Human – Industrial Robot Collaboration
Simulation, Visualisation and Optimisation of Future Assembly Workstations

Fredrik Ore

2015

School of Innovation, Design and Engineering
ABSTRACT

Close collaboration between human operators and industrial robots is one approach to meet the challenges of increased global competition and demographic change for manufacturing companies in the developed countries. These human-industrial robot collaborative (HIRC) assembly systems combine human flexibility, intelligence and tactile sense with robotic speed, endurance and repeatability. However, current personal safety legislation limits the possible collaborative applications that could be implemented in practice, but large research efforts are put in order to enable practical implementation of these future workstations.

When the limitations of safety legislation are addressed and the collaborative systems can be implemented, a need to simulate these systems will rise. Virtual simulations are an important component in modern production system design and will be demanded in future assembly workstation design. No existing software has been found that can simulate and visualise HIRC tasks on an object simultaneously handled by both a human and an industrial robot. The aim of this thesis is to close this gap through development of a software solution that can simulate, visualise and evaluate HIRC assembly workstations. In addition, with the simulations as a base, mathematical optimisation techniques have been employed in order to find the optimal HIRC design.

Industrial assembly cases at a heavy vehicle manufacturer were used as a foundation on which the development was conducted. The software was developed in an iterative search process and combined a number of different software and evaluation techniques. Robotic and human simulation tools were combined in order to achieve the simulation and visualisation elements of the software. Biomechanical load on the human and operation time, for both the human and the industrial robot, were evaluated as output from the simulations. Existing optimisation techniques were incorporated in the demonstrator software to design the most ideal assembly station.

The resulting HIRC simulation demonstrator software makes it possible to simulate, visualise, evaluate and optimise collaborative workstations. This was validated through industrial cases in which improvements of the biomechanical load and operation time in HIRC workstations compared with manual stations were demonstrated. An example of how to optimise the geometric position of the handover between the human and the industrial robot was also presented through the cases. These results present how the simulation software can contribute to design the most suitable future HIRC assembly systems and thus enable increased productivity and reduce biomechanical loads on the assembly operators.
ABSTRACT

Close collaboration between human operators and industrial robots is one approach to meet the challenges of increased global competition and demographic change for manufacturing companies in the developed countries. These human-industrial robot collaborative (HIRC) assembly systems combine human flexibility, intelligence and tactile sense with robotic speed, endurance and repeatability. However, current personal safety legislation limits the possible collaborative applications that could be implemented in practice, but large research efforts are put in order to enable practical implementation of these future workstations.

When the limitations of safety legislation are addressed and the collaborative systems can be implemented, a need to simulate these systems will rise. Virtual simulations are an important component in modern production system design and will be demanded in future assembly workstation design. No existing software has been found that can simulate and visualise HIRC tasks on an object simultaneously handled by both a human and an industrial robot. The aim of this thesis is to close this gap through development of a software solution that can simulate, visualise and evaluate HIRC assembly workstations. In addition, with the simulations as a base, mathematical optimisation techniques have been employed in order to find the optimal HIRC design.

Industrial assembly cases at a heavy vehicle manufacturer were used as a foundation on which the development was conducted. The software was developed in an iterative search process and combined a number of different software and evaluation techniques. Robotic and human simulation tools were combined in order to achieve the simulation and visualisation elements of the software. Biomechanical load on the human and operation time, for both the human and the industrial robot, were evaluated as output from the simulations. Existing optimisation techniques were incorporated in the demonstrator software to design the most ideal assembly station.

The resulting HIRC simulation demonstrator software makes it possible to simulate, visualise, evaluate and optimise collaborative workstations. This was validated through industrial cases in which improvements of the biomechanical load and operation time in HIRC workstations compared with manual stations were demonstrated. An example of how to optimise the geometric position of the handover between the human and the industrial robot was also presented through the cases. These results present how the simulation software can contribute to design the most suitable future HIRC assembly systems and thus enable increased productivity and reduce biomechanical loads on the assembly operators.
Although I am the single author of this thesis, it would never have been realised without a large group of friends of mine, who I would like to thank here:

My supervisors, Professor Magnus Wiktorsson, Professor Lars Hanson and Professor Yvonne Eriksson have all had a huge impact on the research leading to this thesis. The group has, through their various fields of expertise, supported and guided me through the whole research process and the development from being a solution-searching practitioner towards being a researcher understanding the value of rigour in research.

My colleagues at Mälardalen University, and especially my PhD student friends at Innofacture and Forskarskolan. The friendly and generous environment I enjoy in our group is an enabler for our individual advancements. I would particularly like to thank Mats Jackson for managing the Innofacture research school in an excellent way.

My Scania colleagues, the division of Global Industrial Development in general, but also my TER group friends: Anders, Anders, Hanna, Mariam, Micke and Christer (yes, you fit in here). Without your help and support my road to this thesis would have been longer and even more winding.

Fraunhofer-Chalmers Research Centre, and specifically Niclas and Peter, for fruitful collaboration; much is possible in this group.

The Swedish Knowledge Foundation, which founded this work through its framework the Innofacture Research School, the partner companies and Mälardalen University. The research was also conducted in the context of the XPRES research and education environment at Mälardalen University.

Last, but most importantly, my family and friends. The process of a PhD education occasionally puts demands on patience from the closest ones. So, thank you Maja for all your love, support and encouragement. And thank you Axel and Klara for being yourselves.
ACKNOWLEDGMENTS

Although I am the single author of this thesis, it would never have been realised without a large group of friends of mine, who I would like to thank here:

My supervisors, Professor Magnus Wiktorsson, Professor Lars Hanson and Professor Yvonne Eriksson have all had a huge impact on the research leading to this thesis. The group has, through their various fields of expertise, supported and guided me through the whole research process and the development from being a solution-searching practitioner towards being a researcher understanding the value of rigour in research.

My colleagues at Mälardalen University, and especially my PhD student friends at Innofacture and Forskarskolan. The friendly and generous environment I enjoy in our group is an enabler for our individual advancements. I would particularly like to thank Mats Jackson for managing the Innofacture research school in an excellent way.

My Scania colleagues, the division of Global Industrial Development in general, but also my TER group friends: Anders, Anders, Hanna, Mariam, Micke and Christer (yes, you fit in here). Without your help and support my road to this thesis would have been longer and even more winding.

Fraunhofer-Chalmers Research Centre, and specifically Niclas and Peter, for fruitful collaboration; much is possible in this group.

The Swedish Knowledge Foundation, which founded this work through its framework the Innofacture Research School, the partner companies and Mälardalen University. The research was also conducted in the context of the XPRES research and education environment at Mälardalen University.

Last, but most importantly, my family and friends. The process of a PhD education occasionally puts demands on patience from the closest ones. So, thank you Maja for all your love, support and encouragement. And thank you Axel and Klara for being yourselves.
PAPER A

Ore initiated the paper, set the demands on the geometric simulation software development, performed the case simulations, evaluated the results and wrote the paper. Delfs performed the geometric simulation software programming. Hanson and Wiktorsson reviewed and carried out quality-assurance of the paper.

PAPER B

Ore initiated the paper, set the demands on the geometric simulation software development, performed the case simulations, evaluated the results and wrote the paper. Delfs performed the geometric simulation software programming. Hanson and Wiktorsson reviewed and carried out quality assurance of the paper.

PAPER C

Ore initiated the paper, developed the optimisation work method, performed the case simulations and wrote the paper. Reddy Vemula developed the optimisation algorithms and assisted in writing the text describing them. Hanson and Wiktorsson reviewed and carried out quality assurance of the paper.

ADDITIONAL PUBLICATIONS
PUBLICATIONS

APPENDED PUBLICATIONS

PAPER A

Ore initiated the paper, set the demands on the geometric simulation software development, performed the case simulations, evaluated the results and wrote the paper. Delfs performed the geometric simulation software programming. Hanson and Wiktorsson reviewed and carried out quality-assurance of the paper.

PAPER B

Ore initiated the paper, set the demands on the geometric simulation software development, performed the case simulations, evaluated the results and wrote the paper. Delfs performed the geometric simulation software programming. Hanson and Wiktorsson reviewed and carried out quality assurance of the paper.

PAPER C

Ore initiated the paper, developed the optimisation work method, performed the case simulations and wrote the paper. Reddy Vemula developed the optimisation algorithms and assisted in writing the text describing them. Hanson and Wiktorsson reviewed and carried out quality assurance of the paper.

ADDITIONAL PUBLICATIONS
# Table of Contents

1. Introduction ............................................................................................................... 1  
   1.1 Background ........................................................................................................... 1  
   1.2 Research objective and research questions ....................................................... 3  
   1.3 Delimitations ...................................................................................................... 3  
   1.4 Outline of the thesis ......................................................................................... 3  

2. Frame of reference .................................................................................................. 5  
   2.1 Human–industrial robot collaboration ............................................................. 5  
   2.2 Simulation in production system design ......................................................... 8  
   2.3 Simulation of human–industrial robot Collaboration ...................................... 9  
      2.3.1 Digital Human Modelling simulation ...................................................... 9  
      2.3.2 Robotic simulation ............................................................................... 10  
   2.4 Optimisation in assembly workstation design .............................................. 10  

3. Research method .................................................................................................. 13  
   3.1 The methodological approach – design science research ............................... 13  
   3.2 The research process ...................................................................................... 14  
      3.2.1 Literature search .................................................................................... 16  
      3.2.2 Development of software .................................................................... 16  
      3.2.3 Study A – HIRC simulation, Case A ................................................... 18  
      3.2.4 Study B – HIRC simulation, Case B .................................................... 19  
      3.2.5 Study C – Optimisation of HIRC ......................................................... 20  
   3.3 Research quality ............................................................................................. 22  
      3.3.1 Seven DSR guidelines .......................................................................... 22  
      3.3.2 Being an industrial PhD student ........................................................... 23  
      3.3.3 Connection with the research area of innovation and design ................. 23  

4. Research findings .................................................................................................. 25  
   4.1 HIRC definition ............................................................................................... 25  
   4.2 HIRC demonstrator software and method .................................................... 26  
   4.3 HIRC Application ......................................................................................... 29
1. INTRODUCTION

This introduction gives a brief background of the research area. This results in a presentation of the reasons for the research and, with this as a base, the resulting objective and the research questions.

1.1 BACKGROUND

Increased global competition is one of the main challenges for manufacturing companies in the developed countries (European Commission, 2004; IF Metall, 2014). This puts higher demands on productivity improvements to compete with the challenges from emerging markets. These improvements have to be made at all levels in the companies, from effective and efficient business strategies to well-designed production systems and work methods. Another challenge is the demographic change problem arising from two issues, increasing average life length concurrent with decreasing fertility rate, resulting in negative population growth (United Nations, 2013). This increasing average age of the available workforce has to be addressed by adapting workstations to meet the needs of the elderly, since the increase in age also increases the risk for musculoskeletal disorders (Fritzsche, 2010; Zaeh and Prasch, 2007).

Both these obstacles for future growth of industries in the developed countries can be overcome, among other things, through closer physical collaboration between human operators and industrial robots. Such systems are named Human–Industrial Robot Collaborative (HIRC) systems. In this thesis these systems are defined as systems in which humans and industrial robots share workspaces and collaborate towards a common goal.

An industrial robot is defined as an “automatically controlled, reprogrammable multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications” (ISO, 2011a, p. 2).

The benefits from collaboration between humans and industrial robots are accomplished by combining their individual desired characteristics in a new collaborative production system. The robotic features preferred are handling speed, endurance and repeatability, and from the human, flexibility, intelligence and tactile sense are desired (Krüger et al., 2005; Stopp et al., 2002). In addition to improved ergonomics (Oberer-Treitz et al., 2013; Reinhart et al., 2012), the main reason to introduce robots in industry workstations is to increase productivity (Krüger et al., 2009), thus supporting humans in using their skills to perform their value-adding task more efficiently (Unhelkar et al., 2014). The vision of closer collaboration between human and robots was expressed by Tan et al. (2009, p. 29): “Human–robot
1. INTRODUCTION

This introduction gives a brief background of the research area. This results in a presentation of the reasons for the research and, with this as a base, the resulting objective and the research questions.

1.1 BACKGROUND

Increased global competition is one of the main challenges for manufacturing companies in the developed countries (European Commision, 2004; IF Metall, 2014). This puts higher demands on productivity improvements to compete with the challenges from emerging markets. These improvements have to be made at all levels in the companies, from effective and efficient business strategies to well-designed production systems and work methods. Another challenge is the demographic change problem arising from two issues, increasing average life length concurrent with decreasing fertility rate, resulting in negative population growth (United Nations, 2013). This increasing average age of the available workforce has to be addressed by adapting workstations to meet the needs of the elderly, since the increase in age also increases the risk for musculoskeletal disorders (Fritzsche, 2010; Zaeh and Prasch, 2007).

Both these obstacles for future growth of industries in the developed countries can be overcome, among other things, through closer physical collaboration between human operators and industrial robots. Such systems are named Human–Industrial Robot Collaborative (HIRC) systems. In this thesis these systems are defined as systems in which humans and industrial robots share workspaces and collaborate towards a common goal. An industrial robot is defined as an “automatically controlled, reprogrammable multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications” (ISO, 2011a, p. 2).

The benefits from collaboration between humans and industrial robots are accomplished by combining their individual desired characteristics in a new collaborative production system. The robotic features preferred are handling speed, endurance and repeatability, and from the human, flexibility, intelligence and tactile sense are desired (Krüger et al., 2005; Stopp et al., 2002). In addition to improved ergonomics (Oberer-Treitz et al., 2013; Reinhart et al., 2012), the main reason to introduce robots in industry workstations is to increase productivity (Krüger et al., 2009), thus supporting humans in using their skills to perform their value-adding task more efficiently (Unhelkar et al., 2014). The vision of closer collaboration between human and robots was expressed by Tan et al. (2009, p. 29): “Human-robot
collaboration (HRC) is a dream combination of human flexibility and machine efficiency”. In this quotation, Tan et al. describe both the benefits of human–robot collaboration and highlight the visionary ”dream” status that such collaboration still has; it has not yet been realised or evaluated to any wider extent. The reason for this is current safety legislation that does not allow physically close collaboration between humans and traditional industry robots (ISO, 2011a; ISO, 2011b). The standards harmonised to the legislations require fences (physical or certified sensors acting as a fence) surrounding a traditional industrialised robot (Vasic and Billard, 2013). Passing these sensors or gates and entering the robotic work area automatically shuts off the robotic motion, thus hindering collaboration between human and robots. One prerequisite before the HIRC systems can be introduced on a wider scale is to guarantee the personal safety of the humans. When these issues have been resolved there is a huge potential market for HIRC workstations in all manufacturing industries. Large research efforts are currently put in order to enable practical implementation of these future workstations.

One other current development in order to meet increased global competition is to focus on virtual simulations of products and production processes in the manufacturing industry (Kagermann et al., 2013). Through these computerised tools it is possible to reduce the product development time, which is crucial for the success of a manufacturing company. The simulation and visualisation tools can give the possibility to view, design and evaluate the most appropriate production system. These tools are in general already an integral part of all engineering activities that take place in a typical manufacturing organisation (Mourtzis et al., 2015). However, no existing software have been found, that simulate and visualise HIRC tasks on an object simultaneously handled by both a human and an industrial robot.

The goal in any kind of design task is always to design the optimum solution given a number of objectives and constraints. In the design of production systems these design decisions have historically often been made on the basis of experienced workforce and best practice (Bellgran and Säfsten, 2010). But with the simulation and visualisation possibilities available today should it be possible to use the numerical data from the software together with optimisation techniques to achieve the optimal solution to a production system design problem.

The work in this thesis combines the virtual simulation and optimisation possibilities of HIRC production system design with the aim of designing and evaluating them in a time- and cost-effective way. Since no existing software has been found that simulates simultaneous HIRC systems must this kind of tools firstly
be developed. This demonstrator software can then be used together with optimisation techniques to design an optimal HIRC workstation.

1.2 RESEARCH OBJECTIVE AND RESEARCH QUESTIONS

The objective of this research is to develop a demonstrator software and its application method, for simulating, visualising, evaluating and optimisation of human–industrial robot collaborations (HIRC) in a heavy vehicle assembly environment. This objective is met through addressing the following research questions:

RQ1: How can simulation, visualisation and evaluation of human–industrial robot collaboration workstations be performed?

RQ2: How can human–industrial robot collaborative workstations be optimised?

RQ3: How can simulation, visualisation, evaluation and optimisation of human–industrial robot collaboration be applied in industrial heavy vehicle assembly workstation design?

1.3 DELIMITATIONS

The cases simulated in this licentiate thesis are from a single heavy vehicle manufacturer. The main purpose of using the cases is not to design the best HIRC systems but to develop the demonstrator software; the single case company used does not affect the end result to any large extent.

1.4 OUTLINE OF THE THESIS

Chapter 1 presents the background of the research, including the objective and research questions. Chapter 2 presents the frame of reference applied and Chapter 3 the methodological approach in the research together with how it was applied in the research studies conducted. Chapter 4 presents the research results, and in Chapter 5 these are discussed and related to the research questions. Chapter 6 concludes the thesis by describing the academic and industrial contribution and suggesting a future research direction.
This chapter introduces the frame of reference and previous research on which the thesis is based. The sub chapters below are derived from the keywords in the research questions: HIRC, simulation in production system design and in HIRC, and optimisation in workstation design.

2.1 HUMAN–INDUSTRIAL ROBOT COLLABORATION

The research area of human–robot collaboration is new and fast-growing. A literature search performed in the Discovery database (described in detail in Chapter 3.2.1) shows an increasing trend from the mid 1990s until today. From a handful of papers presented per year between 1996 and 2007, the number has now grown to more than 20 papers per year for the last three years (2012 -2014). The earlier research papers focused more on cognitive and communication research while the more current papers also present applications in manufacturing industries.

In a seminal paper from 1996, Colgate et al. describe "cobots" as passive robotic devices that move with human force as their power source. In 2002 Schraft et al. presented "man–robot cooperation" in which a demonstration system of a HIRC workplace is presented (Schraft et al.). The "man–robot cooperation" term is further discussed and developed by Krüger et al. (2005). The research field has grown and the expression human–robot collaboration (HRC) has now become the main term used.

Another related term is human–robot interaction (HRI). Interaction is a more general term than collaboration, involving only acting on someone else, while collaboration is acting with someone else to achieve a common goal (Grosz, 1996). HRI includes a combination of a number of research areas such as cognition, linguistics and physiology research combined with engineering, mathematics, computer science and human factors (Goodrich and Schultz, 2008). The HRI term also covers HRC and thus HRC is a subset of HRI. This classification is displayed in Figure 1, where definitions and application examples of HRI and HRC are given.
2. FRAME OF REFERENCE

This chapter introduces the frame of reference and previous research on which the thesis is based. The subchapters below are derived from the keywords in the research questions: HIRC, simulation in production system design and in HIRC, and optimisation in workstation design.

2.1 HUMAN–INDUSTRIAL ROBOT COLLABORATION

The research area of human–robot collaboration is new and fast-growing. A literature search performed in the Discovery database (described in detail in Chapter 3.2.1) shows an increasing trend from the mid 1990s until today. From a handful of papers presented per year between 1996 and 2007, the number has now grown to more than 20 papers per year for the last three years (2012-2014). The earlier research papers focused more on cognitive and communication research while the more current papers also present applications in manufacturing industries.

In a seminal paper from 1996, Colgate et al. describe “cobots” as passive robotic devices that move with human force as their power source. In 2002 Schraft et al. presented “man–robot cooperation” in which a demonstration system of a HIRC workplace is presented (Schraft et al.). The “man–robot cooperation” term is further discussed and developed by Krüger et al. (2005). The research field has grown and the expression human–robot collaboration (HRC) has now become the main term used.

Another related term is human–robot interaction (HRI). Interaction is a more general term than collaboration, involving only acting on someone else, while collaboration is acting with someone else to achieve a common goal (Grosz, 1996). HRI includes a combination of a number of research areas such as cognition, linguistics and physiology research combined with engineering, mathematics, computer science and human factors (Goodrich and Schultz, 2008). The HRI term also covers HRC and thus HRC is a subset of HRI. This classification is displayed in Figure 1, where definitions and application examples of HRI and HRC are given.
Walther and Guhl (2014) present a classification of HRI that helps to describe the wide variety of human–robot systems in a structured way. The HRI classification includes robots used in healthcare and in public and home environments, with anthropomorphic or zoomorphic interfaces with the human and with various kinds of mobility levels.

Operation modes in human and industrial robot collaboration are, according to the ISO standard ISO 10218 (ISO, 2011b) divided into four modes: safety-rated monitored stop, hand guiding, speed and separation monitoring, and power- and force-limiting. These are described (Fryman, 2014; ISO, 2011a; ISO, 2011b) in the following way: “Safety-rated monitored stop” is the simplest of them: when an operator enters the robotic work area, the robot stops and when the human leaves the area, the robot system automatically resumes its actions. “Hand guiding” enables the human to control the robotic end-effector through designated controls while standing in the robotic work area and moving the end-effector to a designated position. When the human leaves the area, the robot starts its operation from that new position. “Speed and separation monitoring” enables the human to be present in the robotic work area while the robot is in operation. The distance between the human and the robot is constantly measured and when predefined thresholds are passed, the robot either slows down, stops or moves backwards from the human, all
depending on the programmed responses. A “power- and force-limiting” system includes a weak and slow robot (compared to the standard industry robot) that is designed so as not to hurt humans in case of a collision.

Even though the collaborative modes are defined in the current robotic standard, the possibilities to build these HIRC systems in industry are limited. Personal safety legislations in manufacturing industries are governed by the machine directive (European Union, 2006), which refers to harmonised standards to meet safety demands. ISO 10218 regulates robots and robot system safety. The standard requires some kind of fences (physical or certified sensors acting as a fence) surrounding a traditional industrialised robot (Vasic and Billard, 2013). In HIRC systems the robot is still considered dangerous, and the safety of the human has to be guaranteed by other systems than fences; great research efforts are made in this development. Current state of the art includes multiple depth cameras supervising the HIRC area (Fischer and Henrich, 2009; Morato et al., 2014; Wang et al., 2013), robotic control systems having control of robot positions and movements (Morato et al., 2014; Salmi et al., 2014; Wang et al., 2013), certified sensors assisting the depth cameras (Salmi et al., 2014; Wang et al., 2013) and a network connecting all these systems into the goal of “a safe network of unsafe devices” (Pedrocchi et al., 2013, p. 1).

This state of the art is constantly under development in order to enable use of HIRC systems in manufacturing industries. There are a number of international research projects in this field in Europe: LIAA (LIAA Project, 2015), Robo-Partner (Robo-Partner, 2015), SAPHARI (SAPHARI, 2015) and SMErobotics (SMErobotics, 2015). They all have a common focus on physical HIRC workstations. Two focus more on the cognitive communication between the human and the robot (SAPHARI and SMErobotics), while the other two primarily investigate personal safety issues.

Today there are actually fenceless industrial robots introduced in production environments. They are power- and force-limiting systems with small robots that have been installed without fences within the current machine directive. This is possible when the mandatory risk analysis shows that the risk for a human to work next to these robots is low, as discussed in Matthias et al. (2011) and Tan et al. (2010). These robots are designed to be weak, move with slow speeds, lack sharp edges and allow fenceless installation. Some examples of these robots are Baxter (Baxter, 2015), Universal Robots (Universal Robots, 2015a) and Kuka’s LBR iiwa (Kuka, 2015). An industrialised example of such an installation is from the engine assembly plant at Volkswagen in Salzgitter (Universal Robots, 2015b). A Universal Robots robot (UG5) has been installed to insert glow plugs in the head assembly.
line in a fenceless environment, and work “shoulder to shoulder” with an human operator, Figure 2.

Figure 2: A Universal Robots robot installed in a fenceless environment at the engine assembly plant at Volkswagen in Salzgitter (Universal Robots, 2015b).

2.2 SIMULATION IN PRODUCTION SYSTEM DESIGN

Virtual simulations of production system design play a vital part in any typical manufacturing organisation (Mourtzis et al., 2015). They replace the previously used physical prototypes. The benefits of virtual simulations compared to those of the physical prototypes are summarised by Murphy et al. (2002) into five categories: early identification of design errors, fewer physical prototypes that demand time and cost, faster responses to design changes, less time wasted on building new experiments, and shorter lead times. These systems make it possible to study how changes in the system design affect its overall performance (Baldwin et al., 2000). This in turn results in more efficient product development processes, which is another important aspect to consider in the global competition facing all manufacturing industries.

Simulation tools for production engineering are normally assigned to two categories, discrete event simulation and geometric simulation (Klingstam and Gullander, 1999; Ng et al., 2008). Discrete event simulations present the system at a distinct point in time. Between two points nothing happens, time does not proceed linearly but in irregular intervals (Pidd, 1994). In geometric simulation the three-dimensional geometry of the part is simulated in a system where time proceeds linearly (Klingstam and Gullander, 1999).
There are a number of software solutions developed to geometrically simulate manufacturing systems. Dassault Systems has their manufacturing simulation package including DELMIA (Delmia, 2015), Siemens their NX/Tecnomatix (Siemens, 2015), and PTC their PTC Creo (PTC Creo, 2015). These software programs provide simulation possibilities for a wide variety of manufacturing systems, including machining, robotics, assembly and human simulations. None of them include the possibilities of simulating HIRC in a hand-guiding operation mode.

2.3 SIMULATION OF HUMAN–INDUSTRIAL ROBOT COLLABORATION

The research area of computerised simulation of HIRC is immature and under development. One early result came in 2000 (Luh and Sroon), when a tool was presented by which a human virtual hand could be placed on an object in a CAD environment where a robot carries the load. The hand was then controlled by keyboard commands and the robotic movement was stored. The idea was to use the stored robotic data in a physical environment in order to save energy and effort of the human co-worker. A more recent paper by Busch et al. (2013) presents a welding cell where the human does the welding and the robot holds the objects that are to be united. A character-animation system and the software FAMOS are used to create a virtual simulation of the system. The aim is to give a sufficient representation of the human worker to perform collision, visibility and reach analysis and to include a biomechanical load analysis of the human in the simulation. However, these earlier efforts show limitations in the evaluation possibilities and the accuracy of the human model.

No current manufacturing simulation software are found that can perform HIRC simulations where robots and humans collaboratively work on a moving object. The following chapters describe the two tools needed to create a HIRC simulation and visualisation software; digital human modelling and robotic simulation.

2.3.1 DIGITAL HUMAN MODELLING SIMULATION

Digital human modelling (DHM) tools use computer manikins in a virtual CAD environment to simulate, visualise and optimise human workstation interaction with regard to ergonomic evaluation. There are a number of commercial DHM tools on the market with realistic representation of the human body, such as AnyBody (Rasmussen et al., 2002), Jack (Badler et al., 1993), RAMSIS (Seidl, 1997), SAFEWORK/DELMIA V5 (Fortin et al., 1990), Santos (Abdel-Malek et al., 2006). In the production development context all of the existing software products are complex to use and require expert knowledge and/or a substantial amount of time.
to produce a representative simulation output (Busch et al., 2013; Fritzsche, 2010). The need of a non-expert DHM software is one of the drivers in the current development of a new DHM software, Intelligently Moving Manikins (IMMA) (Hanson et al., 2011).

2.3.2 ROBOTIC SIMULATION

The standard industrial robot has six to seven degrees of freedom and is used in various applications in manufacturing industries, including welding, painting, assembly and materials handling in machining environments. One of the problems that users of industrial robots must overcome is the amount of time needed for programming. According to Pan et al. (2012), the manual programming time is approximately 360 times the execution time of a large welding process. Thus the main purpose of using robot simulation tools is to create programs off-line for industrial robots in a computerised environment and not waste value-adding production time with manual programming. In addition, the software is also used for optimisation of workspace layout and planning of robot tasks (Pan et al., 2012).

There are two types of commercial industrial robotics software solutions, specific ones developed by robot manufacturers and generic ones developed by large digital manufacturing software suppliers. Almost all robot manufacturers have their own specific robotic software, such as ABB’s RobotStudio, KUKA’s KUKA.Sim (Vollmann, 2002) and Motoman’s MotoSim. Some commonly used generic software programs are DELMIA (Brown, 2000), Robcad (Wan et al., 2007), RoboSim (Lee and ElMaraghy, 1990) and IPS (Tran, 2013). The general difference between the two types is that the generic ones have better data exchange possibilities than the specific ones. Robot-specific software usually has its own data format that cannot be used in any other system. The advantage of the generic ones comes with a higher cost for licenses (Pan et al., 2012).

2.4 OPTIMISATION IN ASSEMBLY WORKSTATION DESIGN

Optimisation techniques have been used in workstation design research for many years. The overall objective has for any company always been to optimise profit, and in workstation design that has resulted in operation time optimisation (Braun et al., 1996). In 1996 the design system, called EMMA, was introduced, which also included ergonomic considerations to the workstation design problem (Braun et al.). The best design was achieved through a manual iterative planning and evaluation process done by the designer. This human involvement implies that a mathematically optimal solution is not always possible to find.

Ben-Gal and Bukchin (2002) present a method to find the optimal layout considering economic and ergonomic goals by including the statistical techniques
of factorial experimentation and response surface methodology. Factorial experimentation is used to screen what workstation design factors influence the response, and then the response surface methodology is applied to fine tune the best values from the factorial experiments to get the optimal response. Ben-Gal and Bukchin considered four objectives in their workstation design example; a weight is put on each of them in order to find one optimised result. The DHM tools are introduced to the workstation optimisation problem in del Rio Vilas et al. (2013). They also put the predefined weights on the optimisation objective to solve the multi-objective optimisation problem.
This chapter introduces the methodological approach of the research. It also presents an overview of the research process and the individual studies performed. The chapter ends with a discussion of the quality of the research performed.

### 3.1 The Methodological Approach – Design Science Research

The research presented includes software development in the growing human–industrial robot collaboration area. The design science research (DSR) concept is used as a methodological approach since it describes how to perform, evaluate and present design science research in a clear manner (Hevner, 2007; Hevner et al., 2004). The aim of the DSR concept is to provide methods and practices that enable information systems researchers to conduct, evaluate and present design science research (Hevner et al., 2004).

Information systems can be defined as "an applied research discipline ... to solve problems at the intersection of information technology and organisations" (Peffers et al., 2007, p 46). This definition also corresponds to the research performed in this thesis. Figure 3 presents a simplified original framework developed for DSR as defined by Hevner (2004, p. 80).

![Figure 3: A simplified sketch of the design science research framework presented by Hevner (Hevner et al., 2004, p. 80). It presents the three main elements (in the bold frames) and the information flow between them (in the arrows).](image-url)
3. RESEARCH METHOD

This chapter introduces the methodological approach of the research. It also presents an overview of the research process and the individual studies performed. The chapter ends with a discussion of the quality of the research performed.

3.1 THE METHODOLOGICAL APPROACH – DESIGN SCIENCE RESEARCH

The research presented includes software development in the growing human–industrial robot collaboration area. The design science research (DSR) concept is used as a methodological approach since it describes how to perform, evaluate and present design science research in a clear manner (Hevner, 2007; Hevner et al., 2004). The aim of the DSR concept is to provide methods and practices that enable informational systems researchers to conduct, evaluate and present design science research (Hevner et al., 2004). Information systems can be defined as “an applied research discipline ... to solve problems at the intersection of information technology and organisations” (Peffers et al., 2007, p 46). This definition also corresponds to the research performed in this thesis. Figure 3 presents a simplified original framework developed for DSR as defined by Hevner (2004, p. 80).

![Figure 3: A simplified sketch of the design science research framework presented by Hevner (Hevner et al., 2004, p. 80). It presents the three main elements (in the bold frames) and the information flow between them (in the arrows).](image)

The framework in Figure 3 presents three main elements that are of importance in DSR, environment/application domains, design cycle of artefacts and knowledge.
base/foundations. These three elements have been useful in the research presented since an artefact (the demonstrator software) has been designed in order to meet demands from manufacturing industries (how to design HIRC systems). Existing knowledge from the academic field (biomechanical and time evaluations as well as optimisation technique theories) has been used in order to support the design process. The process has resulted in new demonstrator software that has been used to design a HIRC system in the manufacturing industry.

Hevner presents seven guidelines (Hevner et al., 2004, p. 83) to consider when performing DSR. They are design as an artefact, problem relevance, design evaluation, research contribution, research rigour, design as a search process and communication of research. The guidelines are not to be considered mandatory in all research, but they should be addressed in some manner for DSR to be complete. They have, however, been used as a support in this research process; the connection with the research performed is discussed in Section 3.3.

3.2 THE RESEARCH PROCESS

The research process can be described as a design project in simulation of HIRC. The process resulting in this licentiate thesis is presented in Figure 4 and described in this chapter.
These three elements have been useful in the research presented since an artefact (the demonstrator software) has been designed in order to meet demands from manufacturing industries (how to design HIRC systems). Existing knowledge from the academic field (biomechanical and time evaluations as well as optimisation technique theories) has been used in order to support the design process. The process has resulted in new demonstrator software that has been used to design a HIRC system in the manufacturing industry.

Hevner presents seven guidelines (Hevner et al., 2004, p. 83) to consider when performing DSR. They are design as an artefact, problem relevance, design evaluation, research contribution, research rigour, design as a search process and communication of research. The guidelines are not to be considered mandatory in all research, but they should be addressed in some manner for DSR to be complete. They have, however, been used as a support in this research process; the connection with the research performed is discussed in Section 3.3.

3.2 THE RESEARCH PROCESS

The research process can be described as a design project in simulation of HIRC. The process resulting in this licentiate thesis is presented in Figure 4 and described in this chapter.

Table 1 presents the connection between the research questions and the activities in the research process presented in Figure 4.

<table>
<thead>
<tr>
<th>RQ1: How can simulation, visualisation and evaluation of human–industrial robot collaboration be performed?</th>
<th>Literature study</th>
<th>Software develop.</th>
<th>Study A</th>
<th>Study B</th>
<th>Study C</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RQ2: How can human–industrial robot collaborative workstations be optimised?</th>
<th>Literature study</th>
<th>Software develop.</th>
<th>Study A</th>
<th>Study B</th>
<th>Study C</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RQ3: How can simulation, visualisation, evaluation and optimisation of human–industrial robot collaboration be applied in industrial heavy vehicle assembly workstation design?</th>
<th>Literature study</th>
<th>Software develop.</th>
<th>Study A</th>
<th>Study B</th>
<th>Study C</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>
3.2.1 Literature Search
The first task performed was a literature search in the area of human robot collaboration focusing on simulation of such systems. The aim of this search was to gather basic knowledge of the state of the art of human robot collaboration and simulation of such collaboration. The Discovery database at Mälardalen University was used; it covers several databases including IEEE Xplore, ScienceDirect, Scopus and Web of Science. The search method used was a systematic search (Rienecker and Stray Jørgensen, 2008), with the following search terms: “Robot AND (human OR man) AND (collaboration OR cooperation OR interaction) AND (manufacturing OR assembly)”.

In the articles found a chain search (Rienecker and Stray Jørgensen, 2008) was also made in order to find other interesting literature in order to make the review more comprehensive. This literature search has been performed continuously during the research project and has later been supplemented with searches in optimisation of workstation design by using “optimisation”, “workstation” and “workplace” in combination in order to answer research question 2.

3.2.2 Development of Software
The development of the software is divided into one general requirement and design activity and five different elements of the demonstrator software; “geometric HIRC simulation software programming”, “manual operation time evaluation”, “robotic operation time evaluation”, “biomechanical load evaluation”, and “optimisation of HIRC workstations”, as described in Figure 4.

The author of this thesis set out requirements on the design of the resulting demonstrator software. The geometric HIRC simulation software programming was one major part of this. The programming was performed by Fraunhofer-Chalmers Research Centre (FCC), with which the author had the opportunity to collaborate. The FCC group had already developed simulation tools in the robotic and ergonomic analyses areas. Their software developed for robotic simulation is Industrial Path Solutions (IPS) (Tran, 2013). It contains methods and algorithms to automatically generate collision-free assembly paths and has an industrial robot path planning optimisation feature. In the robotic simulation mode it can handle multiple industrial robots and evaluate optimal robot paths for each of them in their internal collaboration (e.g., welding of multiple car body positions). The ergonomics simulation software is called Intelligently Moving Manikins (IMMA) (Hanson et al., 2011). The IMMA software is developed to verify that a human can perform collision free assemblies in a manufacturing environment. The manikin in IMMA is built on a skeleton that consists of 81 segments connected by 74 joints resulting in 162 degrees of freedom as visualised in Figure 5.
The first task performed was a literature search in the area of human robot collaboration focusing on simulation of such systems. The aim of this search was to gather basic knowledge of the state of the art of human robot collaboration and simulation of such collaboration. The Discovery database at Mälardalen University was used; it covers several databases including IEEE Xplore, ScienceDirect, Scopus and Web of Science. The search method used was a systematic search (Rienecker and Stray Jørgensen, 2008), with the following search terms: “Robot AND (human OR man) AND (collaboration OR cooperation OR interaction) AND (manufacturing OR assembly)”.

In the articles found a chain search (Rienecker and Stray Jørgensen, 2008) was also made in order to find other interesting literature in order to make the review more comprehensive. This literature search has been performed continuously during the research project and has later been supplemented with searches in optimisation of workstation design by using “optimisation”, “workstation” and “workplace” in combination in order to answer research question 2.

3.2.2 DEVELOPMENT OF SOFTWARE

The development of the software is divided into one general requirement and design activity and five different elements of the demonstrator software; “geometric HIRC simulation software programming”, “manual operation time evaluation”, “robotic operation time evaluation”, “biomechanical load evaluation”, and “optimisation of HIRC workstations”, as described in Figure 4.

The author of this thesis set out requirements on the design of the resulting demonstrator software. The geometric HIRC simulation software programming was one major part of this. The programming was performed by Fraunhofer -Chalmers Research Centre (FCC), with which the author had the opportunity to collaborate. The FCC group had already developed simulation tools in the robotic and ergonomic analyses areas. Their software developed for robotic simulation is Industrial Path Solutions (IPS) (Tran, 2013). It contains methods and algorithms to automatically generate collision-free assembly paths and has an industrial robot path planning optimisation feature. In the robotic simulation mode it can handle multiple industrial robots and evaluate optimal robot paths for each of them in their internal collaboration (e.g., welding of multiple car body positions). The ergonomics simulation software is called Intelligently Moving Manikins (IMMA) (Hanson et al., 2011). The IMMA software is developed to verify that a human can perform collision free assemblies in a manufacturing environment. The manikin in IMMA is built on a skeleton that consists of 81 segments connected by 74 joints resulting in 162 degrees of freedom as visualised in Figure 5.

The two existing software solutions for robotic and human simulations were combined into one new geometric HIRC simulation software. Figure 6 shows a sketch of this process.

Figure 5: The IMMA male manikin, with mesh to the left and skeleton to the right. The white segments represent the links that are combined with the red spheres that represent the joints.

Figure 6: Sketch describing the merging of the existing software solutions IPS and IMMA into one.
From the literature search, ergonomic factors and productivity were identified as important factors in HIRC systems. Evaluation of these factors should be included in the demonstrator software. Ergonomic assessments were limited to biomechanical load calculations on the human, and productivity was evaluated through total assembly operation times. In order to make this possible the evaluation elements biomechanical load and manual and robotic operation time were included in the demonstrator software.

The calculations of the biomechanical load on the human were based on IMMA simulation, but developed solely by the author of this thesis. Manual operation time calculations were developed in the IMMA software during this research project, and were supported by the author of this thesis. Robotic operation time was included in the robotic software (IPS).

The last element in the demonstrator software, optimisation of a HIRC workstation, was developed separately from the other four. The optimisation problem is to find the best solution to a HIRC workstation design problem considering operation time and biomechanical load; it is described in Section 3.2.5.

The author of this thesis evaluated the total demonstrator software through industrial cases and developed the tool through an iterative process in each of the performed studies in collaboration with FCC.

3.2.3 STUDY A – HIRC SIMULATION, CASE A

The aim of Study A was to present a method for virtual evaluation of HIRC workstations (Ore et al., 2014). In this process the first version of the demonstrator software was developed. An industrial case was used as the base on which the work was evaluated.

A case at the heavy vehicle manufacturer was used for this purpose. The flywheel cover assembly station at the engine assembly factory had prior to this project been identified as a potential case to be used in another research project (collaborative team of man and machine, ToMM). It was of interest to simulate a HIRC in that station since there were potential ergonomic difficulties when new and heavier components were to be introduced at the same time as the station tact time needed to be reduced.

The HIRC geometric simulation software was developed by FCC in response to the demands stated by the author of this thesis. The demands came from the literature search and the needs in the specific industrial case. The initial demand from the author was that it “should be possible to simulate and visualise a human and a robot holding the same moving product (with the human controlling the motion). From
this simulation, values should be derived needed to make a biomechanical load analysis of the human as well as time assessments of the human and robotic motions”.

The assembly station was first designed in a standard CAD tool, in this case CATIA V5. The assembly station layout was imported into the software and the iterative development of the tool began. The author of this thesis performed simulations and gave immediate feedback to the programmer on issues to solve and how to develop the software further.

When the geometric simulation and visualisation could be performed, the focus changed to extracting the information needed to evaluate biomechanical loads and operation time. The observational posture assessment tool RULA (Rapid Upper Limb Assessment) (McAtamney and Corlett, 1993) was used to generate the biomechanical load assessments. The robotic operation time was obtained from the distance of each robotic axle together with the maximum speed of the axle. In order to consider acceleration and retardation, 80% of the maximum robotic axle speed was used in the calculations. An existing predetermined time standard method, SAM (Laring et al., 2002), included in the IMMA software was used in order to generate the human operation time.

RULA investigates the musculoskeletal injury risk on humans by evaluating the individual poses and assessing the injury risks of those positions on the human body (McAtamney and Corlett, 1993). It gives quantitative numbers on the risk of musculoskeletal injuries on a scale from one to seven, where a high score represents a higher injury risk. It was included in the demonstrator software to evaluate biomechanical load. It is performed through an Excel document where the human motions derived from IMMA are divided into a number of postures, each of which is expressed by 59 joint rotations. These postures are analysed through the Excel document to get a RULA score each. From all the poses a time-weighted average RULA score was calculated.

In order to evaluate the proposed benefits from literature of HIRC systems compared to manual assembly (increased productivity and lower ergonomic load), a comparative study was performed in the simulated assembly case. Three assembly scenarios, manual, robotic and HIRC, were analysed using two production parameters, biomechanical load and operation time.

3.2.4 STUDY B – HIRC SIMULATION, CASE B
A second industrial case was simulated with the aim to further develop the demonstrator software (Ore et al., 2015a). The process to reach this goal was similar to that in Study A; it consisted of iterative development of the demonstrator
software together with FCC. In this study the tyre assembly station of trucks was modelled and evaluated. The case was identified by the author as a potential station in which industrial robots could assist the human operator. It was chosen since the assembly line works continuously and is thus difficult to fully automate. In addition this specific station includes a large and clumsy manual lifting equipment that is in use today.

The main development from Study A was the time evaluations. The robotic paths were generated through the part of the IPS software that was developed to derive optimum robotic paths (Segeborn et al., 2014). From these paths the robotic times were obtained. In study B 70 % of the maximum robotic axle speed was used. The SAM evaluations included in the IMMA software were also improved through the author’s increased SAM knowledge. Thus the demonstrator software was further developed; it also evaluated three assembly scenarios with regard to the two production parameters. Ore et al. (2015a) presents both Case A and B and compare the results with these improved demonstrator software.

3.2.5 STUDY C – OPTIMISATION OF HIRC
The aim of Study C was to present a method for using optimisation techniques on HIRC simulations to design productive and healthy workstations (Ore et al., 2015b). The HIRC workstation developed in Study A (flywheel cover assembly) was used as a base for this work. The previously developed demonstrator software was used as a tool to collect the data on which the optimisation was executed.

A number of different optimisation problems were discussed, and the problem of finding the optimal handover position between robotic and human motions was chosen. The red curved plane in Figure 7 represents the possible area where the solution should be found. Figure 7 also presents the two variables Z and α visible together with the constrained distance (1.2 m) to the solution space.

Figure 7: Graphical representation of parameters and variables that create the solution space (visualised as a red curved plane).
The optimal solution should then consider both biomechanical load and operation time.

In order to find the optimal value of Z and α, a metamodel was created. Metamodels are used to approximate real systems through a finite number of computerised simulations of the factors. This saves simulation time compared to simulating a higher number of factors and also creates an understanding of the relation between the factors and their response (Simpson et al., 2001). This model was then optimised to find the best solution to the handover design problem.

The method used to address this optimisation problem is presented in Figure 8.

![Graphical representation of parameters and variables that create the solution space (visualised as a red curved plane).](image)

Figure 8: The optimisation method used in Study C.

14 pairs of factors in the solution space were randomly chosen through a Latin hypercube sample. These were simulated in the HIRC demonstrator software developed in Study B. The responses from the simulation were quantified results of biomechanical loads (through RULA scores) and total operation time (through robotic and SAM times). These responses were used to create two metamodels describing the connections of the factors (Z and α) to these two responses. These metamodels were developed using the DACE Matlab Kriging toolbox (Lophaven et al., 2002).

The metamodels were then used in the optimisation process. Since two conflicting objectives (biomechanical load and operation time) were considered in the optimisation problem, multi-objective optimisation techniques were used. The goal was to create a trade-off curve between biomechanical load and time, and for this the concept of Pareto-optimal solutions was used (Kasprzak and Lewis, 2000). In order to create this trade-off curve, a weighted sum objective function was created. This was then executed through multiple optimisation runs using a complex optimisation algorithm (Box, 1965) with 200 different weighting factors. The best combination between biomechanical load and operation time could then be chosen in the trade-off curve.
3.3 Research Quality

In this chapter the seven DSR guidelines are presented with their applications in the scope of this research. The role of being an industrial PhD student and the connection with the research area are also described in the text below.

3.3.1 Seven DSR Guidelines
This chapter describes how each of the seven guidelines defined by Hevner (2004) have been considered in order to ensure the quality of the research process.

Guideline 1: Design as an artefact
The resulting artefact from the research presented is a demonstrator software solution developed to virtually evaluate HIRC workstations. The demonstrator includes a geometric simulation software as well as evaluation methods used to derive time and biomechanical load data. The method of how to apply the software in HIRC workstation design is also a resulting artefact. In Study C the artefact is the actual method applied in order to create optimal solutions to a multi-objective HIRC workstation design problem.

Guideline 2: Problem relevance
The demonstrator software met previously unsolved problems in the design of HIRC workstations. With the tool it is possible to simulate HIRC in hand-guiding environments. Even though large industrial robots cannot perform these collaborative tasks with current legislation, it is possible to use the demonstrator software to design systems where smaller, power- and force-limiting robots collaborate with humans. The relevance of the problem used in Study C is to visualise how the optimisation method can be used to support in HIRC production system design.

Guideline 3: Design evaluation
The demonstrator software is evaluated through real industrial cases where HIRC workstations are designed and compared on specific measures (biomechanical load and operation time). The quantitative results from the software or the multi-objective optimisation have neither been evaluated nor compared with data from physical experiments. These evaluations are difficult to perform since the physical workstations cannot be implemented in practice in the industry due to personal safety legislation.

Guideline 4: Research contribution
This research contributes with a design artefact, the demonstrator software, used to simulate HIRC workstations. In addition, a method to perform the actual simulations is also presented. The HIRC optimisation study (Study C) contributes
with a method for how to solve similar multi-objective problems. An additional contribution is the definition of the new term human–industrial robot collaboration (HIRC). The term is also categorised in the previously defined terms human–robot interaction (HRI) and collaboration (HRC) environments.

**Guideline 5: Research rigour**

To get the desired output from the demonstrator software, scientifically established methods have been incorporated in the design, RULA for biomechanical load assessment (McAtamney and Corlett, 1993) and SAM for time predetermination of work tasks (Laring et al., 2002). In the third study established optimisation methods were used: creation of metamodels through the DACE Matlab Kriging toolbox (Lophaven et al., 2002) and complex optimisation algorithms (Box, 1965).

**Guideline 6: Design as a search process**

The iterative nature of the design process is a natural part of the research performed. The demonstrator software has evolved from a number of iterations between the author of this thesis and FCC. The actual optimisation technique used (the complex optimisation algorithm) is a search method in itself used to find optimum numerical values.

**Guideline 7: Communication of research**

The research has been presented in various forms to different groups; to academia in the form of papers and conference presentations, to industrial partners in the real case evaluations and to research colleagues in a number of presentations.

3.3.2 **Being an industrial PhD student**

The author is an industrial PhD student at the heavy vehicle manufacturer where the simulated cases used originated, a company that has been his employer for more than ten years. This offers a number of benefits and access to the company, but this can also be a problem in the context of research. It can in many cases be problematic to see beyond the company and its values and perform the research critically against this background. However, in the specific work presented in this thesis, these challenges are not as critical since the research field is new and no preconceived ideas in HIRC are incorporated in the company. The benefit of having access to the whole company for potential cases still remains.

3.3.3 **Connection with the research area of innovation and design**

The research performed was conducted in the context of the Innofacture research school and in the research area of innovation and design, which is the area of examination. The objective of this research is to develop a demonstrator software solution that simulates, visualises, evaluates and optimises HIRC in a heavy vehicle assembly environment. Such software is novel since it cannot be found in
commercialised products or in the research papers presented, and thus the resulting demonstrator software is considered to be innovative. The process of developing the demonstrator is a design process in which the software is the artefact that is designed.
4. **RESEARCH FINDINGS**

This chapter presents the empirical and theoretical results from the research project. The HIRC definition is introduced, as well as the resulting demonstrator software. The results from the individual simulated cases are also presented.

4.1 **HIRC DEFINITION**

This thesis introduces the term human–industrial robot collaboration (HIRC). It is based on the HRC (human robot collaboration) term but limits the collaborative robots to industrial robots. HIRC represents systems in which humans and industrial robots share workspace and collaborate towards a common goal. These systems are also included in the HRC term, but HRC includes a wider selection of robots than HIRC, thus HIRC is a subset of HRC. This classification is described in Figure 9, which is a developed version of Figure 1 and includes definitions and application examples of HRI (human robot interaction), HRC and HIRC.

![Figure 9: Definition of HIRC, HRC and HRI and application examples.](image-url)
4.2 HIRC DEMONSTRATOR SOFTWARE AND METHOD

The HIRC demonstrator software was developed during the whole research process. Figure 10 shows the simulation and evaluation elements that are included. It also presents in what software the simulation and evaluations are performed.

Figure 10 shows the five elements of the demonstrator software. More information is needed on how to apply them all in a HIRC simulation, including how to manage the data transfer between all these elements. Figure 11 presents the method developed in this research on how to apply the HIRC demonstrator software.
The HIRC demonstrator software was developed during the whole research process. Figure 10 shows the simulation and evaluation elements that are included. It also presents in what software the simulation and evaluations are performed.

![Figure 10: The five elements included in the HIRC demonstrator software.](image)

The method is described in the following text. First a 3D CAD drawing of the assembly station is needed. It can either be imported from existing layout software in the company or be modelled manually. The layout is imported to the software in WRLM format.

The next step is to import the robot model. Any type of serial industrial robots can be used. The existing robot skeleton has to be dressed by the individual robot’s own 3D wireframes that are available from the homepages of the robot suppliers. The layout and the exact robot position have to be optimised in order to make it possible for the robot to reach the handling positions.

The manikins are then to be imported in the software. Currently the Swedish anthropometric database is used (Hanson et al., 2009). A family of manikins can be simulated in order to get accurate representations of the human anthropometric diversity.

In the research presented, three assembly scenarios are evaluated, human, robotic and HIRC. The individual tasks to perform in each of these has to be defined.

Then the geometric simulations are performed. In this process collision-free paths for all three assembly scenarios are created in the IPS software. These robotic motions and object paths are imported into the geometric simulation software.

In the next step the production design parameters will be evaluated and analysed.
Biomechanical load on the human has in this work been evaluated through RULA calculations performed with data from the human simulation in an Excel spreadsheet. Total operation time has been calculated through robotic times and human predetermined time standard SAM, both of these included in the simulation software IPS and IMMA.

The last step in the demonstrator method is the optimisation. This step is not included in Studies A and B and can be excluded from the method when a mathematical optimisation of a HIRC system is not required. Study C resulted in a method to use in multi-objective optimisation problem solving (Ore et al., 2015b). Figure 12 presents this method graphically.

![Diagram of optimization process](image)

**Figure 12: Method used in the multi-objective optimisation problem in Study C.**

The first activity in Figure 12 is data collection/simulation and this includes the HIRC demonstrator simulation method presented above. A number of different design parameters are chosen as input factors in these simulations. The results from the simulations are denoted responses and are together with the factors the input to the next activity, i.e. metamodelling. A numerical model representing the factors and their responses is created in this activity. The resulting metamodel is then used in the following optimisation activities. The multi-objective optimisation problem in the case presented is then addressed and solved through a weighted sum approach, resulting in a trade-off curve with Pareto-optimal solutions.
4.3 **HIRC APPLICATION**

This chapter describes the results from the two industrialised cases that are simulated, visualised, evaluated and optimised with the HIRC demonstrator software.

4.3.1 **RESULTS FROM CASE A**

Case A was used in two studies, A and C. In Study A, a first version of the demonstrator software was developed. It was done with the flywheel cover assembly industrial case as a base. This case is presented in paper A (Ore et al., 2014). Figure 13 visualises the HIRC assembly motion simulated in the demonstrator software.

![Figure 13: Visualisation of HIRC simulation of Case A, to be read from A to D.](image)

The quantified results from the simulations with respect to the production parameters operation time and biomechanical load are presented in Table 2. The results presented here are updated numbers on the flywheel cover assembly station presented in Paper B. That paper includes both HIRC simulation cases. Since the demonstrator software had been further developed in Study B, there was a need for a new simulation of the flywheel cover assembly station.
Study C resulted in a trade-off curve showing Pareto-optimal solutions to the multi-objective optimisation problem, Figure 14. This is presented in paper C (Ore et al., 2015b).

Each of the black dots in Figure 14 represents optimal solutions to the metamodel with different weights on the operational time function and the RULA function. All of them can be traced back to a position on the solution space visible in Figure 7. In Figure 14 the best solution to the HIRC problem is then selected, depending on the preferences of importance of RULA compared to time of the decision makers. The red star corresponds to one solution that can be considered to be the “optimal” one and it is corresponding factors are visualised in Figure 15.
Table 2: Results from simulation of flywheel cover assembly station

<table>
<thead>
<tr>
<th></th>
<th>Human</th>
<th>HIRC</th>
<th>Robot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (s)</td>
<td>25.7</td>
<td>14.5</td>
<td>11.6</td>
</tr>
<tr>
<td>RULA</td>
<td>4.5</td>
<td>4.1</td>
<td>-</td>
</tr>
</tbody>
</table>

Study C resulted in a trade-off curve showing Pareto-optimal solutions to the multi-objective optimisation problem, Figure 14. This is presented in paper C (Ore et al., 2015b).

Figure 14: Trade-off chart presenting Pareto-optimal solutions in the selection between time and RULA.

Each of the black dots in Figure 14 represents optimal solutions to the metamodel with different weights on the operational time function and the RULA function. All of them can be traced back to a position on the solution space visible in Figure 7. In Figure 14 the best solution to the HIRC problem is then selected, depending on the preferences of importance of RULA compared to time of the decision makers. The red star corresponds to one solution that can be considered to be the “optimal” one and its factors are visualised in Figure 15.

Figure 15: Visualisation of one “optimal” solution to the multidimensional optimisation problem presented in Study C.

4.3.2 RESULTS FROM CASE B
Case B was used in one study, B. In Study B, the development of the demonstrator software from Study A was continued, with the truck tyre assembly as an industrial case; this is presented in paper B (Ore et al., 2015a).

The resulting motion from the HIRC simulation for Study B is presented in Figure 16.
Figure 16: Visualisation of HIRC simulation of Case B, to be read from A to D.

The quantified results from the simulations are presented in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>Human</th>
<th>HIRC</th>
<th>Robot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (s)</td>
<td>14.8</td>
<td>9.8</td>
<td>5.7</td>
</tr>
<tr>
<td>RULA (-)</td>
<td>3.3</td>
<td>3.0</td>
<td>-</td>
</tr>
</tbody>
</table>
5. DISCUSSION

This chapter discusses the results of the research in a broader context in connection with the three research questions. This is followed by a discussion regarding the HIRC term as well as the need of simulation of HIRC. Also a wider discussion covering HIRC at a more general level is presented. The chapter ends with a text discussing the research method chosen.

5.1 SIMULATION OF HIRC WORKSTATION

RQ1: How can simulation, visualisation and evaluation of human–industrial robot collaboration be performed?

The first research question is answered by Studies A and B, introducing one demonstrator software. Figure 10 and 11 summaries the demonstrator software and presents a method on how to apply it. The four first elements “geometric HIRC simulation”, “biomechanical load evaluation”, “manual operation time evaluation”, and “robotic operation time evaluation” from Figure 10 are together with the first six steps in the HIRC simulation method in Figure 11 discussed below.

5.1.1 GEOMETRIC HIRC SIMULATION

The geometric HIRC simulation part of the demonstrator software is the centre on which all evaluations are based. It is also a combination of the software solutions IMMA and IPS.

The IMMA software manikin is developed to predict and validate industrial assembly tasks (Hanson et al., 2011). The motions generated from the IMMA software visualise one possible option to perform the task. The motion is achieved through a comfort function where IMMA constantly calculates the posture with the lowest penalty, based on human biomechanical loads (Bohlin et al., 2012). The function takes kinematic constraints, balance, contact forces and collision avoidance into consideration. The resulting manikin motion can then be evaluated with regard to time and the ergonomic evaluation method of interest in the industrial case and answer whether it is possible to perform the task in the time available and with acceptable ergonomic load. There are other possible motions for a human to use in order to complete the task, but the IMMA software presents one that is preferred considering the penalties on the joints of the manikin. This single possible motion is enough in order to judge the biomechanical load on the operator early in the production design process. This IMMA functionality is implemented in the HIRC demonstrator.
The other software included in the HIRC demonstrator is IPS, that include the robotic simulation. Robotic kinematics and dynamics are combined with collision avoidance and optimisation algorithms in order to create the best robot path to solve the current handling problem (FCC, 2015).

5.1.2 BIOMECHANICAL LOAD ANALYSIS
Biomechanical load is evaluated in order to assess the ergonomic factors in the assembly workplace. A commonly used method to analyse biomechanical load on operators in industry is to use observational posture assessment methods (Genaidy et al., 1994). These are developed to analyse a work operation by evaluating postures of the human body when performing tasks. The posture assessment methods are well suited to be used in computerised simulations when the positions of the body segments can be derived from the software in quantitative numbers.

A number of different posture observation methods are used in the industrialised environment; OWAS (Karhu et al., 1977), RULA (McAtamney and Corlett, 1993) and REBA (Hignett and McAtamney, 2000) are some of the most commonly used in industry (Kee and Karwowski, 2007). RULA was chosen since it is a widespread, easily accessible, method and focuses on the upper body motions (as the IMMA software also does). Another company-specific observation method for evaluating biomechanical load is used at the heavy vehicle manufacturer. It is a method that combines a number of different ergonomic evaluation methods into a tool that aims to cover a broad spectrum of ergonomic considerations and presents the result in traffic light form (red for high risk of strain problems, yellow to indicate that further inspection might be needed and green for low risk of strain problems). This tool has not been used for the evaluation since it has not been academically verified or published. The individual evaluation methods of this company-specific observational approach cannot be combined into general results regarding the total biomechanical load on the humans without methodical demonstration of the accuracy of the results. Since this is lacking, the RULA method has been used to evaluate biomechanical load instead of the company-specific method.

RULA has (together with the other observational methods presented above) the weakness that it does not include time as a factor. Its calculations are based on static human poses. Time is nevertheless of great importance in musculoskeletal injury evaluation. A lightweight task performed in a suitable pose can be dangerous from an injury point of view if it is highly repetitive (Punnett and Wegman, 2004). A search for biomechanical observational methods that also include time as a factor will be conducted in future research studies.
Another common weakness of the observational methods mentioned above is that they were developed to assess human joint angles though manual observations. Thus the exact angular values of human joints cannot be assessed. In the DHM software the joint angles are defined by deterministic values. This results in a possibility to distinguish between, for example, zero and minus one degree of neck rotation in the Y direction (moving the head slightly upwards in a nodding motion). The difference in RULA evaluation value between these two cases is huge and greatly affects the total RULA score. This problem shall be addressed in future research.

5.1.3 Manual operation time evaluation
Productivity improvements are in this thesis evaluated through operation time assessments. Human operational time is generated in the demonstrator software from the predetermined time standard SAM. It is based on the detailed MTM-1 (methods-time measurement) method (Maynard et al., 1948) but groups several MTM-1 movements into one SAM movement (Laring et al., 2002). The resulting times are less precise than the original MTM-1 standard but SAM requires less data and shorter calculation time. The 59 different joint data derived from the IMMA software in each posture are suitable to use in the SAM evaluations in the full-body simulations performed in this work.

The SAM system is incorporated in the demonstrator software. There are, however, still improvement potentials in the implementation of SAM in the software in performing HIRC motions (e.g., how to calculate time for walking while preparing to grasp an object) that need to be further developed in the future.

5.1.4 Robotic operation time evaluation
In sole-robot motions the operation time is accessed from the robotic simulation software IPS. The software creates optimum robotic motion paths (Segeborn et al., 2014) and returns the total robotic handling time in the simulations. The inputs in these simulations are the robotic joint velocities, and maximum speeds are collected from the robot supplier’s homepage. These maximum speeds are seldom used in practice. In order to reduce stress on the robots and limit wear of the equipment, the robots are not pushed to their speed limits. There are also acceleration and retardation times in each of the robotic joints to consider. In the research presented, 80 % (Study A) and 70 % (Study B) of the maximum speed were used as the robotic speed. Further discussions with practitioners have resulted in even lower values. In future simulations approximately 50 % joint speed will be maintained in handling tasks and as low as 5 % for the last decimetre before reaching a pick or place position (these have not yet been implemented in any simulations presented in this thesis).
5.1.5 HIRC SIMULATION METHOD

The first version of the initial six steps in the method described in Figure 11 has been developed through the two HIRC simulations performed. In both these cases three assembly scenarios have been evaluated, human, robotic and HIRC. The six-step method has to be adjusted if there are other demands on a future HIRC simulation. The steps presented are discussed in the following text.

The first step includes creation of a CAD model of the assembly station. The ideal solution would be to use existing 3D layout drawings of the station. One of the ideas behind the widely spread digital factory concept is to create information once and reuse it where needed (Kühn, 2006). Currently the accuracy of the layout drawings available in the manufacturing company is not high enough. They also lack some 3D characteristics and other workstation information. This is the reason why a separate task of creating a CAD model of the assembly station is included in the method.

The second step includes importing the robot model. Currently is it only possible to use one serial robot in the HIRC simulations. This will be further developed in future research. Use of multiple industrial robots is one part of this work. Parallel and gantry robots are also of interest to incorporate in further HIRC simulations.

The third step includes importing the manikins in the workstation. In the simulations performed only one manikin was used, a 50th percentile male from a Swedish anthropometric database (Hanson et al., 2009). In future work manikin families will be included in the simulations. Through these families the workstation can be designed to fit a group of operators, not only the male median. In the future it will also be interesting to simulate HIRC workstations with multiple manikins.

The fourth step includes defining the human, robotic and HIRC tasks in the assembly. In the examples simulated in this research the value-adding tasks were performed by the human and the non-value-adding tasks by the robot, as described by Unhelkar et al. (2014). The area of task allocation between human and machine is a huge research field in itself. The MABA-MABA list from the 1950s discusses what men are better at and what machines are better at (Fitts, 1951). This task allocation will be investigated further in future research. This could be included in the HIRC optimisation problem: what is the optimal work division between human and industrial robot?

The fifth step is to create the simulation. Today both the IMMA and the IPS software are used and the data is transferred between these systems. In the future these software solutions will be merged into one, facilitating the simulation process.
The sixth step includes the time and biomechanical load evaluation, as these two parameters have been identified as two of the most important in a HIRC workstation. Biomechanical load is evaluated through RULA, human time through SAM and robotic time through the maximum speeds of the robot axis.

5.2 Optimisation of HIRC Workstations

RQ2: How can human-industrial robot collaborative workstations be optimised?

The answer for research question two are also presented in Figure 10 and 11, and finalise the demonstrator software and the work method applying it.

Study C uses the demonstrator software developed in Studies A and B to include optimisation techniques in the workstation design issue. As discussed in Ore et al. (2015b), there are a number of optimisation problems in HIRC workstation design that all can be met through the geometric simulation software. Workstation layout, task allocation and assembly sequence are all problems that can be optimised. In all of these the geometric simulation and the evaluation elements of the demonstrator software can be used to create mathematical models of how the input (factors) effects the output (responses) in the HIRC systems. These models are called metamodels and can then be optimised. In Study C another workstation design parameter was optimised, the handover position between the human and the industrial robot. The result is an optimal handover position in the specific case, but more interesting a method of how to perform multi-objective optimisation of a HIRC workstation design problem with operation time and biomechanical load as conflicting objectives. This method is presented in Figure 12.

In the case presented a kriging approximation is created based on 14 pairs of factors and their corresponding responses through the DACE-Matlab Kriging toolbox (Lophaven et al., 2002). There are other methods to create the metamodel; a review of metamodels by Wang and Shan (2007) summarises these. Wang and Shang also state that “there is no conclusion about which model is definitely superior to the others” (Wang and Shan, 2007, p. 418). The metamodel created in Study C was validated through comparing simulated results with the metamodel, resulting in 97.9 % accuracy. These results are considered to be accurate enough and the metamodel can be used to represent the HIRC system.

These metamodels were then used to create a trade-off curve of the multi-objective optimisation problem. A weighted sum approach with 200 weight factors and the complex optimisation algorithm (Box, 1965) was used to create this. Figure 14 shows the Pareto-optimal trade-off curve presenting approximately the 50 most
optimal solutions. The other 150 responses are worse than the results presented in Figure 14.

The benefit of this method compared with the multi-objective optimisation methods presented in the frame of reference chapter is that the relative importance of each of the objectives can be determined after the trade-off curve has been developed. In both Ben-Gal and Bukchin (2002) and del Rio Vilas et al. (2013) this is done before the multi-objective optimisation problem is solved. The importance of this is particularly visual in the case presented, as the Pareto-optimal solutions in Figure 14 show little difference in the biomechanical RULA score. From this figure it is obvious that choosing the most preferable time does not affect the biomechanical value to any significant extent, and in this case the selected value marked by a red star in Figure 14 represents a valid selection in order to get the optimal solution.

It is not correct to describe a solution gained from metamodels to be an optimal solution to an existing practical problem. The solution is optimal from the metamodel point of view. In this case was the accuracy of the model calculated to almost be 98%, good enough to say that it represents the real system, but there might be other solutions that are slightly more optimal in the industrialised setting.

Studies A and B can also be said to be used to create optimal systems as they both present manually optimised solutions to the workstation design problem (e.g., task allocation selection, positioning of the robot and selection of handover position). In these studies, heuristics are used to find a good solution to a design problem, but the solutions cannot be defined as mathematical optimal solutions. This manual selection lacks the numerical evaluation among all possible solutions. Optimisation as described in Study C focuses on use of numerical optimisation techniques.

**5.3 Application in Industrial Assembly Workstation Design**

*RQ3: How can simulation, visualisation, evaluation and optimisation of human–industrial robot collaboration be applied in industrial heavy vehicle assembly workstation design?*

In all simulations, visualisations, evaluations and optimisations performed in this research, industrial practical cases have been used as applications to develop the demonstrator software. This has been a vital part of the development for multiple reasons. One is that the author is an industrial PhD student with close connections to the heavy vehicle manufacturer and uses that opportunity to connect the research to practical cases. One other reason is that it is easier to discuss the software development based on an industrialised case rather than on an imaginary problem.
This use of industrialised cases is also a vital part in the design science research concept, which highlights the need of solving real industrial problems.

5.3.1 **Other applications than assembly**

Both cases presented in this thesis were performed in a heavy vehicle assembly environment. However, it ought to be possible to generalise the result from this research to other fields than heavy vehicle assembly. For instance, in their master thesis in the spring of 2015, with the author of this thesis as their supervisor, two students have shown examples of a wider use of the software. They have used cases from machining and logistic environments in the same heavy vehicle manufacturing company to highlight that the possibilities of HIRC simulation extend the assembly environment (Caliskan and Khalid, 2015). The aim of future work is to include cases from other manufacturing branches than heavy vehicles.

5.3.2 **Use of the optimisation method outside the HIRC problem**

The optimisation method presented in this thesis could be used to solve other multi-objective optimisation problems using metamodels. If the optimisation problem has two variables and two conflicting objectives, the method can be applied directly. Traditional workstation design problems can be described in such terms. However, in practice, most workstation design problems (including most HIRC problems) include more than two variables. In such cases the metamodel cannot be visualised as in this study. In addition, to be able to present the trade-off curve visually (Figure 14), the number of objectives in the multi-objective optimisation problem does not exceed three (it is not possible to visualise a Pareto frontier in a four-dimensional graph).

5.4 **HIRC workstations in a wider context**

This chapter discusses HIRC in a wider context. First the term HIRC is discussed in connection with the simulations. Then potential implementations in manufacturing industries and the need of HIRC simulations of these systems are further discussed.

5.4.1 **HIRC definition and operation modes**

The HIRC term introduced is required to distinguish the industrial problem addressed from other types of human-robot collaboration. Figure 15 describes this connection between HIRC, HRC and HRI, where HIRC is a subset of HRC, which in turn is a subset of HRI. Thus there are no clear-cut boundaries between these three terms, but since total research in human–robot interaction and collaboration is growing there is a need to distinguish the industrial robots collaboration from humanoid and service robots.
HIRC systems are classified according to the ISO 10218 standard into four operation modes, safe-related monitored stop, hand guiding, speed and separation monitoring, and power- and force-limiting (ISO, 2011b). All these classes require different technical solutions and challenges, and it is important to differentiate between them in the discussion of HIRC systems. The collaborative assembly in both simulated cases in the thesis presented can be categorised as a hand-guided collaborative assembly, since both require a human to guide a robot grasping an object.

The fourth operation mode, power- and force-limiting systems, is actually realised in a few industrial environments, which are discussed below.

5.4.2 REALISATION OF HIRC WORKSTATIONS

A common question that often arises in the discussion of HIRC systems is when these systems can be installed and used in running production in the manufacturing industries. The simple answer is today or in many years from now, depending on what operation mode is considered. In Section 2.1 an industrially installed Universal Robot in a fenceless environment at Volkswagen was presented. Another example of HIRC systems existing today is the coolant expansion tank assembly at Audi in Germany (Audi, 2015). An industrial robot has been installed in a fenceless environment and assists the human operator in picking the coolant expansion tank from a large materials box (Figure 17).

![Figure 17: An example of a HIRC installation in running production from the assembly plant of Audi AG in Ingolstadt, Germany (Audi, 2015).](image)

This task was previously performed by the operator, resulting in frequent back-bending operations with a risk of future back problems. These two examples from
Volkswagen and Audi have been implemented in the current machine directory and robotic safety standards. These systems can, according to ISO 10218, be categorised into “power- and-force limiting systems”, in which the robot is designed to be weak and harmless to a human that may interfere with the robotic motion. Both systems are equipped with force sensors that detect when an object interferes with it and automatically stop the motion.

5.4.3 NEED FOR HIRC SIMULATIONS

Even before the personal safety issues have been resolved and hand-guided work tasks are possible, HIRC systems are developed, as described above.

It would also be beneficial to use HIRC simulation software to evaluate the workstation in the more simplified HIRC solutions from Volkswagen and Audi. It is, however, possible to simulate the industrial examples above in two separate software programs, one DHM tool and one robotic simulation tool.

But when the HIRC research has continued and the personal safety issues have been resolved, the need to design more complex HIRC systems will increase. These systems are difficult to simulate through physical prototypes since that requires building the full workstation in advance and most often outside the production area, since otherwise it would disturb running production. From the HIRC simulation software it is possible to evaluate the human and robotic work area, to position the robot and its surrounding, create off-line robot programs, evaluate the human and robotic operation time, assess biomechanical loads, compare different task allocations between human and robot and optimise the total layout. All these evaluations would demand considerable efforts in terms of time and money if performed without a HIRC simulation software.

5.4.4 HIRC RELATIVE INDUSTRIAL CHALLENGES

The general aim of the HIRC workstation presented in the introduction of this thesis, to address global competition and demographic change problems through transforming assembly stations from manual to HIRC stations, is supported by the results from the two simulated industrial cases. In order to meet global competition, productivity improvements are constantly needed. In this thesis productivity has been measured by operation time. And since total operation time has decreased in the collaborative systems compared with the manual ones, productivity has increased. Demographic change results in an older workforce. This group demands more ergonomic workstations in order to stay healthy. In this thesis this has been measured through biomechanical loads on the human. Compared with the manual assembly stations the biomechanical load has decreased in the collaborative stations, thus resulting in workstations better suited to an elderly workforce.
However, both productivity and ergonomics include many other parameters. Productivity measurements also include cost for purchasing, manpower, maintenance, space utilisation as well as assessments of mean time between failures. Ergonomic measurements include, for example, personal and organisational psychology, cognitive loads and work area lighting. None of these factors have been considered in this thesis.

There are other parameters of importance in HIRC design, such as flexibility of human performance, need of tactile sense, technical limitations and requirements arising from risk assessments. These are difficult to consider in HIRC simulations and have not been considered in the work presented.

The presented demonstrator software enable possibility to verify the vision the vision described by Tan et al. (2009, p. 29) as “…a dream combination of human flexibility and machine efficiency”. It is possible to quantify and evaluate the HIRC workstation designs and compare them with manual and automatic workstation designs, even though these evaluations are performed with simulated values. The cases presented in this thesis validate the Tan’s dream compared to manual, but not compared to the automatic workstations. As discussed above more parameters than biomechanical load and operation time are needed to be able to make a complete comparison.

The presented demonstrator software closes the gap in simulation possibilities of HIRC workstations in hand-guided environments. Two possible reasons why this gap exists are personal safety legislation and demands on DHM software. With current safety legislations are hand-guided collaboration between humans and industrial robots not possible to implement in industry today. The other reason are the high demands on the DHM software. In order to make full use of the simulations the manikin must represent an accurate model of a human. This puts high demands on the simulation software and implies that only advanced DHM tools can be used in the simulations. This limits the number of possible software developers.

A clarification of the goal of the research presented is a suitable way to conclude this discussion regarding HIRC workstations. The aim of this research is not to promote HIRC systems in all kinds of environments but to get quantifiable numbers on production system design parameters used to compare and evaluate these systems.

5.5 RESEARCH METHOD DISCUSSION

This subchapter discusses the research method applied. It focuses on the design science research that has been used as a methodological framework.
5.5.1 Use of Design Science Research

In the research presented the design science research (DSR) framework has been used in order to ensure the validity and reliability of the research. In particular seven guidelines are considered in the research process. Narrowing DSR down to these seven guidelines can be considered as a limitation in the application of DSR. A more general DSR process model is described in Peffers et al. (2007), which also includes the different research entry points in a research process. The simplified DSR guidelines are, however, used in this research since they provide easy assistance in the process of connecting the research with a scientific method.

Analysing the use of the individual guidelines (Section 3.3.1) shows that some of them have been included to a higher extent than others. One guideline with a weaker connection with the research is “design evaluation”, in which the results from the simulated cases have not been compared or evaluated with practical industrialised cases. The reason is that these systems cannot be implemented in practice due to current safety standards. However, there are plans to build a demonstration station in a laboratory environment in the future, and this will then be used for evaluation of the HIRC simulations.

Another interesting factor of the DSR framework described in Figure 3 is that it corresponds well with the process of being an industrial PhD student. Interpreting the “design cycle of artefacts” as the process of the PhD student research project, gives an interesting picture. It shows that the research project has to solve practical problems from the industry by using applicable research methods. The result from the research shall then make both academic and industry contributions. Through this wide interpretation of the “design cycle of artefacts”, the presented industrialised PhD student project and process can be described through this DSR framework.
6. CONCLUSION AND FURTHER RESEARCH

This chapter presents the major conclusions drawn from the research. It also includes academic and industrial relevance as well as a suggestion on how this work can continue in the further work aiming at a doctoral thesis.

6.1 CONCLUSION FROM THE RESEARCH

The general conclusion from the research performed is that it is possible to simulate, visualise, evaluate and optimise HIRC workstations through the presented demonstrator software solution. With this software it is possible to design the future assembly workstation that can be used to meet the globalisation demand for higher productivity as well as future demographic changes for manufacturing industries in the developed countries.

6.2 ACADEMIC AND INDUSTRIAL CONTRIBUTIONS

The main academic contribution is the demonstrator software itself. It combines a number of different research contributions into one tool. At the centre is the geometric simulation, which consists of the digital human modelling tool IMMA and the robotic geometric simulation software IPS. Together with other scientific methods (biomechanical load evaluation, operation time evaluation, and mathematical optimisation techniques), the tool can be used to design HIRC workstations. The demonstrator software needs to be further developed before it can be used in a wider context.

The definition of the HIRC term is another academic contribution. It can help to distinguish human collaboration with industrial robots from other types of collaborations, with humanoid or service robots.

The demonstrator software is also a part of the industrial contribution. Through it the HIRC systems can be designed early in the production design process. However, a number of issues have to be resolved before the software can make a major impact in the industries. One is that the maturity of the software has to increase through further development in order to make it a tool that could be used in industry. One other obstacle is current safety legislation, which makes it impossible to install HIRC systems in hand-guided environments. However, there is still a need to combine humans and industrial robots in other collaborative workstations where human and robots already share workspace, e.g., in power- and force-limiting systems. In these systems can the software be used in order to do efficient workstation designs.
6. CONCLUSION AND FURTHER RESEARCH

This chapter presents the major conclusions drawn from the research. It also includes academic and industrial relevance as well as a suggestion on how this work can continue in the further work aiming at a doctoral thesis.

6.1 CONCLUSION FROM THE RESEARCH

The general conclusion from the research performed is that it is possible to simulate, visualise, evaluate and optimise HIRC workstations through the presented demonstrator software solution. With this software it is possible to design the future assembly workstation that can be used to meet the globalisation demand for higher productivity as well as future demographic changes for manufacturing industries in the developed countries.

6.2 ACADEMIC AND INDUSTRIAL CONTRIBUTIONS

The main academic contribution is the demonstrator software itself. It combines a number of different research contributions into one tool. At the centre is the geometric simulation, which consists of the digital human modelling tool IMMA and the robotic geometric simulation software IPS. Together with other scientific methods (biomechanical load evaluation, operation time evaluation, and mathematical optimisation techniques), the tool can be used to design HIRC workstations. The demonstrator software needs to be further developed before it can be used in a wider context.

The definition of the HIRC term is another academic contribution. It can help to distinguish human collaboration with industrial robots from other types of collaborations, with humanoid or service robots.

The demonstrator software is also a part of the industrial contribution. Through it the HIRC systems can be designed early in the production design process. However, a number of issues have to be resolved before the software can make a major impact in the industries. One is that the maturity of the software has to increase through further development in order to make it a tool that could be used in industry. One other obstacle is current safety legislation, which makes it impossible to install HIRC systems in hand-guided environments. However, there is still a need to combine humans and industrial robots in other collaborative workstations where human and robots already share workspace, e.g., in power- and force-limiting systems. In these systems can the software be used in order to do efficient workstation designs.
The optimisation method presented in the research is also an industrial contribution. It is also possible to use this method to optimise other multidimensional production systems than HIRC.

6.3 Future research

Further development of the demonstrator software is required before it can be a commercial tool used in industry. The demonstrator software consists of five individual elements and the data transfer between them has to be improved in the future. In Chapter five a number of improvement issues have been identified and these must also be considered in the future research:

- A biomechanical observational method that also includes time as a factor should be included.
- In the selection of new biomechanical method shall also the current problem in RULA with deterministic limits between a good and very bad postures be considered.
- The SAM standard implemented in the demonstrator software must be improved.
- It should be possible to use multiple industrial robots or humans in the simulations.
- Parallel and gantry robots should be included in future simulations.
- Manikin families should be included in future simulations.
- Optimisation of task allocations between human and industrial robot shall be included in the HIRC optimisation problem.
- Include cases from other manufacturing branches than heavy vehicles.
- Evaluate HIRC simulations results with physical demonstrations.

All of these issues shall be addressed within the scope of this thesis project in order to improve the demonstrator software.

However, parallel with the software development described in the bullets above, the main aim of future development of the research is in optimisation techniques. There is an opportunity to use the quantitative numbers derived from the HIRC simulations together with optimisation techniques in order to design optimal HIRC workplaces. Study C in this thesis is a first introduction to this area, and the plan is to follow up that study with new and more advanced examples of how these two areas, simulation of production system design and optimisation techniques, can be combined.
However, parallel with the software development described in the bullets above, the need to improve the demonstrator software.

All of these issues shall be addressed within the scope of this thesis project in order to create a more comprehensive solution. Combined, these must also be considered in the future research:

- Include cases from other manufacturing branches than heavy vehicles.
- Evaluate HIRC simulations results with physical demonstrations.
- Optimisation of task allocations between human and industrial robot shall be considered.
- Evaluate with deterministic limits between a good and very bad postures be included.
- A biomechanical observational method that also includes time as a factor should be included.

In the selection of new biomechanical method shall also the current problem be considered.

6.3 FUTURE RESEARCH

In Chapter five a number of improvement issues have been identified and further development of the demonstrator software is required before it can be a commercial tool used in industry. The demonstrator software consists of five individual elements and the data transfer between them has to be improved in the future. In Chapter five a number of improvement issues have been identified and further development of the demonstrator software is required before it can be a commercial tool used in industry. The demonstrator software consists of five individual elements and the data transfer between them has to be improved in the future.

The optimisation method presented in the research is also an industrial contribution.


