factory is categorised by having multiple authentic process stations manufacturing a physical product. Furthermore, a narrow sense learning factory must be changeable and resemble a real value chain [Abele, 2016]. The didactic use, communication channel, of the learning factory may either be on-site or remote learning together with formal and/or informal learning. The on-site learning categorizes the narrow sense of learning factory. A broader sense of learning factory is what falls outside the definition of a narrow sense learning factory, such as; the value chain is virtual, the manufactured product is a service, or the communication channel is remote [Abele, 2016].

In recent years, many newly established learning factories have focused on the key technologies of Industry 4.0 and how to train the new qualifications. Erol et al. [2016] introduce how a scenario-based Industry 4.0 learning factory concept may use the facility to explore future product engineering. Prinz et al. [2016] focus on how the learning of Industry 4.0 qualification can be divided from awareness pathways to more specific topics as information flow and automation. Baena et al. [2017] argue also that learning factories can contribute to strength the engineering training process in relation to Industry 4.0. Lastly, Klippert et al. [2017] state that learning factories enables Industry 4.0 proactive workers that through their training in the learning factory can immediately implement the learned at their own workplace.

As presented, the **acquisition of the new qualifications will be essential for realise the potential at digitalisation. Learning factories has proven to be an efficient and versatile tool for learning and research.**

2.5 Conclusion

This chapter has established that the design and principles of changeable manufacturing are well defined and well described in the literature. However, industrial implementation is still missing partly because of lack of awareness, knowledge, and tools for supporting the multi-dimensional and complex nature of reconfiguration and commissioning phase. Furthermore, the traditional commission is time-consuming and costly mainly due to the late correction of control software.

Virtual commissioning has demonstrated great potential to reduce the commissioning time but has similar challenges as changeable manufacturing in lack of awareness, knowledge and methodology tools. Only limit research in virtual commissioning in a changeable manufacturing context has been performed. Knowledge and work procedure about the use of virtual commissioning in the reconfiguration phase of changeable manufacturing is lacking.

The introduction of the digital transformation, Industry 4.0, of the manufacturing industry the need for digital qualifications is rising. The new qualifications must be explored, enlightened, and learned to be competitive in the future. One of the mean for archive this is learning factories that are widespread and acknowledged platform for research, education and teaching in the new digital qualifications.

Chapter 3

Research Objectives and Methodology

The state-of-the-art analysis emphasises that changeable manufacturing systems enable manufacturers to change their production setup to follow the oscillating demand better. Virtual commissioning was identified as a tool to lower the commissioning time which will be essential to lower with multiple commissioning phase in the life-cycle of changeable manufacturing. However, a lack of tools and competence in the utilisation of virtual commissioning was identified in the state-of-the-art analysis. Learning factories, presented in the state-of-the-art analysis, will help build digital competence. Based on the focus area; virtual commissioning, digital competence, and reconfigurable manufacturing system, the following research objectives are presented:

3.1 Research Objectives

Main Objective 1 - *Develop a Changeable Industry 4.0 Learning Platform*

Specific research objectives related to main objective 1:

1.1 Establish a changeable Industry 4.0 learning platform at Aalborg University – (AAU Smart Production Lab)

1.2 Investigate how Industry 4.0 awareness can be facilitated by the learning factory

Main Objective 2 - *Definition of Qualifications for Virtual Commissioning*

Specific research objectives related to main objective 2:

2.1 Describe virtual commissioning workflow and identify the general virtual commissioning tasks

2.2 Identify and quantify qualifications needed for virtual commissioning

2.3 Develop and investigate a learning environment for obtaining the needed virtual commissioning qualifications

Main Objective 3 - *Definition of a Recommissioning Framework for Changeable Manufacturing*

Specific research objectives related to main objective 3:

3.1 Decompose of the reconfiguration complexity

3.2 Decompose of reconfiguration abilities

3.3 Develop working procedure for recommissioning and virtual recommissioning of changeable manufacturing systems

3.2 Project Delimitation

The following delimitations for the Ph.D. project are set:

Changeable manufacturing levels This Ph.D. project research will focus on the system, cell, and station level and the associated changeability classes in relation to the hierarchic of production level, presented in *Figure* 2.3.

Qualifications This Ph.D. project research will focus on the technical qualifications.

3.3 Research Methodologies

The methodology of this thesis has been a combination of different research methodologies. However, the overall method has been iterative research approach illustrated in *Figure* 3.1. Iterative research combine two iterative systems, ”research system” and ”practice system” [Ellström, 2008]. Both iterative systems are problem/issues driven where the research system iteration apply theories and concepts from the literature to perform data collection, analysis, and evaluation whereas the practice system iteration applies local theories, such as best practice to produce organisational actions. The combination of the two systems will both result in new theories, concepts, and models concerning the research domain and result in new insight and ways of working for the practice domain [Ellström, 2008].

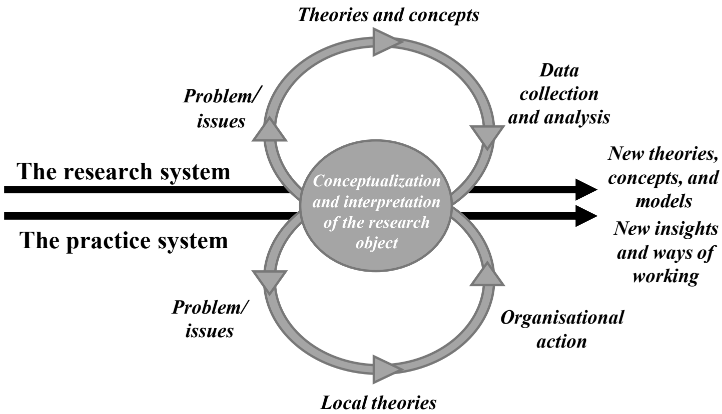


Fig. 3.1: Illustration of iterative research method. [Andersen, 2017]

For "Main Objective 1 - *Develop a Changeable Industry 4.0 Learning Platform*" iterative research method has been used with the practice research applied at the AAU Smart Production Lab. In addition, for *research objective 1.2* qualitative research methods are used to measure the impact of the learning game, presented in [Paper D | Mortensen et al., 2019].
Likewise, was iterative research method used for "Main Objective 2 - *Definition of Qualifications for Virtual Commissioning*" again with AAU Smart Production Lab as the practice research. For *research objective 2.1 and 2.2* qualitative research methods are used for the hypothesis for virtual commissioning qualifications and later quantification.
The iterative research method was also applied to "Main Objective 3 - *Definition of a Recommissioning Framework for Changeable Manufacturing*". The AAU Smart Production Lab serves as practice domain for the preliminary test of *research objective 3.4*.

3.4 Structure of Thesis

The following summary part of the thesis are structured in three chapters. Chapter 4 address the main research objective 1 and its specific research objectives 1.1 and 1.2. Chapter 5 address the main research objective 2 and its specific research objectives 2.1, 2.2, and 2.3. Chapter 6 address the main research objective 3 and its specific research objective 3.1, 3.2, and 3.3. Lastly, Chapter 7 concludes the thesis.

Part II

Summary

Chapter 4

Industry 4.0 Awareness

This chapter will firstly address research objective 1.1 and introduce the establishment of a learning factory at Aalborg University and the classification and impact on education, research, and industry of the AAU Smart Production Lab. Lastly, it concludes with the presentation of an Industry 4.0 Awareness Game coupled with evaluations from its use in academic and industrial scope, to address research objective 1.2.

Learning factories, as stated in the Digital Qualifications, Section 2.4 and Abele et al. [2017b], is a strong platform for research, education and industrial training. With the hypothesis that a learning factory at Aalborg University would support teaching, research, and industrial collaboration in Industry 4.0 technologies and strategies, Aalborg University decided to establish a learning factory.

4.1 AAU Learning Factory

This section will present AAU learning factory, named AAU Smart Production Lab, also described in [Paper B | Mortensen and Madsen, 2018], [Paper E | Brunoe et al., 2019] and [Paper D | Mortensen et al., 2019].
Using the multi-dimensional description model "Learning Factory Morphology" from Tisch et al. [2015] the AAU Smart Production Lab can be classified as a narrow learning factory. In the following table contains a short summary of the classification of the AAU Smart Production Lab, more details can be found in [Technical report i | Mortensen, 2019a]. The blue coloured boxes are the features of the AAU Smart Production Lab.

Classification of AAU Learning Factory

Name of the learning factory: **AAU Smart Production Lab**
Operator: **Department of Materials and Production, Aalborg Univeristy, Denmark**
Year of inauguration: **2016**
Floor Space in learning factory: **200 sqm**
Manufacture product: **Electronic device**
Main topics / learning content: **Industry 4.0, System Learning, Digital Manufacturing**

2.1	**main purpose**	education	vocational training	research						
2.2	**secondary purpose**	test environment / pilot environment	industrial production	innovation transfer	advertisement for production					
3.1	**product life cycle**	product planning	product development	product design	rapid prototyping	manufacturing	assembly	logistics	service	recycling
3.2	**factory life cycle**	investment planning	factory concept	process planning	ramp-up	manufacturing	assembly	logistics	main-tenance	recycling
3.3	**order life cycle**	configuration & order	order sequencing	production planning and scheduling		manufacturing	assembly	logistics	picking, packaging	shipping
3.4	**technology life cycle**	planning	development	Virtual testing		manufacturing	assembly	logistics	main-tenance	moderni-zation
3.5	**indirect functions**	SCM	sales	purchasing	HR	finance / controlling	QM			
4.1	**learning environment**	purely physical (planning + execution)	physical LF supported by digital factory (see line "IT-Integration")	physical value stream of LF extended virtually	purely virtual (planning + execution)					
4.2	**environment scale**	scaled down	life-size							

4.1.1 Developing Process

The author has been a key member of a team, AAU Smart Production, who has set the vision, developed, commissioned, maintain, demonstrated, and operated the AAU Smart Production Lab since 2015.
The AAU Smart Production initiative was launched in the fall of 2015 to kick-start a new research area: Industry 4.0 technologies and strategies at Aalborg University [2015]. The need for an interdisciplinary platform to act as a learning factory that will meet the requirements for research, education, and collaboration with the Danish industry were quickly acknowledged as a necessarily facilitator as described in Madsen and Møller [2017].

As a fist phase a low-cost learning factory was established illustrated in *Figure* 4.1, manufacturing a dummy product (assemply of lego bricks). To minimize the cost, reuse of already purchased equipment and software combined with the use of cheap sensors, micro-controllers (e.g., Raspberry Pi 3

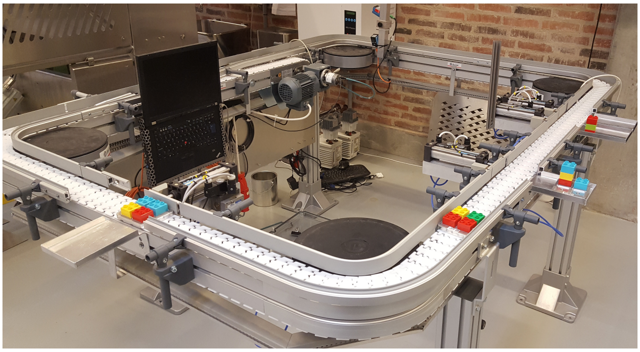


Fig. 4.1: Illustration of the first phase of a low-cost learning factory.

and Arduino), and free, open-source software was the foundation of the learning factory. The purpose of the learning factory was to handle orders, inventory and production status, customer feedback, manufacturing, packing, personalization, reconfiguration of the production setup and fast delivery. During the construction and commissioning phase of the low-cost learning factory, it became clear that the integration of the technologies, both vertical and horizontal, was the major challenge. It became evident that building a state-of-the-art learning factory is too demanding in both time and resources. However, useful knowledge was acquired about the integration of cheap electronic and industrial automation, such as integration of the Arduino with the industrial PLC. In addition, even with only a partly working learning factory and mostly on a conceptual level, the industrial partners showed an interest in the opportunity to a more "hands-on" experience of the high-level concept of Industry 4.0. Finally, the experience from building the first version was used for specify the AAU Smart Production Lab.

The second phase for the establishment of a state-of-the-art learning factory, was to acquire a learning factory, using the experience from the first low-cost learning factory. It was chosen to buy "The Cyber-Physical Didactic Learning Factory" (Festo CP factory) from Festo Didactic [2018], purchased in the beginning of 2016, with delivery in August 2016 illustrated in *Figure* 4.2.

4.1.2 Changeability

The Festo CP Factory has the ability to change its scope of functionality by utilizing standard mechanical, information, and supply interfaces to reconfigure the system, categorizing the system as a changeable manufacturing system. The standard interfaces are vital for a modular and changeable manufacturing setup, especially with the use of equipment from multiple vendors [Weyer et al., 2015].

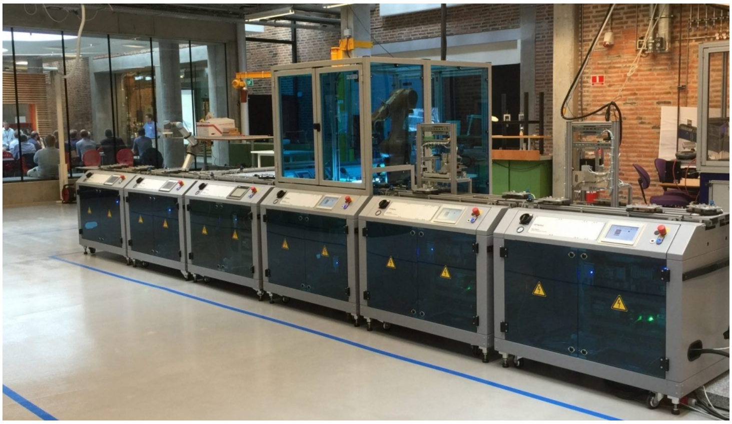


Fig. 4.2: The Festo CP Factory installed at Aalborg University in August 2016.

The Festo CP Factory consists of conveyor modules, transporting parts around in the system, where process and assembly modules can be attached at predefined places. The seven conveyor modules enable 224 different layouts of the conveyor system, adding the combination of placement of the 11 processes and assembly modules (5 modules from FESTO, 6 modules develop by Aalborg University) leading to over 9 million different combinations [Brunoe et al., 2019; Mortensen and Madsen, 2018]. The AAU Smart Production Lab utilize the Festo CP Factory as a platform for further development and research as cover in the next section. In addition, will the AAU Smart Production Lab changeability levels be addressed later in this thesis as an example to describe the system model view of a changeable manufacturing system (Section 6.1, page 87).

4.1.3 Learning Environment and Product

Physical Learning Environment The physical AAU Smart Production Lab is with its open area of 200 sqm is the largest research activity within the Department of Materials and Production. A video of the AAU Smart Production Lab can be seen here: `https://youtu.be/amFCnIgI67Q`. The physical environment is a scaled down factory with several assembly tasks both manual and automated. The physical manufactured product is a further development of the original external developed electronic device, a dummy phone, without function and only for demonstration purpose. The original dummy product, from Festo is illustrated in *Figure* 4.3.

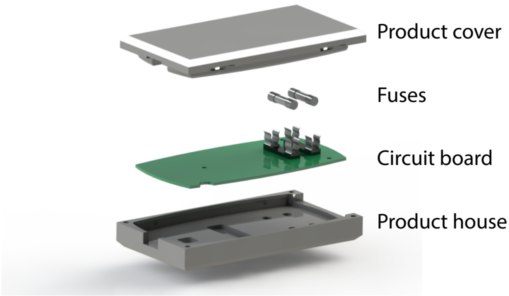


Fig. 4.3: Exploded view of the electronic device manufactured by the AAU Smart Production Lab .

The variety of the dummy phone was increased with the introduction of blue and white houses and covers together with green and red fuses. The product variant master is illustrated in *Figure* 4.4. In addition, personalized product house can be made with addictive manufacturing. The product can be produced in 816 variants, without counting the personalized components, categorizing it as a mass customized product, as presented in [Paper E | Brunoe et al., 2019].

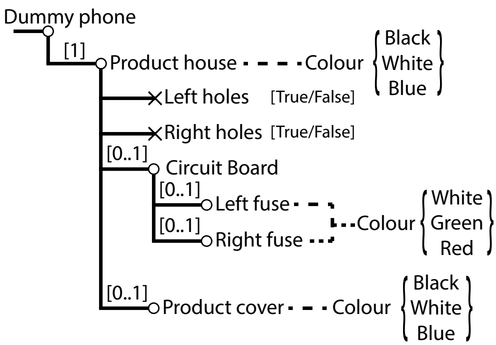


Fig. 4.4: The product variant master of the dummy phone.

The physical learning factory is controlled with a MES enabling control of: order executing, product variants, product recipes, and topology of the manufacturing system. An external product configurator was developed and implemented to facilitate non-standard production orders, as described in [Paper E | Brunoe et al., 2019].

Several activities for development has been performed by Aalborg University to add functionality and incorporate new technologies to the AAU Smart Production Lab as illustrated in *Figure* 4.5. The added technologies are with selected from Industry 4.0 technology stack. The author has been involved in the implementation of some of the activities listed in *Table* 4.1. Most of the activities are performed in collaboration with companies and/or students semester projects under the AAU problem based learning model.

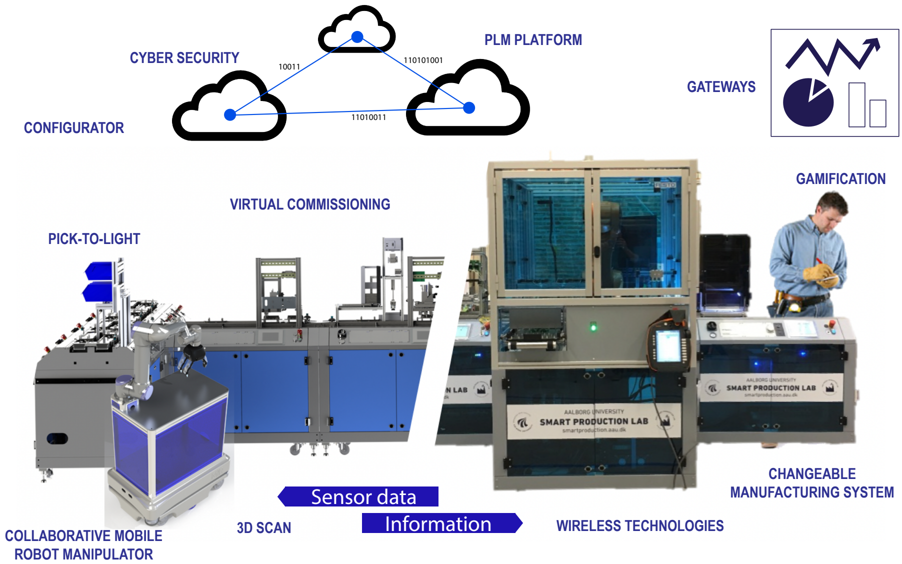


Fig. 4.5: Illustration of the AAU Smart Production Lab and some of the technologies implemented.

Name	Description
Pick-to-light	To handle the large product variety a pick-to-light system was developed and implemented
Cover dispenser	A cover dispenser was developed and implemented to illustrate modularity and scalability
Mobile collaborative robot	A collaborative robot was programmed to illustrated easy up or down scaling of automation
Collaborative mobile robot manipulator	An AGV with a collaborative robot was implemented to illustrated how autonomous robots can be integrated into a manufacturing system [Andersen et al., 2017b]
Gamification	Easy understandable interface to configure of typology of the AAU Smart Production Lab for non-experts
Augmented reality	Service and maintenance support to operators
Blackbird–gateway	An implementation to illustrate how a commercially available product can present the production data at a dashboard without using the production infrastructure
Kuka Smart Production (IIoT system)	An implementation to illustrate a commercially available product can present the production data at a dashboard using the production infrastructure
Raspberry Pi	An implementation to illustrate how low-cost electronic platfroms can obtain data by a vibration sensor
MES	Development and implementation of a MES in an open framework software
Cyber Security	Test of the security of the AAU Smart Production Lab and recommendation for increasing cyber security in an industrial environment
Auto. PLC code	Automatic generation of PLC code for AAU Smart Production Lab
Wireless technologies	Development and implementation of wireless communication between the PLC and MES level

Table 4.1: Selection of some of the Industry 4.0 related technologies implemented in the AAU Smart Production Lab.

Virtual Learning Environment Several virtual learning environments have been established based on the physical learning environment. An overview of the different virtual learning environments are shown in *Table* 4.2.

Name	Description
Modular discrete event	A modular discrete event virtual environment has been developed in Enterprise Dynamics with regular update from the physical system.
3D scan	A complete 3D scan have been performed of the AAU laboratory. The virtual environment can be experienced with virtual reality (VR) glasses.
PLM platform	The 3DEXPERIENCE platform, form Dassault Sytémes, has been a virtual learning environment for several disciplines:
	• Product Lifecycle Management (PLM)
	• 3D-modelling such as part and assembly design
	• Process planning
	• Robot simulation
Virtual Commissioning	Virtual commissioning learning environment has been developed in cooperation with Xcelgo and explored as later described in this thesis
Configurator	Development and implementation of a configurator

Table 4.2: Selection of the Industry 4.0 related virtual environments founded on the AAU Smart Production Lab .

4.1.4 Operation

The procurement and expansion of the AAU Smart Production Lab enabled a platform for teaching, research and industrial collaboration and demonstration described further in the following.

Teaching Several course have and still are using the AAU Smart Production Lab since its establishment spanning from dedicated PLC programming courses on undergraduate level to Ph.D. courses on Industry 4.0. In total, the AAU Smart Production Lab has been a platform for over 20 different courses from hands-on teaching to using the facility to illustrated the flow in a manufacturing system. Over 350 students, from various faculties and departments, have used the AAU Smart Production Lab as a foundation of mini- and semester projects, developed hardware and software, investigating areas like digital manufacturing, cyber-security, reconfigurability, virtual commissioning, gamification, big-data, business analytics to name a few. In general, the students have rated the use of the AAU Smart Production Lab as positive in the semester evaluation forms and highlighted the benefit of the resemblance with a real manufacturing system. The successful teaching in Industry 4.0 and classical topics support our hypothesis that the establishment of a learning factory support the teaching environment.

Research Several research projects have and still are using the AAU Smart Production Lab as a platform for research. The AAU Smart Production Lab facilitates a broad range of research e.g., collaborative robots, indoor drone positions, 5G network, big data and analysis, automatic generation of PLC code, Industry 4.0 maturity check, and of course the research presented in this thesis. More than 20 academic papers have so far been published. The use of industrial automation, real process, dummy product, and an integrated information flow facilitated the research to conduct experiments and implementation that are close to industrial environment where several industrial challenges can be addressed. Furthermore, the AAU Smart Production Lab have managed to invite and facilitate research across several departments and faculties. Overall the AAU Smart Production Lab has had a positive impact on the research in Industry 4.0 related subjects at Aalborg University.

Collaboration with Industry From the opening day in 2th September 2016 an interest in 'seeing' Industry 4.0 from the industry has been present. In total over 250 companies and more than 1000 people have taken part in a demonstration of the AAU Smart Production Lab over the past years. The demonstration varies from showing the line producing variants of the dummy product to also include presentation of different topics related to Industry 4.0 such as, collaborative robots, virtual commissioning or big data analytics. In additional to the many demonstrations, many companies has been involved in student semester projects and/or research activities. However, even with the high amount of companies visiting the AAU Smart Production Lab, industry still express that they lack information and knowledge sharing about Industry 4.0 possibilities and potential. The issues will be addressed in Section 4.2.

4.2 Industry 4.0 Awareness

Industry 4.0 utilize data, new technology, and new organization to improve the manufacturing industry. However, the missing Industry 4.0 awareness in small and medium-sized enterprises will later have an impact on the enterprises, ability to compete on efficient and flexibility at the same time [Sommer, 2015]. We have experienced that traditional tools and methods from the academic world, PowerPoint presentations, brainstorming sessions, and industrial fairs are not sufficient to kickstart innovative activities in SMEs. The traditional academic PowerPoint presentation have the tendency to either be on a high academic level or on a general level. In both cases the company can not relate the presented technologies and strategies to their own business. Industrial fairs also provide the enterprises with an insight in the new technologies. However, the insight is often only information and interaction with current brown field applications are missing.

To address the associated challenges of traditional awareness introduction, a different approach was developed. Inspired by the Aalborg Problem Based Learning (PBL) model, [Kolomos et al., 2004], and learning games, a learning game was developed as presented in **Paper D:** *Outline of an Industry 4.0 Awareness Game* [Mortensen et al., 2019].

4.2.1 Industry 4.0 Awareness Game

This section will give a short description of the Industry 4.0 Awareness Game at Aalborg University with the following learning goal. For more information please visit [Paper D | Mortensen et al., 2019].

> *The learning goal of the AAU Industry 4.0 Awareness Game is to provide insight in the potential of Industry 4.0 through a physical, simulation-based, role-play game founded in the driving technologies of Industry 4.0. The primary expectation of the game is to train the participants' conditional systematic knowledge in addressing which technologies/strategies to apply for the right process, on the right module, at the right time with considering the appropriate dependencies. In addition to the technologies and strategies, the participants will gain awareness about the need for new qualifications driven by the latest technologies.*
>
> [Mortensen et al., 2019]

The game is centralised around the AAU Smart Production Lab, and facilitated by a facilitator. The participants should coordinate and collaborate as a team to produce the right variant of the dummy phones in to the right time. Every successfully executed order delivers points, whilst quality issues in the production, delays in delivery and/or faulty assembly withdraw points. The competitive element of the game lie in the real-time update of the score on the scoreboard.

The participants are divided into six different roles, five production roles and one observer role. The AAU Smart Production Lab is initially operated as an Industry 3.0 factory and the participants are then regularly introduced to new Industry 4.0 technologies. The technologies are prepared in advance so they can be utilised in a plug'n'play fashion. In addition to the introduction of new technologies, various challenges are also introduced in the gameplay, such as recovering from a power failure, hacker attacks on the database, or lack of raw material.

The game time, without introduction, is 2.5 hours and for every 20 minutes, a 10 minutes reflection and perspective round is executed. The reflection and perspective round provides the participants with time to evaluate their performance and collaboration, change strategies, and the opportunity for a short discussion on how the encountered technologies and challenges are related to their business. The facilitator supports the reflection and perspective round. A longer reflection and perspective round is performed at the end of the game to evaluate the game and the gained awareness about Industry 4.0 technologies and qualifications.

4.2.2 Evaluation of the Industry 4.0 Awareness Game

Several sessions of the game have been performed with different segments of participants. Based on the first sessions, a questionnaire was developed to quantitatively evaluate the gameplay and the impact of the game. The survey is inspired by custom satisfactions questionnaires Gerson [1993] and make use of the Likert Scale (Strongly Disagree, Somewhat Disagree, Neither Agree nor Disagree, Somewhat Agree, Strongly Agree). Comment fields were provided to each page of the questionnaire, enabling the participants to add additional information or comments. In this thesis only a summary of the result will be presented. A manual factor reduction have been performed based on an unweighted mean for summarizing the results. A full overview of the questionnaire and statistics report can be seen in [Technical report ii | Mortensen, 2019b].

Several games with subsequent follow-up with the questionnaire have been performed. The conducted games can be divided into academic use, where the game was used as a teaching activity with students, or industrial use, with participants from the industry.

Academic Use Three games with university students were performed as part of the course "Flexible Automation" on 2nd semester of the Master's programme in Industrial Design at Aalborg University. Each game included 12 students were a joint introduction was given to all 36 students about Industry 4.0 and the game rules. The questionnaire was emailed to the students afterwards resulting in a response rate at 56% (n=20).

Industrial Use Three games with industrial participants have been completed. The first game was with 8 participants, second with 3 and last with 8 participants. 79% of the participants answered the questionnaire (n=15). The industrial participants was from various companies profiles, such as small to medium-sized enterprises, and from different fields, such as services, logistic, and manufacturing companies.

Learning Environment

This section will evaluate the background knowledge of the participants, the game instruction, and the learning environment (the game).

The participants were asked to rate their own technology understanding. The technology understanding factor is a summary of: technology interest, skills with IT, the view of others on one's own technology understanding, and manufacturing knowledge. The technology understanding rating is illustrated in *Figure* 4.6, first column, as a boxplots for the academic and industrial participants. As seen in the figure, both groups had a good technology understanding prior to the game.

The second column of boxplots in *Figure* 4.6 illustrates the evaluation of the instruction before the game. The instruction factor is a summary of understanding of: Industry 4.0 background, gameplay, roles in the game, manufactured product, process flow of AAU Smart Production Lab , and if the introduction of Industry 4.0 was sufficient. In general both the industrial and academic participants express that the introduction of the gameplay, gameroles and the AAU Smart Production Lab were sufficient. However, it was clear that the Industry 4.0 theme was new for many of the students and therefore a short introductory presentation was not sufficient in comparison with the industrial runs.

The last column of boxplots in *Figure* 4.6 is the evaluation of the learning environment. The learning environment factor is a summary of: Fun while playing, recommend the game for others, lost track of time, would like to play again, length of the game, game format, and help from the facilitator. The game scores a high satisfaction from the majority of academic and industrial participants with the use of physical production of a dummy product in the AAU Smart Production Lab . The majority of both groups also rate the 'fun' factor and entertainment as good. Multiple participants highlight in the comments that they want to play the game again and would differently recommend the game to others. Both groups highlight that the facilitator is important to increase the understanding, learning, and facilitate the reflection rounds.

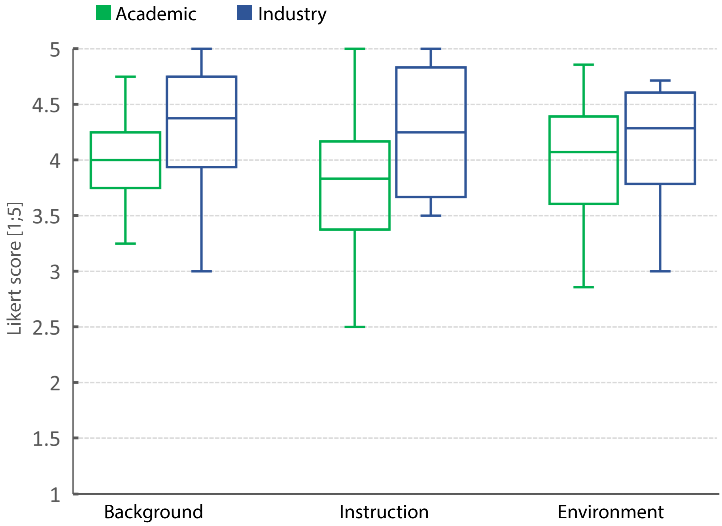


Fig. 4.6: Evaluation of technical background, instruction, and the learning environment.

Game Performance

This section will evaluate the game performance of the participants in their own equanimity, teamwork, and manufacturing performance. The participants were ask to evaluate their own performance after the first game round and the last game round.

The first factor variable is equanimity or mental calmness in the game and is a summary of: understanding of the game role and tasks, technical knowledge to perform the tasks, and encountered personally mistakes. For obtaining an improved learning the participants must not be bored or distressed [Stevenson and Harper, 2006], therefore, the aim is to keep the participants' equanimity level stable. The equanimity level from first round to last round for each person is represented in *Figure* 4.7 and *Figure* 4.8 respectively for the academic and industry participants. The red lines illustrated the average participants.

In general both groups express a positive development in the understanding of the game role, related tasks and technology knowledge to operate the AAU Smart Production Lab leading to a higher equanimity level. However, both groups reported the encountering of more mistakes in the production leading to a lower equanimity level. *Figure* 4.7 and *Figure* 4.8 also illustrated that some participants were more relaxed in the beginning of the game and became more stressed in the end of the gameplay other participants vice versa. The participants express they could see that the stress represented a real-life manufacturing setup, and why it was crucial to maintain the communication continuous across the different roles.

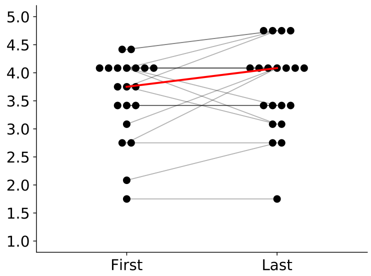


Fig. 4.7: Academic equanimity level from first round to last round. The red line illustrated the average participant.

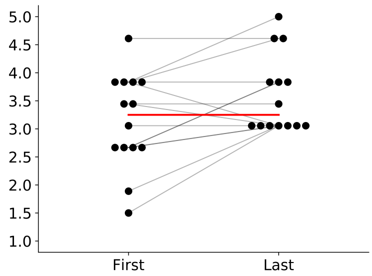


Fig. 4.8: Industrial equanimity level from first round to last round. The red line illustrated the average participant.

The second factor is organisation level a summary of: performing tasks outside the own assigned role (rated positive in this context) and understanding others role. *Figure* 4.9 and *Figure* 4.10 illustrate the development in teamwork with the academic and industrial participants, respectively. In the academic run only a few participants express that they have improved their understanding of the other game roles and deviated from their original tasks. The industrial participants express that in the first round every one was focusing on their own task and not how the organisation was performing. However, as also seen in *Figure* 4.10, the industrial participants had the ability to reorganise the organisation.

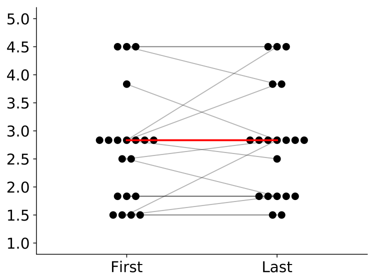


Fig. 4.9: Academic organisation level from first round to last round. The red line illustrated the average participant.

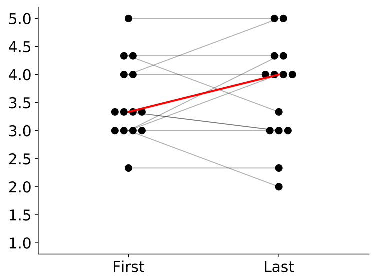


Fig. 4.10: Industrial organisation level from first round to last round. The red line illustrated the average participant.

The last factor of game performance is about production level summary of the participants, perception of production performance, and implementation of new technologies. The development of the academic participants from the first to the last round is illustrated in *Figure* 4.11 and *Figure* 4.12 for the industrial participants. The majority of the industrial participants increased their production and technology implementation performance from the first round to the last round. In relation, the majority of the academic participants did not express a difference in any of the categories from the first round to the last round. Some academic participants rate their ability to quickly install new technology as slightly worse in the last game round; this might be due to the increasing complexity of the introduced technologies.

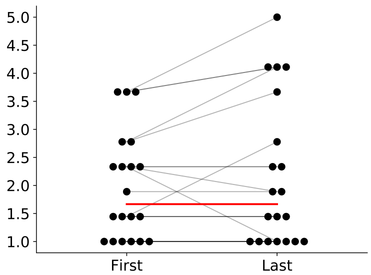


Fig. 4.11: Academic production level from first round to last round. The red line illustrated the average participant.

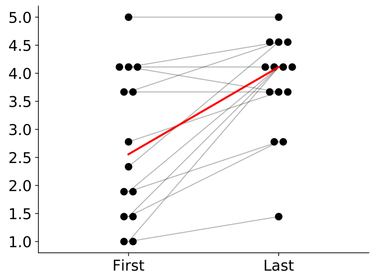


Fig. 4.12: Industrial production level from first round to last round. The red line illustrated the average participant.

A summary of the responses of the participants when asked about the factor with the largest impact on their production performance is presented in Figure 4.11

Academic runs

- Missing the right information from the right persons
- The need for overview
- Missing communication
- Missing robot skills
- Inability to adapt

Industrial runs

- Organisation of the work
- The importance of good team work
- Missing the right information from the right persons

Fig. 4.13: Summary of comments for largest impact on the production performance.

Learning Achievement

Lastly the participants were asked to indicate their learning in several categories. The factor technologies summarise gained insight in: potential and challenges of Industry 4.0 together with Industry 4.0 technologies and their dependencies. The technologies factor is illustrated as the first column in *Figure* 4.14. As seen for both the academic and industrial participants the main part gain insight in the technologies factor.

The qualification factor is a summary for the gained insight in: how the technologies are depending on the qualifications and organisation. The qualification factory is illustrated as the second column in *Figure* 4.14. The academic participants rated their insight in technology qualification dependency as highest. Where as the industrial participants rated the gained insight in the need for new organisation as highest. Some industrial participants highlights the insight of the importance of managements of introduction of new technologies while the production is running. In addition, highlighted by several participants, that knowledge sharing is essential.

The potential factor is a summary for the outlook and positive impact of industry 4.0 technologies and qualifications. The academic participants were asked to relate it to their view on an industrial contexts. Whereas the industrial participants where asked to relate their own workplace. The majority of the academic participants can see how Industry 4.0 technologies can be implemented in the industry. Indications of low knowledge about manufacturing and seeing the potential of Industry 4.0 exist. Some of the industrial participants did not have a workspace with a physical production and could thereby not relate the potential of Industry 4.0 at their workplace. However, as writing in the comments, they could related the potential to a manufacturing company.

Figure 4.14 shows that the vast majority of the academic and industrial participants increased their awareness in all parameters. The participants were asked to describe the largest impact on their learning, summarised in the *Figure* 4.15.

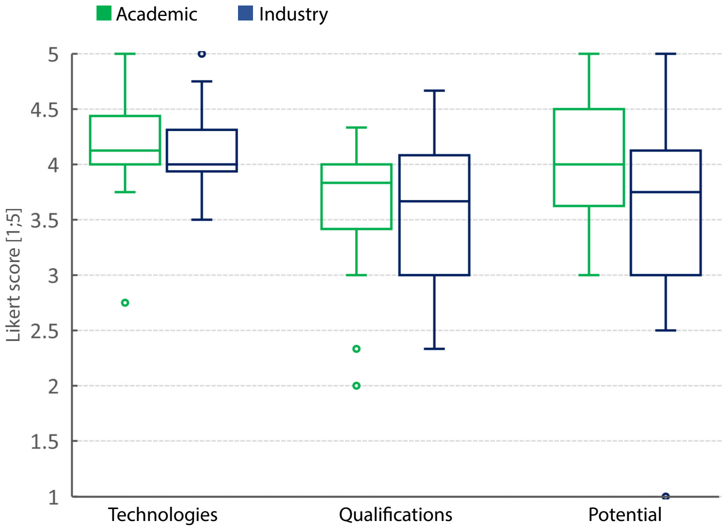


Fig. 4.14: Insight in industry 4.0 technologies, qualifications and potential of Industry 4.0.

Academic runs

- Reflections rounds
- Hands on experience
- The fun factor
- Introduction of technologies
- Challenges faced

Industrial runs

- Reflections rounds
- Similar to industrial stressors
- The use of AAU Smart Production Lab
- Implementation of real technology
- The stepwise journey from Industry 3.0 towards Industry 4.0

Fig. 4.15: Summary of comments for largest impact on the learning.

Implication for Education

The game facilitates the impact of more transparent organisation to support Industry 4.0. The game manages to highly involve the students in the game and thereby improve their learning of new technologies and workflows. The facilitator is essential for the participants understanding, to draw examples, control the stress level and support with technical know-how. For later use in an education context a longer introduction to Industry 4.0 is needed. General feedback is that the game is a fun way to learn about the complexity of Industry 4.0 using AAU Smart Production Lab.

With more than 45 academic participants divided on five games, including the initial trials, the implication that the AAU Industry 4.0 Awareness is a strong learning tool can be stated with confidence.

Implication for Companies

The implication after using the game in connection with companies, is based on three occasions with a total of 19 industrial participants.

The game can replicate industrial challenges such as bustle, organisational barriers, lack of know-how, and uncertainty about where to begin. The game enables the participants to recognise the encountered challenges in their own workplace settings during the reflection and perspectively rounds. Strong implications are drawn that the game concretise and exemplify Industry 4.0 buzzwords enabling the industrial participants to increase their understanding. With the focus on the interaction between the different key technologies in Industry 4.0, the companies gain awareness about the dependency of the different technologies and, thereby, an idea of how and where to start the journey towards adopting Industry 4.0 principles.

4.3 Conclusion

This chapter has introduced the establishment and operation of a learning factory at Aalborg University, together with the presentation of the Industry 4.0 Awareness Game addressing Main Objective 1 - *Develop a Changeable Industry 4.0 Learning Platform*.

Aalborg University has invested in the purchase and further development of a learning factory to establish a platform for learning, research, and engagement with industry. The AAU Smart Production Lab enables students to investigate, learn, and implement solutions in a near real manufacturing setup, such as illustrated in **Paper E:** *Learning Factory with Product Configurator for Teaching Product Family Modelling and Systems Integration* [Brunoe et al., 2019]. The students gain a holistic understanding of how their topic fits within the manufacturing system environment. The AAU Smart Production Lab has successfully connected several departments and faculties in working on different aspects of Industry 4.0, resulting in implementations both in the physical and virtual world. Lastly, the AAU Smart Production Lab has supported the industry with a platform both for disseminating knowledge of Industry 4.0 but also a platform where companies can test new concepts and technologies. The AAU Smart Production Lab use of standard interfaces and modules, enabling changeability of the system, increasing its usability.

Teaching of over 350 students and publication of more than 20 academic research papers together with 1000 industrial visitors since its establishment renders the AAU Smart Production Lab a successful implementation and a credible response to research objective 1.1 - *Establish-*

ment of a changeable Industry 4.0 learning platform at Aalborg University – (AAU Smart Production Lab).

The Industry 4.0 awareness game has addressed the challenges of how to begin the journey towards Industry 4.0 as presented in **Paper D:** *Outline of an Industry 4.0 Awareness Game* [Mortensen et al., 2019]. A role-play game, using the AAU Smart Production Lab , facilitates the participants with getting first-hand experience and knowledge about Industry 4.0 technologies, technology dependency, the effect on the organisation and demand for new qualifications. The game has been used for teaching purposes with 45 student participants and 19 industrial ones. In total, around 80 participants, including the initial trials, have tested the game.

The positive feedback on the awareness game, both from academic and industrial participants, in all parameters, such as 'fun' factor, duration, and learning achievements concludes that the Industry 4.0 Awareness Game is a a strong cue to raise Industry 4.0 awareness and a respond to research objective 1.2 - *Investigate how Industry 4.0 awareness can be facilitated by the learning factory.*

Future work

Despite the fact that the Industry 4.0 Awareness Game and the AAU Smart Production Lab are successful, there are still many aspects that can be improved and plenty of directions the forthcoming research can follow. To name a few, 1) Continuous development of the learning factory to embrace new technologies. 2) Documentation of the learning impact of the AAU Smart Production Lab on students. 3) Identification of how the learning factory may support new areas in the industrial and educational system, such as the economic parameters or high school level. 4) Investigation on how companies move from the awareness game to implement the lessons learned from it. 5) Identification of new qualifications of future employers and how to train those.

Chapter 5

Virtual Commissioning Workflow and Qualifications

This chapter will address the qualifications as the cause of the missing prevalence of virtual commissioning in the Danish industry. Firstly, a detailed description of the virtual commissioning workflow and tasks is performed addressing research objective 2.1. Secondly, research objective 2.2 are addressed with the description of the needed qualifications for performing virtual commissioning. Lastly, a case study is presented on how interdisciplinary and multidisciplinary worker profiles can interact with virtual commissioning using a learning platform addressing research objective 2.3.

5.1 Virtual Commissioning Workflow

This section describes the workflow of virtual commissioning as a foundation for the later dissection of virtual commissioning qualifications. This section is based on literature studies, expert interviews, and deduction from previous virtual commissioning projects. The workflow in this Section will not include automatic generation of models or code, integrated virtual commissioning, or reuse/extend use of the models, described in Section 2.3.1.

The design procedure for virtual commissioning consists of several steps as illustrated in *Figure* 5.1. Firstly, the construction of virtual devices involves modelling of the internal logics as well as modelling of the device kinematics and geometrics. Afterwards, the virtual devices can be combined to construct the virtual plant. The system control modelling is the control logic design resulting in the control program, often as a PLC program. By integrating the virtual plant and generated control program, the virtual model can be used to evaluate and debug the control program. This procedure is called virtual commissioning.

A more in-depth description of the various sub-tasks is performed in the following, a continuous example is done for concretising the steps, highlighted with the grey example-boxes.

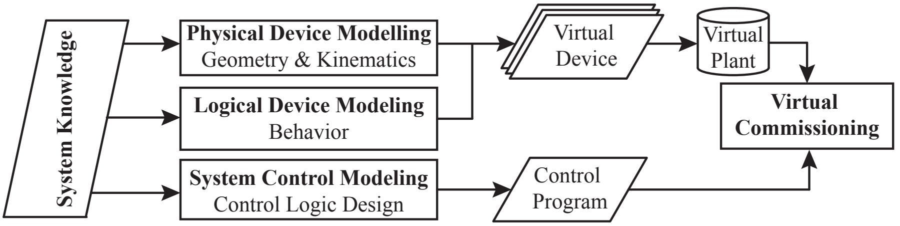


Fig. 5.1: The design procedure for virtual commissioning. Drawn with inspiration from [Lee and Park, 2014a] and [Ahrens et al., 2018].

The example is of a small process station, from the AAU Smart Production Lab , with a process of two cylinders performing a simple pick sequence. A video of the process module can be seen at `https://youtu.be/yp4B68SNtT0`. The mechanism has been designed and drawn in CAD format see *Figure* 5.2. *Figure* 5.3 illustrate the device with the name convention for cylinder A and its sensor for fully extent a+ or retract a-, similar for cylinder B. The name convention is used later in the logical modelling. We will later use the commercial virtual commissioning software Experior from Xcelgo A/S [2018].

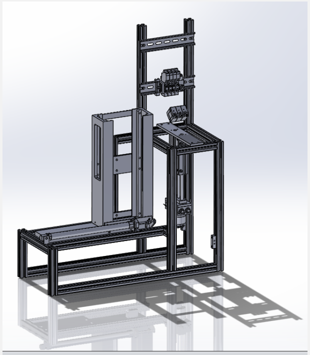


Fig. 5.2: CAD drawing of the process module.

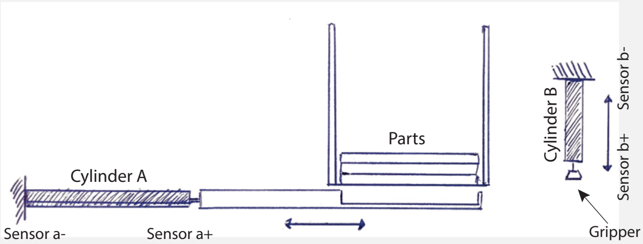


Fig. 5.3: A sketch for name convention of the feeder with two cylinders.

5.1.1 System Knowledge

The requirements for the manufacturing system are the foundation for the system knowledge base. The system knowledge base contains the system specifications e.g., plant topology, sequence of operations, mechanical and electrical properties and communication protocols [Lüder et al., 2015]. The system knowledge base can be facilitated in different ways from pure paper driven to virtual engineered, however, it is crucial that everyone involved have access to the system knowledge base [Pellicciari et al., 2009].

In our example, the system knowledge base consists of the CAD-drawings, electrical drawing, and sequence of operations. The sequence of operation may be described by a pneumatics phase diagram as illustrated in *Figure* 5.4

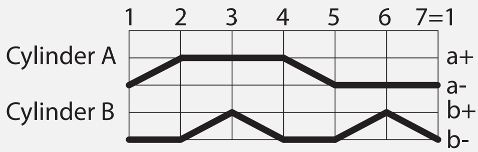


Fig. 5.4: Pneumatic phase diagram showing the sequence of operations for the two cylinders.

5.1.2 Physical Device Modelling

The physical device modelling transform the mechanic design of the device to a virtual representation which include kinematic information of the device. The geometrical representation may be adapted for the CAD representation or in some cases a compound of standard geometric primitives, like cubes, cylinders, or spheres. In many cases, the CAD drawings can be downloaded from a vendor's homepage and are in a generic CAD format like STL or STEP. The virtual commissioning software's CAD format is normally a lightweight representation to save cost and to enable faster simulation. A conversion from STL/STEP is, therefore, needed to import the geometric models. Some virtual commissioning software has an internal conversion engine other virtual commissioning software needs external conversion tools. The kinematic properties are added to the virtual representation giving the model information about how the device is moving. Each moving joint is described (rotation or prismatic), additional information is given about the acceleration, speed, range, and friction etc.. The implementation of the kinematics to the virtual representation varies according to different virtual commissioning software. Some software vendors provide an integrated graphical user interface to support the programming of the kinematics while other tools use integrated development environment like Microsoft Visual Studio.

In our example, we acquired the cylinders CAD drawing from the cylinder vendor, together with product sheets. We converted the CAD drawings to a lightweight representation after which we added the kinematic prismatic joint, acceleration, and velocity of the cylinders. Lastly, we added the boundary information about the travelling length of the pistons. *Figure* 5.5 illustrates the kinematic sketch of the system.

Fig. 5.5: Kinematic drawing of the system.

5.1.3 Logical Device Modelling

The logical device modelling is the behavioural representation of the device. In the logical modelling, input and output (I/O) signals to the device is coupled with the behaviour of the device. Thus an input will trigger the corresponding action utilising the kinematic rules made in the physical devices model. Likewise, the output signals generated by the virtual representation of physical sensors will be modelled. The sensors may be modelled as a wait function waiting for an event to happen before triggering the output signal for interacting with the virtual device. As the case was for the physical device modelling, some software has a graphical user interface for support the logical device modelling while others use integrated development environment. Besides, adding the internal logic to the device, a preparation for the connection towards the PLC connection is also done. As a result of integrating the modelling of the logical with the physical device, the virtual devices are created.

In our example the logical device model of the cylinders is the relationship between the input signals for extending or extracting the cylinder. The logical model will utilize the acceleration and velocity parameters from the kinematic modelling. The output signal of the model is the information about the position of the piston, either fully retract, fully extended or in between. Here, a function will compare the piston position to the threshold values of the sensors.

The virtual devices can be categorised for display in the catalogue of virtual devices. While using the virtual devices, we may alter some of the properties even after the physical and logical modelling stages are finished if these were parametrised under the modelling. The parameterisation provides the possibility to have ordinary virtual devices such as conveyors able to change in size and physical characteristics as friction and speed. Furthermore, virtual devices could also be "dead" devices like permanent inventory e.g. transformer, pips, wires, fences and so on.

Figure 5.6 illustrates the virtual device in the virtual environment of our example with the properties we are able to change from the graphical user interface, like the PLC tags. Note the lightweight representation and the virtual device catalogue.

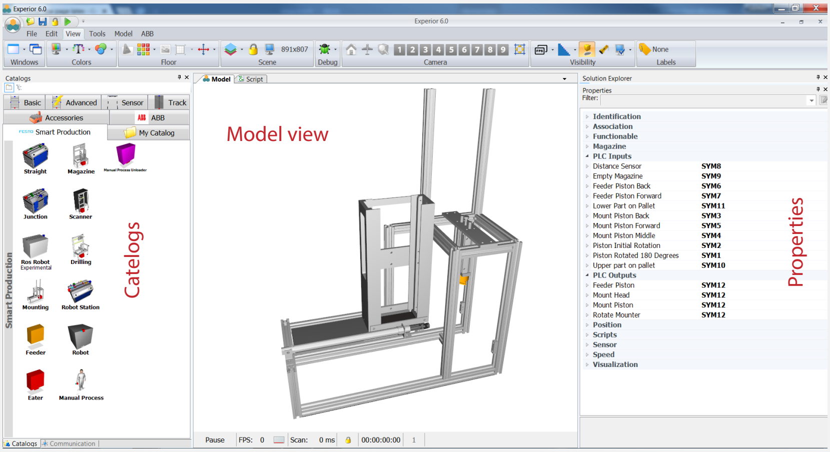


Fig. 5.6: Virtual representation of the virtual devices, centre of the figure, with its properties such as the I/O mapping towards the PLC, shown in the right side of the figure. In the left side of the figure the "catalogue" window is shown with the thumbnail representation of the different virtual devices. From the virtual commissioning software Experior [Xcelgo A/S, 2018].

5.1.4 System Control modelling

The system control modelling is the formalisation of the sequence of operation to control logic design. The sequence of operations executed by programmable logical controllers (PLC). The PLC executes the program in scan cycles, firstly scan all inputs to the PLC, then carry out the program followed by updating all outputs. PLCs scan is typically in the range of 10 to 50 milliseconds [Bolton, 2006]. Several PLC program languages exist, from graphical program languages such as ladder diagram, sequential function chart, continuous function chart, and functional block diagram towards more script-based languages like instruction list and structured text [Gyulai et al., 2016]. The most common program form is ladders diagram. In addition, a list of variables which needs to be read/written from the virtual commissioning program is created. The exchange of variables uses, in many cases, a communication protocol for communication with the virtual commissioning program.

The protocol depends on the preference of the virtual commissioning program. If the sharing of variables is not real-time/near-real-time depending, open sharing communication protocols like OPC (Open Platform Communications) and OPC UA (Unified Architecture) can be used. Otherwise, more dedicated communication protocols must be used, like TCP/IP (Transmission Control Protocol / Internet Protocol) or OPC UA TSN (Time-Sensitive Networking). Lastly, the PLC code is compiled and uploaded to the physical PLC.

In our example, we program our sequence of operations in a ladder diagram, shown in *Figure* 5.7 and *Figure* 5.8, and share our downloaded to the physical PLC together with the I/O tag-list running on an OPC server as our variables are not real-time critical. M1, M2, and M3 are internal memory variables.

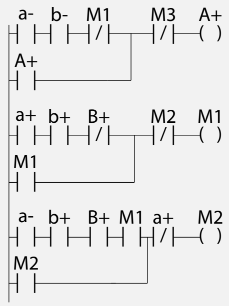


Fig. 5.7: First part of the Ladder-diagram.

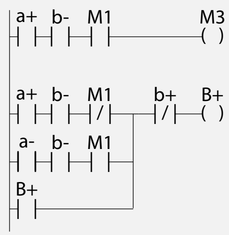


Fig. 5.8: Second part of the Ladder-diagram.

5.1.5 Virtual Plant

The virtual plant is constructed with virtual devices taken from the catalogue. The topology plan specifies the layout of the virtual plant. Many virtual commissioning programs have the possibility of adding walls and floors as well as other equipment to resemble an appearance virtual environment. By adding walls, floor, pipes, and other permanent inventory to the virtual plan modelling layout conflicts problems may be avoided. The connection between the physical PLC and the virtual plant is performed with a specified network protocol.

Figure 5.9 depicts our virtual device example mounted in the context of a small manufacturing system. The virtual plant is connected to the physical PLC with the OPC protocol.

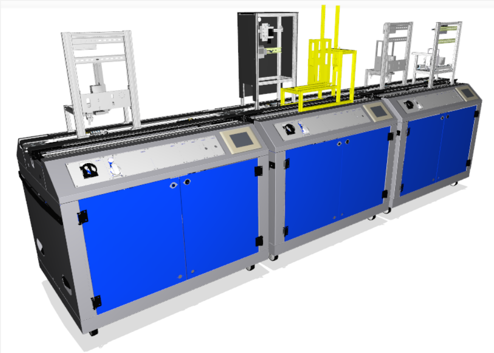


Fig. 5.9: Virtual representation of the virtual device example, highlighted in yellow, in the context of a virtual plant.

5.1.6 Virtual Commissioning Evaluation

The next step after the system control model and the virtual plan model are finalized is the evaluation of virtual commissioning. With the system control model and the virtual plan model done, virtual commissioning evaluation can be performed. Firstly, the validation of virtual devices is performed. The mapping of I/O from the PLC to each virtual device is tested by changing the value of the I/O in the PLC program and verify if the virtual device responds with the correct action. Hereafter, a holistic test is performed on a system level, such as if the parts can be transported around in the system and be correctly processed also unusual cases test like emergency stop, filling, and empty sequence is performed. The high-level control software may also be tested, like MES.

In our small scaled example, we connect the virtual device with the OPC server and begin the I/O test by setting the signal for extending cylinder 1 high and watch the accordingly response in the virtual environment. We check in the PLC program that the sensor signal $a+$ is set high by the program. We now execute the PLC program and watch the virtual device to see if it performs the right sequence of operations.

5.1.7 Virtual Commissioning Tasks Overview

This section summarizes the tasks in the workflow of virtual commissioning under each phase.

Physical Device Modelling:

- Import of geometric model
  - CAD reduction
  - CAD conversion
- Add kinematic to virtual devices

System Control Modelling:

- Executable control code on the hard PLC
  - Construct PLC code
  - Configurer the hard PLC
- I/O connections preparation

Virtual Commissioning Evaluation:

- Validation of the virtual devices
- Validation of the virtual plant

Logical Device Modelling:

- Add internal behaviour logic to virtual devices
- I/O connections preparation

Virtual Plant Modelling:

- Construct the virtual plant
- Establish connection with PLC

5.2 Virtual Commissioning Qualifications

This section will describe the needed qualifications to perform a virtual commissioning task. The respective qualifications are a result of the examined learning cases, interviews with virtual commissioning experts, and a survey among virtual commissioning users.

5.2.1 Literature Survey

A systematic literature review based on the method presented in [Kayunze, 2010], has been conducted to establish the state-of-the-art of virtual commissioning qualification. The full systematic literature review methodology is presented in [Technical report iii | Mortensen, 2019c].

The literature search result in 115 papers, 84 without duplicates, retracted papers, and conference descriptions. 25 papers were found relevant from the title and abstract. Based on the full paper text, 14 papers were found relevant for not only treating virtual commissioning but also the qualifications to perform virtual commissioning. The various disciplines were identified by an iterative process and an overview which paper that discloses which disciplines are shown in *Table* 5.1.

Discipline	Reference to paper disclose the discipline
Mechanical engineering	[Ahrens et al., 2018; Hincapié et al., 2014; Neugebauer and Schob, 2011; Neumeyer et al., 2017; Park et al., 2013; Pellicciari et al., 2009; Reinhart and Wünsch, 2007; Schmidt and Fay, 2015; Vergnano et al., 2017]
Electrical engineering	[Ahrens et al., 2018; Auris et al., 2018; Hincapié et al., 2014; Neugebauer and Schob, 2011; Neumeyer et al., 2017; Park et al., 2013; Pellicciari et al., 2009; Schmidt and Fay, 2015; Vergnano et al., 2017]
Software engineering	[Ahrens et al., 2018; Auris et al., 2018; Hincapié et al., 2014; Neugebauer and Schob, 2011; Neumeyer et al., 2017; Pellicciari et al., 2009]
Control engineering	[Auris et al., 2018; Neumeyer et al., 2017; Park et al., 2013; Pellicciari et al., 2009; Reinhart and Wünsch, 2007]
Automation engineering	[Bartelt et al., 2014; Hincapié et al., 2014; Ko and Park, 2014; Reinhart and Wünsch, 2007; Schmidt and Fay, 2015]
Process engineering	[Hincapié et al., 2014; Ko and Park, 2014; Vergnano et al., 2017]
Simulation engineering	[Ahrens et al., 2018; Hincapié et al., 2014; Ko and Park, 2014; Neugebauer and Schob, 2011; Park et al., 2013]

Table 5.1: Disciplines specified in the literature review.

The articles were additionally searched for information regarding which competence, skills, or knowledge that were represented under each discipline presented in the following.

General Knowledge and Skills: Neugebauer and Schob [2011]; Schmidt and Fay [2015] and Pellicciari et al. [2009] argue that knowledge generated in the early design and engineering phases, called *case related knowledge* is important knowledge for the later modelling tasks. In addition, *system knowledge* about the choice of resources, such as machinery, sensors, or actuators capability is also general knowledge to the modelling and testing phases. Lastly, Schmidt and Fay [2015] and Vergnano et al. [2017] adds that knowledge about the needed model detail level is needed to avoid missing model information or over complicate the model together with knowledge about what can be modelled in the virtual commissioning software tools.

Mechanical: Ahrens et al. [2018]; Hincapié et al. [2014]; Neumeyer et al. [2017]; Pellicciari et al. [2009]; Schmidt and Fay [2015]; Vergnano et al. [2017] and Park et al. [2013] highlight that the mechanical skills are related to drawings and constructed virtual representations in CAD environments. Neugebauer and Schob [2011]; Pellicciari et al. [2009] and Hincapié et al. [2014] adds that the kinematic modelling knowledge also lies under the qualifications of mechanical engineers. Vergnano et al. [2017] also highlights the need for skills in relation to conversion between different CAD formats.

Electrical Engineering: Ahrens et al. [2018]; Auris et al. [2018]; Hincapié et al. [2014]; Neugebauer and Schob [2011]; Neumeyer et al. [2017] and Vergnano et al. [2017] state that electrical engineering skills are needed to construct the circuit plan used later in system behaviour knowledge. Vergnano et al. [2017] adds the I/O skills are needed to set up the connection between the virtual world and the physical controller along with knowledge about communication protocols.

Software Engineering: Hincapié et al. [2014]; Pellicciari et al. [2009] and Neugebauer and Schob [2011] mention the skills of mapping of the I/O connection between the control program and the virtual model are needed to connect the virtual model with the PLC. Auris et al. [2018]; Neumeyer et al. [2017] and Ahrens et al. [2018] express that specified knowledge is needed in the behaviour modelling of the virtual devices, together with skills in modelling the communication processes.

Control Engineering: The control engineer must possess PLC skills and knowledge to construct the control code [Ahrens et al., 2018; Auris et al., 2018; Hincapié et al., 2014; Neumeyer et al., 2017; Park et al., 2013; Pellicciari et al., 2009]. Park et al. [2013] and Hincapié et al. [2014] adds that the control engineer have the skills and knowledge to verify and optimize the control code. The control engineer must also have the knowledge and skills to construct the I/O list towards the virtual model. Hincapié et al. [2014] stresses the need for skills and knowledge to operate and fine-tune settings related to the physical PLC.

Automation Engineering: Schmidt and Fay [2015] and Ko and Park [2014] mention PLC code skills as the major skill for programming the control software. Ko and Park [2014] also indicated that the automation engineer need the knowledge and skills about standard test, e.g., FAT for utilizing the virtual model for validation of the PLC program.

Process Engineering: Vergnano et al. [2017] and Hincapié et al. [2014] list process knowledge, about the modelled process, is needed to perform virtual modelling.

Simulation Engineering: Hincapié et al. [2014]; Park et al. [2013]; Schmidt and Fay [2015] and Neugebauer and Schob [2011] describe how skill to construct new plant models based on virtual devices are essential. Neugebauer and Schob [2011] adds that the software engineer have the skills to validate the control code in the virtual environment.

Summary

The virtual commissioning skills and knowledge cover a broad spectrum of disciplines as documented in recent literature. In the examined literature some, but little information, about the knowledge and skills of virtual commissioning are present in the literature, but it generally focus on roles or disciplines. In addition, a structural view of how the tasks are related to the needed knowledge and skill is absent.

5.2.2 Delphi Research Based Investigation

To further investigate and structure the virtual commissioning qualification a Delphi research method is conducted [Dalkey and Helmer, 1963]. The Delphi method combine the informed judgements from a panel of independent experts and are highly relevant when no or little information is established about the topic [Dalkey and Helmer, 1963]. *Figure* 5.10 illustrate the actions taken based on the Delphi study.

According to the findings in the literature, deduction from the found task in Section 5.1.7, and experience the first hypotheses for how each task can be divided in the skills and knowledge domain is forwarded and grouped under each theme in the design procedure of virtual commissioning. After the first round of the Delphi study new hypotheses of qualifications were forwarded and disputed in a survey with a larger sample size.

Qualifications Survey Details

The survey was sent out to a focus group of 28 participants with various virtual commissioning qualifications, ranging from novices(beginner) to daily user (user), and to virtual commissioning software developer (expert). The initial group was asked to further distribute the survey among colleagues or others with virtual commissioning qualifications, utilizing the snowball sampling method [Goodman, 1961], in total the survey reached 39 individuals. With one reminder, the finally respond rate reach 51%, with 18% partly answers and no respond from the remaining.

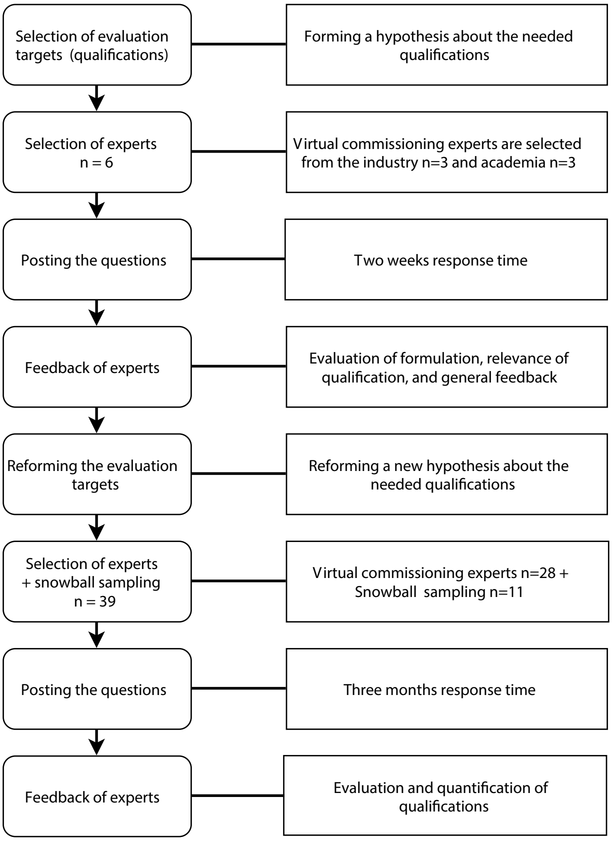


Fig. 5.10: Steps of the construction and quantification of the qualifications based on the Delphi research method [Dalkey and Helmer, 1963].

The responders were asked to evaluated the knowledge and skills provided inside each sub-task of virtual commissioning on a scale from 0 - 6. The scale was founded in Blooms revised Taxonomy Anderson et al. [2001] within the six dimensions of the cognitive dimension, illustrated in *Table* 5.2. In addition, the responders have the opportunity to add comments to the question to obtain missed knowledge or skills and comments about misleading questions.

The responders were ask to evaluated their own qualification inside each of five categories. A critical comparison between experience year, profession, and educational background and self-evaluation score was performed to counteract overestimation of own abilities. However, no discrepancies were found between the self-evaluation and the years of experience, profession, and educational background. The distribution among the participants inside each category is shown in *Table* 5.3. The high percentages of users and experts support the use of the Delphi study.

Score	Description	Knowledge/ Skill
0	The knowledge/skill is not needed	
1	Ability to perform simple tasks under supervision	Basic
2	Ability to perform tasks under supervision	
3	Ability to perform series of task without supervision	Intermediate
4	Ability to identify needed methods and technologies to use	
5	Ability to improve current known methods and technologies	Expert
6	Ability to generate new methods and technologies	

Table 5.2: Presented scale for the responders in the quantification of virtual commissioning qualification.

	Beginner	**User**	**Expert**
Physical Device Modelling	25%	45%	30%
Logical Device Modelling	10%	40%	50%
System Control Modelling	25%	45%	30%
Plant Design Modelling	10%	45%	45%
Virtual Commissioning Evaluation	25%	45%	30%

Table 5.3: Overview of the self-evaluation of virtual commissioning qualifications in relation to virtual commissioning sub-tasks.

The following sections will firstly present the final qualification hypotheses for each virtual commissioning phase, as well a graphical representation of the needed technical knowledge and skills too fulfil the tasks. In addition, information about the quantification of the qualification is also presented. Please note that the hypotheses are founded on the questionnaire and have not been presented for the participants in the Delphi study.

5.2.3 Physical Device Modelling

The physical device modelling qualifications are knowledge and skills needed for the transformation of 'dead' CAD models to kinematic enriched virtual models. The hypothesis of the physical device modelling qualification and the relationship between the knowledge, skills, and tasks, is presented in *Figure* 5.11 with extended description of the qualifications in *Table* 5.4.

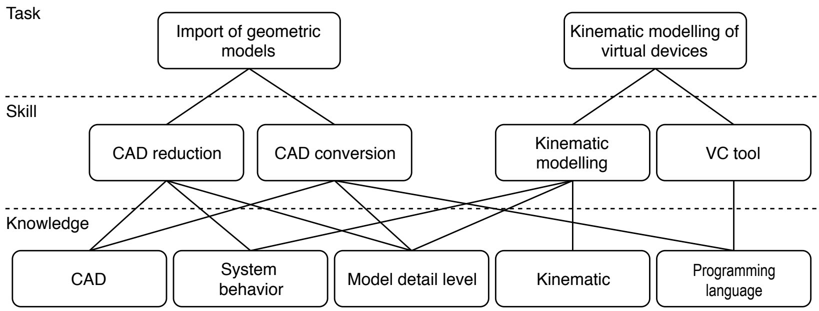


Fig. 5.11: Physical device modelling qualifications.

Qualification	**Description**
CAD reduction	The ability to delete irrelevant information in the geometric representation for later increase model performance
CAD conversion	The ability to reduces the geometric representation from CAD to a format readable by the virtual commissioning software
Kinematic modelling	The ability to add kinematic to the virtual devices
VC tool	The ability to navigate, program and implement the virtual devices in the (backend) virtual commissioning software
CAD	Knowledge about CAD use and drawing practise
System Behaviour	Knowledge about the functionality of the to-be modelled system
Model detail level	Knowledge about the needed model detail to have an efficient model
Kinematic	Knowledge about kinematics
Programming language	Knowledge about integrated development program environments, e.g. c#

Table 5.4: Description of knowledge and skills in solving the physical device modelling.

Quantification

The assessment of the skills and knowledge of the physical device modelling from the qualification survey is illustrated in *Figure* 5.12. As illustrated in the figure the majority of the knowledge and skills are needed on an intermediate level in order to perform the physical devices modelling tasks. The expert group rated the knowledge about the programming knowledge (e.g. C#) to an expert level. One responder added that the level of programming knowledge is depending on how the software interface is designed as also addressed in this thesis under the descriptions in Section 5.1.2. In addition, the skills of CAD conversion and kinematic modelling might require a more experienced user as seen in *Figure* 5.12. No comments were given from the questionnaire responders about any missing qualifications.

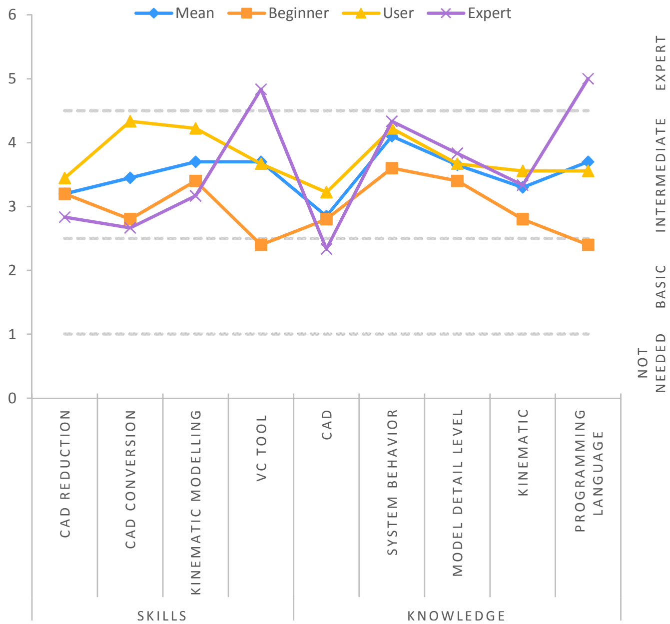


Fig. 5.12: Quantification of qualifications for modelling of physical devices.

5.2.4 Logical Devices Modelling

The logical devices modelling is the activations of the enriched kinematic models made in the kinematic devices modelling. The logical device modelling qualification hypothesis, and relationship between the knowledge, skills, and tasks, are presented in *Figure* 5.13 with extended description of the qualifications in *Table* 5.5.

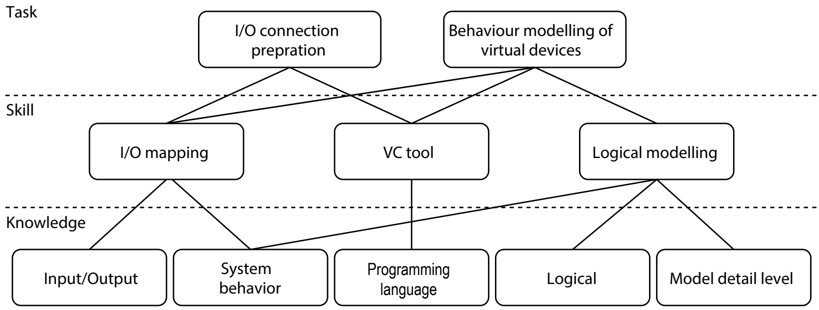


Fig. 5.13: Logical device modelling qualifications

Qualification	**Description**
I/O mapping	The ability to detect and map the I/O features in the model
VC tool	The ability to navigate, program and implement the virtual devices in the (backend) virtual commissioning software
Logical modelling	The ability to enrich the virtual representation with internal logic behaviour
Input/Output	Knowledge about how input/output is set up
System Behaviour	Knowledge about the functionality of the to-be modelled system
Programming language	Knowledge about integrated development program environments, e.g. c#
Logical	Knowledge about logical modelling
Model detail level	Knowledge about the needed model detail to have an efficient model

Table 5.5: Description of knowledge and skills in solving the logical device modelling.

Quantification

The assessment of the skills and knowledge of the logical device modelling from the qualification survey is illustrated in *Figure* 5.14. As illustrated in the figure, all knowledge and skills are needed between intermediate to experience level in order to perform the logical devices modelling tasks. The questionnaire participants have no further comments and did not find any unnecessary knowledge or skills in the survey in relation to the logical device modelling.

Fig. 5.14: Quantification of qualifications for modelling of logical devices.

5.2.5 System Control Modelling

The system control modelling is the writing of the logical control code for the PLCs. The system control modelling qualification hypothesis, and relationship between the knowledge, skills, and tasks, is presented in *Figure* 5.15 with extended description of the qualifications in *Table* 5.6.

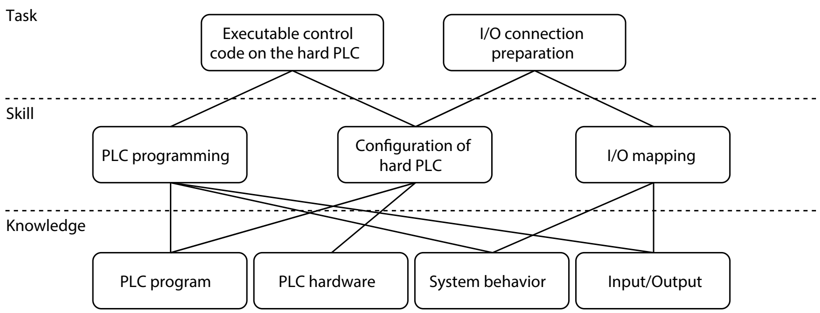


Fig. 5.15: System control modelling qualifications

Qualification	Description
PLC programming	The ability to construct a PLC code
Configuration of hard PLC	The ability to configurer a hard/real PLC
I/O mapping	The ability to detect and map the I/O features in the system
PLC program	Knowledge about PLC programming
PLC hardware	Knowledge about PLC hardware
System Behaviour	Knowledge about the functionality of the to-be modelled system
Input/Output	Knowledge about how input/output setup

Table 5.6: Description of knowledge and skills in solving the system control modelling.

Quantification

The assessment of the skills and knowledge of the system control modelling from the qualification survey is illustrated in *Figure* 5.16. As illustrated in the figure, all knowledge and skills are scored in the level of intermediate to experienced level in order to perform the system control modelling tasks. The questionnaire participants had no further comments and did not found any unnecessary knowledge or skills in the survey in relation to the logical device modelling.

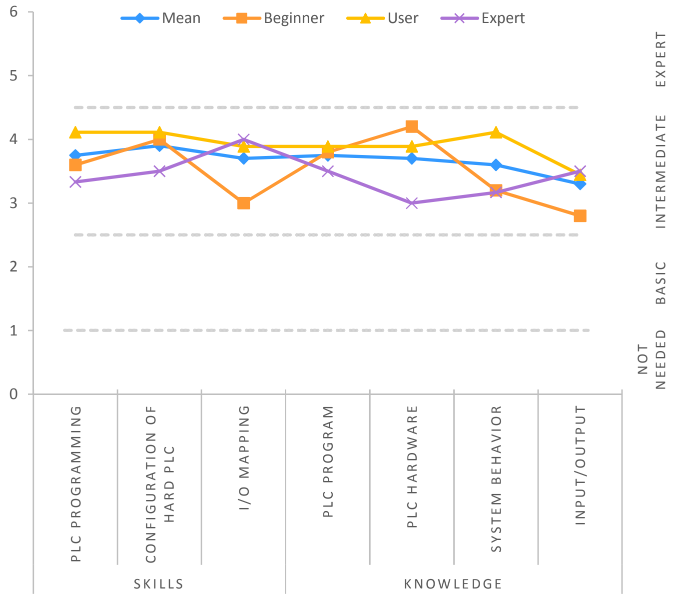


Fig. 5.16: Quantification of qualifications for modelling of system control.

5.2.6 Virtual Plant Design

The virtual plant design is the construction of the virtual plant with the use of the virtual devices. The virtual plant design qualification hypothesis, relationship between the knowledge, skills, and tasks, is presented in *Figure* 5.17 with extended description of the qualifications in *Table* 5.7.

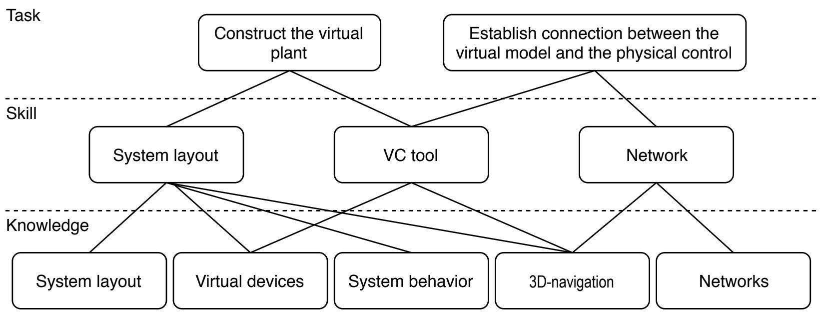


Fig. 5.17: Plant design modelling qualifications

Qualification	**Description**
System layout	The ability to model the system layout
VC tool	The ability to navigate in the virtual commissioning software
Network	The ability to work with network protocols
system layout	Knowledge about system layout of the to-be modelled system
Virtual devices	Knowledge about the behaviour and properties of the virtual devices
System behaviour	Knowledge about the functionality of the to-be modelled system
3D-navigation	Knowledge about navigating in a 3D environment
Network	Knowledge about different network protocols

Table 5.7: Description of knowledge and skills in solving the plant modelling.

Quantification

The assessment of the skills and knowledge of the plant modelling from the qualification survey is presented in *Figure* 5.18. As illustrated in the figure, both the user and expert groups assess the knowledge and skills between intermediate and experience level in relation to the system control modelling tasks. The beginner group assessed the network qualifications level lower than the other two groups. This might be a reflection of difference in the encountered complexity of plant design model in the experience between beginner and the user/expert group. Similarly, the questionnaire participants had no further comments and did not find any unnecessary knowledge or skills in the survey in relation to the virtual plant modelling.

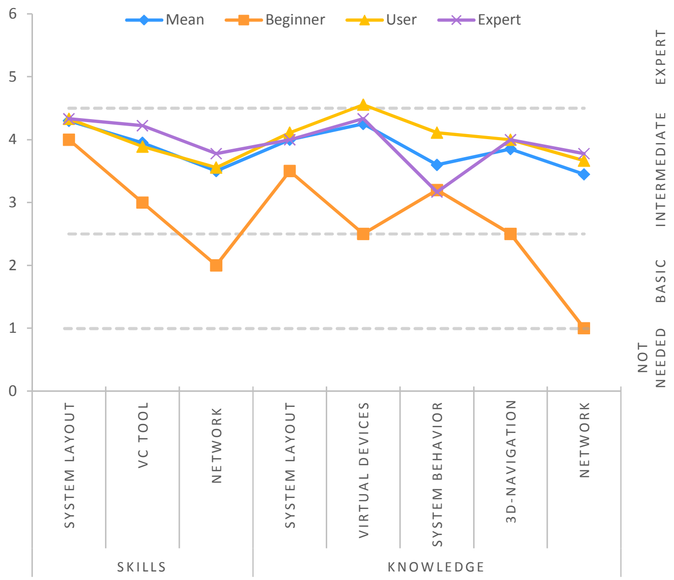


Fig. 5.18: Quantification of qualifications for modelling of the virtual plant.

5.2.7 Virtual Commissioning Evaluation

Virtual commissioning evaluation is the verification of the virtual devices and virtual plant together with the validation of the control code running against the virtual environment. The virtual commissioning evaluations qualification hypothesis and relationship between the knowledge, skills, and tasks, is presented in *Figure* 5.19 with extended description of the qualifications in *Table* 5.8.

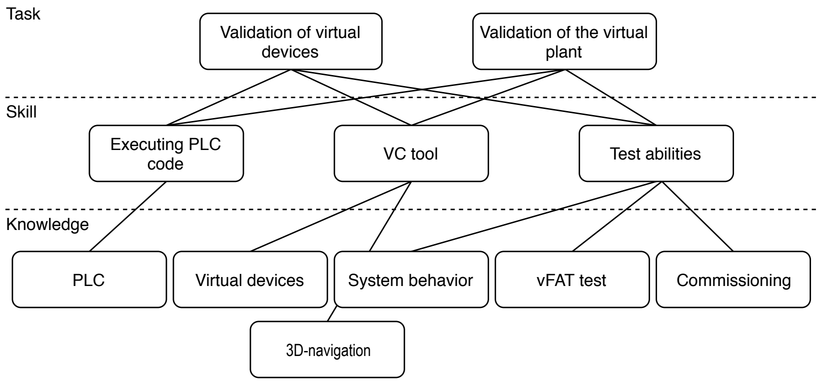


Fig. 5.19: Virtual commissioning evaluation qualifications

Qualification	Description
Executing PLC code	The ability to executing the constructed PLC code
VC tool	The ability to navigate in the virtual commissioning software
Test abilities	The ability to perform standard and non-standard test of manufacturing setup
PLC	Knowledge about general PLC code and executing of programs
Virtual devices	Knowledge about the behaver and properties of the virtual devices
3D-navigation	Knowledge about navigating in a 3D environment
vFAT test	Knowledge about virtual test methods, e.g., vFAT
System Behaviour	Knowledge about the functionality of the to-be modelled system
Commissioning	Knowledge about the commissioning phase of a manufacturing setup

Table 5.8: Description of knowledge and skills in solving the virtual commissioning evaluation.

Quantification

The assessment of the skills and knowledge of the virtual commissioning evaluation from the qualification survey is presented in *Figure* 5.20. As illustrated in the figure, the majority of the knowledge and skills level are assessed between intermediate to experienced level in relation to the virtual commissioning evaluation tasks. Please note that the "Executing PLC code" was identified after the survey and therefore was quantified by estimation to a score of 3 for all groups. The expert group rate the needed virtual commissioning software tool and test abilities skills towards expert-level. The questionnaire participants had no further comments and did not find any unnecessary knowledge or skills in the survey in relation to the virtual plant modelling.

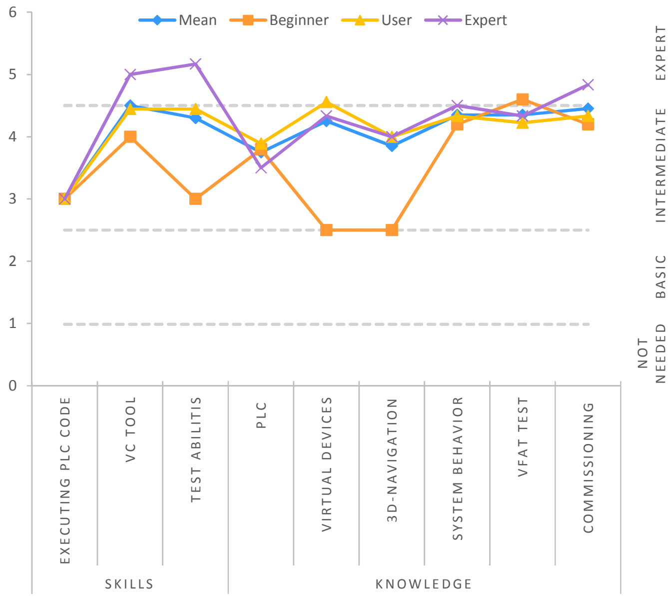


Fig. 5.20: Quantification of qualifications for virtual commissioning evaluation.

5.2.8 Summary

The literature review revealed a lack of the relationship between the virtual commissioning tasks and needed qualifications. The present tasks from Section 5.1.7, literature review, and Delphi study were used to map the virtual commissioning tasks to the needed skills and knowledge. The skills and knowledge were quantified in relation to beginner, intermediate, or experts level. In general, all knowledge and skills for performing virtual commissioning are needed on and intermediate level summarized below within the different groups in the workflow.

- **Physical Device Modelling** General intermediate skill and knowledge level are needed in relation to the geometric modelling and the implementation of the kinematic characteristics. However, the surveyed physical devices modelling experts believe that expert knowledge is needed to incorporate the physical device modelling into the virtual commissioning software.

- **Logical Device Modelling** General intermediate skills and knowledge level are needed in relation to create the behaviour model of the virtual devices. However, the logical device modelling experts assess the needed for skills and knowledge relate to the virtual commissioning software to be lower than the physical device modelling.

- **System Control Modelling** Intermediate skills and knowledge are needed for programming the control program and preparing the I/O connection.

- **Virtual Plant Design** General intermediate skills and knowledge are needed for construct the virtual plant and establish the connection between the virtual model and the physical controller. The beginner group rated some of the skills and knowledge to a beginner level.

- **Virtual Commissioning Evaluation** General higher intermediate skills and knowledge level, adjacent to expert level, are needed. The expert-responders highlight that skills and knowledge related to the validation of virtual devices and the virtual plant calls for expert skills and knowledge level.

The mapped skills and knowledge give the insight that virtual commissioning qualifications include several skills and knowledge from a variety of classic knowledge domains. Hence, can virtual commissioning qualification be classified as a multidisciplinary task.

The presented quantification of needed virtual commissioning skills and knowledge provides several opportunities for improved dissemination of virtual commissioning. Companies may use this knowledge to evaluate the company/employees in order to gain awareness about missing qualifications or employer profiles for employment. Educational institutions may form new curricula to supporting the expansion of virtual commissioning. Both industry and education institutions may use the result directly due to the embodiment of the skills and knowledge. The mapping and quantification of the virtual commissioning qualification also presents the opportunity to divide the tasks between different domain experts and removing the need of one virtual commissioning expert. Hence, the majority of the skills and knowledge are needed on an intermediate level. This leads to the hypothesis that virtual commissioning task may be solved by domain expert.

However, even though only intermediate qualifications are needed for virtual commissioning, awareness and training in virtual commissioning qualification is still needed to stressful achieve the potential of virtual commissioning.

5.3 Virtual Commissioning Dissemination

This section will present a virtual commissioning learning factory as a mean to obtaining and training virtual commissioning qualifications. Secondly, a case study of how a multidisciplinary team can be trained to solve a virtual commissioning is presented. Lastly, a illustration of how an interdisciplinary team of profession bachelors may solve a virtual commissioning task by dividing the tasks is presented.

5.3.1 Virtual Commissioning Learning Platform

To address the challenges of the missing impact of virtual commissioning due to the missing awareness and training of virtual commissioning qualifications **Paper B:** *A Virtual Commissioning Learning Platform* [Mortensen and Madsen, 2018] presents a Virtual Commissioning Learning Platform (VCLP). The learning platform is based on the AAU Smart Production Lab, present in Section 4.1. The learning platform may server as an awareness tool were interested can get hands-on on virtual commissioning. In addition, the learning platform may also serve as a teaching platform illustrated in Section 5.3.2 and Section 5.3.3.

The Learning Platform Components

The learning platform consists of three components; a plant controller (MES), PLC racks and a virtual environment, see *Figure* 5.21. The plant controller is the MES, also controlling the AAU Smart Production Lab, using the same on-site communication protocol (TCP/IP). The MES communicate with the PLCs in the manufacturing system. The Festo PLCs in the AAU Smart Production Lab use the software CODESYS which supports a compiler for Raspberry PI [3S-Smart Software Solutions GmbH, 2017]. This is utilized to expands the AAU Smart Production Lab PLC resources for a tenth of the price compared with Festo PLCs. Four Raspberry PI 3 Model B [Raspberry Pi Foundation North America, 2019], a switch, and a power transformer are built together as a PLC rack. By having three PLC racks and copy the individual PLC programs to Raspberry PI, the whole AAU Smart Production Lab can be emulated (hardware-in-the-loop), without seizing the PLC resource in the physical system. The PLCs communicate with the virtual plant with the communication protocol OPC UA. The virtual plants are constructed in a commercial virtual commissioning software Experior from the vendor Xcelgo [Xcelgo A/S, 2018].

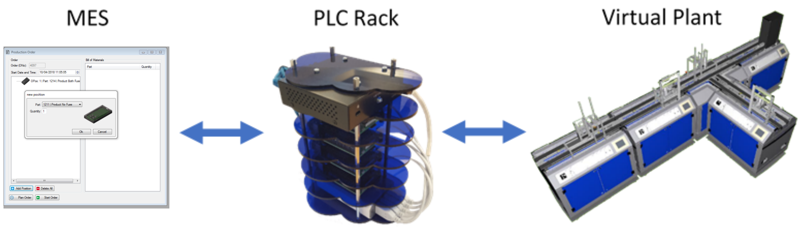


Fig. 5.21: Components of the virtual commissioning learning platform. Modified from [Mortensen and Madsen, 2018].

The virtual environment is illustrated in *Figure* 5.22 consisting of a catalogues window, a model window, a solution explorer window and a properties window. The catalogues window have multiple taps each with a different branch of virtual devices. A special catalogue with the process and transport modules from the AAU Smart Production Lab has been constructed. The virtual devices can be combined in the model window to construct the desired layout of the virtual line. The solution explore window gives an overview of the virtual devices in the model window. If the virtual device has changeable properties, it can be changed in the properties window.

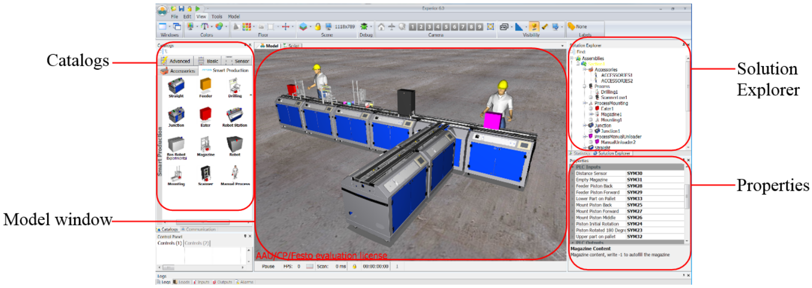


Fig. 5.22: The virtual environment for the Virtual Commissioning Learning Platform. [Mortensen and Madsen, 2018]

Classification of the Virtual Commissioning Learning Platform

The VCLP is categorised as a broader sense of learning factory in relation to the classification of learning factories in [Abele et al., 2015a], see *Figure* 5.23. The use of the AAU Smart Production Lab MES and use of the AAU Smart Production Lab PLC programs categorise the VCLP in the on-site communication channel frame. Even-though, the manufactured product in the VCLP, is virtual it is still categorized in the physically manufactured product, rather than a service, inside the learning factory frame in relation to the categorisation made by Abele et al. [2015a]. Lastly, the value chain in the learning factory has change from real to virtual distinguishes the VCLP from the narrow sense of learning factory.

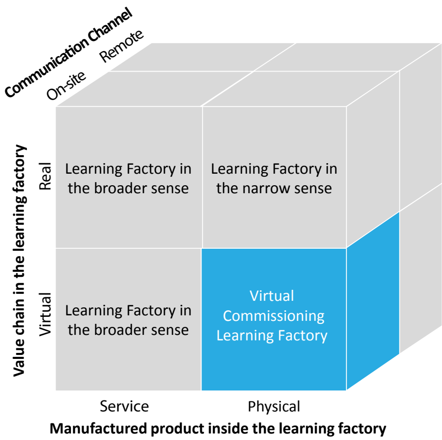


Fig. 5.23: Classification of the virtual commissioning learning factory in relation to narrow and broader sense of learning factory. Modified from [Abele et al., 2015a].

5.3.2 Multidisciplinary Team

In [Paper B | Mortensen and Madsen, 2018] a description of how a multidisciplinary non-expert team obtained the required qualifications of virtual commissioning is presented. The multidisciplinary team consisting of four master students, 2nd semester of Manufacturing Technologies at Aalborg University, and familiarised them self with virtual commissioning qualifications through a problem-based learning semester project. The multidisciplinary team were firstly asked to perform virtual commissioning of a single device, also described in [Paper B | Mortensen and Madsen, 2018]. The multidisciplinary team workflow was similar to the sequence of tasks illustrated in the example of Section 5.1. Second task was to perform virtual commissioning of several conveyor and process modules of the AAU Smart Production Lab.

The multidisciplinary team was able to obtain a deep knowledge of the concept of virtual commissioning and basic skills and knowledge to perform virtual commissioning. The VCLP mirror of the AAU Smart Production Lab assist the multidisciplinary team in their understanding of the system knowledge and train virtual commissioning in a recognisable environment. The VCLP similarity with the AAU Smart Production Lab also allowed performing real commissioning of the PLC program after testing in the virtual environment.

It can be concluded that the VCLP have potential to support the education of multidisciplinary teams of graduate students for obtaining deep knowledge about the concept of virtual commissioning together with basic skills and knowledge to perform virtual commissioning tasks.

5.3.3 Interdisciplinary Team

With the experience with a multidisciplinary team performing virtual commissioning task a hypothesis was formed that a interdisciplinary team can perform virtual commissioning, based on the general need for intermediate qualifications to solve virtual commissioning tasks. It is important to emphasise, as also mentioned in the Section 2.4.2, that the disciplines and thereby the domains differ between cultures and countries. The following is, therefore, a proposal fitting the Danish educational levels.

A case study was conducted as part of the project "Labour 4.0" [Waehrens et al., 2018] with the help of Aalborg University College North (UCN) where students with various background were given the task to solve a virtual commissioning problem at a case company. The students, background were diverse spanning from technical designer [Aalborg UCN, 2019b], automation engineering [Aalborg UCN, 2019a], computer science [Aalborg UCN, 2019c] to production technology [Aalborg UCN, 2019d].

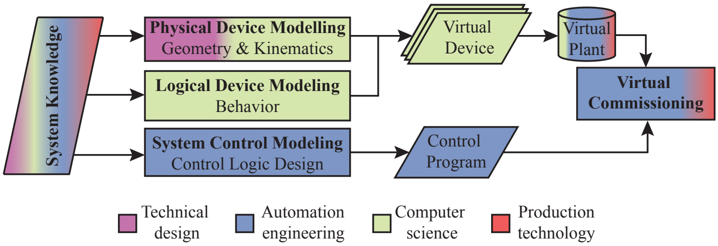


Fig. 5.24: Division of tasks between the four domains.

Figure 5.24 illustrate the division of tasks and combined effort in the interdisciplinary team for successfully developed a virtual commissioning solution. The interdisciplinary firstly solve the same virtual commissioning task using the VCLP as the multidisciplinary team, virtual commissioning of a single device of the AAU Smart Production Lab, familiarise themselves with virtual commissioning workflow and qualifications. Before solving the virtual commissioning task at the case company. *Figure* 5.24 illustrates the division of tasks and combined effort in the interdisciplinary team for successfully developed a virtual commissioning solution for the single device task and the task at the case company.

The case study of an interdisciplinary team illustrate that virtual commissioning tasks can be divided and solved by a team of professional bachelors. This indicates that by raising virtual commissioning awareness and training, virtual commissioning may a wider and larger impact in the industry. Especially SMEs might benefit from the division of virtual commissioning task and knowledge that domain experts may possess virtual commissioning qualification in the future.

5.4 Conclusion

This chapter has presented a decomposition of the virtual commissioning tasks, quantification of virtual commissioning qualifications, a learning platform and two case study for addressing Main Objective 2 - *Definition of Qualifications for Virtual Commissioning*.

This chapter has presented a decomposition of the virtual commissioning tasks from the needed shared system knowledge based on the virtual commissioning evaluation. The thorough review of the virtual commissioning has lead to the identification of the virtual commissioning workflow and tasks. The addressing of research objective 2.1 - *Describe virtual commissioning workflow and identify the general virtual commissioning tasks* has **laid the foundation for understanding the virtual commissioning qualifications.**

For the investigation of the virtual commissioning qualifications, a systematic literature review has been conducted. It was identified that the relationship between virtual commissioning tasks and needed skills and knowledge are absent in the literature. A Delphi study has been conducted, where virtual commissioning experts have participated in the survey. Based on the literature review and Delphi study, virtual commissioning tasks are decomposed in skills and knowledge. Quantification of the skills and knowledge was performed based on the Delphi study. **It can be concluded that the major skills and knowledge needed to perform virtual commissioning are needed on an intermediate-level**, equivalent to level three and four on Bloom's taxonomy addressing research objective 2.2 - *Identify and quantify qualifications needed for virtual commissioning.*

With the identification of virtual commissioning qualifications, a virtual commissioning learning platform has been developed based on the AAU Smart Production Lab , for education and dissemination of virtual commissioning as presented in **Paper B:** *A Virtual Commissioning Learning Platform* [Mortensen and Madsen, 2018]. Two case-studies have been conducted to indicate that a multidisciplinary team of non-experts and an interdisciplinary team of domain-experts can both solve virtual commissioning tasks. **The virtual commissioning platform may serve as a platform for 1) Increasing virtual commissioning awareness 2) Educating multidisciplinary graduate students 3) Educate an interdisciplinary team of professional bachelors. The students gain a deeper knowledge of the concept of virtual commissioning and obtain basic virtual commissioning qualification with the aid of the learning platform** addressing research question 2.3 - *Develop and investigate a learning environment for obtaining the needed virtual commissioning qualifications.*

Future work

The presentation of virtual commissioning workflow, qualifications, and quantification of skills and knowledge provides several opportunities for further development.

Further research might be conducted in the verification of the proposed virtual commissioning qualifications and their quantification. With the description of skills and knowledge for the current workflow, an interesting investigation could be performed on how virtual qualification evolve for a future workflow, such as the impact of automatic generation of models and automatic generation of PLC code.

An industrial validation of the hypothesis that an interdisciplinary team of non-experts may solve an industrial case be conducted in future research providing us with useful insights on the necessary aspects and viewpoints that a non-expert can identify in an industrial case. In addition, further research on the various ways that a virtual commissioning learning platform can be established at a university college. Such implementation will support broader dissemination purposes and assist with drawing useful conclusions on the novel challenges required for the education of virtual commissioning qualifications.

Chapter 6

Recommissioning of Changeable Manufacturing System

This chapter firstly presents reconfiguration levels and the definition of virtual recommission. Secondly, reconfiguration complexity and novelty are classified in three groups addressing research objective 3.1. Four elementary reconfiguration abilities are presented to address research objective 3.2. Lastly, research objective 3.3 are addressed with the presentation of an operational recommissioning method for recommissioning of changeable manufacturing system.

Changeable manufacturing system is designed to alter its topology and functionality. The reconfiguration of a changeable manufacturing system can be enabled in several production levels as described by ElMaraghy and Wiendahl [2009] and Section 2.1. Section 6.1 will illustrate how the changeability on different production levels is perceived and processed in this dissertation.

6.1 Reconfiguration levels

Inspired by the hierarchies of production levels presented in *Figure* 2.3, page 14 a breakdownt of the reconfiguration levels of a changeable manufacturing system is presented.

The following presents a decomposition of a changeable manufacturing system/line in cell, station, tool/machine level. *Figure* 6.1 uses the AAU Smart Production Lab to exemplify the different production levels regarding control software and hardware. As defined in Section 2.1, a reconfiguration consists of both a hardware and software change; this is illustrated in *Figure* 6.1 as a substitution of a module, while the different elementary reconfiguration abilities are examined later in Section 6.3.2.

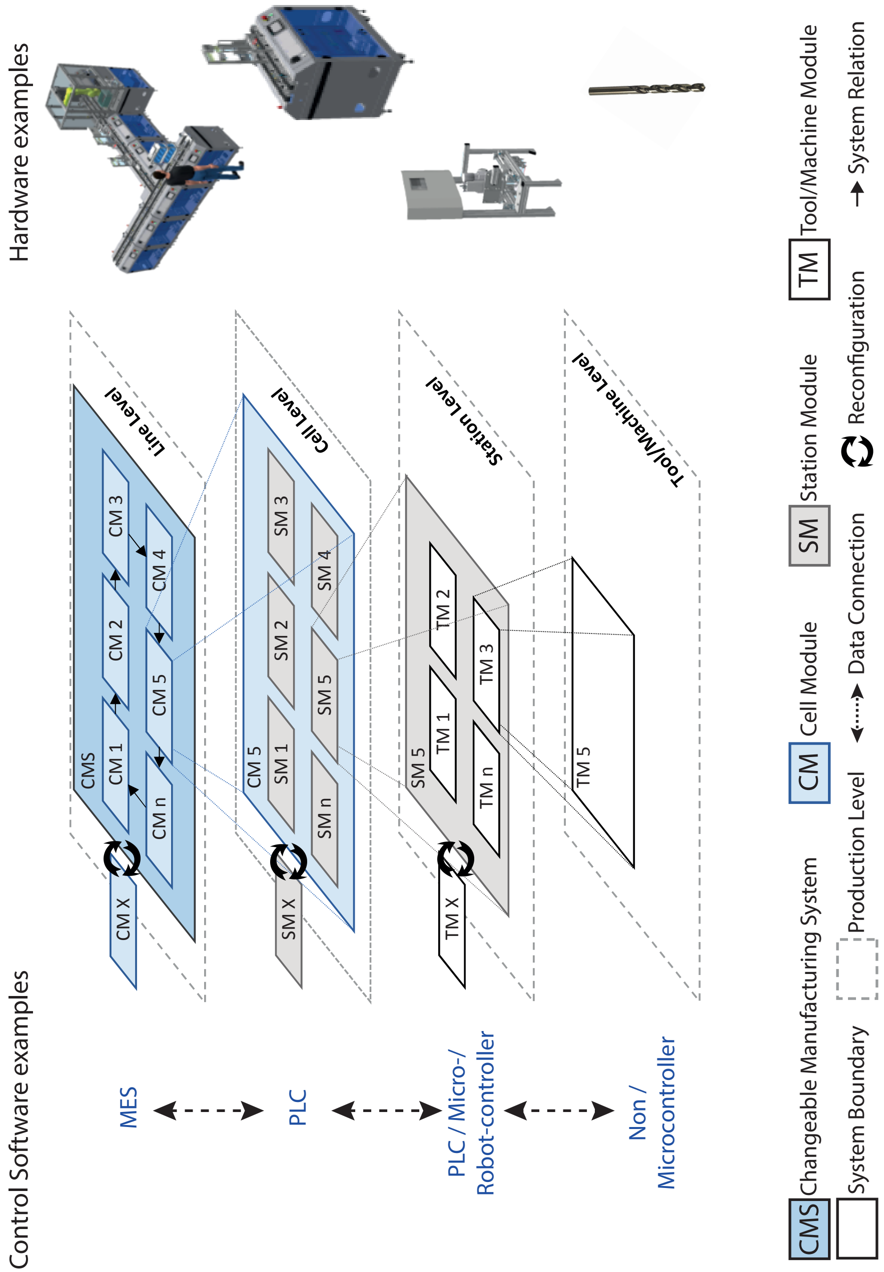


Fig. 6.1: Production model view of a changeable manufacturing system. Drawn with inspiration from ElMaraghy and Wiendahl [2009].

Line Level

On the line level in *Figure* 6.1 a changeable manufacturing system is illustrated consisting of a number of cell modules (CM 1 ... CM n). The cell modules have a system relation to each other as a result of the fixed conveyor sequence, transporting the parts from cell to cell. Please note that the fixed sequence do not apply for the use of AGVs. The line level is, in many cases, controlled by software tools controlling the sequence of operations, such as a manufacturing executing system (MES). AAU Smart Production Lab line, described in Section 4.1, is a hardware example on a changeable manufacturing system on a line level. The reconfiguration on the line level is achieved by changing the relation of the cell modules.

Cell Level

The cell module in *Figure* 6.1 may consists of several stations modules (SM 1 ... SM n). Each cell module communicates vertical to the line level controller (MES) and with the lower level controller. Commonly is the cell module controlled by a PLC. The AAU Smart Production Lab cell modules are an example of a hardware view of a cell module. The changeability in each cell module is achieved by reconfiguring the interaction between the station modules.

Station Level

Each station module can also consist of several tools or pieces of machinery modules (TM 1 ... TM n) and has its own control software, see *Figure* 6.1. The software is directed towards controlling the I/O on the tool level. Examples of controllers are PLC, robot controller, or micro-controller. If several controllers are present, horizontal communication may be present but is not required. The station modules are also communicating vertically with the cell level and tool level if controllers are present. As for the line and cell level, changeability is achieved by reconfiguration of the lower level modules, in this case, the change is the interaction between the tool/machine modules. An example of hardware on station-level may be an industrial robot, a conveyor, or a process modules, all present in the AAU Smart Production Lab line.

Tool/Machine Level

The lowest production level, examined in this thesis, is tool and machine level. Hardware examples of this level could be active tools or machinery like cylinders, grippers, or motors. It may also be passive tools/machinery like a drill, guiders or fixtures. The active tools/machinery may have a controller like a micro-controller. Otherwise, the controller on the station level (PLC) may control the tool/machine level. The tool/machine level have a vertical communication towards the station level.

The illustrated reconfiguration in *Figure* 6.1 on multiple level support the understanding of the later presented reconfiguration method in Section 6.4.

6.2 Virtual Recommissioning

Changeable manufacturing systems has several commissioning phases in its life-cycle as presented in Section 2.3.2, page 20. The recommissioning phase may lead to long commissioning phases, as seen in traditional commissioning. It is therefore natural to use virtual commissioning to shortening the recommissioning phase.

Paper A: *A Novel Framework for Virtual Recommissioning in Reconfigurable Manufacturing Systems* [Mortensen et al., 2017] presents the definition on virtual recommissioning as:

> *Virtual recommissioning is defined as the virtual commissioning phase between two configurations in a changeable manufacturing system.*
>
> Modified from [Mortensen et al., 2017]

Please note that the definition has been modified to include all changeable manufacturing systems not only the subcategory of reconfigurable manufacturing systems.

Virtual recommissioning utilise the existing knowledge and models created in the first virtual commissioning of the manufacturing system. As a result of this, reuse of existing virtual devices and virtual plants can be reconfigured to construct the new virtual plant configuration [Jain et al., 2010]. However, as discovered in the state-of-the-art, Section 2.3.2, minimal attention has been given to how the workflow in virtual recommissioning. The following section will explore how the recommissioning phase of changeable manufacturing systems, including virtual recommissioning, can be classified for later development of recommissioning methods.

6.3 Classification Framework

From the hypothesis that not all reconfigurations are identical but differ in complexity and nature, a novel classification framework was developed.

The "change extend", one of the foundations of changeable manufacturing described in Section 2.1 page 11, may be different in the different production levels covered in Section 6.1. Furthermore, it may also differ in complexity and time; to address this a framework was presented in **Paper A:** *A Novel Framework for Virtual Recommissioning in Reconfigurable Manufacturing Systems* [Mortensen et al., 2017].

The paper presents a framework for classification of changeable manufacturing systems in regards to reconfiguration complexity, time, and reconfiguration elementary abilities in a matrix. The reconfiguration classification matrix is used as a framework to describe, decompose, and classify reconfiguration of changeable manufacturing systems, see *Table* 6.1. A detailed description of the reconfiguration complexity and reconfiguration elementary abilities is provided in the following sections.

		Reconfiguration Complexity		
		Known-to -Known	Known-to -Familiar	Known-to -Unknown
Elementary Abilities	Rearrangeability			
	Scalability			
	Capability			
	Convertibility			

Table 6.1: Framework for classification of reconfiguration of changeable manufacturing systems. Modified from [Mortensen et al., 2017]

6.3.1 Reconfiguration Complexity

Reconfiguration of a changeable manufacturing system may differ in complexity from simple changes of tools on a machine level to complex changes on several levels as described in Section 6.1. [Paper A | Mortensen et al., 2017] presents a framework illustrated in *Figure* 6.2 that incorporates the classification of the novelty of the reconfiguration inspired from Almgren [1999]. The framework is made with the assumption that when reconfiguring a changeable manufacturing system the previous/current configuration may be known or obtainable. A configuration is *Known* when the configuration is known to a sufficient level so that the configuration can be reproduced both regarding software and hardware. The *Known* configuration may be used as an origin for the classification of the reconfiguration complexity. The complexity can be divided into three categories: Known-to-Known (K2K), Known-to-Familiar (K2F), and Known-to-Unknown (K2U).

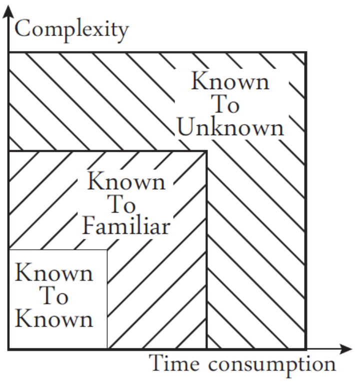


Fig. 6.2: Reconfiguration complexity based on the novelty of the reconfiguration. [Mortensen et al., 2017].

Known-to-Known

A Known-to-Known reconfiguration is the least complex and time-consuming reconfiguration. In a K2K a reconfiguration to a previous known configuration of the changeable manufacturing system is performed. An example of K2K reconfiguration is the adaptation of a company's production due to seasonal goods.

Known-to-Familiar

A Known-to-Familiar reconfiguration is a reconfiguration to a new (but anticipated) configuration. The K2F configuration utilises the predefined interfaces and standardised modules of the entities of the changeable manufacturing system and is a new configuration inside the intended solution space of the changeable manufacturing system. The K2F reconfiguration is more time consuming and complex than the K2K reconfiguration. An example of a K2F reconfiguration is the introduction of a new product within the same product family.

Known-to-Unknown

A Known-to-Unknown reconfiguration is a reconfiguration to a configuration outside the intended solution space of the changeable manufacturing system. The new configuration of the changeable manufacturing system will be in the periphery of the solution space utilising modified interfaces and/or modified standardised modules from the changeable manufacturing system to obtain the new configuration. The K2U reconfiguration is most complex and time consuming compared to K2K and K2F. An example of a K2U reconfiguration is the introduction of a new product outside the product family.

6.3.2 Reconfiguration Elementary Abilities

The second dimension of the classifications framework is called "Elementary Abilities". Here the hypothesis is that any reconfiguration of a changeable manufacturing system may be decomposed in to a combination of elementary abilities.

Example of elementary reconfiguration abilities of changeable manufacturing systems can be found in the literature. Chryssoluris [2005] divides the elementary reconfiguration abilities in relation to *product flexibility*, *operation flexibility*, and *capacity flexibility*. *Product flexibility* is the scope of functionality of each modules, *Operation flexibility* is related to rerouteing and changing the sequence of operations, and lastly *capacity flexibility* is related to change in output volume. Benkamoun et al. [2015] use *Extensibility* (similar to *capacity flexibility*) and *convertibility* the ability to exchange modules.

[Paper A | Mortensen et al., 2017] present four elementary abilities based on the reconfiguration of a changeable manufacturing systems. Please recall that a reconfiguration in this thesis is defined as a change both in hardware and software. The reconfiguration, as described, may occur on different production levels. In the following, the reconfiguration is exemplified on a cell level. *Figure* 6.3 exemplify the four elementary abilities in a schematic view: Rearrangeability, Scalability, Capability, and Convertibility. In the upper part of *Figure* 6.3 the original system configuration is illustrated with four process modules, with duplication of one of the process modules, enabling the system to manufacture the arbitrary product A&B. *Figure* 6.4 illustrates the impact of the different elementary abilities on the scope of functionality and capacity (production volume).

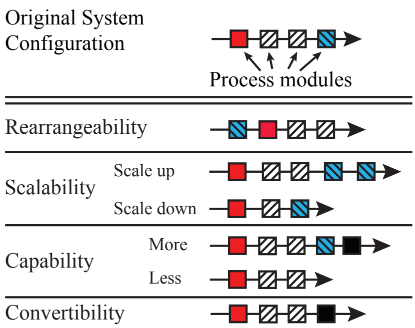


Fig. 6.3: Reconfiguration elementary abilities [Mortensen et al., 2017; Mortensen and Madsen, 2019]

Rearrangeability

Rearrangeability is the elementary ability to change the sequence of the process modules in the changeable manufacturing system typically by changing the relative location of the modules. The scope of functionality of the changeability manufacturing system will not change when rearranging the system. However, the rearrangeability could have an impact on the lead-time and thereby the capacity as illustrated in *Figure* 6.4 b). Referring back to *Figure* 6.3 the changeable manufacturing system now may produce product B&A.

Scalability

Scalability is the elementary ability to duplicate one or more process modules to obtain a higher capacity of the changeable manufacturing system. Alternatively, remove duplicated process modules to lower the capacity of the system illustrated in *Figure* 6.3. The scope of functionality is not affected by the scalability for more capacity as illustrated in *Figure* 6.4 c) or less *Figure* 6.4 f).

Capability

Capability is the elementary ability to add or remove process modules to expand or decrease the scope of functionality, respectively illustrated in *Figure* 6.4 d) and *Figure* 6.4 g). The capability enables reconfiguration of the changeable manufacturing system to handle a lower or higher product variety, e.g. in *Figure* 6.3 manufacturing product A or product A&B&C.

Convertibility

Convertibility is the elementary ability to interchange modules with each other. The convertibility enables the changeable manufacturing system to change the scope of functionality. In *Figure* 6.3 this is illustrated by reconfiguration to a configuration manufacturing product A&C. The Convertibility can be with "legacy" in the scope of functionality illustrated in *Figure* 6.4 e), e.g., manufacturing product A&C or to a new scope of functionality illustrated in *Figure* 6.4 h), manufacturing product C.

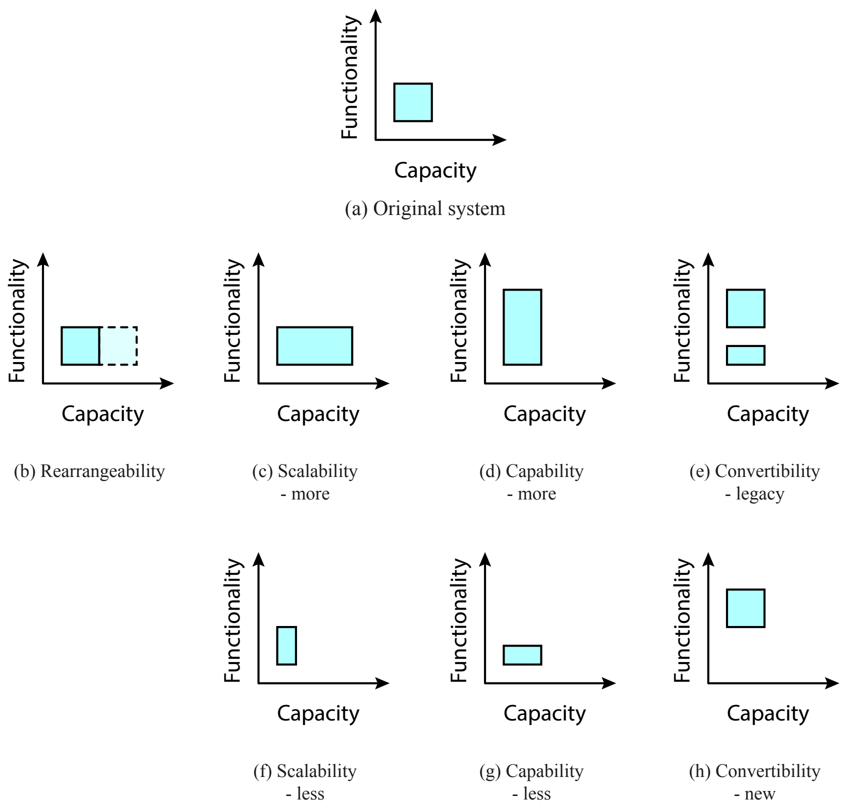


Fig. 6.4: Comparison of elementary reconfiguration abilities. (a) is the the origins of system's functionality and its capacity is presented. Following the chart (b) presents the rearrangeability while (c) and (f) the effect of more/less scalability. Chart (d) and (g) the effect of more/less capability. Lastly, (e) and (h) the effect of convertibility with or without legacy.

6.4 Recommissioning Method

With the identification and classification of reconfiguration in changeable manufacturing systems presented in [Paper A | Mortensen et al., 2017] and *Table* 6.1 further development of the framework is present in **Paper C:** *Operational Classification and Method for Reconfiguration & Recommissioning of Changeable Manufacturing Systems on System Level* [Mortensen and Madsen, 2019] which present an operational method with four steps:

1. Recognize reconfiguration complexity.
2. Identify needed elementary reconfiguration ability.
3. Select class in the support tool, Tables 6.2 to 6.5, for reconfiguration and recommissioning of changeable manufacturing systems.
4. Perform the actions indicate in Tables 6.2 to 6.5 for the class within hardware, software, optional: virtual commissioning, and physical commissioning.

[Mortensen and Madsen, 2019]

The first step is to recognise the reconfiguration complexity and categorised it in Known-to-Known (K2K), Known-to-Familiar (K2F), or Known-to-Unknown (K2U) illustrated in *Figure* 6.2. Step two is to identify the needed elementary reconfiguration ability, presented in *Figure* 6.3. Step three is to select the responding class in the support tool for reconfiguration and recommissioning of the changeable manufacturing system, Tables 6.2 to 6.5. Step four is to perform the actions related to the commissioning phase concerning hardware, software, virtual recommissioning, and the physical commissioning in each category, see Tables 6.2 to 6.5.

	K2K	K2F	K2U
Rearrangeability	**Hardware:**	**Hardware:**	**Hardware:**
	Rearrange positions of standard modules in the system to previous known position	Rearrange positions of standard modules by use of predefined interfaces	Rearrange positions of standard modules by use modified interfaces
	Software:	**Software:**	**Software:**
	Load previous used software into low-level controllers	Interchange standard software modules to program low-level controllers	Modified or modified & interchange standard software modules to program low-level controllers
	Load previous topology model to the high-level controller	Rearrange the topology model in the high-level controller	Modify the topology model in the high-level controller
	Virtual Commissioning:	**Virtual Commissioning:**	**Virtual Commissioning:**
	Load previous used virtual plant model	Rearrange plant model based on used standard virtual devices	Modified interfaces of standard virtual devices
	Virtual plant commissioning	Virtual plant commissioning	Rebuild plant model based on standard virtual devices with modified interfaces and with/without standard virtual devices
			Virtual device commissioning
	Physical Commissioning:	**Physical Commissioning:**	Virtual plant commissioning
	Physical calibration	Physical calibration	**Physical Commissioning:**
	High-level test	High-level test	Physical calibration
			I/O test
			High-level test

Table 6.2: Support tool for reconfiguration and recommissioning of CMS. Part I. [Mortensen and Madsen, 2019].

	K2K	K2F	K2U
Scalability	**Hardware:** Duplicate/remove duplicated standard modules to obtain precious known capacity **Software:** Load previous used software into low-level controllers Load previous topology model to the high-level controller **Virtual Commissioning:** Load previous used virtual plant model Virtual plant commissioning **Physical Commissioning:** Physical calibration High-level test	**Hardware:** Duplicate/remove duplicated standard modules to obtain a new capacity **Software:** Clone software for duplicated modules to program low-level controllers Expand/decrease the topology model in the high-level controller **Virtual Commissioning:** Modify plant model based on standard virtual devices Virtual plant commissioning **Physical Commissioning:** Physical calibration High-level test	**Hardware:** Add modified standard modules with/without duplicate/remove duplicated standard modules to obtain a new capacity **Software:** Clone and modify standard software modules to program low-level controllers Modify the topology model in the high-level controller **Virtual Commissioning:** Modify standard virtual devices Rebuild plant model based on modified virtual devices and with/without standard virtual devices Virtual device commissioning Virtual plant commissioning **Physical Commissioning:** Physical calibration I/O test High-level test

Table 6.3: Support tool for reconfiguration and recommissioning of CMS. Part II. [Mortensen and Madsen, 2019].

	K2K	K2F	K2U
Capability	**Hardware:** Add/remove standard modules to obtain precious known functionality **Software:** Load previous used software into low-level controllers Load previous topology model and variant model to the high-level controller **Virtual Commissioning:** Load previous used virtual plant model. Virtual plant commissioning **Physical Commissioning:** Physical calibration High-level test	**Hardware:** Add/remove standard modules to obtain new functionality **Software:** Load new standard software modules to program low-level controllers Adjust the topology model and expand/decrease the product variant models in the high-level controller **Virtual Commissioning:** Modify plant model based on standard virtual devices. Virtual plant commissioning **Physical Commissioning:** Physical calibration High-level test	**Hardware:** Add modified standard modules with/without adding/removing standard modules to obtain a new functionality **Software:** Combine and modify standard software modules to program low-level controllers Modify the topology and product variant models in the high-level controller **Virtual Commissioning:** Modify standard virtual devices Rebuild plant model based on modified virtual devices and with/without standard virtual devices Virtual device commissioning Virtual plant commissioning **Physical Commissioning:** Physical calibration I/O test High-level test

Table 6.4: Support tool for reconfiguration and recommissioning of CMS. Part III. [Mortensen and Madsen, 2019].

	K2K	K2F	K2U
Convertibility	**Hardware:** Exchange standard modules to obtain precious known scope of functionality **Software:** Load previous used software into low-level controllers Load previous topology model and variant model to the high-level controller **Virtual Commissioning:** Load previous used virtual plant model Virtual plant commissioning **Physical Commissioning:** Physical calibration High-level test	**Hardware:** Exchange standard modules to obtain new scope of functionality **Software:** Exchange standard software modules to program low-level controllers Adjust the topology and product variant models in the high-level controller **Virtual Commissioning:** Modify plant model based on standard virtual devices Single virtual device commissioning Virtual plant commissioning **Physical Commissioning:** Physical calibration High-level test	**Hardware:** Exchange modified standard modules to obtain a new scope of functionality **Software:** Change and modify standard software modules to program low-level controllers Modify the topology and product variant models in the high-level controller **Virtual Commissioning:** Modify standard virtual devices Rebuild plant model based on modified virtual devices and with/without standard virtual devices Virtual device commissioning Virtual plant commissioning **Physical Commissioning:** Physical calibration I/O test High-level test

Table 6.5: Support tool for reconfiguration and recommissioning of CMS. Part IV. [Mortensen and Madsen, 2019].

6.5 Example of Recommissioning

A number of reconfiguration of AAU Smart Production Lab has been performed over the year, such as introducing new process station to increase the scope of functionality and capability. This section will present two examples of reconfiguration for exemplification of the presented reconfiguration method. The first example, (1), is in the reconfiguration complexity **Known-to-Familiar** and with the elementary reconfiguration ability **Rearrangeability**. Second example, (2), is in the reconfiguration complexity **Known-to-Familiar** and with the elementary reconfiguration ability **Scalability**.

		Reconfiguration Complexity		
		Known-to -Known	Known-to -Familiar	Known-to -Unknown
Elementary Abilities	Rearrangeability		(1)	
	Scalability		(2)	
	Capability			
	Convertibility			

Table 6.6: Marks of example 1 and 2 in the framework for classification of reconfiguration of changeable manufacturing systems. Modified from [Mortensen et al., 2017].

(1) – K2F – Rearrangeability

A reconfiguration of the AAU Smart Production Lab from one configuration (Known), *Figure* 6.5, to a new configuration (Familiar), *Figure* 6.6, with the same functionality (Rearrangeability) has been performed at Aalborg University the 20th December 2017. A video of the reconfiguration can be seen at `https://youtu.be/pX74QVfZ-6A`. In the following, a stepwise description of the reconfiguration is made with the use of the support tool (highlighted in italic) *Table* 6.2.

Fig. 6.5: Configuration of the AAU Smart Production Lab before the reconfiguration.

Fig. 6.6: Configuration of the AAU Smart Production Lab after the reconfiguration.

Hardware:

- *Rearrange positions of standard modules by use of predefined interfaces:*

For reconfiguration the AAU Smart Production Lab to the new configuration, several positions of the modules have been rearranged. Most of the cell modules (conveyor module and mounted process modules) are rearranged on a line level taking advantage of the modularisation of the AAU Smart Production Lab (no physical connection between the cell modules) and the multi-plug that with one plug support the cell module with air, power, and network from the neighbour module. In addition, a reconfiguration of on a cell level is performed (mounting of a process module on a new conveyor module). The predefined mechanical interfaces are used to attach the process module to the rails of the conveyor module. The air hose, the power plug and the network connector are connected to the predefined interfaces, located on the top of the conveyor module.

Software:

- *Interchange standard software modules to program low-level controllers:*

Most of the process modules in the AAU Smart Production Lab are controlled with the PLC in conveyor module they are mounted on. Interchanges of programs between the two PLC, uploading the control program for the process module to the new PLC and uploading a control program without a process module to the previous PLC.

- *Rearrange the topology model in the high-level controller:*

To support the new configuration of the AAU Smart Production Lab the topology model in the MES system has to rearrange. The sequence of the modules is changed in the MES, enabling the pallet to be routed correctly.

Virtual Commissioning:

- *Rearrange plant model based on used standard virtual devices:*

For reconfiguration of the virtual plant model of the AAU Smart Production Lab , the virtual devices have to be rearranged. The previous configuration plant model is retrieved, *Figure* 6.7, in Experior and by drag-and-drop the new plant model *Figure* 6.8 is constructed. The drag-and-drop function is possible with the previous modelled predefinition snapping points in the virtual devices, similar to the predefined interfaces in the physical world.

- *Virtual plant commissioning:*

With the reconfiguration PLC program installed, a virtual commissioning evaluation of the new configuration of the plant is performed towards the AAU Smart Production Lab MES.

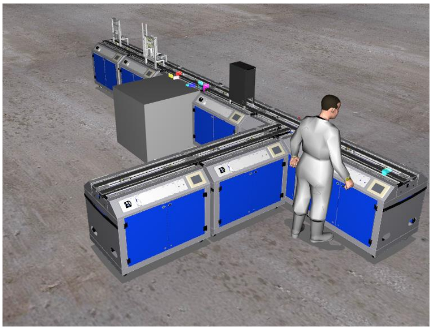


Fig. 6.7: Virtual plant model of the AAU Smart Production Lab in Experior before the reconfiguration.

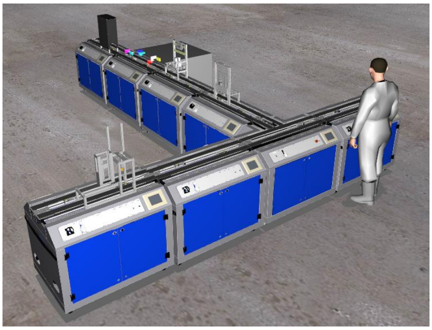


Fig. 6.8: Virtual plant model of the AAU Smart Production Lab in Experior after the reconfiguration.

Physical commissioning:

- *Physical calibration:*

A physical calibration of the modules is performed to ensure a robust and smooth transport of pallets from one conveyor model to the next. The calibration of heights is also necessary due to the uneven factory floor in AAU Smart Production Lab.

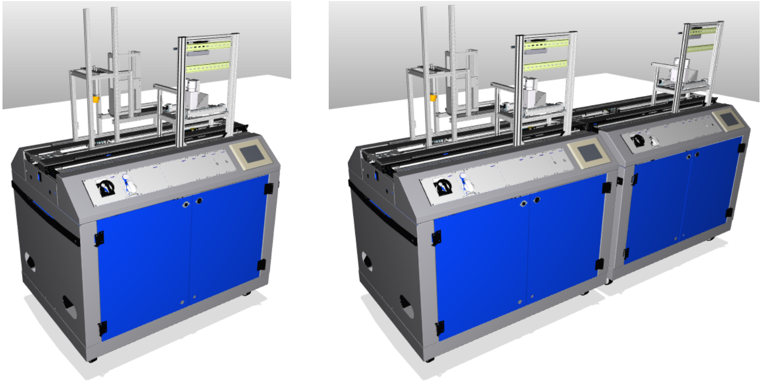
- *High-level test:*

A test of the MES is performed to ensure correct routing of parts in the AAU Smart Production Lab.

With the passed test of the MES, a successful reconfiguration of the AAU Smart Production Lab has been performed, and the system is ready to produce new parts.

(2) – K2F – Scalability

A reconfiguration of AAU Smart Production Lab from one configuration, *Figure* 6.9 a) (Known), to a new configuration *Figure* 6.9 b) (Familiar) with increased capacity by duplicate one of the process modules (Scalability) was forwarded. This example has a focus on the virtual recommissioning phase of the AAU Smart Production Lab. The example is also presented shortly in [Paper A | Mortensen et al., 2017] and further elaborated in [Paper B | Mortensen and Madsen, 2018]. In the following, a stepwise description of the reconfiguration is made with the use of the support tool (highlighted in italic) *Table* 6.3. In the scaling, we introduce a duplication of a conveyor module and a process module.



(a) Virtual plant model before the reconfiguration. Modified from [Mortensen et al., 2017]

(b) Virtual plant model after the reconfiguration. Modified from [Mortensen et al., 2017]

Fig. 6.9: Known-to-Familiar reconfiguration with the use of scalability.

Virtual Commissioning:

- *Modify plant model based on standard virtual devices:*

Firstly the old configuration is retrieved. Secondly, the standard virtual devices are added to construct the new plant model configuration.

- *Virtual plant commissioning:*

With the new plant model, a virtual commissioning evaluation can be performed towards the AAU Smart Production Lab MES where the new topology model is implemented. The virtual commissioning evaluation revealed that the current state of the AAU Smart Production Lab MES cannot handle duplication of a process module. The AAU Smart Production Lab MES is not able to utilise the duplicated process module due to the setup of the sequence of operations in the product recipe.

A physical implementation of a duplication of a process module has not been performed yet at the AAU Smart Production Lab. However, the development of a new manufacturing execution system has been begun partly to address the highlighted challenge of scaling.

6.6 Conclusion

This chapter has presented a recommissioning method to address Main Objective 3 - *Definition of a Recommissioning Framework for Changeable Manufacturing.*

Firstly, an examination of a system model view of a changeable manufacturing system and how the changeability is obtained at each level is performed as the foundation of the recommissioning method. The system model view illustrated how the different production levels, from line level to tool/machine level are connected. In addition, the system model view exemplifies the hardware and software on each level with the use of AAU Smart Production Lab. Virtual recommissioning was defined as the virtual commissioning phase between two configurations of a changeable manufacturing system.

A classification framework for reconfiguration complexity and novelty of the reconfiguration was presented. The **reconfiguration complexity and novelty** of a changeable manufacturing system can be classified into three categories: **Known-to-Known**, **Known-to-Familiar**, and **Known-to-Unknown** concerning previous configurations, presented in **Paper A:** *A Novel Framework for Virtual Recommissioning in Reconfigurable Manufacturing Systems* [Mortensen et al., 2017] for addressing research objective 3.1 - *Decompose of the reconfiguration complexity.* The novel framework enables an opportunity to recognise and utilise the obtained knowledge from the previous configurations.

Besides, the reconfiguration of changeable manufacturing systems can be divided into **four elementary reconfiguration abilities**. **Rearrangeability** is the ability to change the topology of the system that might result in a higher capacity. **Scalability** is the ability to duplicate or remove duplicates to adjust the capacity. **Capability** is the ability to expand or shrink the scope of functionality. Lastly, **convertibility** is the ability to change the scope of functionality. The elementary reconfiguration abilities are presented in **Paper A:** *A Novel Framework for Virtual Recommissioning in Reconfigurable Manufacturing Systems* [Mortensen et al., 2017] and address research objective 3.2 - *Decompose of reconfiguration abilities.*

The classifications were merged and explored resulting in an **operational recommissioning method for recommissioning of changeable manufacturing systems** presented in **Paper C:** *Operational Classification and Method for Reconfiguration & Recommissioning of Changeable Manufacturing Systems on System Level* [Mortensen and Madsen, 2019] addressing research objective 3.3 - *Develop working procedure for recommissioning and virtual recommissioning of changeable manufacturing systems.* The method utilises a support tool given instructions to actions to perform in changes in hardware, software, virtual recommissioning, and physical commissioning. Two examples of reconfiguration of the AAU Smart Production Lab have been performed using the developed recommissioning method.

Future work

An industrial investigation of the different forms of reconfiguration and the use of the recommissioning method can be conducted in future research. The initial steps for this investigation might be to conduct the investigation at the AAU Smart Production Lab firstly. Another theme for investigation is how the reconfiguration method could shape future virtual commissioning tools to increase the use of virtual commissioning in changeable manufacturing systems.

Chapter 7

Conclusions

This chapter summaries the contributions of this Ph.D. thesis and presented the conclusion remarks and remarks on future research.

7.1 Summary of Contributions

This section will summarise the contributions of this thesis based on the research objectives presented in Chapter 3.

Main Objective 1 - *Develop a Changeable Industry 4.0 Learning Platform*

1.1 **Establish a changeable Industry 4.0 learning platform at Aalborg University**
The author have been a key member of the team for establishment of a changeable Industry 4.0 learning platform at Aalborg University; AAU Smart Production Lab as presented in Chapter 4. With the continuous development of AAU Smart Production Lab , a platform for research, resulting in more than 20 academic papers within various domains, and education, used in more than 20 courses such as illustrated in [Paper E | Brunoe et al., 2019], has been established. AAU Smart Production Lab has been a platform for disseminate knowledge about Industry 4.0 for around 250 companies and more than 1000 peoples in the Industry.

1.2 **Investigate how Industry 4.0 awareness can be facilitated by the learning factory**
The developed serious learning game of Industry 4.0, presented in Section 4.2 and [Paper D | Mortensen et al., 2019], facilitates a first-hands-on learning experience for increasing the awareness level of Industry 4.0. The game created awareness about the driving technologies in Industry 4.0 and how they may impact and depend on each others. Around 80 participants have tested the game. The learning game can be used for both education and industry participants. The participants indicated a positive impact learning achievements.

Main Objective 2 - *Definition of Qualifications for Virtual Commissioning*

2.1 **Describe virtual commissioning workflow and identify the general virtual commissioning tasks**
Virtual commissioning workflow is described with the aid of 5 subgroups, as presented in Section 5.1. The groups are: System Knowledge, Physical Device Modelling, Logical Device Modelling, System Control modelling, Virtual Plant, and Virtual Commissioning Evaluation. The general virtual commissioning tasks under each group are identified and presented.

2.2 **Identify and quantify qualifications needed for virtual commissioning**
Based on the identified virtual commissioning tasks an identification of the virtual commissioning qualifications was presented in Section 5.2. The qualifications were identified based on a structured literature survey and a Delphi research method among virtual commissioning experts. The qualifications were divided and a mapping of the task, skills and needed knowledge were performed. Each skill and knowledge was quantified as part of the Delphi study. The majority of virtual commissioning qualifications are required on an intermediate level.

2.3 **Develop and investigate a learning environment for obtaining the needed virtual commissioning qualifications**
A virtual commissioning learning platform has been developed as presented in [Paper B | Mortensen and Madsen, 2018]. The virtual commissioning platform has been used to educate both multidisciplinary and interdisciplinary groups in virtual commissioning. A pre-study has proven that a interdisciplinary team of professionals from a University college level can obtain the needed virtual commissioning qualifications to solve virtual commissioning tasks.

Main Objective 3 - *Definition of a Recommissioning Framework for Changeable Manufacturing*

3.1 **Decompose of the reconfiguration complexity**
The reconfiguration complexity was divided into three categories; Known-to-Known, Known-to-Familiar, and Known-to-Unknown, as presented in [Paper A | Mortensen et al., 2017]. The categorization considers that reconfiguration between to configuration may differ in complexity due to novelty of the new configuration compared to the previous configuration and thereby has affect on the time and complexity of the reconfiguration.

3.2 **Decompose of reconfiguration abilities**
Four elementary reconfiguration abilities was identified and presented in [Paper A | Mortensen et al., 2017]. The elementary reconfiguration abilities rearrangeability, scalability, capability and convertibility enable the description of any reconfiguration of a changeable manufacturing system by a combination of the abilities.

3.3 **Develop working procedure for recommissioning and virtual recommissioning of changeable manufacturing systems**
An operational classification framework and method for reconfiguration and recommissioning of changeable manufacturing systems was developed, as presented in [Paper C | Mortensen and Madsen, 2019]. The method firstly requires a classification of the reconfiguration in terms of reconfiguration complexity and use of elementary abilities. With the selected reconfiguration class, a support tool will aid in the reconfiguration of the changeable manufacturing system by the specification of action to perform within hardware reconfiguration, software reconfiguration, virtual recommissioning, and physical recommissioning.

7.2 Concluding Remarks and Future Research

Since the beginning of this Ph.D. in 2015, an iterative development of the research focus has been performed. The following will present concluding remarks and propose several directions for future research based on the summarised contributions of this thesis.

Industry 4.0 Awareness

This PhD has contributed to the establishment of a new research area at Aalborg University: Learning Factories. The establishment of the AAU Smart Production Lab has provided the opportunity to research how different technologies impact a manufacturing system at a systemic level. Future research in the learning impact with the use of AAU Smart Production Lab may be conducted. Special focus on how SME might obtain Industry 4.0 awareness and qualifications is an interesting challenge.
Serious learning games in other aspects of the new digital qualification for the manufacturing industry might also be an interesting new research topic. How can we identify the new qualifications of future employers and educate those?

Virtual Commissioning

Further research might be conducted in the verification of the proposed virtual commissioning qualifications and their quantification. Besides, an investigation

if the identified task, skills, and knowledge are generic across all virtual commissioning could be a future research topic. In addition, the identified skills and knowledge are based on the current workflow. An interesting topic is how the impact of automatically generated models and automated generation of PLC code and hence a new workflow may affect the future need for virtual commissioning qualifications. An industrial validation of the hypothesis that an interdisciplinary team of non-experts can solve an industrial case could be performed in future research.
Research of how we may obtain not only the technical qualifications but also the personal, social and methodological qualifications can be investigated.

Recommissioning of Changeable Manufacturing Systems

Several research opportunities lie within the recommissioning of changeable manufacturing systems based on the research conducted in this thesis. Firstly, an experiment of the different forms of recommissioning and the use of the recommissioning methods can be investigated with the use of AAU Smart Production Lab. Secondly, industrial cases with the use of the recommissioning methods may be conducted. Investigation of how a virtual recommissioning tool could be designed and operated for increasing the use of virtual commissioning in the context of changeable manufacturing systems could be forwarded.

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Part III

Papers

Paper A

A Novel Framework for Virtual Recommissioning in Reconfigurable Manufacturing Systems

Steffen Tram Mortensen, Dimitrios Chrysostomou and Ole Madsen

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A Novel Framework for Virtual Recommissioning in Reconfigurable Manufacturing Systems

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***Abstract*—This paper defines a framework for virtual recommissioning in reconfigurable manufacturing systems. The need for virtual recommissioning arises with the multiple commissioning tasks in the life span of a reconfigurable manufacturing system. A classification of reconfiguration complexity and elementary abilities are combined in a reconfiguration matrix. The reconfiguration matrix serves as a framework for future research in virtual recommissioning. Lastly a preliminary exploration of virtual recommissioning is conducted on models of an Industry 4.0 Smart Factory demonstrator.**

I. Introduction

The continuous fluctuating and uncertain market, caused by customers' demands for personalized products, together with increased competition from low-wage countries challenge traditional manufacturing companies and require new strategies [1]. Manufacturing companies should not only be flexible, but also efficient at the same time. Mass customization coupled with reconfigurable manufacturing systems (RMS) have been proven to be promising as a manufacturing system able of being both flexible and efficient [1, 2].

By reconfiguring the manufacturing system, we change abilities of the system such as the capacity and functionality. Each time we alter the manufacturing system we have a commissioning phase similar to a traditional manufacturing system, see *Fig.* 1. However, as *Fig.* 1 illustrates, a RMS is reconfigured and commissioned several times in its life cycle resulting in higher impact of the commissioning leading to loss of capacity and revenue [3]. The commissioning phase is costly and expands the time to market. Studies have shown that 15-25% of the project time for a traditional manufacturing system is related to the commissioning time where, 63% of the time is used in software debugging [4].

A tool to lower the commissioning time is virtual commissioning (VC). VC enables the full verification of the manufacturing system using a virtual plant and real controllers (often Programmable logic controllers (PLCs)). The topic of this paper is virtual recommissioning.

Virtual recommissioning is defined as the virtual commissioning phase between two configurations in a reconfigurable manufacturing system.

II. Related Work

VC enables the identification of design and control faults before the real commissioning and, thereby, reduce the implementation time in the real factory [4, 6, 7, 8]. Studies have shown that VC can lower the commissioning time up to 75% [4]. However, despite its large potential VC has not yet the same success as other simulations tools [7, 9, 10].

The missing success for VC is caused by the traditional themes such as: cost, time consumption, and the demand for high level skills [6]. Three general ideas are presented in the literature for making VC obtainable both for larger companies as well as Small and Medium Size Enterprises: I Automated generation of factory models from existing data [11, 12], II use of integrated VC in the earlier stages of engineering [13], III reusing the factory models for other purposes than just the commission, e.g. maintenance or operator training [14]. All three ideas have been tested in lab and/or pilot projects but still they are missing larger implementations in industry [11, 12, 13, 14].

These three ideas of lowering the time and cost of VC are all inspired by the traditional engineering process of a manufacturing system which only have one commissioning in its life span. However, as shown in *Fig.* 1, RMS will have multiple commissioning in its life span.

While a large amount of literature exists to describe various techniques applied to RMS and VC, their combination still remains a novel research theme.

In [15] a research software tool for VC, from Loughborough University, is presented and compared to existing commercial tools. The software utilises a component-based architecture of core components that allow virtual models to be built easier by the use of libraries of sub-models. Thus, it enables the modelled components to be reused and reconfigured. However, the main focus of the paper lies on the first engineering phase of a RMS and does not treat the reconfigurations.

In [16] and [17] a method is presented for designing, enhancing, and optimizing changeability in a hybrid RMS with the use of virtual prototyping and digital engineering tools. A hybrid RMS is a system where humans and full automation work together but only one at the time in the work-zone. In [16] the focus is on the engineering phase of a RMS, especially on how modularization of the product, process and resources

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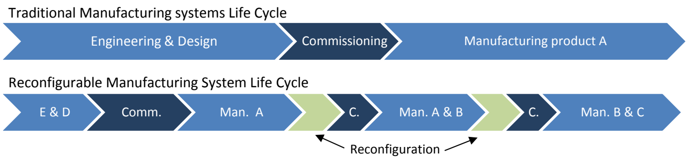

Fig. 1. Traditional manufacturing system life cycle compared to RMS life cycle. Based on [5].

(PPR approach) may enable parametric-based modular models. The paper categorizes these in four different spaces: I/O space, Graphical space, Visualization space, and Interaction space. The different spaces are used to define the interfaces of the different sub-modules/models in the engineering phase of the RMS.

In [17] a layout optimisation of the RMS is performed followed by a detailed optimization for mechanic and electronic parts. Lastly, VC is performed for a robot program and the high-level control logic such as the manufacturing executing system (MES) layer. The VC uses "hard" and "soft" modules to create reusable modules. Both papers have the same view on reconfiguration as [15], treating every reconfiguration as a new manufacturing system, however the changing of product dependent elements, e.g. fixture and grippers, will enable faster engineering of a new models.

III. Research Objective

It is apparent that traditional VC tool may enables virtual recommissioning. However, traditional VC tools treat each reconfiguration as a greenfield project, without utilising the knowledge, modules, and competence created in previous commissioning task. As described in [17], soft and hard modules may be used to reduce the skills needed for building the virtual model but still treat it as a greenfield project. The reconfiguration tasks may vary in complexity and time, as well as have distinctive characteristics e.g. a change in process sequence might not be the same as a change in capacity.
Our hypothesis is by classifying different elementary reconfigurations in a framework we can later identify the virtual recommissioning tasks. The remainder of this paper is divided into four sections; Section 4 will present the classification of reconfiguration while the reconfiguration matrix framework is presented in Section 5. Preliminary exploration of virtual recommissioning is presented in Section 6 and we conclude the paper in the last seventh Section.

IV. Reconfiguration Classification of RMS

A clarification and classification of the different kinds of possible reconfiguration configurations in a RMS is performed in this section. This classification of reconfiguration abilities is related to the physical and logical manufacturing systems reconfiguration methods presented in [18]. Note in this paper a reconfiguration is defined as a both physical (hard) and logical (soft) change.

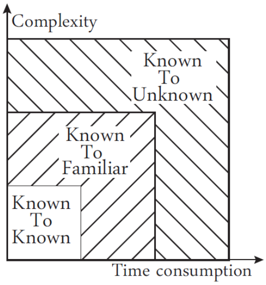

Fig. 2. Different clasification of reconfiguration in relation to complexity and time consumption.

A. *Reconfiguration Complexity*

Reconfiguration can be divided in three categories according to the complexity of the task: Known-to-Known, Known-to-Familiar and Known-to-Unknown as illustrated in *Fig.* 2. A configuration is classified as "known" when a given setup is known to a sufficient level that allows the setup to be reproduced.

A Known-to-Known reconfiguration is defined as the change from a current configuration setup to another previously used configured setup. The reconfiguration complexity and time consumption of a Known-to-Known reconfiguration are considered to be low, since knowledge related to this type of configuration already exists. A Known-to-Familiar reconfiguration is defined as the change from a current configuration setup to a new configuration that is inside the intended solution space of the system. A Known-to-Familiar reconfiguration introduces more complexity and higher time consumption compared to Known-to-Known reconfiguration. In a Known-to-Familiar reconfiguration only parts of the current software program and/or current hardware setup are reused. A Known-to-Unknown reconfiguration is defined as a change from a current configuration setup to a new configuration with marginal similarities to the current configuration and is a configuration outside the intended solution space. The Known-to-Unknown reconfiguration has a higher complexity and significant time consumption compared to the Known-to-Known reconfiguration, hence new software program(s) and hardware equipment must be engineered and implemented in the reconfiguration.

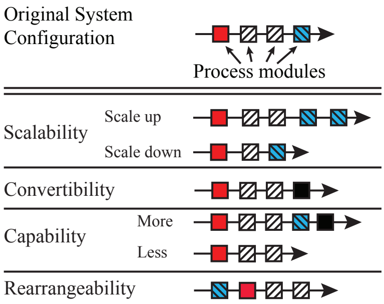

Fig. 3. Categorisation of reconfiguration abilities of a RMS.

B. *Reconfiguration Abilities*

Reconfiguration of a RMS can be categorised in four elementary abilities in accordance to its physical configuration as seen in *Fig.* 3: *Scalability, Convertibility, Capability and Rearrangeability*. Let us imagine a RMS in a current configuration producing parts A&B, using four process modules as illustrated in the top of *Fig.* 3. Two of the process modules are common for both parts and, thus, duplicated. The first category of reconfiguration is *Scalability*, which is the ability to change the capacity of the system. This is done by adding or removing one or more of the process modules in the system and, thereby, producing a higher or lower volume of parts A&B compared to the original configured system. *Convertibility* is the ability to exchange a process module with another, thus changing the scope of functionality. By exchanging one of the process modules with another one we can produce parts A&C instead of parts A&B. *Capability* is the ability to add or remove process modules leading to a higher or lower scope of functionality in the system. By adding or removing a process module we can produce parts A&B&C or only part A in the system. Lastly, *Rearrangeability* is the ability to change the topology of the system. By changing the sequence of the process modules we may now produce parts B&A with the assumption that A&B $\neq$ B&A, e.g. changing the sequence part B has a faster lead time.

V. Reconfiguration Matrix a Framework

The aforementioned classification of reconfiguration leads us to our hypothesis where we combine the complexity and abilities of reconfiguration in a matrix in attempt to classify all feasible reconfiguration tasks of a RMS, see *Tab.* I. The reconfiguration matrix will assist in identification of needs together with classification of virtual recommissioning tasks in a RMS context. An iterative process will be used for exploring each of the different reconfiguration classes one by one. Each iteration will conduct an experiment on a virtual model of a RMS platform. Furthermore, verification of the VC models against real commissioning will be performed on selected scenarios.

TABLE I
The proposed reconfiguration matrix presented as an empty template.

	Known-to-Known	Known-to-Familiar	Known-to-Unknown
Scalability			
Convertibility			
Capability			
Rearrangeability			

VI. Preliminary Exploration of Virtual Recommissioning

A baby case was conducted to explore one of the fields in the reconfiguration matrix framework. The baby case was based on a current configuration of a RMS where the capacity was too low. Thereby, identify the needed reconfiguration ability as *Scalability*. The system has not previously had a configuration to support the higher capacity, eliminating the possibility of having a Known-to-Known reconfiguration. The needed capacity can be achieved by duplicating one of the existing process modules. The reconfiguration complexity is identified as a Known-to-Familiar complexity. After concluded where the reconfiguration is located in the reconfiguration matrix, we proceed with the identification of the required virtual recommissioning tasks by preforming an experiment.

Traditional VC was used in the first configuration of the RMS. The Smart Production lab, an Industry 4.0 smart factory demonstrator platform, at Aalborg University was used as our main RMS platform [19]. The Smart Production Lab consists of modular transportation modules from the Cyber Physical learning factory from FESTO and produces multitude variants of dummy products [20]. Moreover, a local MES controls the order and handles the execution. Various process modules can be mounted on top of these modular stations. Each one of the transportation modules carries two PLCs on board with individual IP-addresses. The VC software tool Experior, from Xcelgo, is used for hosting the virtual environment [21]. The virtual recommissioning was performed by non-experts. *Fig.* 4a shows the configuration before the scaling, containing two transportation PLCs and two process PLCs. *Fig.* 4b shows the configuration after scaling which adds one process model and one transportation module. The system now contains four transportation PLCs and three process PLCs in total of 94 I/Os.

By conducting the virtual recommissioning Known-to-Familiar and *Scalability* task preliminary results was found. A traditional VC tool is able to perform virtual recommissioning, however, some drawbacks were identified. The experiment revealed that the virtual plant can be built by non-experts when predefined virtual modules are available. However, a need for improved data-structure arises in the traditional VC tool to support virtual recommissioning. An ongoing work is done from the authors and Xcelgo to improve the VC tool to support virtual recommissioning in the future.

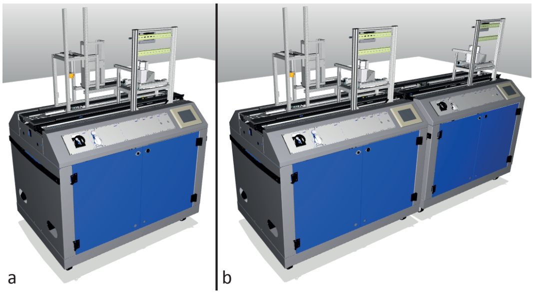

Fig. 4. Visualisation of the virtual model before and after scaling.

VII. Conclusion and Future Work

Virtual recommissioning has potential to become a powerful tool for lower the commissioning time in RMS. The reconfiguration matrix combines classification of reconfiguration complexity and elementary abilities of RMS in one framework. The matrix enables classification of virtual recommissioning tasks. Preliminary exploration of the matrix is performed with virtual recommissioning of scalability in Known-to-Familiar reconfiguration. The experiment was conducted by non-experts and shown promising results. It can be concluded that virtual recommissioning has passed the preliminary test. However, further exploration of the framework needs to be performed.

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Paper B

A Virtual Commissioning Learning Platform

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A Virtual Commissioning Learning Platform

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Abstract

The introduction of reconfigurable manufacturing systems (RMS), Industry 4.0 and the associated technologies requires the establishment of new competencies. Towards that goal, Aalborg University (AAU) has developed an Industry 4.0 learning factory, the AAU Smart Production Lab. The AAU Smart Production Lab integrates a number of Industry 4.0 technologies for learning and research purposes. One of the many techniques is virtual commissioning. Virtual commissioning uses a virtual plant model and real controllers (PLCs) enabling a full emulation of the manufacturing system for verification. Virtual commissioning can lower the commissioning time up to 63%, allowing faster time to market. However, virtual commission is still missing industrial impact one of the reasons being lack of competencies and integration experiences. The paper presents the setup of the virtual commissioning learning platform and demonstrates how various students have worked with the platform acquiring knowledge in virtual commissioning. The construction of a virtual commissioning learning platform enabled a well-defined setup to support training of researchers, students, and companies.

Peer-review under responsibility of the scientific committee of the 8th Conference on Learning Factories 2018 - Advanced Engineering Education & Training for Manufacturing Innovation.

Keywords: Virtual Commissioning; Smart Production Lab; Learning Factory; Training Platform, Industry 4.0

1. Introduction

The introduction of mass customization and reconfigurable manufacturing systems (RMS) established the requirement for the development of certain skills in the production floor. In order to handle the oscillating market demand the question arises; how the required skills can be achieved? Moreover, the introduction of Industry 4.0 provides the necessity for new skills both in the industrial and the academic world.

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In the recent decade, Learning Factories have rapidly emerged as a platform for learning about new manufacturing strategies, novel technologies and exploration of new skills to learn [1-4]. In many cases, learning factories produce a dummy product, and are used both for teaching and research purposes [4]. The scope of the learning factories has substantial variants. A number of learning factories have a narrow scope e.g. are only used for PLC training whereas others have a more holistic scope focus on all aspects of a production such as production planning and optimisation, PLC and robot programming, production execution, and process optimisation. Many of the recent commissioned learning factories are based on some of the technical cornerstones of Industry 4.0 e.g., Cyber-physical systems, RFID-tags, robot technologies, and vertical and horizontal integration [2,3]. In addition, many of the learning factories utilise modules to embrace changeability and reconfigurability adopted from changeable and reconfigurable manufacturing systems [4]. One of the major challenges for a RMS is to reduce the commissioning time due to cost and extended time to market [5]. Traditionally, 15-25% of the project time in a manufacturing system, is used in the commissioning phase. In the commissioning phase itself, up to 63% of the time is used in debugging the software [6]. During its lifetime a RMS will undergo multiple commissions, thus, it is crucial to lower the commissioning time. Virtual commissioning (VC), is also known as hardware-in-the-loop verification, a tool to lower the commissioning time up to 75% with the use of virtual plants and real controllers [6]. Despite the fact that VC has been introduced almost two decades ago, it is still not widely used in industry partly due to the lack of the necessary competencies and experience [7,8]. Therefore, it is vital to provide an appropriate training platform where cross-disciplinary skills can be acquired. Towards that end, the main focus of this work is the presentation of a virtual commissioning learning platform (VCLP) built in order to obtain a well-defined setup where all the relevant industrial and academic stakeholders can be trained in virtual commissioning.

The remainder of this paper is divided into four sections. Section 2 will present the Aalborg University learning factory which lies the foundation for the VCLP presented in Section 3. Section 3 gives also a brief introduction to virtual commissioning. Section 4 describes our learning activities within the VCLP exemplified by two cases and our reflections. Lastly, we conclude the paper in Section 5.

Fig. 1. Illustration of the AAU Smart Production Lab. [8]

2. Aalborg University Smart Production Lab

Aalborg University (AAU) has commissioning a Smart Production lab in August 2016 [9]. The Smart Production lab is built around the FESTO Cyber-Physical didactic learning factory, stationary and mobile collaborative robots, automated guided vehicle (AGV) and a traditional robot cell, see Fig. 1. The learning factory is classified as a narrow sense learning factory, due the physical manufactured product, the real value chain, and the on-site communication channel [1].
The physical manufactured product is a dummy cellphone. The cellphone has a variety of options; 3 different colored product houses, number and location of holes drilled in the product house, with/without circuit board, with/without product cover also in 3 colors, and lastly the number and location of fuses in the circuit board. In total, 252 variants of the product are possible, in the same learning factory. The real value chain can be changed/reconfigured in the physical system by exchange, add, and/or remove modules using the principles of RMS [10].

The AAU Smart Production Lab has two main categories of modules: Transportation modules and Process modules. The transportation modules are stationary modules which use conveyors to transport carriers around in the manufacturing system. Currently there are 3 different types of transportation modules; a linear transportation module, a T-junction module with the possibility to divert the carries path and a sidetrack module which gives the possibility to overtake carries. The linear module has two place holders for the process modules whereas the others only have one placeholder. The AAU Smart Production Lab consists of 6 linear modules, 1 T-junction module, and 1 sidetrack module. This availability creates the opportunity of having 224 different layouts of the transportation modules.
The value-adding modules are the process modules. These are either mounted on the top of the transportation modules or by the side as, e.g., a robot cell, collaborative robot, and manual stations. The AAU Smart Production lab currently has 11 process modules. The on-site communication is between the PLCs programmed in CODESYS [11], robot controller and the Manufacturing Executing System (MES). Each transportation module has two PLCs, one for each side, controlling the conveyor and the process module on top. In total, the AAU Smart Production Lab has 14 PLCs, note the T-junction and sidetrack module only have one PLC each. When a carrier arrives at a station, a RFID reader reads the carrier ID, product information, product recipe, next operation, and status. The information is then sent to the MES where process information is sent back to the process module, e.g., drill two holes in the left side in the product house. The industrial robot (part of a process module) and the collaborative robot have their own controller and communicate through the PLC. The OPC UA standard is used to exchange data between the PLCs and the MES.

3. The Virtual Commissioning Learning Platform

VC consists of a virtual plant and the real controls enabling a full emulation of the manufacturing system for verification. VC is identified as one of the topics under the broader term sense learning factory [1,12]. The design procedure for VC consists of four major steps as illustrated in Fig. 2. The first step is process planning which provides a process plan stating the sequence of operations. The second step is the physical device modeling, which involves the modelling of the geometry and kinematics of the devices. The logical device modelling, gives the device its behavior model in the third step. By combining the physical and logical devise model we get virtual devices. As a final fourth step is the system control modeling, where the control logic (in our case PLC-code) is created. The virtual plant is an assembly of the virtual devices. The control code can hereby be tested against the virtual plant. [13]

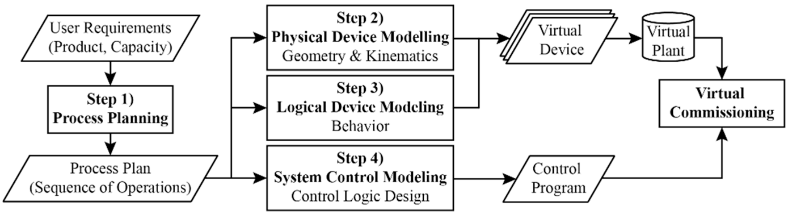

Fig. 2. Design procedure for virtual commissioning. Based on: [10].

3.1. The platform

A VCLP has been constructed based on AAU narrow sense learning factory. The platform is designed to serve two main objectives: for training of step 2-3 of Fig. 2 (i.e. modelling new entities of VC tasks) and for training step 1 and 4 of Fig. 2 (i.e. task planning, system setup and PLC coding/testing). The learning platform consist of three parts the MES, PLC racks and virtual plant, illustrated in Figure 3.

The real MES of AAU Smart Production lab is used to control the PLCs as in the real setup. The real AAU Smart Production lab PLC programs are also used. CODESYS supports a compiler to Raspberry PI 3 making it possible to use Raspberry PI as PLCs and perform hardware-in-the-loop. By having three PLC racks, in total 12 Raspberry PIs, we can expand our PLCs capacity for the tenth of the price compared to commercial PLCs. The virtual plants are built in the commercial software Experior, from the vendor Xcelgo [14]. The virtual plant is built in the model window by

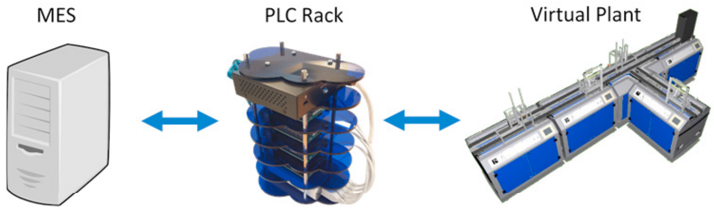

Fig. 3. Setup of the virtual commissioning learning platform

utilizing the modularity of the AAU Smart Production Lab. The AAU Smart Production Lab modules are visually represented in the catalog window, see Figure 4.
Predefined connection points permit snap-fitting of the modules, rendering the task of assembling the virtual plant model easier. The solution explorer gives an overview of the models in model window and a tree structure of the modules. The properties window allows the user to add/change each module's properties like PLC input/output. The PLC input/outputs are linked to the model, in the properties window, by associating the PLC tags (the tags shared by the PLC program by the communication protocol OPC) to the input/output of the modules such as "start conveyor", "piston up" and many more.

4. Learning Activities

Several learning activities have been conducted within the VCLP both Problem Based Learning (PBL) [15] and traditional lectures in courses. The virtual learning platform has been supplementary added in lectures with conventional PLC training in the lab to introduce VC to the students. Firstly, they work with simple PLC tasks in the VCLP before evaluating them in the physical learning factory facilities. In the following, two learning activities that took place within one master student project under the study program Manufacturing Technology are described. The learning activities reflect the two main objectives of the VCLP. The students were working as a group of 4 persons under PBL education.

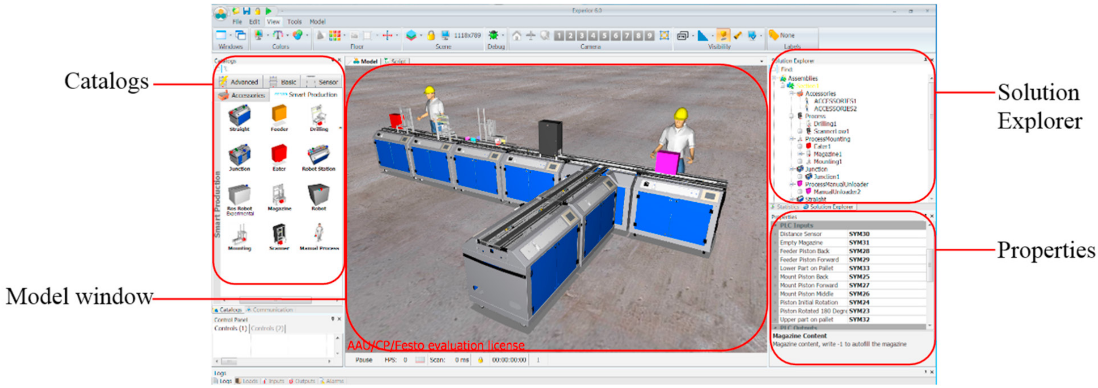

Fig.4. Illustration of the modelling building software.

4.1. Virtual Commissioning of a Single Device

The first challenge was to accomplish a full VC of one of the existing process modules, exploring the flowchart shown in Figure 2, and thereby learning about VC. The first objective was to analyze the desired process module producing firstly a sequence of operations and an I/O list for use in the later design of the logical device modeling. Hereafter, CAD drawings should be converted for virtual representation of the module. Traditionally, in order to lower the need for computational power when running the virtual model, many simulation/emulation tools lower the graphical representation. Converting the CAD drawings is not a trivial task since CAD drawings contain many details that are not necessary for the virtual representation e.g., the inner design of the modules is not needed to model the behavior of the module. The students, therefore, learn how to disassemble, evaluate, simplify and convert the CAD drawing from SLDPRT (SolidWorks format) to COLLADA (open standard format), so a virtual representation of the module could present the needed geometric and kinematic behavior of the module. To set up the kinematic and logic behavior the students had to learn the overall structural of the source code and studied the code of other virtual devices in Experior. Hereby, the students could reuse code samples from other modules to assembly the kinematic and logical behavior code for the new process module. Furthermore, the control program (PLC program) was rewritten and optimized from ladder-diagram to structured text. The virtual process module and control program were hereafter finalized by debugging iterations in the virtual environment. After the VC of the control code was performed, it was implemented and commissioning on the physical process module. The code was executed at the PLC and the process module was able to work within the AAU Smart Production Lab without any software errors.

4.2. Virtual Commissioning of a Reconfigurable Manufacturing System

The second challenge was to explore the reconfiguration abilities of the AAU Smart Production Lab. The challenge was to conduct a virtual *recommissioning* task, increase the throughput of the RMS by duplicated the one of the process modules. Note: "*Virtual recommissioning is defined as the virtual commissioning phase between two configurations in a reconfigurable manufacturing system*" in [16]. The students firstly had to learn the principles and terminology of RMS. Afterwards, understand and learn to operate the AAU Smart Production Lab and obtain the following competencies in the MES; setup of new product, setting sequence of production, reconfiguring the topology settings, order handling and order executing. An understanding of communication between the MES, PLC and RFID tags was also obtained. With the obtained knowledge about the AAU Smart Production Lab the students could manufacture a complete I/O and function list of all transportation and process modules. This lead to the fabrication of the virtual model of all the modules, manufactured by Xcelgo. To reduce the working load, a simple product with only a single-color product house and cover was chosen as the case product. The reconfiguration task was performed from a setup with two transportation modules and 3 process modules (product house dispenser, product cover dispenser and manual unloader) to a new setup with an additional cover dispenser. Note that since the physical learning factory does not have two product cover dispenser modules, the VCLP lets us explore configurations and possibilities that otherwise were not possible to explore. Firstly, a functional virtual model was conducted of the first setup to validate the virtual models working as the physical system with particular focus on the communication with the MES. Afterwards the upscaling of the setup was performed, adding an extra product cover dispenser to the virtual model. The product cover dispenser PLC code was loaded in the respective PLCs. The students revealed that the MES cannot support scaling of the process modules due to the way the MES sets the sequence of operations for the product with specification of resources.

4.3. Reflections Upon Using the Virtual Commissioning Learning Platform

The fact that the students had to perform VC of a single device before the real commissioning provided a deeper understanding of the underlying processes while they developed the appropriate competencies and skills in VC. Our reflection upon the challenges is, by using PBL and a small structured case is that the students were able to clarify the various skills needed for conducting VC. A number of this skills which was acquired was not specified prior to the exercise but was identified by the students on the need basis. The students were forced to learn and familiarize themselves with subjects outside of their own study fields, such as programming and setup of PLCs, C# programs, virtual devices, kinematic and logic modeling, CAD modelling and CAD conversion. Consequently, the students acquired a multidisciplinary set of skills, useful for their future carriers. The second task particularly challenged the students in their overall system thinking. The students obtained understanding about the limitations of the AAU Smart Production lab and were able to formulate suggestions for improvements of the physical learning factory and the VCLP.

In addition to the learning activities we used the VCLP for dissemination activities in industrial events, company training, presentation of the AAU Smart Production Lab and national industrial fairs. The VCLP has proven itself to be excellent in communicating the principles of RMS and VC to non-expert users.

5. Conclusion and Perspective

The construction of a VCLP enabled a well-defined setup to support training of researchers, students, and companies. The VCLP can connect the narrow sense of learning factories with the broader sense of learning factories. The connection lies in the use of real PLCs, with the working code from a narrow sense learning factory, and then is used to emulate the virtual plant. Having a physical learning factory in AAU Smart Production Lab offers the opportunity to perform real commissioning after the VC increased the learning and understanding of the system. The paper has illustrated, with two cases, how the VCLP can support learning of VC skills such as; system control modelling, control programing, physical device modelling (geometric & kinematic), logical device modelling, and virtual plants and devices construction. The VCLP also proved adequate in terms of supporting the teaching of system thinking, process planning and manufacturing strategies.
Future development of the VCLP incorporates the robot process module and collaborative robots in the virtual environments. The VCLP has also clarified the need for a more flexible MES to fully support our reconfigurable learning factory. The VCLP can also support the development and testing of higher level systems like MES and enterprise resource planning systems.

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Paper C

Operational Classification and Method for Reconfiguration & Recommissioning of Changeable Manufacturing Systems on System Level

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International Conference on Changeable, Agile, Reconfigurable and Virtual Production

Operational Classification and Method for Reconfiguration & Recommissioning of Changeable Manufacturing Systems on System Level

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Abstract

During the last decade, consumers have become accustomed to having access to a high variety of products and the expectation of frequent new product releases. Mass customization and changeable manufacturing systems are recognized as enablers. In particular, changeable manufacturing systems can quickly adapt to new market trends due to their ability to alter the manufacturing system according to the market demands. However, the ability to change also introduces unstructured and time-consuming reconfigurations and commissioning phases. This paper proposes an operational method to support reconfiguration and recommissioning in changeable manufacturing systems on a system level. The method is based on classification of elementary reconfiguration abilities and reconfiguration complexity. The proposed approach provides actions related to reconfiguration of hardware and software as well as actions related to commissioning tasks. In addition, the method also supports actions related to virtual commissioning.

Keywords: Changeable Manufacturing System; Operational Classification; Reconfiguration; Commisioning; Virtual Commissioning

1. Introduction

In the recent decades, consumers have become accustomed to having a high variety of products to choose from together with the expectation of frequent new product releases. Manufacturers have struggled to cope with the low-volume/high-mix with traditional dedicated manufacturing paradigms and manufacturing systems.

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Mass customization has proven itself as a powerful manufacturing strategy for enabling low-volume/high-mix production. One of the enablers of mass customization is adaptable manufacturing systems such as Changeable Manufacturing System (CMS) [1]. CMS utilize modules with different functionalities enabling manufacturers to follow the market's demand while the system can change by reconfiguring the modules, e.g., exchange of modules on a system level to obtain a new scope of functionality [2]. A recent survey among industrial manufacturing companies indicated that reconfigurability enablers are only implemented to a very limited extent, thus indicating a need for methodological support for designing and operating changeable manufacturing systems [3]. Additional, recurrently unstructured and time-consuming reconfiguration and recommissioning phases (recommissioning is the commissioning phase following each reconfiguration in the system.) contribute to the fact that CMSs are not fully integrated in the industry yet [4]. Therefore, the scope of this paper is to address how:

Combination, classification, and operationalization of reconfiguration abilities and complexity can assist reconfiguration and recommissioning in changeable manufacturing system.

The modules of a CMS are usually mechatronics modules, containing both mechanic and controllable actuators/motors. Figure 1a, illustrates a CMS consisting of conveyor modules with placeholders for process modules, each side of the conveyor module has its own low-level controller, illustrated with the software demarcation line, controlling the conveyor and any attached process modules. The illustration is based on the AAU Smart Production Lab, further described in [5]. This paper will investigate a reconfiguration as a change both in hardware and software. In addition, we will only address reconfiguration on a system level, as defined in [6]. The remainder of this paper is divided into three sections. Section 2 gives an introduction to related work addressing the unstructured and time-consuming reconfiguration and recommissioning phase. A classification and operational method for differentiating the reconfiguration and recommissioning tasks are presented in section 3. Lastly, we discuss the developed method and present our considerations for further work in section 4.

2. Related Work

2.1. Reconfiguration Abilities

Several researchers have been addressing reconfiguration abilities in the literature. ElMaraghy and Wiendahl define one reconfiguration ability (org. *changeability classes*), for system level as *Flexible Reconfigurability* [7]. *Flexible Reconfigurability* is the ability to change the entire system by adding/removing modules altering the logistical, manufacturing, and material functions. Moreover, three reconfiguration abilities on system level have been presented in [8]. The first category refers to *product flexibility,* which categorizes modules in the system according to their flexibility, e.g., a module that may processes two products has higher *product flexibility* than a module only able of processing one product. *Operation flexibility* is the ability to reroute and choose a different sequence of operation to

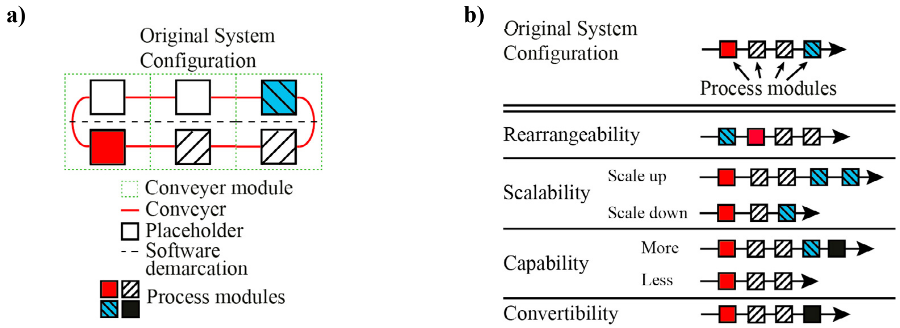

Figure 1: **a)** Illustrated a small configuration of a CMS with three conveyor modules, each with two conveyors and placeholders for process modules. A low-level controller controls each side of the conveyor module; **b)** Illustrated elementary reconfigurations abilities with an illustration of how the reconfiguration change the original system. Modified from [10].

produce various products. Lastly, *Capacity flexibility* is the ability to change the output volume. [9] present two reconfigurable abilities (org. *reconfiguration classes*): *Extensibility* and *Convertibility*. *Extensibility* is the ability to adjust the outcome, equivalent *capacity flexibility* in [8]. *Convertibility* is the ability to exchange modules with each other, thereby obtaining a new scope of functionality in the manufacturing system. In relation to the classification of reconfigurations abilities in [7], [8], and [9] we have previously identified four elementary reconfigurations abilities at the system level: *Rearrangeability*, *Scalability*, *Capability,* and *Convertibility*, illustrated in Figure 1b [10]. Note that for simplicity reasons, the conveyor in the illustration is straight and only the process modules are illustrated in comparison with Figure 1a. We can describe any hardware-and-software reconfiguration with the four elementary abilities. *Rearrangeability* is the elementary ability to change positions and thereby the sequence of modules in the system without changing the functionality of the CMS. Functionality is defined as the number of product variants the system can address. *Rearrangeability* can to some extent be related to *operation flexibility* in [8]. *Scalability* is the ability to handle changes of needed capacity for the system by duplicating or removing models without changing the functionality of the CMS, like *capacity flexibility* [8]or *extensibility* [9]. *Capability* is the ability to expand or decrease the functionality e.g., to handle larger or lower product variety within the system. Capability is related to *product flexibility* in [8]. *Convertibility* is the ability to exchange modules for changing the scope of functionality e.g., to change from being able to produce one product family to another, as also defined in [9].

2.2. Reconfiguration Complexity

It is recognized that reconfiguration of CMS may have different complexities. [11] presents a model describing the increasing complexity of changes in a manufacturing system in relation to the change of product. The classification of change of products and manufacturing systems is divided into three categories: *Exiting, Modified,* and *New*. *Exiting* is the ability to use the manufacturing system without any changes. *Modified* is the ability to modify the manufacturing system to produce the desired product, like in a CMS. Lastly, *New* refers to the need for a completely new manufacturing line. In [10] we presented a model for capturing the complexity of a reconfiguration inside a CMS. A reconfiguration task of a manufacturing system can be divided into three categories in relation to complexity and time consumption. *Known-to-Known* (K2K), *Known-to-Familiar* (K2F), and *Known-to-Unknown* (K2U). A *Known* configuration is a configuration known to a sufficient and document level that allows the configuration to be reproduced. A K2K reconfiguration is changing from a *Known* configuration to a previously used configuration. K2F reconfigurations are changing from a *Known* configuration to a configuration that exists inside the desired solution space of the system utilizing standard modules and standard interfaces. A K2U is a reconfiguration from a *Known* configuration to a configuration outside the solution space of the system but peripheral to the solution space, hence it requires a modification of standard modules and/or standard interfaces.

2.3. Reconfiguration and Commissioning Tasks

Reconfiguration from one configuration to another encompasses multiple steps. As defined previously a reconfiguration involves both hardware and software changes. The hardware changes involve physical work, e.g., unscrewing the modules, unplugging the power, air, and network supplies, physically movement of modules and reattaching modules in the new configuration. Software changes may involve, back-up of code, updates, programming changes and uploading of software to support the new configuration. In addition, software changes also might affect the high-level controller, e.g., change the product variant model (sequence of operation for the products) and/or the topology model (system layout model) in the Manufacturing Execution Systems (MES). After the reconfiguration is performed, it is time for the commissioning. The commissioning phase is both testing the physical setup and testing of low- and high-level software programs. 63% of the commissioning time is used to debug software [12]. It is, therefore, relevant to have particularly focus on lowering the commissioning time of the control software. One tool to assist this is virtual commissioning that may lower the commissioning time up to 75% [12]. Virtual commissioning, also called hardware-in-the-loop verification, test the real physical low-level controllers, in many cases programmable logical controllers (PLCs), against virtual devices. A virtual device is a virtual model of a physical entity, containing a physical device modeling (geometry and kinematic) and a logical device modeling (behavior). The virtual devices can be combined to realizing a virtual plant. A low- and high-level controller, such as MES and PLCs, can be verified by control of the virtual plant before implemented in the physical manufacturing system, thus, saving time in the commissioning phase. The physical commissioning follows the virtual commissioning and may contain, calibration of modules, level out the modules, check if I/Os are connected properly, standard test, e.g., emergency stop protocols, and test of that the product can physically be process in each module and may be transported in-between.

As stated above, several classifications of reconfigurability have been published. However, an operational method, with concrete action for each class to supporting the reconfiguration and commissioning phase in changeable manufacturing system was not found in the literature based on our literature review. In the following section, such method will be proposed on an operational level.

3. Method for Reconfiguration and Recommissioning of Changeable Manufacturing Systems

By combining elementary reconfiguration abilities and reconfiguration complexity, we can differentiate and classify reconfigurations on a system level in a CMS. Table 1 presents a comprehensive operational method for all combinations of elementary reconfigurable abilities and reconfiguration complexity. Each class of reconfiguration is divided into four subgroups; *Hardware* and *Software* reconfiguration, *Virtual Commissioning* and *Physical Commissioning*, described in the previous section. Action(s) related to each subgroup are listed in each class. The actions are identified as a result of combining knowledge from experience with changeable learning factories, deduction, and inspiration from the literature. In our view of CMS, Figure 1a, elementary abilities can be performed in two scenarios 1) Rearranging, scaling, adding/removing or exchanging process modules on top of the conveyor modules. 2) Rearranging, scaling, adding/removing or exchanging the conveyor modules without demounting the attached process modules. We have chosen actions related to scenario 1) since this is the most comprehensive scenario and contain actions for the second scenario. Note that performing virtual commissioning is not required for the use of Table 1 in order to support reconfiguration of CMS. It is evidence that moving from a K2K or K2F configuration towards K2U reduces the reuse of standardized modules in the manufacturing system and introduces a higher need for design and modification of standard modules. This also applies to the control software. The virtual recommissioning task also utilizes standardized virtual devices for constructing the virtual plant. We also assume that standard modules that are not currently present in the system are present in a catalog/warehouse or similar in order to obtain K2F *capability* and *convertibility*. Based on the support tool for reconfiguration and recommissioning of changeable manufacturing systems shown in Table 1, we propose the following method when performing reconfiguration and recommissioning of a CMS:

1) Recognize reconfiguration complexity
2) Identify needed elementary reconfiguration ability
3) Select class in Table 1
4) Perform the actions indicate for the class within hardware, software, optional: virtual commissioning, and physical commissioning.

Table 1: Support tool for reconfiguration and recommissioning of changeable manufacturing systems.

	K2K	K2F	K2U
Rearrangeability	**Hardware:** • Rearrange positions of standard modules in the system to previously known position **Software:** • Load previously used software into low-level controllers • Load previously used topology model to the high-level controller **Virtual Commissioning:** • Load previous used virtual plant model • Virtual plant commissioning	**Hardware:** • Rearrange positions of standard modules by use of predefined interfaces **Software:** • Interchange standard software modules to program low-level controllers • Rearrange the topology model in the high-level controller **Virtual Commissioning:** • Rearrange plant model based on used standard virtual devices • Virtual plant commissioning	**Hardware:** • Rearrange positions of standard modules by use modified interfaces **Software:** • Modified or modified & interchange standard software modules to program low-level controllers • Modify the topology model in the high-level controller **Virtual Commissioning:** • Modified interfaces of standard virtual devices • Rebuild plant model based on standard virtual devices with modified interfaces and with/without standard virtual devices • Virtual device commissioning • Virtual plant commissioning

	Physical Commissioning: • Physical calibration • High-level test	**Physical Commissioning:** • Physical calibration • High-level test	**Physical Commissioning:** • Physical calibration • I/O test • High-level test
Scalability	**Hardware:** • Duplicate/remove duplicated standard modules to obtain precious known capacity **Software:** • Load previously used software into low-level controllers • Load previously used topology model to the high-level controller **Virtual Commissioning:** • Load previous used virtual plant model • Virtual plant commissioning **Physical Commissioning:** • Physical calibration • High-level test	**Hardware:** • Duplicate/remove duplicated standard modules to obtain a new capacity **Software:** • Clone software for duplicated modules to program low-level controllers • Expand/decrease the topology model in the high-level controller **Virtual Commissioning:** • Modify the plant model based on standard virtual devices • Virtual plant commissioning **Physical Commissioning:** • Physical calibration • High-level test	**Hardware:** • Add modified standard modules with/without duplicate/remove duplicated standard modules to obtain a new capacity **Software:** • Clone and modify standard software modules to program low-level controllers • Modify the topology model in the high-level controller **Virtual Commissioning:** • Modify standard virtual devices • Rebuild plant model based on modified virtual devices and with/without standard virtual devices • Virtual device commissioning • Virtual plant commissioning **Physical Commissioning:** • Physical calibration • I/O test • High-level test
Capability	**Hardware:** • Add/remove standard modules to obtain precious known functionality **Software:** • Load previously used software into low-level controllers • Load previously used topology model and variant model to the high-level controller **Virtual Commissioning:** • Load previous used virtual plant model. • Virtual plant commissioning **Physical Commissioning:** • Physical calibration • High-level test	**Hardware:** • Add/remove standard modules to obtain new functionality **Software:** • Load new standard software modules to program low-level controllers • Adjust the topology model and expand/decrease the product variant models in the high-level controller **Virtual Commissioning:** • Modify the plant model based on standard virtual devices. • Virtual plant commissioning **Physical Commissioning:** • Physical calibration • High-level test	**Hardware:** • Add modified standard modules with/without adding/removing standard modules to obtain a new functionality **Software:** • Combine and modify standard software modules to program low-level controllers • Modify the topology and product variant models in the high-level controller **Virtual Commissioning:** • Modify standard virtual devices • Rebuild plant model based on modified virtual devices and with/without standard virtual devices • Virtual device commissioning • Virtual plant commissioning **Physical Commissioning:** • Physical calibration • I/O test • High-level test
Convertibility	**Hardware:** • Exchange standard modules to obtain previously known scope of functionality **Software:** • Load previously used software into low-level controllers • Load previously used topology model and variant model to the high-level controller **Virtual Commissioning:** • Load previous used virtual plant model • Virtual plant commissioning **Physical Commissioning:** • Physical calibration • High-level test	**Hardware:** • Exchange standard modules to obtain new scope of functionality **Software:** • Exchange standard software modules to program low-level controllers • Adjust the topology and product variant models in the high-level controller **Virtual Commissioning:** • Modify the plant model based on standard virtual devices • Single virtual device commissioning • Virtual plant commissioning **Physical Commissioning:** • Physical calibration • High-level test	**Hardware:** • Exchange modified standard modules to obtain a new scope of functionality **Software:** • Change and modify standard software modules to program low-level controllers • Modify the topology and product variant models in the high-level controller **Virtual Commissioning:** • Modify standard virtual devices • Rebuild plant model based on modified virtual devices and with/without standard virtual devices • Virtual device commissioning • Virtual plant commissioning **Physical Commissioning:** • Physical calibration • I/O test • High-level test

4. Discussion and Future work

The presented method enables more frequent reconfiguration of changeable manufacturing system, leading to a larger industrial implementation of changeable manufacturing systems. Previous related work has suggested that the introduction of reconfigurability can potentially lead to significant profits. However, in order to transform this potential into actual savings, a great effort is required to design the manufacturing systems in such wat that enable reconfigurability, and secondly to perform the actual reconfigurations. This paper contributes to filling the theory to practice gap in relation to the latter, by introducing high-level methodological steps. The identification and classification of elementary reconfiguration abilities lead to a more structured reconfiguration. The classification of complexity of the reconfiguration task supports a mindset and introduces the discussion of the reusability in a reconfiguration. The development of an operational method for reconfiguration and recommissioning on a system level of changeable manufacturing systems supports future working procedures. As future work, we consider to expand the proposed method further and test it in actual industrial environments.

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Paper D

Outline of an Industry 4.0 Awareness Game

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9th Conference on Learning Factories 2019

Outline of an Industry 4.0 Awareness Game

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Abstract

The introduction of Industry 4.0 brought a demand outside the academic world for understanding the Industry 4.0 principles and how they will influence the industry and education domain. Aalborg University has developed an Industry 4.0 Awareness Game to address the new paradigm and rapidly emerging technologies. The game is based on the Aalborg University learning factory, AAU Smart Production Lab. The game is an introduction to Industry 4.0 where the participants gain knowledge about the driving technologies and new qualifications. The scope of the game is to provide a platform where the participants will produce the right product at the right time. The participants, who are non-experts and may have different educational backgrounds were divided into six roles/departments: Operator, Production Managers, Logistics, Circular Economy, Service Technician, and Game Observer. Role cards, given to each group, at the beginning of the game, stating the responsible areas and the task descriptions. By introducing new Industry 4.0 technologies, by a deck of game cards, continually in the game, e.g., collaborate robots, data mining, analysis tools, and reconfiguring manufacturing systems, the participants gain first-hand experience on how these technologies influence the production but also on the impact of needed qualifications and management of the production. The game cards may introduce disruptions, e.g., errors of process or conveyors, to create awareness of a weakness in the production and how vital adaptability is in the production. The game received favorable reviews from both participants from the industry and the education domain. Through the experience in the AAU Smart Production lab, the participants gain an understanding of the complexity of a holistic approach. They gain awareness and get inspired on the various ways that different technologies may be integrated and create impact across several traditional functions. As main outcome of this game we highlight the need for an interdisciplinary approach for utilizing Industry 4.0 technologies.

Peer review under the responsibility of the scientific committee of the 9th Conference on Learning Factories.

Keywords: Smart Production Lab; Learning Factory; Learning Game; Game-based Learning; Industry 4.0

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1. Introduction

The introduction of Industry 4.0 (I4.0) technologies will enable manufacturers to cope with the increasing product variety and global competition. However, adapting the rapid and frequently is a challenging task. Companies must learn new technologies and develop new products, processes, and services with ever-increasing frequency. Furthermore, the nature of many of the solutions involves multi-disciplinary activities involving experts, which may not be present in the companies (in particular true in small and medium-sized enterprises (SMEs)). This requires fundamentally different approaches to knowledge acquisition and learning. One way of learning is the use of learning games. Learning games, also known under the name game-based learning or serious game, have been used in centuries, from war-games in the 19th century over Lean Games in the late 20th century to high-tech realistic flight simulation games in the recent years, and have proven to be an effective learning approach [1]. Serious games motivate the participates in achieving new conceptual knowledge and transforming it into conditional knowledge by taking part in the game [1–3]. In the recent decades learning factories have been acknowledged as a platform for both academic and the industry to learn about new technologies and strategies in the manufacturing domain [4–7]. The learning factories utilize the benefit of having a realistic manufacturing environment and recently commissioning learning factories to integrate I4.0 technologies such as cyber-physical systems, RFID-tags, collaborative robot technologies, and vertical and horizontal integration [5,7]. Several learning factories have merged learning factories with learning games, e.g., a logistic game [8], a holistic lean game [9], and an energy efficiency game [3]. Even with the use of learning factories and learning games, SMEs are challenged, due to limited resources in time and money, in gaining new knowledge about the I4.0 technologies and how the new ideas may be implemented [10]. Fairs and typical presentations about I4.0 technologies may give a brief introduction to the various utilized methods, but they lack to provide useful, practical information on the integration of these technologies into the context of an SME. This paper will try to provide a platform to bridge this gap between theory and practice with the proposal of an interactive and immersive I4.0 Awareness game. There the participants will gain experience through playing in a modular, changeable, I4.0 learning factory while they become aware of the implementation potential of I4.0 technologies in SMEs.

The remainder of the paper is divided into four sections. Section 2 will present Aalborg University's learning factory which is the foundation of the Industry 4.0 Awareness Game presented in Section 3. Section 4 describes the learning outcomes from three initial use cases and Section 5 concludes the paper.

2. Aalborg University Learning Factory

Aalborg University (AAU) learning factory, AAU Smart Production lab, illustrated in Fig. 1a, is based on the FESTO cyber-physical didactic system and the principle known from changeable manufacturing systems [11,12]. AAU Smart Production lab is classified as a narrow sense of learning factory with the real value chain, on-site communication and physical manufactured product [13]. The AAU Smart Production lab manufactures a dummy cell phone, illustrated in Fig. 1b, consisting of a product house, circuit board, fuses, and product cover which can be manufactured in 816 variants.

Fig. 1. (a) Illustration of the AAU Smart Production Lab; (b) Illustration of the dummy product.

The AAU Smart Production lab consists of three types of conveyor modules, in total eight conveyor modules where nine different process modules may be mounted on top leading to over 9 million configurations of the system. From the commissioning, in August 2016 a constant development and implementation of I4.0 technologies have been realized to support academic and industrial needs both in teaching and research [13,14]. The AAU Smart Production lab has implemented eight of the nine core technologies identified by [15].

The implemented technologies are: collaborative robots, virtual environments, horizontal and vertical system integration, industrial internet of things, cyber security, use of cloud service, additive manufacturing, and big data and analytics.

3. Industry 4.0 Awareness Game

3.1. Learning Goals

The learning goal of the Industry 4.0 Awareness Game is to provide insight into the potential of I4.0 through a simulation-based, role-play game founded in the driving technologies of I4.0. The primary expectation of the game is to train the participants' conditional systematic knowledge in addressing which technologies/strategies to apply for the right process, on the right module, at the right time with considering the appropriate dependencies. In addition to the technologies and strategies, the participants will gain awareness about the need for new qualifications driven by the latest technologies.

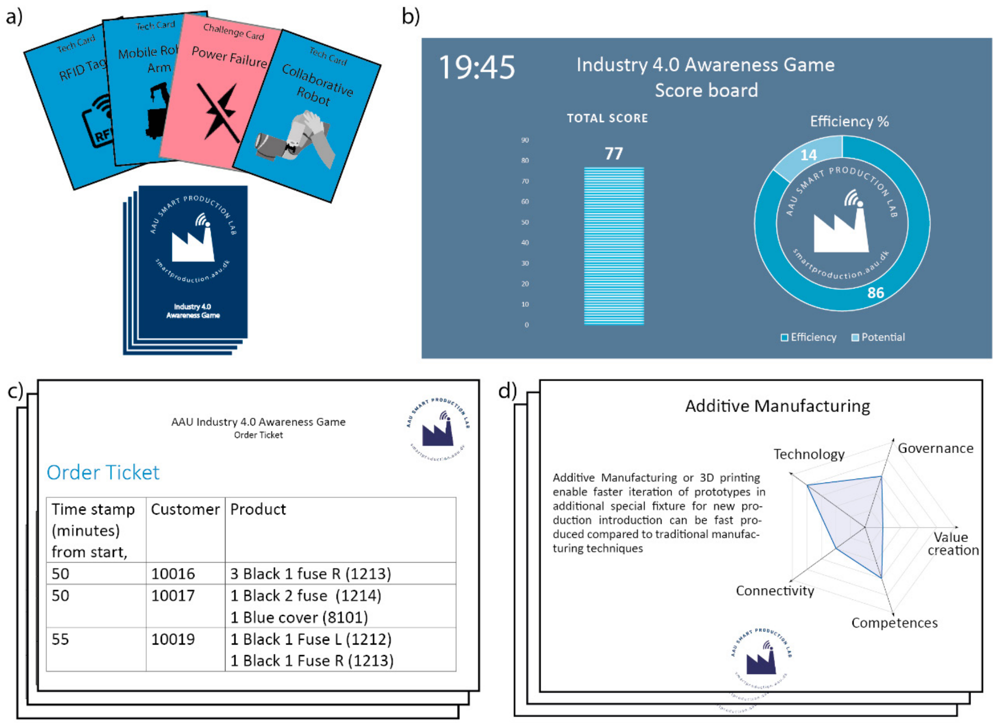

Fig. 2. Illustration of some of the content of the Industry 4.0 Awareness Game. (a) Game Cards; (b) Scoreboard with timer; (c) Order cards; (d) Impact cards.

3.2. Game Contents

The game consists of; the Smart Production Lab as shown in Fig. 1a, Game Cards illustrated in Fig. 2a, a Scoreboard and Timer depicted in Fig. 2b, Order Cards illustrated in Fig. 2c, Impacts Cards illustrated in Fig. 2d, and in addition: Role Cards, Standard Operating Procedure (SOP) sheets, and a Facilitator.

3.3. Game Roles

The participants are divided into six roles/departments: Operator, Production Managers, Logistics, Circular Economy, Service Technician, and Game Observer. The product manager’s role is to plan and start production orders while ensuring the target production time is matched. The operator’s role is to operate all manual operations supported by SOP, e.g., manual packing products and fill up parts for the machinery. The logistics role is to transport the finished products to the circular facility and ensure that parts return to the production system limited by a minimum waiting time. The circular facility is responsible for the disassembly of the finished products for reuse of the raw material in the production system. The game observer updates the scoreboard (Fig. 2b), registers quality issues, and observe the overall development of the game. Each of the participants receives a role card, describing the nature of the role its responsibilities.

3.4. Game Preparation

Before the game begins, the sequence of game cards deck (Fig. 2a), is packed by the facilitator. The fixed sequence ensures the introduced technologies and challenges are executable in relation to their dependency. However, the participants will experience the game card deck as a randomizer in the game. The facilitator also has the option to customize the Game Deck for specific focus areas or tailor it according to the participants’ qualifications. Each technology is prepared for implementation in advance, e.g., if the game card with the collaborative robot is turned a predefined program for the collaborative robot is executed and the right tool is attached before the game starts.

3.5. Game Play

The participants work as a team and must perform accordingly to achieve the game objectives. Fig. 3 illustrates the timeline of the game. The beginning of the game, t0, is an introduction to the game where the AAU Smart Production lab is run as an Industry 3.0 factory. The introduction round familiarizes the participants with the learning factory and sets the conceptional knowledge base for the later reflection of I4.0 technologies and strategies. The introductory manufacturing task is to produce a simple product without any variants (mass production) with dedicated machinery (dedicated manufacturing system). In additional many manual operation tasks and paper information flows are needed to keep producing parts.

After the system familiarization, the first round of the game will begin. The following rounds, game sessions, (t0-t1, t1-t2, t2-t3, t3-t4, t4-t5) are alike in the overall structure. The participants must produce the right product at the right time. This sequence of production orders and product variants are announced by the Order Cards illustrated in Fig. 2c. The Order Cards are given on specific time in the game, so all orders are not known by the participants in advance. The facilitator has the possibility to add “Express orders” or “Cancel orders” to increase or reduce the pressure on the participants. After a product is produced the manufacturing details are added to a spreadsheet updating the scoreboard (Fig. 2b). The scoreboard shows the total score of the game along with an effectivity score, both calculated based on the produced products, the required time and the final product quality.

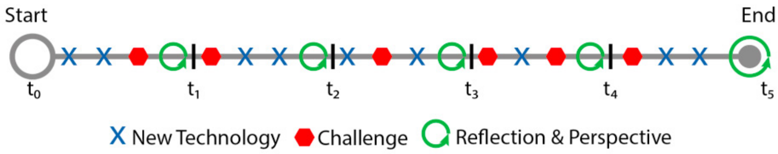

Fig. 3. Timeline of the Industry 4.0 Awareness Game. New technologies introduced by the blue Game Cards and challenges introduced by the red Game Cards. Note that the sequence of technologies and challenges may change from game to game.

Furthermore, to keep producing the right product at the right time, the participants must face changes in the bounding conditions of the manufacturing system introduced by the Game Card deck (Fig. 2a). The participants are asked to draw cards, with an interval of ~3 per section, this interval may be shortening or prolonged depending on the competence level of the participants, from the Game Cards pile to decide if a new I4.0 technology is available (blue background) for the team or a challenge occurs (red background). When a new technology is available the participants will pick the correlating Impact Card (Fig. 2d). The Impact Cards (Fig. 2d), aid the participants in understanding the I4.0 technology and how it will affect the manufacturing system. All Impact Cards hold an explanatory text for the technology along with a spiderweb diagram to visualize its impact. The spiderweb diagram shows the impact on the following topics; technology, governance, value creation competence, and connectivity based on the AAU 360 Digital Maturity Assessment [16]. Each game section concludes with a reflection and perspective session guided by the facilitator. The participants are asked to reflect upon the ways that the newly encountered technologies and/or challenges had affected the manufacturing setup in the learning factory and in which ways they can relate the gained experience in the context of their own business. After the last game session, a longer evaluation and perspective session is performed, t5. The goal of the session is to evaluate the learned awareness level of I4.0 technologies, the appropriate level of qualifications needed, and general evaluation of the Industry 4.0 Awareness Game. The evaluation is performed as an unstructured interview with the participants.

4. Play to be Aware

Two pilot games and one full-scale game test have been conducted to test the prototype idea of the Industry 4.0 Awareness Game. The result from the performed trials indicate that a learning game is a viable approach to create awareness of industry 4.0 technologies for non-expert participant. One of the major learning outcomes from the participants, of all three sessions, was that interdisciplinary qualifications are a requirement for a successful implementation of I4.0 technologies and methods.

The initial pilot game tested the overall concept and interaction with the AAU Smart Production lab as a game platform proved the significance of the respective roles and game goals. The total duration of the first pilot game was two hours including one hour of introduction with 24 non-expert participants. Two 1-hour sessions were conducted where each concluded with a reflection and discussion session. The main learning point from the first pilot was that a reduction of the number of participants was necessary to ensure sufficient immersion and hands-on experience and to create better awareness of the specific technology impact and potential. Furthermore, a reduction of production orders was needed to ensure lower stress factor during the game. Participants expressed strengthened awareness of the technologies impact and effect on the qualification level of the traditional production roles. The participants displayed an awareness of the impact of new technologies and could relate these and their potential to other production scenarios.

The second pilot game experimented with the full game structure and elements as presented in Section 3. The second pilot game was conducted with fewer participants and lasted an hour including the introduction. The participants were a mixture of experts and novices who managed to reach a total score of 27 points. Two game sessions were conducted. The participants expressed that a strong involvement was reached and a general awareness of the complexity of the production was gained.

The first two games pointed out the fact that a higher emphasis on the introduction to the AAU Smart Production lab and general I4.0 knowledge is needed. Therefore, a full-scale game test with a total duration of 3.5 hours including an hour of introduction was conducted with non-expert participants. Four game sessions were conducted, resulting in 1.5 hours game time and an hour of discussions and reflections on both awareness and gameplay. The participants reached a total score of 49 points. Participants expressed high levels of engagement and stressed the importance of the facilitation role during game sessions and discussions. Several challenges experienced by the participants in lower level of the game were addressed by new technology introductions, and the potential impacts discussed between sessions. The challenges in the lower level lead to a discussion on how the traditional operator qualifications need to change for such production line, e.g., a demand for higher IT competencies in relation to work with I4.0 technologies.

5. Conclusion and Discussion

The initial test of the Industry 4.0 Awareness Game indicates that a role-play learning game based on a learning factory platform can provide a deeper understanding of the driving technologies in I4.0 and the derived qualifications. The participants gain awareness and get inspired on the various ways that different technologies may be integrated and create impact across several traditional functions. As main outcome of this game the need for an interdisciplinary approach for utilizing I4.0 technologies were highlighted by the participants. It has been evident that the use of a physical learning factory sets the limitation on the number of participants, to ensure a higher learning outcome. One learning outcome from our tests is that having two participants occupying each role, as presented in Section 3, in total 12 participants is a favorable number for the use of the AAU Smart Production lab as a game platform. Regarding the duration of the game, we can conclude that 2.5 hours per session preceding of an hour of introduction is the optimal point where the participants can remain engaged and reach a satisfactory awareness level of I4.0 technologies and qualifications.

For future research, an awareness level measurement will be developed enabling a more quantitative evaluation of impact of the Industry 4.0 Awareness Game. Ten regional SMEs will be invited to try the Industry 4.0 Awareness Game. It is expected that these SMEs will gain a better insight into which technologies are relevant to their business as well as what qualifications they need to develop themselves or acquire from others. A preliminary study among regional SMEs indicates that 2.5 hours game time is appropriate concerning the SMEs resources. Future development of the game may involve a template for how to introduce new technology to the game.

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Paper E

Learning Factory with Product Configurator for Teaching Product Family Modelling and Systems Integration

Thomas Ditlev Brunoe, Steffen Tram Mortensen, Ann-Louise Andersen and Kjeld Nielsen

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Learning Factory with Product Configurator for Teaching Product Family Modelling and Systems Integration

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Abstract

This paper presents a new approach for teaching product family modelling, product configurator and systems integration in engineering masters educations as well as for teaching industry professionals. Based on a recently acquired smart production lab, containing a reconfigurable manufacturing system with a manufacturing execution system (MES), being able to produce individually configured products, a new learning approach was introduced. Previous approaches to teaching product family modelling and product configuration have focused on achieving specific individual learning objectives in desk exercises. However, in this revised approach, lab resources are increasingly being involved, which gives the students a more in-depth value chain perspective as well learning additional aspects of systems integration.

Keywords: Learning factory, product configuration, product family modelling

1. Introduction

Most industries are today reporting customer demand for increased product variety, implying that manufacturing systems must be able to change more quickly between variants. Additionally, companies experience shorter product life cycles, implying that products and product families are produced over shorter periods of time, and an increasing demand for shorter time to market [1]. Combining this with an ever-increasing international competition, manufacturing companies face great challenges in designing manufacturing systems which are at one time both efficient, able to manufacture large variety, and being able to respond to changes in market requirements, while also meeting new customer requirements for sustainability [2]. Several paradigms have been introduced in literature to address this, including the concept of the reconfigurable manufacturing system (RMS) [3]. A more generalized term

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describing a manufacturing systems ability to cope with changes is changeability [4,5], which encompasses different classes of changeability, ranging from the ability to handle smaller changes during the operation of the system (changeover-ability) to a factory's ability to handle significant changes in product, by e.g. introducing product types never produced before.

The concept of mass customization, introduced by Pine [6] in the early nineties has since then gained acceptance in various industries and is now de facto standard in most industries, stressing the need for changeable manufacturing systems. One among other important enablers of mass customization, is choice navigation, as introduced by Salvador et al. [7]. Choice navigation is often implemented using a product configurator, a software tool, which allows users to define a configuration of a product, based on predefined variety.

Recognizing these needs in industry, higher education teaching in manufacturing engineering must address these challenges, enabling engineering graduates to assist companies in establishing changeable manufacturing systems, supporting mass customization. Combining this with emerging technological trends such as Industrie 4.0 and the Industrial Internet of Things, led the department of Materials and Production at Aalborg University in Denmark to introduce a new course with the name "Flexible Manufacturing". After this course had run for two years, the department invested in a new smart production lab, containing a reconfigurable, cyber-physical manufacturing system. It was then decided to integrate the smart production lab into the "Flexible Manufacturing" course. One element in doing this was to develop a product configurator setup, which would enable the students to analyze the current product range being producible one the manufacturing system, model this, develop a product configurator, and connect this to the manufacturing system, thus being able to initiate the manufacturing of a configured product.

The objective of this paper is to describe the technical setup behind the configurator and manufacturing system integration, and how this is integrated in the course to achieve certain learning objectives. The paper first describes the system which students work on, by first introducing the actual manufacturing system, it's structure and characteristics, as well as the products which may be produced on the system. Then the configurator solution is introduced, and how this is integrated with the manufacturing system. This is followed by a description of the learning approach related to the product configurator and the manufacturing system, including a general context of the course.

2. System description

2.1. Cyber-physical production system and MES setup

The AAU learning factory is an interdisciplinary platform for teaching and research at Aalborg University as described by Madsen & Møller [8]. The AAU learning factory is illustrated in figure 1, and is based on FESTO Cyber-Physical didactic learning factory, classified as narrow sense of learning factory [9]. Over time the AAU learning factory has been expanded with additional technologies (E.g. collaborative robots and Automated Guided Vehicles) and digital twins to obtain also a broader sense of learning factory as illustrated by Mortensen & Madsen [10]. The AAU learning factory utilizes modulization of process and resources, each with various scope of flexibility, from simple conveyer modules with dedicated process modules attached to flexible collaborative robots. The system has two main categories of modules: Conveyer modules and process(resources) modules. The six linear, one T-junction, and one sidetrack conveyer modules can be combine sequential, due to the standardize interfaces. Each conveyer module has two place holders for attaching process modules.

The processes in the AAU learning factory are: 2 different feeders, drilling, assembly, quality check, re-work station, and finally assembly. The modulization of processes and resources ensures 9 million different configurations of the manufacturing system and thereby establishes the foundation for mass customization and the identification as a changeable manufacturing system.

Fig. 1 AAU Learning Factory

The AAU learning factory uses RFID to track the current state of the product in the system, thus one-of-a-kind production can be obtained. The mass customized product is an assembly task of a dummy cellphone with simulated process, such as drilling. The dummy phone consists of a product house, in three different colors, with the options of adding, a circuit board, number and placement of fuses and drilled holes, and a top cover also available in three colors. The AAU learning factory can in is currents state handle 816 variants. The variant of the product is chosen from a list of various products in the manufacturing executing system (MES). However, the MES have some limitation in configurate the product. Each product variant is hard-coded with the sequence of operations, order number, and allocated resources, which leads to only 11 product variants being present in the MES database.

2.2. Development of product configurator solution

The product configurator solution is based on the configurator software “Configit Model” offered by the company Configit [11]. “Configit Model” provides an easy to use modelling interface, which allows users with a short introduction to start modelling product variety. Compiling the product model in the modelling software enables running the runtime configurator, which starts a local web server, running a web application containing the actual configurator. In this configurator, users would be able to configure the product using the variables defined in the modelling environment. The modelling tool allows for defining constraints in the product family model, to delimit the choices the users can make in the final configurator, based on previous choices. As an example, the product manufactured by the manufacturing system may only be configured with fuses, if a printed circuit board is chosen.

Once a configuration is made by making selections for the variables, the configuration can be saved. This produces an XML file, which is structured according to the product model defined in the modelling tool. Using this XML file, it is possible to extract all variables and their vales in the configuration, given the variable name is known.

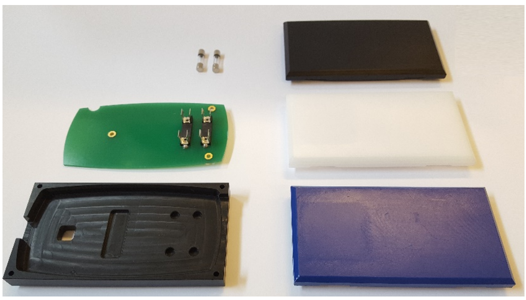

Fig. 2. The product manufactured by the AAU Learning Factory

The manufacturing system is controlled by MES, provided by Festo, named Festo MES 4, which is based on a local relational database. In real life settings, a configuration would often be transferred to an ERP system, and then possibly to a MES. However, in the current lab settings, and ERP system is not part of the setup, and thus the data is transferred directly from the configurator to the MES.

In order to demonstrate that products can be configured and then produced without manual operations, an integration was necessary between the two systems, the runtime configurator and the MES. No standard interfaces however existed which would provide this integration, so a custom interface was implemented. The interface was

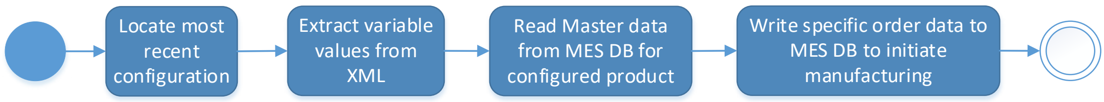

Fig. 3 The process implemented for transferring configurations from configurator to MES

implemented using Microsoft .NET Framework, as a windows application running locally on the MES server. The sequence of operations performed by the interface is shown in fig. 1.

When the user pushes a button in the user interface, the application queries the local file system for the most recent configuration file, which the application assumes is the configuration the user wishes to transfer to the MES. Prior to this, the user must save the configuration in the configurator runtime environment. Once the file is located, the application uses an XPath query to identify the variable, which holds the item number for the configured product, after which the value of this variable is retrieved. In Festo MES 4, products are added to an order by creating order lines (referred to as order positions in Festo MES4), and copying master data regarding the specific operations that are necessary to manufacture a specific product to an order specific table containing pending operations for the manufacturing system. This master data is retrieved from the MES based on the configured item number, and then written to the order specific pending operations table in the MES database. Once order data has been written and master data has been copied, and the order is marked as “Enabled” in the order table, the MES recognizes the new order and initiates manufacturing as soon as possible. In total four tables need to be manipulated to create the order, th “tblOrder” table containing order information, the “tblOrderPos”, containing the individual products in the order, “tblStep” containing the individual operations needed to manufacture the configured product, and “tblStepParameter” containing parameters for each operation that need to be passed to the PLCs in the manufacturing system.

As indicated above, the mapping between the configurator and the MES is done by using item numbers. Hence, in this setup, only products which have been created in the MES system can be configured and produced, which does not allow the same flexibility as a free configuration would have. However, this restriction is due to the way the MES works internally. The MES currently has 11 product variants defined, whereas the number of physically producible variants would be 816.

3. Learning Approach

The course, which is currently applying the AAU Learning Factory, and the configurator setup, is a course on master's level with the title "Flexible Manufacturing". The aim of the course is to provide the students with state of the art knowledge, skills and competences within mass customization and industry 4.0 within the business model domain, and modular and platform based product development and product configuration, and finally manufacturing system design based on changeability and reconfigurability concepts. Furthermore, the students learn the synergies and constraints between these domains as illustrated in figure 4.

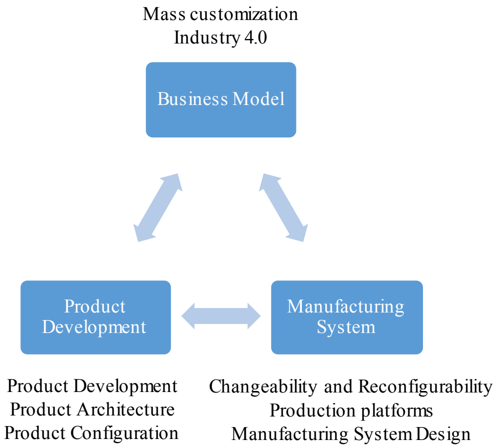

Fig. 4 Elements of the current course at AAU

The course applies a blended, problem based learning approach, implying that all lectures are combined with exercises, either case based or lab based where applicable. The course emphasizes all exercises are done in groups of 4-6 students.

In two lectures, which equals one whole day of student-teacher interaction, not including student self-study and preparations, the students work on product family modelling and development of product configurators. The learning objectives for this part of the course are to understand product family modelling and be able to model a range of products as the basis for developing product configurators. Secondly it is to structure a product configurator, so that it will provide a manufacturing cost or sales price, and provide data necessary for manufacturing the product.

The students are provided with literature on beforehand describing the background as well as specific methods. Furthermore, they are given short lectures by a teacher, elaborating and exemplifying the concepts from the provided literature. Once the lectures are finished, the students do lab exercises, outlined below, in groups.

- The students are given a tour of the lab manufacturing system, where they are introduced to the individual manufacturing processes, and the constraints they imply. Furthermore, they are introduced to the products, and given the physical components of the products, for doing the analysis of the product variety.
- The students are asked to do a product family model, representing the product variety, from a product side perspective, i.e. which variants would be possible from product constraint perspective, thus not taking into account what the MES currently supports. Furthermore, based on the MES database, they are asked to model also the variety, which is represented in the current MES data. Students are free to choose modelling methods; however, they are introduced to the product variant master [9] and class diagrams from the Unified Modelling Language.
- In a plenary session, each group presents their product family models for each other which typically reveals differences in the modelling approach and perception of the product variety. As an outcome the students learn both the technique for modelling product families, but also that given the same method, and same data foundation, different outcomes may be produced by different people based on their perception or preferences.
- The students are then introduced to the Configit Model tool, where they after a one hour introduction are able to do basic modelling. The students are introduced to the configurator-MES transfer interface, and the

requirements for the product configurator, in order for the interface to work. The groups are asked to each develop a product configurator, which is based on the product family model produced in the previous exercise.

- A plenary lab session is organized where the groups each test their product configurator on the MES server, by configuring a number of product variants, which are transferred to the MES and physically produced. This requires the students to adhere to the specifications for the interface, in practice meaning that there must be a variable in the configuration model with a specific name containing the item number of the configured product.
- The students are asked to discuss which would be the best approach if the system was to be expanded to cover all 816, theoretically possible variants rather than the current 11 in the MES database. This requires the students to consider whether to predefine all 816 variants with specific item numbers in the MES system or generate lists of operations dynamically, which is a typical dilemma in real life configuration projects.

4. Conclusion

The activities outlined in this paper introduces engineering master students to concepts of product family modelling and development of product configurators. Different from traditional, and previous years of doing this course, the students are given physical product to model and configure, and an interface to a lab manufacturing system is provided. Using this, students can test their product models and product configurators, by connecting their configurators to the manufacturing execution system, controlling the manufacturing system, and be able to manufacture the products they are able to configure using their configurators. Previously, the students would be asked to do modelling of a fictional product or a product from a commercial website and do a stand-alone configurator for this. Using the new approach, students are likely to be more engaged and learn more deeply, because the products are being manufactured. Also, the students learn more about the challenges of systems integration, and the considerations regarding placement of data and data redundancy, which are included as an objective of the students semester theme in the study programme.

The course receives consistently excellent feedback, and the knowledge, skills and competences, are regularly applied by students in projects with companies, indicating that the learning of the topic itself and learning the ability to apply the learnings in new contexts have been successful.

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Part IV

Technical Reports

Technical Report i

Classification of AAU Smart Production Lab

Steffen Tram Mortensen

This is a technical report which serve as documentation for the presented research in thesis.

Classification of AAU Smart Production Lab

The technical paper present the research objectives of the AAU Smart Production project and a full classification of the AAU learning factory.

i.1 Introduction

With the digitization of manufacturing on a global plan, Aalborg University initiated, AAU Smart Production project in 2015 with the objectives, [Aalborg University, 2015]:

- To research and demonstrate the technologies, concepts and methodologies coming out of Industrie 4.0 (D), Factories-of-the-Future (EU), Industrial Internet Consortium (US) and equivalent initiatives.
- To investigate how manufacturing industries can benefit from these emerging technologies.
- To adapt these technologies and concepts to the needs and characteristics of Danish industries

With the investment of 4.5 million DDK in the laboratory an Industry 4.0 learning factory for researching, teaching, and demonstration for the industry was established.

i.2 Classification of AAU Learning Factory

The following section will present a full classification of AAU Smart Production Lab in regards to the classification method presented in Tisch et al. [2015].

i.2.1 Operational Model

1.1	operator	academic institution			non-academic institution					profit-oriented operator	
		university	college	BA	vocational school / high school	chamber	union	employers' association	industrial network	consulting	producing company
1.2	trainer	professor	researcher	student assistant	technical expert / int. specialist	consultant	educationalist				
1.3	development	own development	external assisted development	external development							
1.4	initial funding	internal funds	public funds	company funds							
1.5	ongoing funding	internal funds	public funds	company funds							
1.6	funding continuity	short term funding (e.g. single events)	mid term funding (projects and programs < 3 years)	long term funding (projects and programs > 3 years)							
1.7	business model for trainings	open models		closed models (training program only for single company)							
		club model	course fees								

Fig. i.1: Operational model of AAU Smart Production Lab

i.2.2 Target and purpose

2.1	main purpose	education	vocational training	research											
2.2	secondary purpose	test environment / pilot environment	industrial production	innovation transfer	advertisement for production										
2.3	target groups for education & training	pupils	students			employees							entrepreneurs	freelancer	unemployed	open public
			bachelor	master	phd students	apprentices	skilled workers	semi-skilled worker	unskilled	managers						
										lower mgmt	middle mgmt	top mgmt				
2.4	group constellation	homogenous	heterogenous (Knowledge level, hierarchy, students+employees, etc.)												
2.5	targeted industries	mechanical & plant eng.	automotive	logistics	transportation	FMCG	aerospace								
		chemical industry	electronics	construction	insurance / banking	textile industry	…								
2.6	subject-rel. learning contents	prod. mgmt & org.	resource efficiency	lean mgmt	automation	CPPS	work system design	HMI	design	Intralogistics design & mgmt	…				
2.7	role of LF for research	research object	research enabler												
2.8	research topics	production management & organization	resource efficiency	lean mgmt.	automation	CPPS	changeability	HMI	didactics	…					

Fig. i.2: Target and purpose of the AAU Smart Production Lab

i.2.3 Process

3.1	**product life cycle**	product planning	product development	product design	rapid prototyping	manufacturing / assembly / logistics	service	recycling	
3.2	**factory life cycle**	investment planning	factory concept	process planning	ramp-up		main-tenance	recycling	
3.3	**order life cycle**	configuration & order	order sequencing	production planning and scheduling			picking, packaging	shipping	
3.4	**technology life cycle**	planning	development	Virtual testing			main-tenance	moderni-zation	
3.5	**indirect functions**	SCM	sales	purchasing	HR	finance / controlling	QM		
3.6	**material flow**	continuous production	discrete production						
3.7	**process type**	mass production	serial production	small series production	one-off production				
3.8	**manufact. organization**	fixed-site manufacturing	work bench manufacturing	workshop manufacturing	flow production				
3.9	**degree of automation**	manual	partly automated / hybrid automation	fully automated					
3.10	**manufact. methods**	cutting	trad. primary shaping	additive manufact.	forming	joining	coating	change material properties	
3.11	**manufact. technology**	physical	chemical	biological					

Fig. i.3: Process of the AAU Smart Production Lab

i.2.4 Settings

4.1	**learning environment**	purely physical (planning + execution)	physical LF supported by digital factory (see line "IT-Integration")	physical value stream of LF extended virtually	purely virtual (planning + execution)	
4.2	**environment scale**	scaled down	life-size			
4.3	**work system levels**	work place	work system	factory	network	
4.4	**enablers for changeability**	mobility	modularity	compatibility	scaleability	universality
4.5	**changeability dimensions**	layout & logistics	product features	product design	technology	product quantities
4.6	**IT-integration**	IT before SOP (CAD, CAM, simulation)	IT after SOP (PPS, ERP, MES)	IT after production (CRM, PLM…)		

Fig. i.4: Settings of the AAU Smart Production Lab

i.2.5 Product

5.1	**materiality**	material (physical product)	immaterial (service)				
5.2	**form of product**	general cargo	bulk cargo				
5.3	**product origin**	own development	development by participants	external development			
5.4	**marketability of product**	available on the market	available on the market but didactically simplified	functional, could be available on the market	without function/ application, for demonstration only		
5.5	**no. of different products**	1 product	2 products	3-4 products	> 4 products	flexible, developed by participants	acceptance of real orders
5.6	**no. of variants**	1 variant	2-4 variants	4-20 variants	...	flexible, depending on participants	determined by real orders
5.7	**no. of components**	1 comp.	2-5 comp.	6-20 comp.	21-50 comp.	51-100 comp.	> 100 comp.
5.8	**further product use**	re-use / re-cycling	exhibition / display	give-away	sale	disposal	

Fig. i.5: Product of AAU Smart Production Lab

i.2.6 Didactic

6.1	**competence classes**	technical and methodological compentencies	social & communication competencies	personal competencies	activity and implementation oriented competencies		
6.2	**dimensions learn. targets**	cognitive	affective	psycho-motorical			
6.3	**learn. scenario strategy**	instruction	demonstration	closed scenario	open scenario		
6.4	**type of learn. environment**	greenfield (development of factory environment)	brownfield (improvement of existing factory environment)				
6.5	**communication channel**	onsite learning (in the factory environment)	remote connection (to the factory environment)				
6.6	**degree of autonomy**	instructed	self-guided/ self-regulated	self-determined/ Self-organized			
6.7	**role of the trainer**	presenter	moderator	coach	instructor		
6.8	**type of training**	tutorial	practical lab course	seminar	workshop	project work	
6.9	**standardization of trainings**	standardized trainings	customized trainings				
6.10	**theoretical foundation**	prerequisite	in advance (en bloc)	alternating with practical parts	based on demand	afterwards	
6.11	**evaluation levels**	feedback of participants	learning of participants	transfer to the real factory	economic impact of trainings	return on trainings / ROI	
6.12	**learning success evaluation**	knowledge test (written)	knowledge test (oral)	written report	oral presentation	practical exam	none

Fig. i.6: Didactic for AAU Smart Production Lab .

i.2.7 Learning Factory Metrics

7.1	no. of participants per training	1-5 participants	5-10 participants	10-15 participants	15-30 participants	>30 participants	
7.2	no. of standardized trainings	1 training	2-4 trainings	5-10 trainings	> 10 trainings		
7.3	aver. duration of a single training	< 1 day	1-2 days	3-5 days	5-10 days	10-20 days	> 20 days
7.4	participants per year	< 50 participants	50-200 participants	201-500 participants	501-1000 participants	> 1000 participants	
7.5	capacity utilization	< 10%	10 – 20%	21 – 50 %	51 – 75 %	76 – 100 %	
7.6	size of LF	< 100 sqm	100 – 300 sqm	300-500 sqm	500-1000 sqm	> 1000 sqm	
7.7	FTE in LF	< 1	2-4	5-9	10-15	> 15	

Fig. i.7: Learning Factory Metrics for AAU Smart Production Lab .

Technical Report ii

Evaluation of Industry 4.0 Awareness Game

Steffen Tram Mortensen

This is a statistics report which presents the questionnaire and respond that serve as documentation for the presented research in thesis..

Evaluation of Industry 4.0 Awareness Game

The technical paper present the questionnaire and evaluation of the activities in the AAU Industry 4.0 Awareness Game.

ii.1 Questionnaire

The following pages will present the evaluation questionnaire for the participants in the AAU Industry 4.0 Awareness Game.

Evaluation of the Industry 4.0 Awareness Game

The purpose of this survey is to evaluate the Industry 4.0 Awareness game and your learning outcome.

The survey will take 7-10 minutes to complete.
We kindly ask you to submit your reply before dd.mm.yy

Kind Regards

Steffen Tram Mortensen

Aalborg University
steffen@mp.aau.dk

GDPR:
You data will be handled according to the GDPR rules and will not be available to any third parties. Publication of the result will be anonymized. The data collected will be deleted after the use in the stated purpose. You can change or delete your reply by contacting the contact person.

Background

Please evaluate your preconditional qualifications.

Do you agree or disagree with the following statement:

	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
I am technology interested	☐	☐	☐	☐	☐
Others describe me as good with technology	☐	☐	☐	☐	☐
I am general good with IT (phones,tablet,PC)	☐	☐	☐	☐	☐
I have a broad knowledge about manufacturing technologies	☐	☐	☐	☐	☐

Comments

Comments

Introduction to the Game

Please evaluate the following in relation to the introduction of the game.

Do you agree or disagree with the following statement:

	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
I understood the background of Industry 4.0	☐	☐	☐	☐	☐
I understood the gameplay	☐	☐	☐	☐	☐
I understood the roles in the game	☐	☐	☐	☐	☐

I understood the manufactured product (dummy phone)	☐	☐	☐	☐	☐
I understood the process flow of AAU Smart Production	☐	☐	☐	☐	☐
The Industry 4.0 introduction was sufficient	☐	☐	☐	☐	☐

Comments

Comments

Gameplay - Duration & Entertainment

Please evaluate your experience in relation to the duration of the game and the entertainment level.

Do you agree or disagree with the following statement:

	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
I had fun during the game	☐	☐	☐	☐	☐
I would recommend the game to others	☐	☐	☐	☐	☐
I lost track of time while playing	☐	☐	☐	☐	☐
I would like to play the game again	☐	☐	☐	☐	☐
The duration of the game was too short	☐	☐	☐	☐	☐
I like the game's format (e.g. cards, physical production)	☐	☐	☐	☐	☐
The game's facilitator help my understanding	☐	☐	☐	☐	☐

Comments

Comments

Gameplay - First Round of the Game

Please evaluate the following in the relation to your experience in the beginning of the game.

Do you agree or disagree with the following statement:

	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
I understood my assigned role	☐	☐	☐	☐	☐
I only did tasks related to my assigned role	☐	☐	☐	☐	☐
I understood my tasks	☐	☐	☐	☐	☐
I had the technical knowledge to perform my task	☐	☐	☐	☐	☐
I only encountered minor mistakes	☐	☐	☐	☐	☐
I understood the roles of the other players	☐	☐	☐	☐	☐
Our production was running good	☐	☐	☐	☐	☐

We were quick to implement new technology	❑	❑	❑	❑	❑

Comments

Comments

Gameplay - Last Round of the Game

Please evaluate the following in the relation to your experience in the end of the game.

Do you agree or disagree with the following statement:

	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
I understood my assigned role	❑	❑	❑	❑	❑
I only did tasks related to my assigned role	❑	❑	❑	❑	❑
I understood my tasks	❑	❑	❑	❑	❑
I had the technical knowledge to perform my task	❑	❑	❑	❑	❑
I only encountered minor mistakes	❑	❑	❑	❑	❑
I understood the roles of the other players	❑	❑	❑	❑	❑
Our production was running good	❑	❑	❑	❑	❑
We were quick to implement new technology	❑	❑	❑	❑	❑

Comments

Comments

Awareness

Please evaluate the following in the relation to your gained experience.

Do you agree or disagree with the following statement:

	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
I gained insight in the potential of Industry 4.0	❑	❑	❑	❑	❑
I gained insight in the challenges of Industry 4.0	❑	❑	❑	❑	❑
I gained insight in some of the Industry 4.0 technologies	❑	❑	❑	❑	❑
I gained insight in how some Industry 4.0 technologies are depending on each other	❑	❑	❑	❑	❑
I gained insight in the required technology qualifications for utilization of Industry 4.0	❑	❑	❑	❑	❑
I gained insight on industrial roles and their importance	❑	❑	❑	❑	❑
I gained insight in the decomposition at traditional industrial roles	❑	❑	❑	❑	❑

I see how Industry 4.0 technologies could positively impact my workplace	☐	☐	☐	☐	☐
I see how Industry 4.0 qualifications could positively impact my workplace	☐	☐	☐	☐	☐

Comments

Comments

Learning outcome

Please answer the following questions..

What had the biggest impact on your performance in the game?

What had the biggest impact on your learning?

List the three most important technologies you have learned

List the three most important qualifications you have learned about

Describe you experience with max 25 words

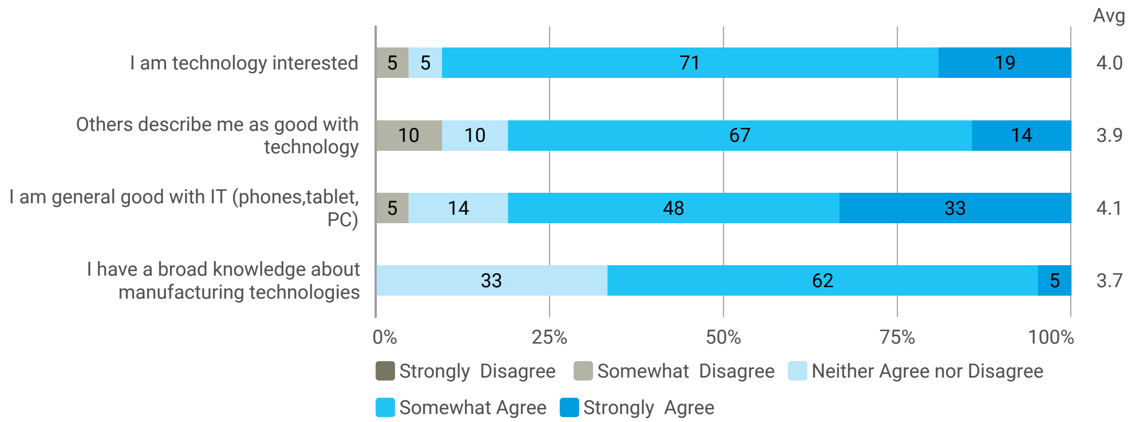
Industry 4.0 Awarness Game

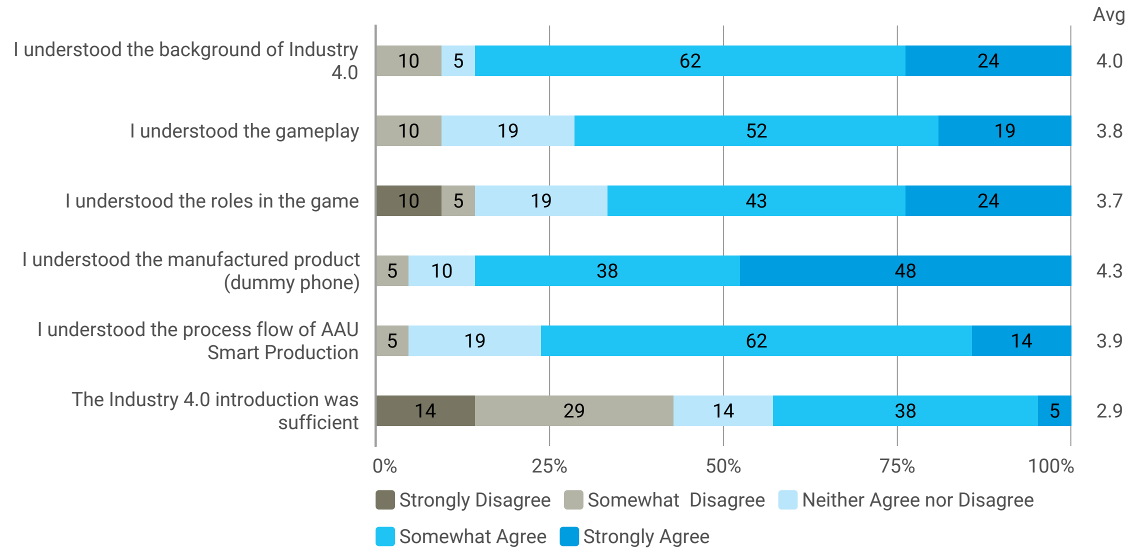
Thank you for your reply

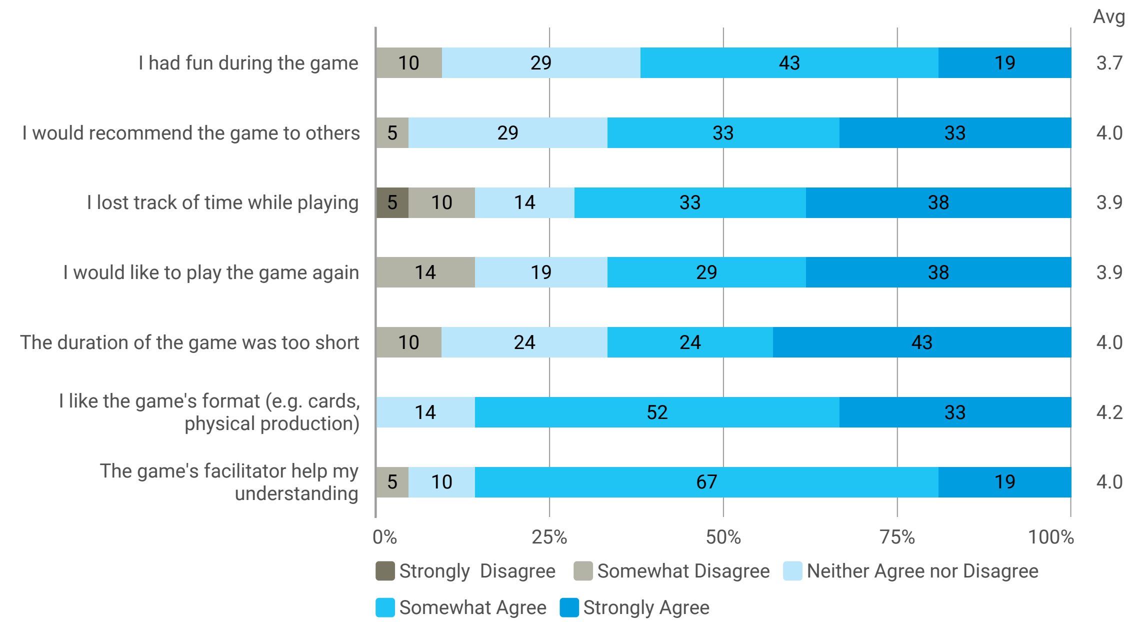
Steffen Tram Mortensen

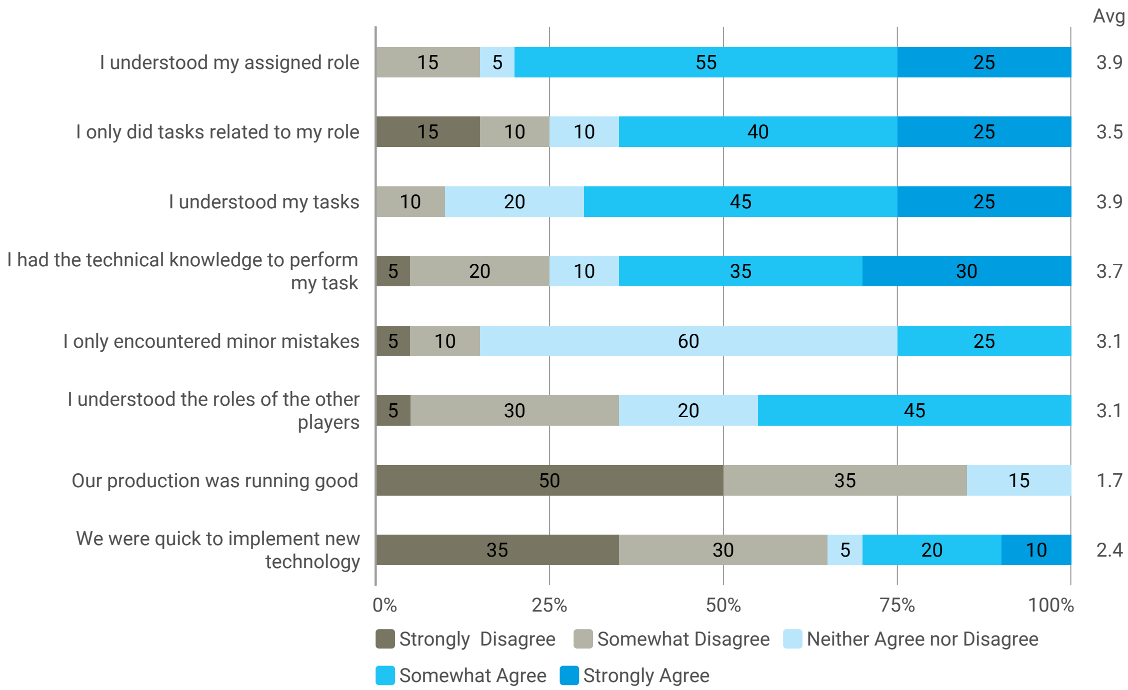
ii.2 Academic Results

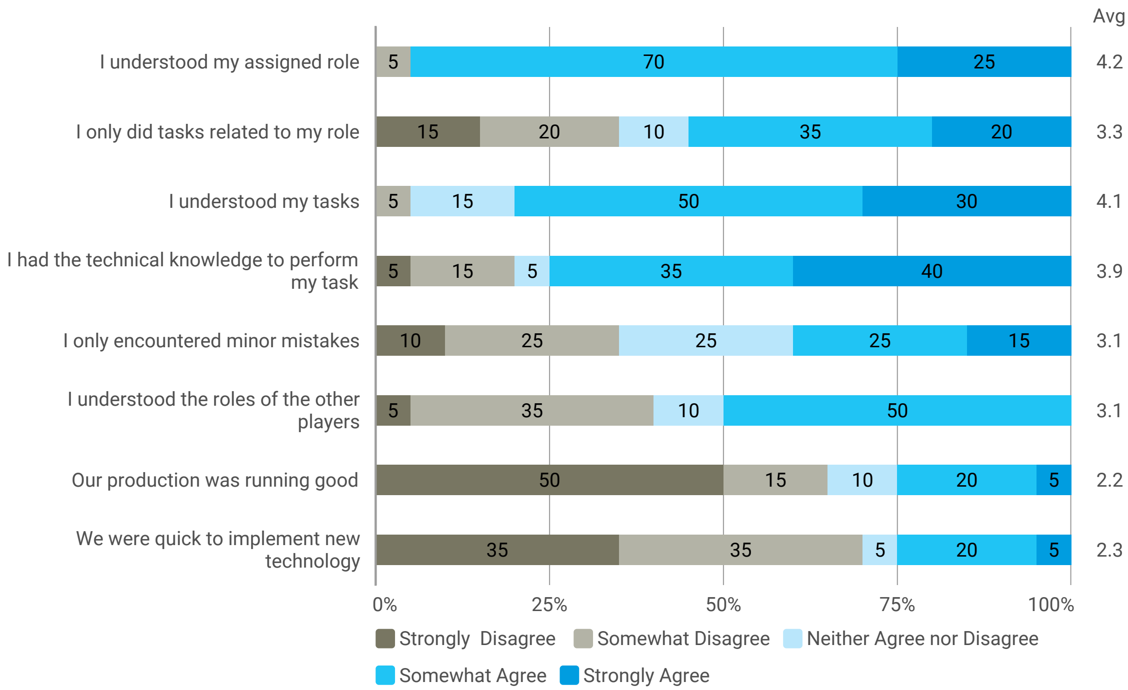
The following pages will present the full report on the questionnaire for the academic participants in the AAU Industry 4.0 Awareness Game.

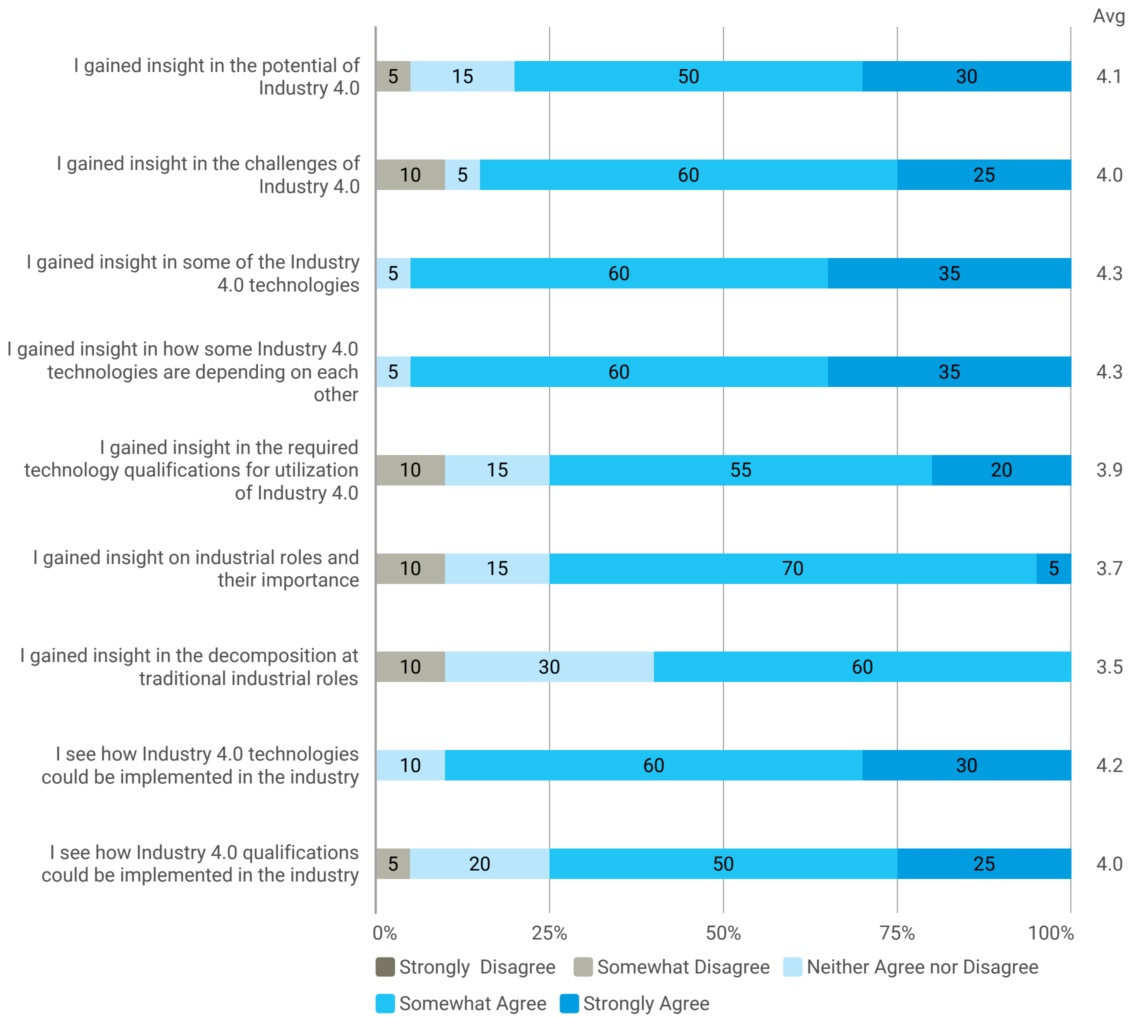

Avg
I am technology interested
5 5 71 19
4.0
Others describe me as good with technology
10 10 67 14
3.9
I am general good with IT (phones,tablet, PC)
5 14 48 33
4.1
I have a broad knowledge about manufacturing technologies
33 62 5
3.7
0% 25% 50% 75% 100%
Strongly Disagree
Somewhat Disagree
Neither Agree nor Disagree
Somewhat Agree
Strongly Agree


Avg
I understood the background of Industry 4.0
10 5 62 24
4.0
I understood the gameplay
10 19 52 19
3.8
I understood the roles in the game
10 5 19 43 24
3.7
I understood the manufactured product (dummy phone)
5 10 38 48
4.3
I understood the process flow of AAU Smart Production
5 19 62 14
3.9
The Industry 4.0 introduction was sufficient
14 29 14 38 5
2.9
0% 25% 50% 75% 100%
Strongly Disagree
Somewhat Disagree
Neither Agree nor Disagree
Somewhat Agree
Strongly Agree


Avg
I had fun during the game
10 29 43 19
3.7
I would recommend the game to others
5 29 33 33
4.0
I lost track of time while playing
5 10 14 33 38
3.9
I would like to play the game again
14 19 29 38
3.9
The duration of the game was too short
10 24 24 43
4.0
I like the game's format (e.g. cards, physical production)
14 52 33
4.2
The game's facilitator help my understanding
5 10 67 19
4.0
0% 25% 50% 75% 100%
Strongly Disagree
Somewhat Disagree
Neither Agree nor Disagree
Somewhat Agree
Strongly Agree


Avg
I understood my assigned role
15
5
55
25
3.9
I only did tasks related to my role
15
10
10
40
25
3.5
I understood my tasks
10
20
45
25
3.9
I had the technical knowledge to perform my task
5
20
10
35
30
3.7
I only encountered minor mistakes
5
10
60
25
3.1
I understood the roles of the other players
5
30
20
45
3.1
Our production was running good
50
35
15
1.7
We were quick to implement new technology
35
30
5
20
10
2.4
0%
25%
50%
75%
100%
Strongly Disagree
Somewhat Disagree
Neither Agree nor Disagree
Somewhat Agree
Strongly Agree

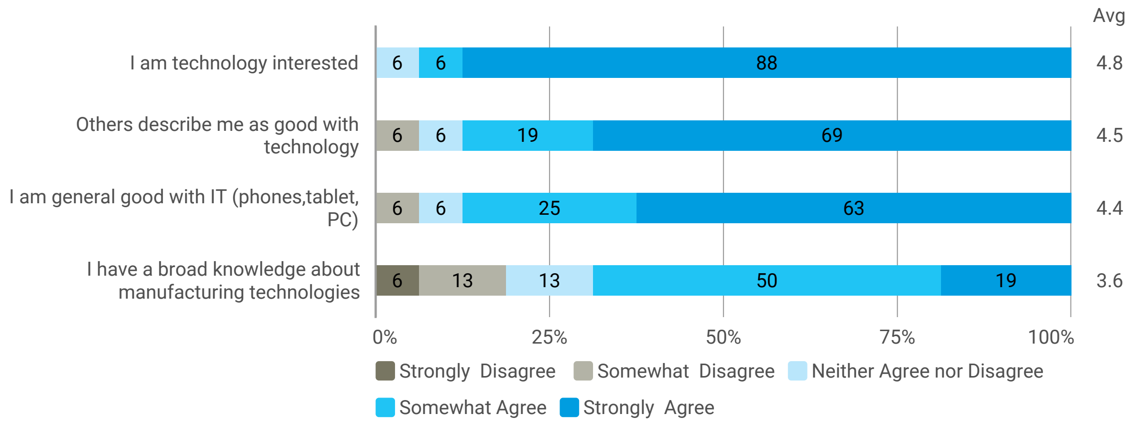

Avg
I understood my assigned role
5
70
25
4.2
I only did tasks related to my role
15
20
10
35
20
3.3
I understood my tasks
5
15
50
30
4.1
I had the technical knowledge to perform my task
5
15
5
35
40
3.9
I only encountered minor mistakes
10
25
25
25
15
3.1
I understood the roles of the other players
5
35
10
50
3.1
Our production was running good
50
15
10
20
5
2.2
We were quick to implement new technology
35
35
5
20
5
2.3
0%
25%
50%
75%
100%
Strongly Disagree
Somewhat Disagree
Neither Agree nor Disagree
Somewhat Agree
Strongly Agree

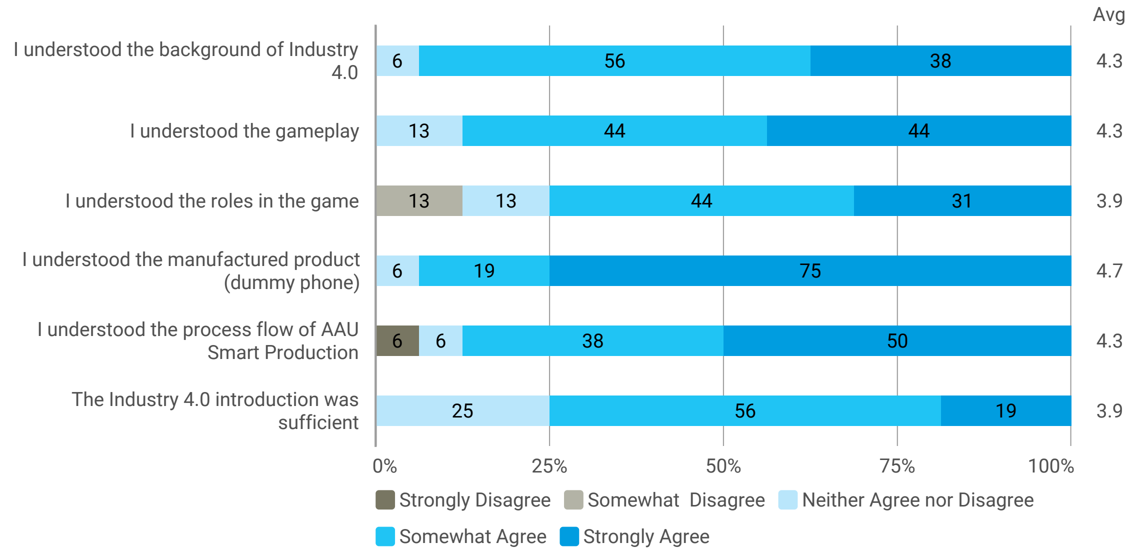


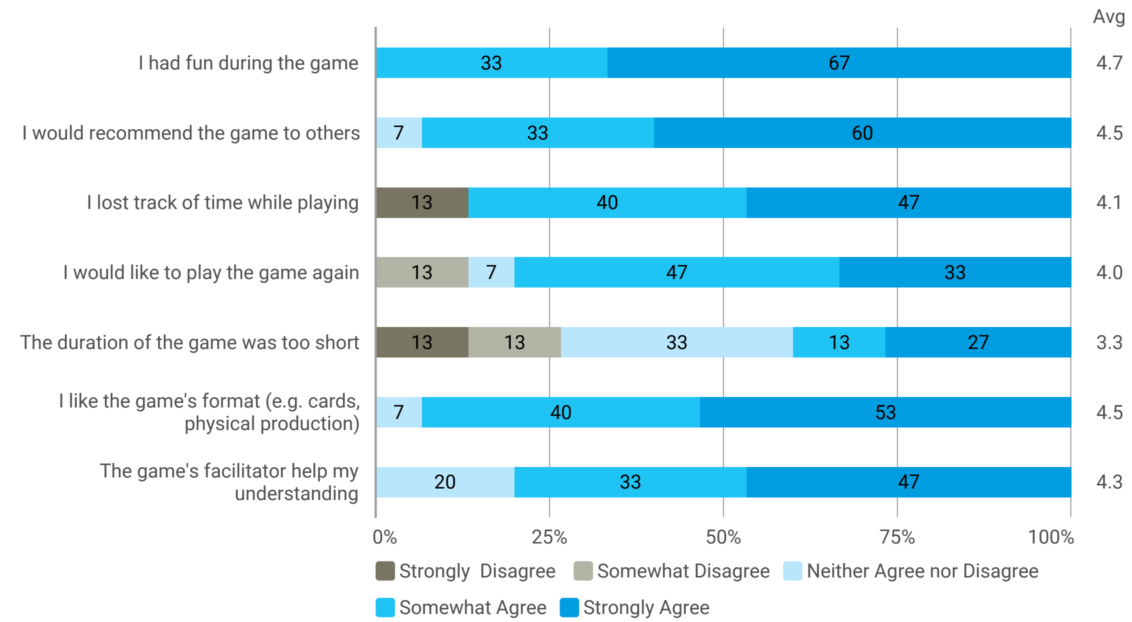
Avg
I gained insight in the potential of Industry 4.0
5 15 50 30
4.1
I gained insight in the challenges of Industry 4.0
10 5 60 25
4.0
I gained insight in some of the Industry 4.0 technologies
5 60 35
4.3
I gained insight in how some Industry 4.0 technologies are depending on each other
5 60 35
4.3
I gained insight in the required technology qualifications for utilization of Industry 4.0
10 15 55 20
3.9
I gained insight on industrial roles and their importance
10 15 70 5
3.7
I gained insight in the decomposition at traditional industrial roles
10 30 60
3.5
I see how Industry 4.0 technologies could be implemented in the industry
10 60 30
4.2
I see how Industry 4.0 qualifications could be implemented in the industry
5 20 50 25
4.0
0%
25%
50%
75%
100%
Strongly Disagree
Somewhat Disagree
Neither Agree nor Disagree
Somewhat Agree
Strongly Agree

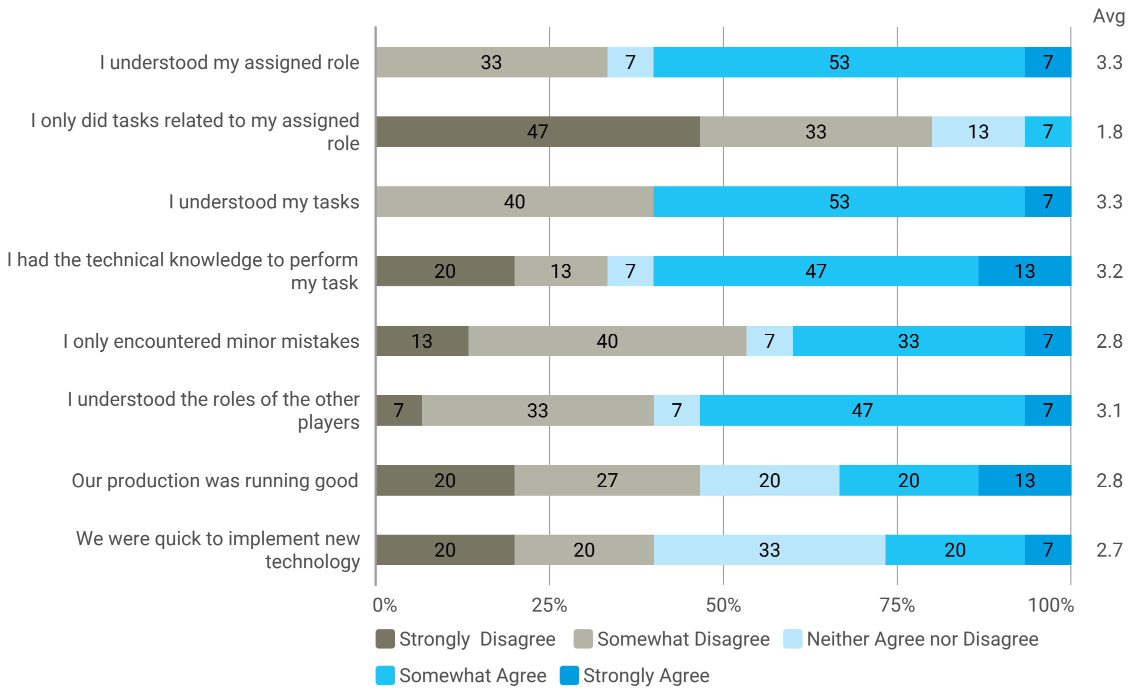
ii.3 Industrial Results

The following pages will present the full report on the questionnaire for the industrial participants in the AAU Industry 4.0 Awareness Game.

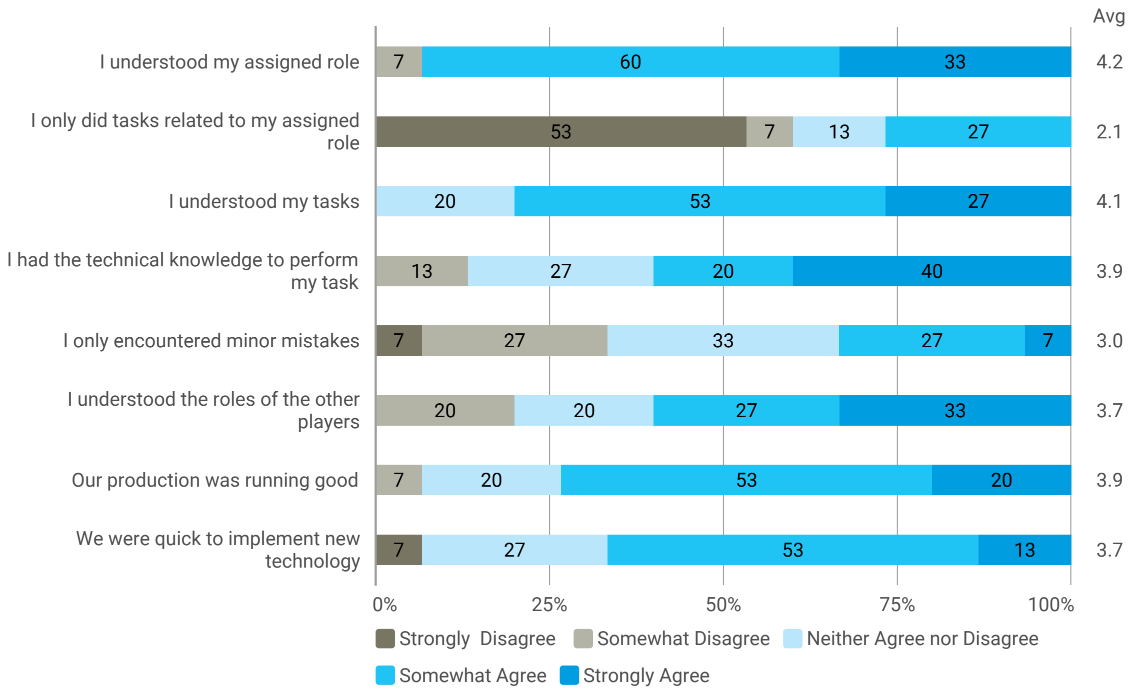

Avg
I am technology interested
6 6 88
4.8
Others describe me as good with technology
6 6 19 69
4.5
I am general good with IT (phones,tablet, PC)
6 6 25 63
4.4
I have a broad knowledge about manufacturing technologies
6 13 13 50 19
3.6
0% 25% 50% 75% 100%
Strongly Disagree
Somewhat Disagree
Neither Agree nor Disagree
Somewhat Agree
Strongly Agree


Avg
I understood the background of Industry 4.0
6 56 38
4.3
I understood the gameplay
13 44 44
4.3
I understood the roles in the game
13 13 44 31
3.9
I understood the manufactured product (dummy phone)
6 19 75
4.7
I understood the process flow of AAU Smart Production
6 6 38 50
4.3
The Industry 4.0 introduction was sufficient
25 56 19
3.9
0% 25% 50% 75% 100%
Strongly Disagree
Somewhat Disagree
Neither Agree nor Disagree
Somewhat Agree
Strongly Agree

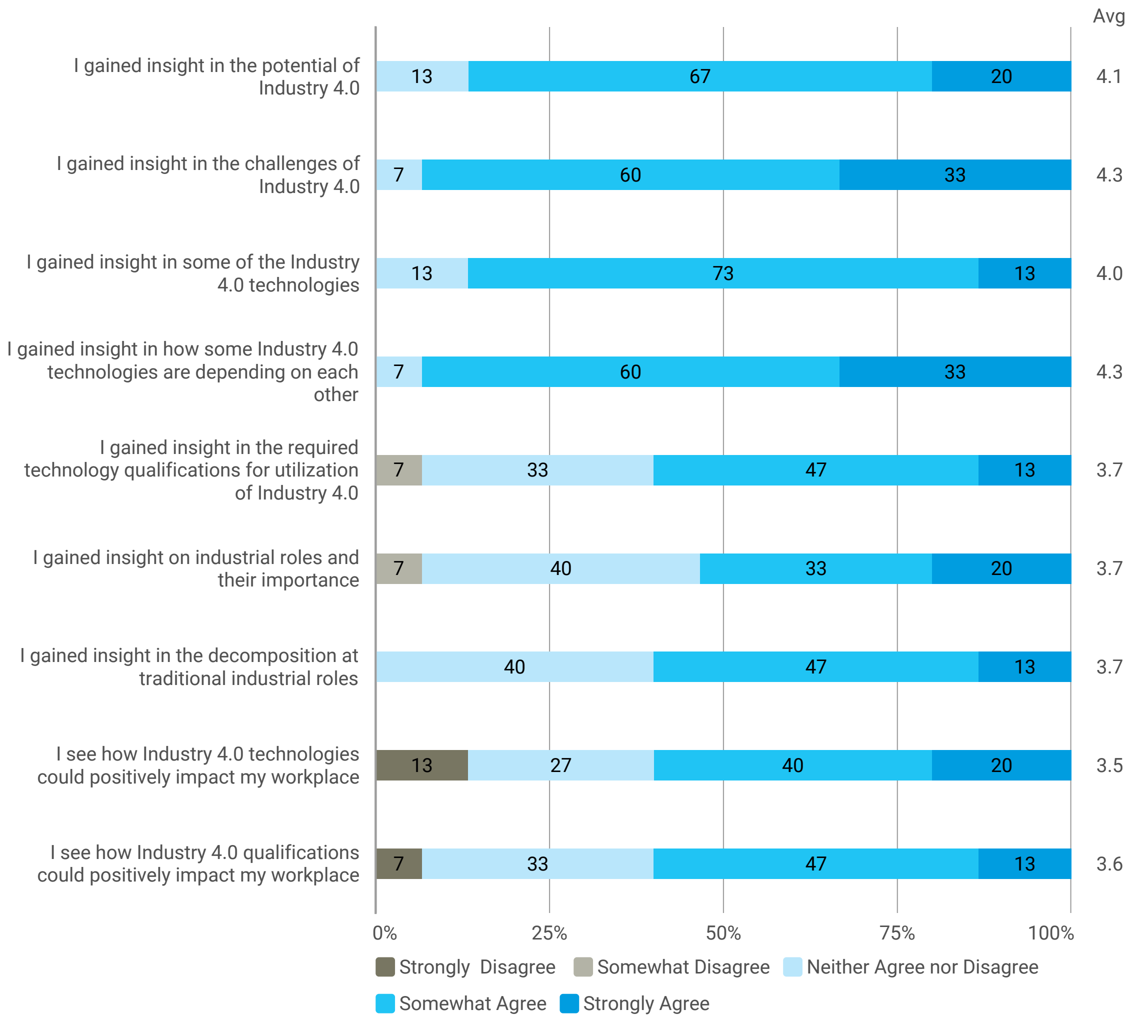

Avg
I had fun during the game
33 67
4.7
I would recommend the game to others
7 33 60
4.5
I lost track of time while playing
13 40 47
4.1
I would like to play the game again
13 7 47 33
4.0
The duration of the game was too short
13 13 33 13 27
3.3
I like the game's format (e.g. cards, physical production)
7 40 53
4.5
The game's facilitator help my understanding
20 33 47
4.3
0% 25% 50% 75% 100%
Strongly Disagree
Somewhat Disagree
Neither Agree nor Disagree
Somewhat Agree
Strongly Agree



Avg
I understood my assigned role
I only did tasks related to my assigned role
I understood my tasks
I had the technical knowledge to perform my task
I only encountered minor mistakes
I understood the roles of the other players
Our production was running good
We were quick to implement new technology
33 7 53 7 3.3
47 33 13 7 1.8
40 53 7 3.3
20 13 7 47 13 3.2
13 40 7 33 7 2.8
7 33 7 47 7 3.1
20 27 20 20 13 2.8
20 20 33 20 7 2.7
0% 25% 50% 75% 100%
Strongly Disagree
Somewhat Disagree
Neither Agree nor Disagree
Somewhat Agree
Strongly Agree



Avg
I understood my assigned role
I only did tasks related to my assigned role
I understood my tasks
I had the technical knowledge to perform my task
I only encountered minor mistakes
I understood the roles of the other players
Our production was running good
We were quick to implement new technology
7 60 33 4.2
53 7 13 27 2.1
20 53 27 4.1
13 27 20 40 3.9
7 27 33 27 7 3.0
20 20 27 33 3.7
7 20 53 20 3.9
7 27 53 13 3.7
0% 25% 50% 75% 100%
Strongly Disagree
Somewhat Disagree
Neither Agree nor Disagree
Somewhat Agree
Strongly Agree


Avg
I gained insight in the potential of Industry 4.0
13
67
20
4.1
I gained insight in the challenges of Industry 4.0
7
60
33
4.3
I gained insight in some of the Industry 4.0 technologies
13
73
13
4.0
I gained insight in how some Industry 4.0 technologies are depending on each other
7
60
33
4.3
I gained insight in the required technology qualifications for utilization of Industry 4.0
7
33
47
13
3.7
I gained insight on industrial roles and their importance
7
40
33
20
3.7
I gained insight in the decomposition at traditional industrial roles
40
47
13
3.7
I see how Industry 4.0 technologies could positively impact my workplace
13
27
40
20
3.5
I see how Industry 4.0 qualifications could positively impact my workplace
7
33
47
13
3.6
0%
25%
50%
75%
100%
Strongly Disagree
Somewhat Disagree
Neither Agree nor Disagree
Somewhat Agree
Strongly Agree

Technical Report iii

Structured Literature Survey - Virtual Commissioning Qualifications

Steffen Tram Mortensen

This is a technical report which serve as documentation for the presented research in thesis.

Structured Literature Survey

This technical paper presents further information to the survey of virtual commissioning qualifications.

iii.1 Methodology

A systematic literature review based on the method presented in [Kayunze, 2010], has been conducted to establish a state-of-the-art view of virtual commissioning qualification described in the literature. The literature review was limit to only English peer-reviewed journal or conference articles. No restriction were imposed on the publication year. The following steps was conducted.

1. Nine literature databased was queried with the search sting: ("virtual commissioning" AND (qualification OR knowledge OR skills OR competences)). In total 110 peer-review articles were found.
2. Reference from previous literature studies regarding virtual commissioning were analysed for qualification relevant literature.
3. Bibliographic mining and citation searching were performed on the identified literature.
4. The results from the steps above were combined into one database. Duplicates, retracted papers, and conference descriptions were excluded from the database.
5. Relevance of the papers were evaluate based on the title and abstract. Irrelevant papers were excluded from the database.
6. The full text of the papers were read to ensure relevance and be able to perform categorization.
7. Classification in disciplines:
   (a) Mechanical engineering
   (b) Electrical engineering
   (c) Software engineering
   (d) Control engineering
   (e) Automation engineering
   (f) Process engineering

(g) Simulation engineering

The presented disciplines were found in an iterative process under the literature review.

iii.2 Search protocol

Define your research subject and describe the specific focus of the performed search

Virtual Commissioning qualifications

List the aspects that your subject contains and the search terms for each of the aspects

Virtual Commissioning	Qualifications
Virtual Commissioning	Qualifications Knowledge Skills competences

Selection of relevant sources

Source (databases, search engines, sources hand searched, persons/organizations contacted...)	Provider (which provider you accessed the source through)	Reason for selection of source (subject coverage, accessibility, key source...)
ABI/Inform Collection	ProQuest	Business research database + management theory
ACM Digital Library	Association for Computing Machinery	Computer science portal
Business Source Premier	EBSCO Industries	Managements
Compendix	Engineering Village - Elsevier	Engineering literature database
IEEE Xplore: Digital library	Institute of Electrical and Electronics Engineers	Scientific and technical database
ProQuest	ProQuest	Database platform with broad coverage
Scopus	Elsevier B. V	Largest abstract and citation database of peer-reviewed literature
SpringerLink	Springer Nature	Covers all academic disciplines
Web of Science	Clarivate Accelerating innovation	Interdisciplinary, bibliographic database

Define your inclusion and exclusion criteria (both formal characteristics (e.g. study design, language, year) and content-related considerations)

Inclusion criteria	English language, peer reviewed journal or conference articles
Exclusion criteria	

The performed searches

Source	Search query (paste your exact query from the searched source to includes field codes in the search query)	Limitations (year, publication type, peer reviewed, ...)
ABI/Inform Collection	"Virtual Commissioning" **AND** (Qualification* **OR** Knowledge **OR** Skill* **OR** Competence")	Peer Reviewed
ACM Digital Library	"Virtual Commissioning" **AND** (Qualification* **OR** Knowledge **OR** Skill* **OR** Competence")	Peer Reviewed
Business Source Premier	"Virtual Commissioning" **AND** (Qualification* **OR** Knowledge **OR** Skill* **OR** Competence")	Peer Reviewed
Compendix	"Virtual Commissioning" **AND** (Qualification* **OR** Knowledge **OR** Skill* **OR** Competence")	Peer Reviewed
IEEE Xplore: Digital library	"Virtual Commissioning" **AND** (Qualification* **OR** Knowledge **OR** Skill* **OR** Competence")	Peer Reviewed
ProQuest	"Virtual Commissioning" **AND** (Qualification* **OR** Knowledge **OR** Skill* **OR** Competence")	Peer Reviewed
Scopus	"Virtual Commissioning" **AND** (Qualification* **OR** Knowledge **OR** Skill* **OR** Competence")	Peer Reviewed
SpringerLink	"Virtual Commissioning" **AND** (Qualification* **OR** Knowledge **OR** Skill* **OR** Competence")	Peer Reviewed
Web of Science	"Virtual Commissioning" **AND** (Qualification* **OR** Knowledge **OR** Skill* **OR** Competence")	Peer Reviewed

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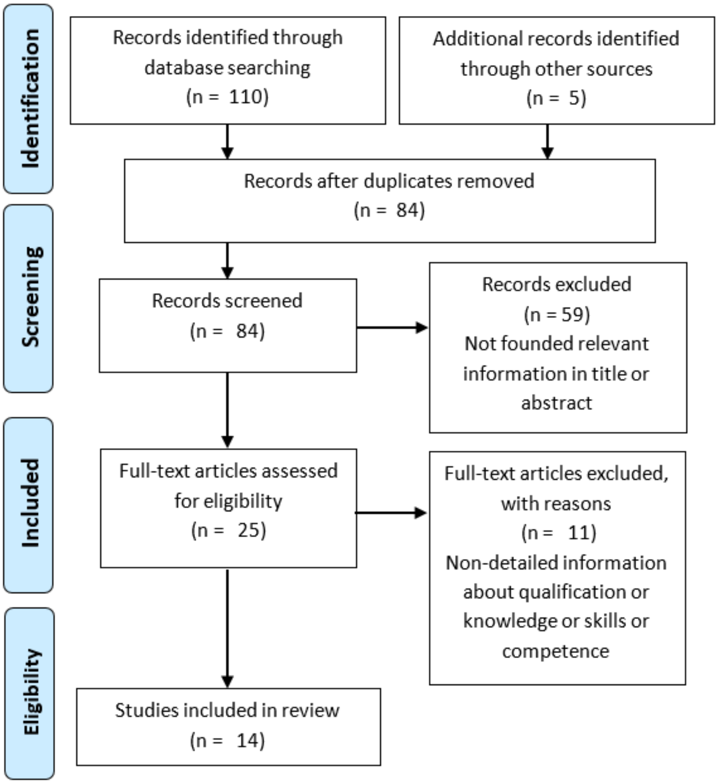
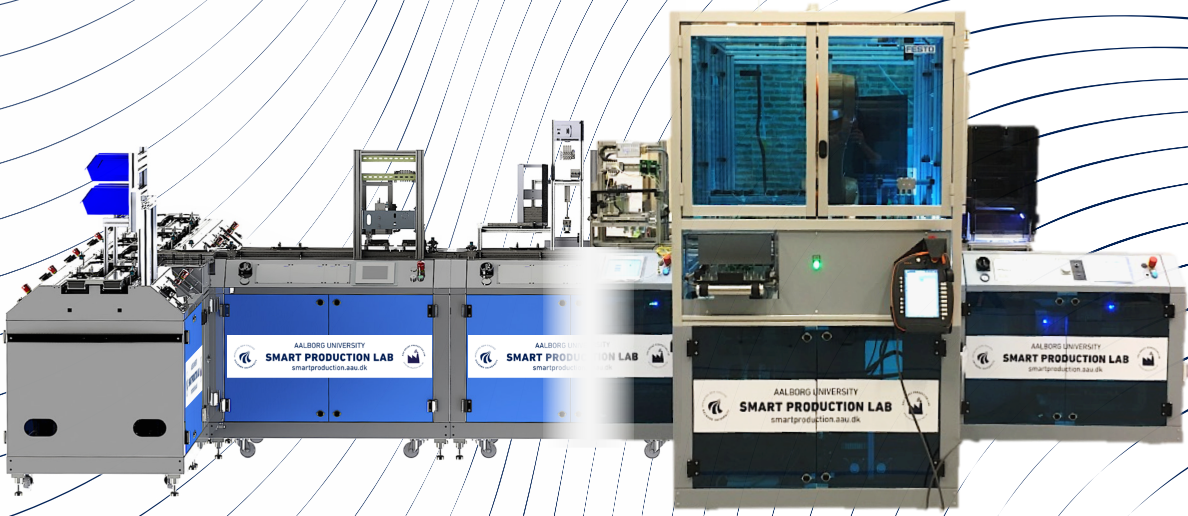
Scopus	12	22/08-2018
SpringerLink	56	23/08-2018
Web of Science	7	23/08-2018

Graphical overview of the systematic review



Last page
Thank you for reading



SUMMARY

Manufacturers are forced to be flexible and efficient at the same time. Digitalisation initiatives, such as Industry 4.0, and changeable manufacturing systems may enable manufacturers to cope with the fluctuating demand and frequently alteration of product variants. However, the frequent change and reconfiguration lead to time-consuming and costly commissioning phases, mainly due to software errors. Virtual commissioning enables faster and cheaper commissioning by testing the software in a virtual environment before the physical commissioning. Despite the benefits, virtual commissioning is not widely used in the industry because of the lack of robust methods and technical qualifications.

This doctoral dissertation firstly exam how education programs and industry can raise awareness about Industry 4.0 using serious learning game. Secondly, this thesis explores how virtual commissioning qualification (skills and knowledge) can be identified, mapped, and quantified. Lastly, an investigation of how a tool for classification and actions support for the reconfiguration process in-between two configurations of a changeable manufacturing system.

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