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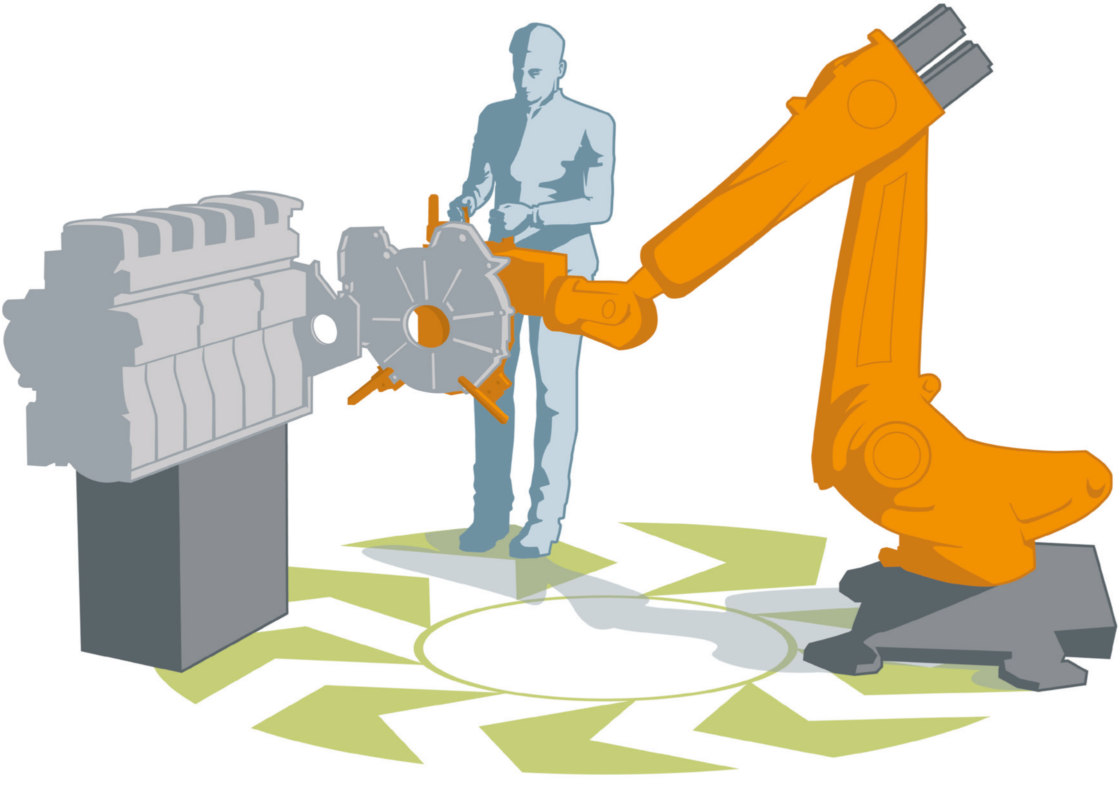
Designing workstations for Human–Industrial Robot Collaboration

Development and application of simulation software

Fredrik Ore



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DEVELOPMENT AND APPLICATION OF SIMULATION SOFTWARE

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2020

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School of Innovation, Design and Engineering

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DESIGNING WORKSTATIONS FOR HUMAN–INDUSTRIAL ROBOT COLLABORATION
DEVELOPMENT AND APPLICATION OF SIMULATION SOFTWARE

Fredrik Ore

Akademisk avhandling

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MÄLARDALEN UNIVERSITY
SWEDEN

Akademin för innovation, design och teknik

Abstract

Human-industrial robot collaboration (HIRC) creates an opportunity for an ideal combination of human senses and industrial robot efficiency. The strength, endurance and accuracy of industrial robots can be combined with human intelligence and flexibility to create workstations with increased productivity, quality and reduced ergonomic load compared with traditional manual workstations. Even though multiple technical developments of industrial robot and safety systems have taken place over the last decade, solutions facilitating HIRC workstation design are still limited. One element in realising an efficient design of a future workstation is a simulation software. Thus the objective of this research is to (1) develop a demonstrator software that simulates, visualises and evaluates HIRC workstations and (2) propose a design process of how to apply such a simulation software in an industrial context.

The thesis comprises five papers describing the development of a HIRC simulation software and its corresponding design process. Two existing simulation software tools, one for digital human modelling and one for robotic simulation, were merged into one application. Evaluation measures concerning operation time and ergonomic load were included in the common software. Existing engineering design methods were applied in a HIRC workstation context to describe the utilisation of a HIRC simulation software. These developments were demonstrated in five actual industrial cases from a heavy vehicle manufacturing company.

The HIRC simulation software developed enables simulation, visualisation and evaluation of all kinds of HIRC workstations where human and robot simultaneously work in a collaborative environment including hand-guiding tasks. Multiple layout alternatives can be visualised and compared with quantitative numbers of total operation time and biomechanical load on the human body. An integrated HIRC workstation design process describes how such a simulation software can be applied to create suitable workstations. This process also includes a safety measure by which the collision forces between the industrial robot and the human are predicted. These forces have to be minimised to tolerable limits in order to design safe HIRC workstations.

The HIRC simulation software developed and the proposed workstation design process enable more efficient HIRC workstation design. The possibility of designing and evaluating HIRC alternatives for hand-guiding activities is rarely found in other simulation software. The evaluation could include different types of layout alternatives and workstations: HIRC, fully manual or fully automatic. All of these could be compared based on their total operation time and biomechanical load and thus be used in workstation design decision making.

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ABSTRACT

Human-industrial robot collaboration (HIRC) creates an opportunity for an ideal combination of human senses and industrial robot efficiency. The strength, endurance and accuracy of industrial robots can be combined with human intelligence and flexibility to create workstations with increased productivity, quality and reduced ergonomic load compared with traditional manual workstations. Even though multiple technical developments of industrial robot and safety systems have taken place over the last decade, solutions facilitating HIRC workstation design are still limited. One element in realising an efficient design of a future workstation is a simulation software. Thus the objective of this research is to (1) develop a demonstrator software that simulates, visualises and evaluates HIRC workstations and (2) propose a design process of how to apply such a simulation software in an industrial context.

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SAMMANFATTNING

Human-industrial robot collaboration (HIRC) möjliggör produktionssystem där mänskliga förmågor kombineras med industrirobotens effektivitet. Mänsklig intelligens och flexibilitet kan tillsammans med robotarnas styrka, uthållighet och noggrannhet skapa arbetsstationer med ökad produktivitet, kvalitet och minskad ergonomisk belastning. Trots en kraftig utveckling inom industrirobotar och säkerhetssystem det senaste decenniet, är processerna och metoderna för att underlätta design arbetet av HIRC-arbetsstationer fortfarande bristfälliga. En simuleringsmjukvara kan ge ett stöd för att effektivt utforma framtida arbetsstationer. Syftet med denna forskning är att (1) utveckla en programvara som simulerar, visualiserar och utvärderar HIRC-arbetsstationer, och (2) föreslå en designprocess för hur en sådan simuleringsprogramvara ska användas i industriellt sammanhang.

Avhandlingen innehåller fem artiklar som beskriver utvecklingen av en HIRC-simuleringsprogramvara och dess designprocess. Två befintliga simuleringsprogramvaror, en för digital human modelling och en för robotsimulering slogs samman till en ny programvara. Kvantitativ utvärdering av tid och ergonomisk belastning inkluderades i den nya programvaran. Användandet av en simuleringsmjukvara beskrevs i processer där utformningen av HIRC-arbetsstationer integrerats in i etablerade design metoder. Denna process appliceras i fem industricase i ett fordonstillverkande företag.

Den utvecklade HIRC-programvaran möjliggör simulering, visualisering och utvärdering av alla typer av HIRC-arbetsstationer där människa och robot samtidigt arbetar i nära samverkan, inklusive hand-guiding aktiviteter. Flera layoutalternativ kan visualiseras och jämföras med kvantitativa värden på operationstid och biomekanisk belastning på människokroppen. En integrerad designprocess för HIRC arbetsstationer beskriver hur en sådan programvara kan användas för att skapa gynnsamma arbetsstationer. Denna process inkluderar även analys av säkerheten där kollisionskrafterna mellan industriroboten och människan beräknas. För att garantera säkra HIRC-arbetsstationer måste dessa krafter understiga standardiserade gränser.

Den utvecklade programvaran och den föreslagna designprocessen möjliggör effektivare utformning av HIRC-arbetsstationer. Att kunna utforma HIRC-alternativ för hand-gudied samarbete saknas i andra kända simuleringsprogram. Utvärderingen kan ske mellan olika typer av layoutalternativ och arbetsstationer: HIRC, helt manuell eller helautomatisk. Alla dessa typer av stationer kan jämföras baserat på total operationstid och biomekaniska belastning, och denna information kan användas vid beslutsfattande av lämpligt produktionssystem.

ACKNOWLEDGEMENTS

A Ph.D. journey could at times be a lonesome endeavour, but that has never been my experience. That is due to all the people I have met during these seven years. You have all been vital in this, so thank you all! However, I would like to specially mention a few people.

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Fredrik Ore

Strängnäs, January 2020

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PUBLICATIONS

APPENDED PUBLICATIONS

PAPER A

Ore, F., Hanson, L., Delfs, N. & Wiktorsson, M. 2015. Human industrial robot collaboration - development and application of simulation software. *International Journal of Human Factors Modelling and Simulation,* 5**,** 164-185.

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

PAPER B

Ore, F., Ruiz Castro, P., Hanson, L., Wiktorsson, M. & Gustafsson, S. Verification of manikin motions in a HIRC simulation. *Submitted to journal 2019*.

Ore was the main author of the paper. He initiated it, designed the experiment, collected the physcial data, created the simulation for one case and wrote the paper. Ruiz Castro participated in one physical data collection, created the simulation for the second case and reviewed the paper. Hanson and Wiktorsson reviewed and carried out quality assurance of the paper. Gustafsson programmed RULA evaluation options in the software and reviewed the paper.

PAPER C

Ore, F., Hanson, L., Wiktorsson, M. & Eriksson, Y. 2016. Automation constraints in human–industrial robot collaborative workstation design. Paper presented at the 7th International Swedish Production Symposium, 25–27 October 2016, Lund, Sweden.

Ore was the main author and presented the paper. He initated the paper, analysed existing HIRC stations, proposed the automation constraints and wrote the paper. Hanson, Wiktorsson and Eriksson reviewed and carried out quality assurance of the paper.

PAPER D

Ore, F., Jiménez Sánchez, J. L., Hanson, L. & Wiktorsson, M. Design Method of Human–Industrial Robot Collaborative Workstation with Industrial Application. *Submitted to journal 2019*.

Ore was the main author. He initiated the paper, developed the proposed design process and wrote the paper. Jiménez Sánchez created the simulation of the industrial example case. Hanson and Wiktorsson assisted in the design process evaluation, reviewed and carried out quality assurance of the paper.

PAPER E

Ore, F., Vemula, B., Hanson, L., Wiktorsson, M. & Fagerström, B. 2019. Simulation methodology for performance and safety evaluation of human–industrial robot collaboration workstation design. *International Journal of Intelligent Robotics and Applications*, 3, 269-282.

Ore and Vemula were the main authors. They both initiated the paper, contributed with their individual research competence (Ore: simulation of the HIRC case; Vemula: collision models between human and indistrial robot systems), developed the design process and wrote the paper. Hanson, Wiktorsson and Fagerström reviewed and carried out quality assurance of the paper.

ADDITIONAL PUBLICATIONS

Ore, F., Wiktorsson, M., Hanson, L. & Eriksson, Y. 2014. Implementing Virtual Assembly and Disassembly into the Product Development Process. In: Zaeh, M. F. (Ed.) *Enabling Manufacturing Competitiveness and Economic Sustainability,* 111-116. Cham, Switzerland: Springer.

Ore, F., Hanson, L., Delfs, N. & Wiktorsson, M. 2014. Virtual evaluation and Optimisation of industrial Human-Robot Cooperation: An Automotive Case Study. Paper presented at the 3rd Digital Human Modeling Symposium (DHM2014), 20–22 May 2014, Tokyo, Japan.

Khalid, O., Caliskan, D., Ore, F. & Hanson, L. 2015. Simulation and evaluation of industrial applications of Human-Industrial Robot Collaboration cases. In: Fostervold, K. I., Kjøs Johnsen, S. Å., Rydstedt, L. W. & Watten, R. G. (Eds.) *Creating Sustainable Work-environments. Proceedings of NES2015 Nordic Ergonomics Society 47th Annual Conference*, Lillehammer, Norway: NEHF (Norwegian Society for Ergonomics and Human Factors).

Hanson, L., Ore, F. & Wiktorsson, M. 2015. Virtual Verification of Human-Industrial Robot Collaboration in Truck Tyre Assembly. In: *Proceedings 19th Triennial Congress of the IEA*, Melbourne 9-14 August.

Gopinath, V., Ore, F. & Johansen, K. 2017. Safe Assembly Cell Layout through Risk Assessment–An Application with Hand Guided Industrial Robot. In: Tseng, M. M., Tsai, H.-Y. & Wang, Y. (Eds.) *Proceedings of the 50th CIRP Conference on Manufacturing Systems, 2017. Manufacturing Systems 4.0*, 430-435.

Gopinath, V., Ore, F., Grahn, S. & Johansen, K. 2018. Safety-Focussed Design of Collaborative Assembly Station with Large Industrial Robots. *Procedia Manufacturing,* 25, 503-510.

Hanson, L., Högberg, D., Carlson, J. S., Delfs, N., Brolin, E., Mårdberg, P., Spensieri, D., Björkenstam, S., Nyström, J. & Ore, F. 2019. Industrial path solutions–intelligently moving manikins. In: Scataglini, S. & Paul, G. (Eds.) *DHM and Posturography*,115-124. Cambridge, MA: Academic Press.

TABLE OF CONTENTS

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 basis, the research aim, its resulting objective and the research questions.

1.1 HUMAN–INDUSTRIAL ROBOT COLLABORATION

Increased global competition is one of the main challenges for manufacturing companies in the developed countries (Manufuture High-Level Group, 2018; Teknikföretagen, 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 strategies to well-designed production systems and work methods. Another challenge is the demographic change problem arising from both increasing average life length and decreasing fertility rate, resulting in negative population growth (United Nations, 2013). Thus the number of elderly people in the workforces of organisations will most likely increase.

One method to meet both these obstacles to future growth of industries in the developed countries is further increased automation in the factories. Industrial robots are an important part of factory automation and have radically changed the manufacturing industries since they were introduced in our factories in the 1970s. They allowed heavy and repetitive tasks to be automated, facilitating an increase in productivity and product quality at the same time as enabling ergonomically better workstations. In the following decade sensor technologies were developed to further increase the automation possibilities of including more advanced machining tasks such as welding, grinding and deburring (Wallén, 2008).

The multiple possible uses together with easy reprogramming made the industrial robot a flexible resource on the industry floor. However, compared with human capabilities, the industrial robot was extremely rigid; it only did the task it was programmed to do. In the last decade the development of advanced sensors (e.g., cameras and force sensors) has enabled a higher degree of flexibility in industrial robots (Robla-Gómez et al., 2017). Even if the sensors are developed to be more capable, they cannot match the flexibility and intelligent decision making of humans (Chen et al., 2011; Savoy and McLeod, 2013). The cost of using these advanced sensors is also too high for most industrial applications (Pini et al., 2015). However, utilising these sensors to enable human–industrial robot collaboration (HIRC) creates a possibility of an ideal combination of human senses and industrial robot efficiency, where the strength, endurance and accuracy of the industrial robots are combined with human intelligence and flexibility (Helms et al., 2002; Krüger et al., 2005) to create improved workstations, Figure 1.

These HIRC systems are meant to assist the human in transforming previously fully manual manufacturing operations into new collaborative systems (Reinhart et al., 2012). Compared with traditional manual workstations, HIRC systems shall improve system productivity and quality and reduce ergonomic loads on the operators (Krüger et al., 2009; Reinhart et al., 2012).

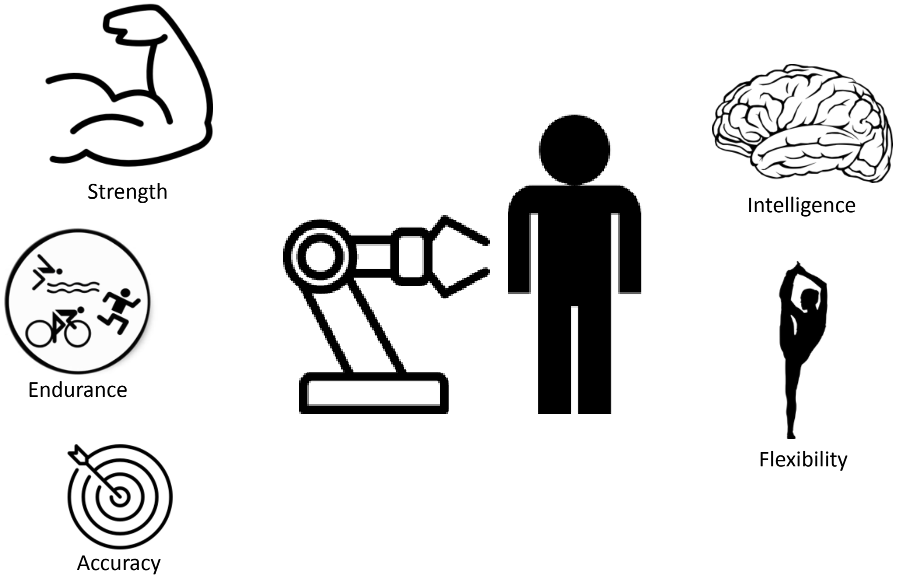


Figure 1 The goal of the HIRC system to combine robotic strength, endurance and accuracy with human intelligence and flexibility.

The term HIRC is used to describe systems in which industrial robots work directly alongside humans in an environment without physical fences, which are required in traditional robot installations. 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).

As mentioned, the general aim of HIRC workstations is to create a “dream combination of human flexibility and machine efficiency” (Tan et al., 2009, p. 29). In this quotation, Tan et al. both pinpoint 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 in the manufacturing industry (Awad et al., 2017). The reason for the small number of actual installations in the industry is current safety legislation that restricts close collaboration between humans and traditional industry robots; it is difficult to install safe HIRC workstations with the existing robot technology and safety equipment (Saenz et al., 2018). When they have been further developed there is a huge potential market for HIRC workstations in all manufacturing industries. Great research efforts are currently made, both by academia and by robot manufacturers, in order to enable implementation of such future workstations. These efforts focus both on development of new robot systems that enable close collaboration and on methods how to utilise the robots in an optimal way.

1.2 VIRTUAL SIMULATION OF HIRC WORKSTATIONS

In order to achieve optimal utilisation of HIRC in workstation design there is a need to simulate future HIRC systems. Simulation of a production process can be done both physically and virtually.

A physical simulation includes models of physical objects that replace the real artefact, e.g., cardboard boxes representing the outer dimensions of a production process to give an impression of sizes of a future system (Kunz et al., 2016). However, as process capabilities in computers are growing fast, computerised virtual simulations are increasingly used in our industries. These virtual simulations make it possible to study how changes in the system design affect its overall performance (Baldwin et al., 2000). Virtual simulations in design of production systems play a vital part in all engineering activities in a modern manufacturing organisation (Mourtzis et al., 2015). Continued research on the development and use of virtual simulation tools is also highlighted as an important area in European and Swedish research agendas and strategic reports (Manufuture, 2018; Produktion2030, 2018; FFI, 2019).

In complex systems such as HIRC the need to consider human as well as industrial robot capacities is very important in order to design optimal workstations (Ogorodnikova, 2008). One efficient way to do this is through virtual simulation software. However, the available simulation software in the area of HIRC workstation design are few (Tsarouchi et al., 2016a). In the few software identified none has no capability to simulate and visualise HIRC tasks on an object simultaneously handled by both humans and industrial robots. Use of the simulation to numerically evaluate and compare different workstation designs (HIRC, fully automatic and fully manual) to support decision making is also interesting. Thus, a need was identified to develop a software for simulation, visualisation and evaluation of close collaboration between human and industrial robot, supporting effective and efficient design of HIRC workstations early in the production development process.

1.3 DESIGN METHODS IN HIRC WORKSTATION DESIGN

A software in itself cannot create optimal HIRC workstations; it is merely a tool enabling evaluation and visualisation of multiple HIRC workstation layouts. The software has to be used in an appropriate way to create relevant workstation designs in a time- and cost-efficient way. The need to establish design methods supporting HIRC workstation design has been highlighted in previous work (Pini et al., 2015; Michalos et al., 2018; Fechter et al., 2018).

There are also a vast number of possibilities in a HIRC workstation to use different kinds of robots and equipment and to move all objects and surrounding fixtures in indefinite combinations, as well as to share the tasks in a workstation between a robot and a human. Thus there could always be another solution that might be superior to the best one found so far. The design of a HIRC workstation is in many ways similar to the design of any general product or artefact; its goal is to create an optimal design considering specific criteria, limited through a number of constraints. Engineering design methods were developed in the later decades of the 20th century in order to systematically describe how design research knowledge can be transformed into practical artefacts (Stauffer and Pawar, 2007; Le Masson and Weil, 2013; Motte et al., 2011). Pahl and Beitz's book *Engineering Design: A Systematic Approach* was first released in 1977 in German, *Konstruktionslehre* (Pahl and Beitz, 1977); it has become the reference work in these engineering design processes (Le Masson and Weil, 2013). Applying systematic design methodology to this workstation design problem facilitates the difficult task to find the most suitable HIRC workstation.

1.4 RESEARCH OBJECTIVE AND RESEARCH QUESTIONS

The aim of the research work is to contribute to more mature knowledge about human–industrial robot collaboration (HIRC) by focusing on digital tools for validation and methods supporting industrial application development. The specific objective of this research is to (1) develop a demonstrator software that simulates, visualises and evaluates HIRC workstations in a heavy vehicle manufacturing environment and (2) propose a design process on how to apply such a simulation software in an industrial context. These objectives are met by addressing the following research questions:

RQ1: How can simulation, visualisation and evaluation of HIRC workstations be performed?

This research question relates to the development of a new software for simulation of HIRC workstations (named "HIRC simulation software" in this thesis). In order to achieve validity of the simulated human motions there is also a need to verify them with actual motions.

RQ2: How can a software for simulation, visualisation and evaluation of HIRC be applied in the workstation design process?

This research question aims at application of a simulation software in a HIRC workstation design process. The focus is on defining a generic design process that could be utilised with any simulation software that quantitatively evaluates HIRC workstations.

1.5 DELIMITATIONS

The cases studied in this Ph.D. thesis have their origin in a single heavy vehicle manufacturer. The main purpose of using the cases is not to design optimum HIRC workstations for these industrial cases, but to develop the software and demonstrate its corresponding workstation design process. Therefore, the specific research context, in terms of the manufacturing company, does not affect the end result to any large extent.

1.6 OUTLINE OF THE THESIS

Chapter 1 presents the background of the research, including the objective and research questions. Chapter 2 introduces the frame of reference of the subject and Chapter 3 the methodological approach in the research together with how it was applied in the individual research studies conducted. Chapter 4 presents the research results, and in Chapter 5 these are discussed; both these chapters are closely connected to the related research questions. Chapter 6 concludes the thesis by describing the academic and industrial contribution and suggesting future research directions.

2 FRAME OF REFERENCE

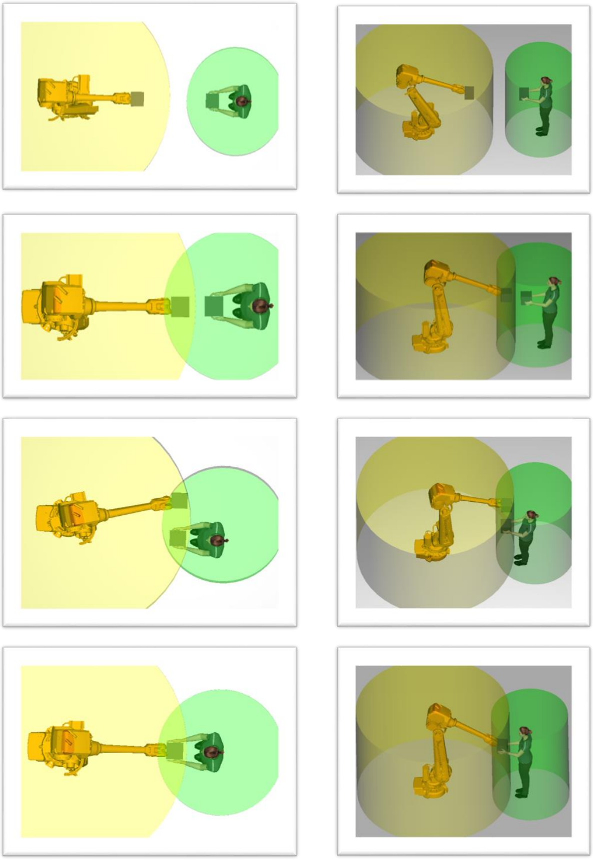
This chapter contains an overview of the frame of reference and previous research on which the thesis is based. The subchapters below are derived from the keywords in the research questions: HIRC, simulation in production system design, simulation, visualisation and evaluation of HIRC and, finally, engineering design methods.

2.1 HUMAN–INDUSTRIAL ROBOT COLLABORATION

Research in the HIRC area has been intense during the last decades. The number of publications has increased four times from 2007 to 2014 (Ore, 2015), and in the broader human–robot Interaction area the trend is similar (Tsarouchi et al., 2016a). Initially many papers focused on the creation of new, smaller, power- and force-limited robots that could sense a collision and stop before an accident occurred, e.g., KUKA lbr iiwa (Bischoff et al., 2010) and ABB YuMi (Kock et al., 2011). Even though other similar robot systems have been developed lately, e.g., Franka Emika (Franka, 2019), the huge growth in academic publications in later years stems from the quest to put the robots into industrial applications. These publications focus on various areas such as HIRC safety systems (Lasota et al., 2017; Robla-Gómez et al., 2017), task allocation in HIRC design (Ranz et al., 2017), psychosocial issues in HIRC (Lichtenthäler and Kirsch, 2016; Gombolay et al., 2017) and multimodal programming of industrial robots (Liu et al., 2018), just to mention a few.

2.1.1 DEFINITION OF HIRC

The academic literature has defined collaboration between human and robot in different ways. The initial term “cobot” was defined in 1996 as “a robotic device which manipulates objects in collaboration with a human operator” by Colgate et al. (1996, p. 433), but the authors also describe their cobots as passive robotic devices that move with the force of the human (Colgate et al., 1996). In 2002 Schraft et al. presented “man–robot cooperation” in which a demonstration system of a HIRC workplace is introduced (Schraft et al., 2002). The “man–robot cooperation” term was further discussed and developed by Krüger et al. (2005). As the research field has grown, the HRC term has become the main one used. The C in the abbreviation can stand for different words; collaboration or cooperation are the two most often used. Fraunhofer IAO has divided the interaction between a human operator and an industrial robot into four different levels: human robot coexistence, synchronisation, cooperation and collaboration, as illustrated in Figure 2 (Bauer et al., 2016).



Coexistence
Human and fenceless robot work side by side, but without a collaborative work area.

Synchronisation
Human and robot have a common workspace, but the planned work process always involves a maximum of one interaction partner in the collaborative work area.

Cooperation
Both human and robot can work simultaneously in the collaborative work area but do not work simultaneously on the same product or component.

Collaboration
Human and robot perform a task simultaneously on the same product or component.

Figure 2 Definitions of four human–industrial robot interaction types (Bauer et al., 2016).

All these definitions are included in the commonly used HRC term. The term HRC in itself describes workstations where robots work directly alongside humans in an environment without physical fences, as is required in traditional robot installations. Since the term robot can imply many different types of robots (e.g., vacuum cleaners, healthcare robots or search and rescue robots (Bauer et al., 2008)), the word “industrial” has been added to the abbreviation for the purpose of this research. Using HIRC in this thesis limits this work to industrial robotics. The HIRC term also refers to all the interaction types presented in Figure 2, even though the word collaboration is used to represent the C in the thesis title.

2.1.2 PERSONAL SAFETY IN HIRC

Personal safety in HIRC can be classified into two major fields, physical and psychological safety. The first one covers the risk of unintentional or unwanted physical contact between human and an industrial robot; this type of contact can physically harm a human (Lasota et al., 2017). Psychological safety, on the other hand, is an indirect harm on the human when the human feel that the robot violates social conventions and norms (Lasota et al., 2017). The focus in the work presented in this thesis is on physical safety.

One prerequisite to enable HIRC installations is to be able to ensure physical safety for everyone that interacts with the workstation, and to include research achievements in the field into standards supporting HIRC workstation design is a major challenge (Haddadin and Croft, 2016). The traditional industrial robot standard ISO 10218-2 “Robots and robotic devices – Safety requirements for industrial robots – Part 2: Robot systems and integration” (ISO, 2011b) describes how to include an industrial robot in a system and make it a safe machine. This standard is harmonised with the machine directive that is European law (European Union, 2006); thus if the robot system is designed according to ISO 10218-2, it also complies with the machine directive and is considered a safe machine. The challenge in collaborative systems is that there are no standards stating how to design such systems in a safe way. ISO (the International Organization for Standardization) has released a technical specification (TS) in the area, ISO/TS 15066 “Robots and robotic devices — Collaborative robots” (ISO, 2016), which is not yet a standard. This TS provides guidance for HIRC operation and supplements the requirements in ISO 10218.

The need to ensure safe workstations in HIRC has motivated a great deal of research. Robla-Gómez et al. (2017) present a comprehensive review and classification of safety systems that have been proposed and applied in HIRC environments. These cover areas such as different kinds of camera systems supervising the collaboration area, tactile sensors on the robot arm or creation of mechanical robot systems with internal compliant behaviour at impact. One specific and very important developed system that has dramatically increased the possibility of humans and industrial robots in a shared environment, is power- and force-limiting robots. These robots are equipped with internal sensors detecting a collision between the robot and another object (e.g., a human) and stopping the robot motion at initial impact, thus reducing the consequences of a collision. These robots are designed to be weak, move with slow speeds and lack sharp edges and thus allow installation in fenceless environments. The goal of power- and force-limiting robots is to keep the impact forces within limits ensuring a safe operation. Appendix A.3 in TS 15066 states maximum values that human body regions can withstand before a minor injury occurs on the human body (ISO, 2016). These values are often used as limits in the design of HIRC workstations and are only valid for systems with power- and force-limiting robots. Some examples of these robots are Motoman HC10 (Yaskawa, 2019), KUKA lbr iiwa (KUKA, 2019) and UR10e (Universal Robots, 2019), Figure 3.

Figure 3 Examples of power- and force-limiting robots Motoman HC10, KUKA lbr iiwa and UR10e.

2.1.3 INDUSTRIAL HIRC INSTALLATIONS

Despite the challenges of using standards to build safe HIRC workstations, these systems are currently being installed in industries. The integrator has to guarantee safety of the workstation through other methods. Academic publications present HIRC designs (e.g., (Scholer et al., 2015; Castro et al., 2018; Michalos et al., 2015)), but it is not always clear whether they are actually installed in manufacturing environments. On the contrary, it is reported that the number of installed HIRC workstations in industry is low (Awad et al., 2017). However, a report from Fraunhofer IAO presents 21 installations of power- and force-limiting robots from German industries (Bauer et al., 2016). The general conclusion from that survey is that the majority of the installations are at the lowest interaction level, coexistence, since these are easier to implement. It is also the recommendation from Fraunhofer IAO that coexistence might be the right way to start an implementation of a HIRC workstation. It enables power- and force-limited applications in a safe environment (Bauer et al., 2016).

2.2 SIMULATION OF PRODUCTION SYSTEM

Virtual simulations to design production systems play a vital part in all engineering activities in a modern manufacturing organisation (Mourtzis et al., 2015). Virtual simulations often replace previously used physical prototypes to evaluate solutions. The benefits of virtual simulations compared to physical prototypes are summarised by Murphy and Perera (2002) into five categories:

- early identification of design errors
- fewer physical prototypes (which require time and money)
- faster responses to design changes
- less time wasted on building new experiments
- shorter lead times

Thus these virtual simulations 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 development processes, which is an important aspect to consider in the global competition facing all manufacturing industries.

Simulation tools for discrete manufacturing systems 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 a geometric simulation the three-dimensional geometry of the part is simulated in a system where time proceeds linearly (Klingstam and Gullander, 1999).

2.3 SIMULATION AND VISUALISATION OF HIRC WORKSTATION

Visualisation is an important part of a virtual simulation. Visualisation possibilities in a three-dimensional geometric system can assist in communication of new workstation design better than traditional 2D drawings.

Existing simulation and visualisation tools in the design of HIRC workstations are, as mentioned, limited (Tsarouchi et al., 2016a). However, in recent years a number of authors have identified this need and presented proposals on how to combine human and industrial robotic motions into one simulation tool. One early result is from 2000 (Luh and Srioon), when a tool was presented by which a human virtual hand could be placed on an object 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. More recently, and more in line with the geometric 3D simulation software proposed in this research, new simulation tools have been presented, often with a lightweight model of the human (Busch et al., 2013; Bobka et al., 2016; Maurice et al., 2017). These simplified virtual skeleton models of the human showcase the difficulty to depict humans and human motions in a representative manner. In order to create humanlike motions, the simplified models are often fed with motion capture data.

One other approach to get accurate human motions is to utilise the development in the advanced digital human modelling (DHM) software. DHM tools enable digital models of humans to interact with virtual workplaces or products in a digital CAD environment The virtual human models in these software are named ‘digital manikins’ or only ‘manikins’. The DHM software are used for the design of a physical product of a manufacturing company or the actual workstation design where the products are being made (Chaffin, 2007). These tools enable more accurate simulation of human motions. To be able to simulate HIRC systems also requires robot simulation functionality. Tsarouchi et al. (2016b) present a study in which the geometric simulation software Process Simulate is used to evaluate multiple design solutions to a HIRC workstation layout problem. In addition, Cencen et al. (2018) presented a HIRC design process in which the simulation and evaluation are carried out with assistance of the 3D CAD software Visual Components.

As the best suited simulation tool for HIRC workstation design needs to include both DHM and robotic simulation capabilities, these two areas are presented in more detail in the following sections.

2.3.1 DIGITAL HUMAN MODELLING SOFTWARE

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) and 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). IMMA is now included in the Industrial Path Solutions (IPS) family (IPS, 2019a). IPS IMMA is a geometric simulation software developed to automatically predict human motions to suit the virtual environment (Högberg et al., 2016). The digital manikin is created as a skeleton model of 82 bones resulting in a system with 162 degrees of freedom with a mesh representing both males and females (IPS, 2019a). It uses inverse kinematics to find joint values such that the position and orientation of hands and feet match target frames; it achieves this through mathematical algorithms that determine an optimal human motion to perform a task (e.g., grasp an object) with the most favourable biomechanical load (Bohlin et al., 2012). These motions consist of a high number of postures and each of these are derived mathematically through normalising the load on each joint by its muscle strength (Bohlin et al., 2012). It calculates collision-free motions of the manikin, the robot and the object that is handled and considers constraints given by the virtual environment including forces on the body and stability of the motions. (Delfs et al., 2013).

2.3.2 ROBOTIC SIMULATION

The standard industrial robot has six 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 robot optimization (Spensieri et al., 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 licences (Pan et al., 2012).

The IPS robot optimization software is the part of the IPS family that focuses on robotic automatic sequencing and task balancing in workstations with multiple industrial robots (IPS, 2019b). Similar to IPS IMMA, the IPS robot optimization software uses mathematical algorithms to optimise robot trajectories (Segeborn et al., 2014). The constraints in the robotic field are, in addition to the virtual environment, the data sheets from the robot supplier.

Both the IPS software IMMA and robot optimization automatically create collision-free motions when the human designers set start and stop positions of the robot tool centre point (TCP) and human hands as inputs and let the software calculate the handling paths.

2.4 EVALUATION METHODS IN HIRC WORKSTATIONS

It is important to be able to numerically compare simulated HIRC configurations. Thus two important evaluation methods are described in this section; they are connected to the initial problem description: productivity and ergonomic load.

2.4.1 PRODUCTIVITY EVALUATION

Productivity evaluation is presented in more detail as it has been identified in the introduction as one of the key industrial challenges and as one of the main drivers in HIRC development (Krüger et al., 2009). Productivity of a manufacturing system is generally defined as output divided by input in a specific time interval, Equation 1.

$$productivity = \frac{output}{input} \qquad (1)$$

Considering an investment in a HIRC workstation as the input in Equation 1, productivity could be boosted by maximising output in terms of products manufactured per time unit. When operation time is minimised, the output is maximised, hence the total operation time of a workstation is considered as a valid parameter of its output. While evaluating various workstation designs of a given HIRC configuration, the input in Equation 1 is constant, and minimising total operation time will in this situation maximise productivity. The operation time in a HIRC system is a combination of human and industrial robot times; evaluations of these are presented in the following section.

A common method to estimate human operation time is using predetermined motion time systems (PMTS). PMTS predict the duration of performing a particular human motion for a set distance (Genaidy et al., 1994). There are numerous PMTS systems, many of them originating from the Methods-Time Measurement-1 (MTM-1) system developed in the USA in the 1940s (Maynard et al., 1948). MTM-1 is a detailed and time-consuming system to use, thus the need of a simplified tool that grouped several MTM-1 motions into one emerged. MTM-2, MTM-3, SAM, MOST and MTS-UAS were all developed to simplify prediction of human times in the second half of the 20th century (Laring et al., 2002).

In the IPS IMMA software the human times are analysed based on MTM-1 times. These operation times for the human motions are calculated automatically in the software based on the digital manikin and geometric positions of the objects that are handled as defined in the simulation software. From this, the distances to move joints of the manikin are calculated, resulting in specific operation times to perform the motions based on the MTM-1 times.

The IPS robot optimization software calculates operation times for the industrial robot performing a motion. It uses joint velocities from the industrial robot data sheet to create optimum robotic motion paths and returns the total robotic handling time (Segeborn et al., 2014).

2.4.2 ERGONOMIC EVALUATION

The second great industrial challenge mentioned in the introduction is the demographic change towards an elderly population. An increase in the average workforce has to be addressed by reducing the ergonomic load in the workstations, since the risk of musculoskeletal disorders increases with age (Fritzsche, 2010; Zaeh and Prasch, 2007). Improved ergonomics is also one other important driver for HIRC workstation design (Reinhart et al., 2012). Ergonomics is a broad discipline, as shown in this definition:

> Ergonomics (or human factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance (IEA, 2019).

There are several factors that affect the total ergonomics of a workstation, physical, organisational and cognitive. In all workstation design tasks physical ergonomics, specifically biomechanics, is of most relevance to evaluate. Biomechanics can be defined as “the study of forces acting on and generated within the body and of the effects of these forces on the tissues, fluids, or materials used for diagnosis, treatment, or research purposes” (Panel on Musculoskeletal Disorders and the Workplace et al., 2001, p. 219). A commonly used technique 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 angular deviations of body segments of the human body when performing tasks. These angular deviations are fed into a score sheet document, that summarise individual joint values to a grand score stating where a grand score states the risk of musculoskeletal injuries. The posture assessment methods are well suited to be used in computerised simulations when positions of the body segments can be derived from the software as quantitative numbers. A number of different posture observation methods are used in industrialised environments; 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 (rapid upper limb assessment) is of most relevance as the IPS IMMA software focuses on upper body motions since most manual manufacturing tasks are performed standing (or seated) with supported legs, focusing on upper body motions. RULA estimates the muscular injury risk on humans by evaluating individual poses and assesses the injury risk of those poses on the human body. For each posture the positions of human joints (angle of arms, wrist, neck and trunk) are evaluated and one grand RULA score combining all of these is set. This score is between one and seven, where a high score indicates a high risk of future musculoskeletal injuries. Table 1 presents the interpretations of the RULA grand score (McAtamney and Corlett, 1993).

Table 1 Interpretations of the RULA grand score (McAtamney and Corlett, 1993)

RULA score	**Interpretations of RULA score**
1–2	Acceptable posture, workstation
3–4	Further investigations of the posture are needed and changes of the workstation might be required
5–6	Investigations and changes of the workstation are required soon
7	Immediate investigations and changes of the workstation are needed

2.5 ENGINEERING DESIGN METHODS

Engineering design methods had been developed in the later decades of the 20th century in order to systematically describe how design research knowledge can be transformed into practical artefacts (Stauffer and Pawar, 2007; Motte et al., 2011; Le Masson and Weil, 2013). The most commonly used models are grouped into systematic design methodologies. These describe a process from problem identification to a product release on the market. A few of the most referred processes are those by Pahl and Beitz (Pahl et al., 2007), Ulrich and Eppinger (Ulrich and Eppinger, 2016) and Pugh (Pugh, 1991). Many of these can be referred back to Pahl and Beitz's first release in German *Konstruktionslehre* from 1977 (Motte et al., 2011). Thus Pahl and Beitz's engineering design framework has become the reference work in systematic design methods and has been used to teach engineers for generations (Le Masson and Weil, 2013). This framework has four main phases: planning, conceptual design, embodiment design and detailed design (Pahl et al., 2007). Despite the apparent linear flow from planning to detailed design, the framework highlights the iterative process of design work, demanding use of new knowledge back in previous phases and activities.

The generic systematic design processes have given inspiration to multiple production system development processes, as presented by, among others, Bennett (1986), Wu (1992; 1994), Bellgran (1998) and Wiktorsson (2000). These all present generic production system development processes, but they are not focused on a workstation design context and do not detail the process for covering HIRC task allocation and layout evaluation.

2.5.1 DESIGN OF HIRC WORKSTATIONS IN THE LITERATURE

Existing methods and tools to design HIRC workstations have limitations in the capacity to study the whole system (Saenz et al., 2018). Lack of planning tools has also been identified as one of the two perceived challenges in a survey of manufacturing companies and robot integrators (Ranz et al., 2017). Successful design of HIRC workstations is a difficult and time-consuming task that relies on the competence and experience of the designer (Fechter et al., 2018). Thus there is a need to establish systematic engineering design methods supporting the HIRC workstation designers in their task (Pini et al., 2015; Michalos et al., 2018).

The systematic design of a HIRC workstation includes two large areas that have to be developed in parallel: *task allocation* and *layout evaluation* (Michalos et al., 2018). Task allocation includes the selection of what resource (human or robot) should perform what task in the workstation, while layout evaluation includes the geometric positioning of all the products and resources in the workstation. Balancing these when designing a workstation is a challenging task. Task allocation between the human and the industrial robot has been addressed by several publications with different approaches. Ranz et al. (2017) presented a task allocation process in which human and robotic capabilities were assessed on a better, equal or worse scale of 25 criteria. Similar principles were presented by Pini et al. (2015), where a manual assessment of the suitability for each resource to perform a task is made. Chen et al. (2013) created a generic algorithm (GA) to minimise assembly time and total cost in a workstation. Dalle Mura and Dini (2019) also used GA and minimised cost and ergonomic factors. They also covered the entire assembly line in the task allocation process. Bänziger et al. (2018) applied the GA in a MATLAB-based simulation tool to optimise human robot task allocation, where the user can put own objectives into the simulation. A few publications present the entire design process including the layout evaluation. Saenz et al. (2018) demonstrated a generic design process for HIRC applications with multiple feedback loops. In this process, risk evaluation and reduction are in focus. Safety considerations are also a key in the design method presented by Awad et al. (2017). They created databases to connect workplace designs to hazards, and then hazards to safety measures, thus suggesting new layouts. Michalos et al. (2018) presented an automatic process for generation of layout options also considering task allocation.

The use of simulation software with capable DHM functionality in HIRC workstation design processes is very limited. Tsarouchi et al. (2016b) proposed a decision making framework where the Process Simulate 3D simulation tool is used to present workstation layouts, and Cencen et al. (2018) presented a HIRC design process composed by four subprocesses, analysis, modelling, simulation and evaluation, where the software Visual Components is used for simulation purposes.

3 RESEARCH METHOD

This chapter introduces the methodological approach of the research. It also presents an overview of the research process and the industrial cases used in the research. The chapter ends with a more detailed presentation of the methods applied for data collection, software and method development and result analysis.

3.1 THE METHODOLOGICAL APPROACH – DESIGN SCIENCE RESEARCH

The objective of this research is to develop a demonstrator software for simulation, visualisation and evaluation of a HIRC workstation, as well as to propose a design method of how to apply this software in an industrial context. The design science research (DSR) concept is used as a methodological approach in this work since it describes methods and practices to assist in scientific development of an IT artefact and its application method (Hevner et al., 2004; Hevner, 2007). The design of an artefact is central in the DSR concept. This artefact shall enhance organisational productivity and effectiveness (Baskerville et al., 2018). Figure 4 presents a simplified original framework developed for DSR as defined by Hevner et al. (2004, p. 80).

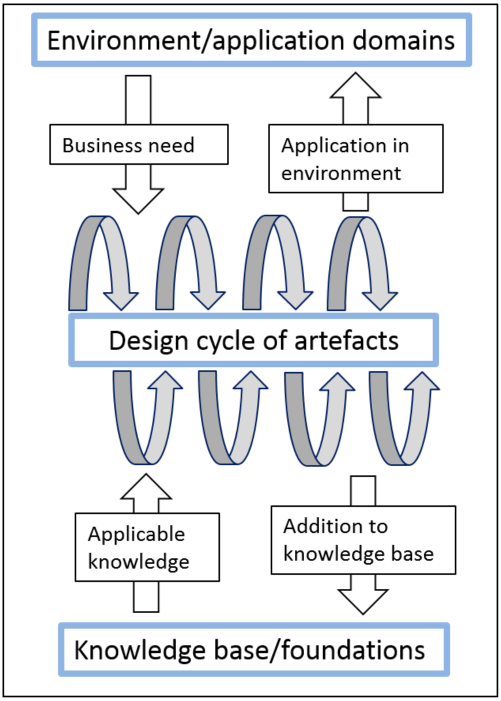


Figure 4 Simplified sketch of the design science research framework presented by Hevner et al. (2004, p. 80).

The framework in Figure 4 presents three main elements that are of importance in DSR: environment/application domains, design cycle of artefacts and knowledge base/foundations. The design cycle is an iterative process that takes a business need and combines it with existing applicable knowledge to design the new artefact, which is the core in DSR. The artefact developed shall also be applied in the environment where the problem was initiated, and the DSR framework shall also complement existing knowledge-base theories (Baskerville et al., 2018). The iterative nature of the design cycle shown in Figure 4 involves numerous evaluations and discussions with the environment, as well as multiple part deliveries to the knowledge base through academic publications and seminars.

Application of this framework in the research presented results in the design of an artefact (the HIRC simulation software) in order to meet demands from manufacturing industries (how to design HIRC workstations). Existing knowledge from the academic field (developed DHM and robotic simulation software, evaluation methods for biomechanical load and operation time theories) has been used in order to support the design process. The process has resulted in a new HIRC simulation software that has been used to design a HIRC workstation in the manufacturing industry, as well as processes on how to apply the software in HIRC workstation design process.

Hevner et al. (2004, p. 83) present seven guidelines to consider when conducting 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 been used as a support in this research process; the connection with the research conducted is discussed in Section 3.5.

3.2 THE RESEARCH PROCESS

The research process leading to this doctoral thesis is presented in Figure 5. This figure describes the phases of the research work, its corresponding papers appended to the thesis as well as the connection to the research questions. Each of these phases is described in the following subsections.

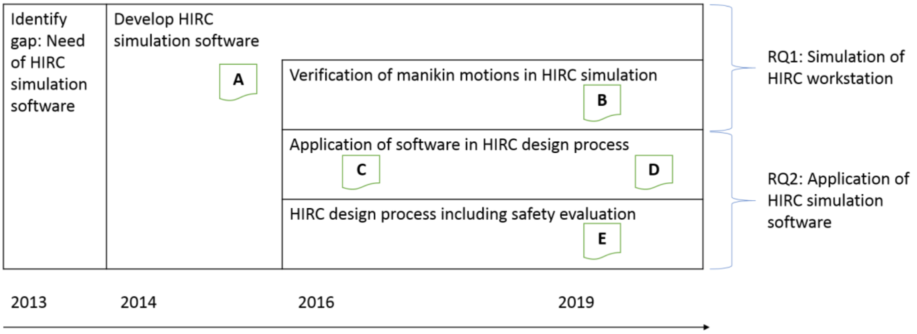


Figure 5 Research process including appended papers and their connection to RQs.

3.2.1 Identify gap: need of HIRC simulation software

The research gap was identified in 2013 based on multiple sources: a literature search, the author's prior work experience and discussions with supervisors. These sources made it clear that there existed a gap in the simulation, visualisation and evaluation possibilities of HIRC workstations. However, one prerequisite to be able to develop a capable HIRC simulation software was an existing collaboration between the Fraunhofer Chalmers Research Centre (FCC) and the heavy vehicle company where the studies were made. In 2013, FCC had initiated the development of the DHM software (IMMA) that enables simulation and design of manual workstations and also had another software enabling robotic simulation (IPS robot optimization).

3.2.2 Develop HIRC simulation software

The literature search that identified the gap of software in academic publications was extended to human robot collaboration (HRC) in manufacturing or assembly. This gave the basic knowledge in the area of HRC, specifically about its applications in industry.

With the existing HRC knowledge as a basis, the initial development of a geometric HIRC simulation software started in order to answer RQ1 "How can simulation, visualisation and evaluation of HIRC workstations be performed?". Through close collaboration with FCC their two existing simulation tools IPS-IMMA and IPS robotic optimization were merged into one interface. The author of this thesis set requirements on the design of the resulting HIRC simulation software, while FCC tried to meet these through programming their software. The new software versions where then evaluated by the author of this thesis.

Paper A presents the HIRC simulation software version in 2015, when HIRC workstations could be simulated, visualised and evaluated. However, the software required expert competence and use of several software programs, and further development was necessary to make it more user-friendly. Thus a new research project was initiated that continued the development of the software; this is visualised as the continuous work in the "Develop HIRC simulation software" phase in Figure 5. With this progress new features in the software have been developed, such as improved and more intuitive programming of the manikin and robotic tasks through addition of language instructions, enabling the digital manikin to walk in the simulation (not slide across the floor) and improved, more natural-looking texture of the manikins. The robotic part of the software has also been developed to include smaller power- and force-limiting robots in the simulation, including the KUKA lbr iiwa that has one extra degree of freedom (DOF) compared to traditional industrial robots, making it a 7 DOF robot. These improvements of the HIRC simulation software are not presented in an individual paper but are included in the simulations performed in all the later papers (B, D and E). However, the features presented in Paper A are still valid and create the basis of the later versions of the HIRC simulation software.

3.2.3 Verification of manikin motions in HIRC simulation

RQ1 also includes validity demands of the digital manikin motions in the HIRC simulation software. It is vital that the motions in the software represent plausible human motions to be able to trust its simulation results and use them in decision making.

The manikin motions in the HIRC simulation software include a high number of static postures. The software developers of the manikin software IPS IMMA have clarified that the objective is not to claim that the motion prediction function is to produce an exact motion performed by a certain human but to confirm that it is possible to accomplish the task in the virtual environment

(Högberg et al., 2016). And if no ergonomically acceptable motion can be found, action must be taken (Bohlin et al., 2012). However, it is of interest to investigate how well the simulation results represent actual human motions in order to build reliability in the simulation software.

To be able to verify simulated human motions with actual ones, HIRC workstations had to be found where human motion could be extracted. However, the number of installed HIRC workstations in European industries is still relatively low, and in the heavy vehicle company in the study no such stations were available. To make the verification with motions from a human, physical mock-ups of two potential HIRC workstations from the manufacturing company investigated were created in a laboratory environment. The selected industrial cases "engine block inspection" and "flywheel cover assembly" are thoroughly described in the industrial case section.

3.2.4 APPLICATION OF SOFTWARE IN HIRC DESIGN PROCESS

The second RQ, "How can a software for simulation, visualisation and evaluation of HIRC be applied in the workstation design process?", is connected to the application of a HIRC software in workstation design tasks. A HIRC simulation software itself cannot meet the HIRC workstation design challenge; its application has to be described in a methodical structure. This structure requires simulation possibilities of HIRC in order to select the most appropriate design; however, any software that enables quantitative evaluation of production system design parameters in HIRC workstations could be used in the processes.

This phase resulted in two appended publications, Papers C and D. Paper C was initiated when the evaluation of two industrial cases in Paper A indicated that a fully automatic system without any human interferences was superior to both manual and HIRC systems, since the robot moves faster than the human and does not have any biotechnical limitations. There are, however, other characteristics of importance to consider, such as need of flexibility, intelligence and tactile sense, typically human features not included in the evaluation. Many of these are difficult to quantify in a simulation software, thus there is a need to include them in the design process. One way to do this is to consider the limitations of what tasks can be automated due to robotic characteristics and safety constraints, thus tasks that require manual input. Paper C aims to identify these automation constraints. To get an input into such automation constraints, a literature search was conducted concerning task division between human and automated work tasks in manufacturing. In Paper D, Pahl and Beitz's engineering design framework (Pahl et al., 2007) was applied in a HIRC workstation design process that included a simulation software. The result from Paper C is included as a part of this design process.

3.2.5 HIRC DESIGN PROCESS INCLUDING SAFETY EVALUATION

The technical specification "ISO/TS 15066: Robots and robotic devices – Collaborative robots" (ISO, 2016) presents guidance on how to design safe collaborative robot applications. These applications can be designed with various safety features and sensors. HIRC stations with the newly developed power- and force-limiting robots, which are developed to stop at initial impact with a human, thus reducing the consequence of a collision, are also described. Appendix A.3 in ISO/TS 15066 presents biomechanical limits, which specify forces and pressures a human body can withstand before a minor injury occurs on the human body. These limits have been applied to design safe HIRC systems with humans and power- and force-limiting robots. The proposed HIRC simulation software does not calculate these collision forces or pressures. In order to meet this gap, a collaboration with a research colleague was initiated, in which a proposed human–

robot collision model was merged with the proposed HIRC simulation software. The resulting HIRC design method including safety evaluation is presented in Paper E. Through this process it is possible to optimise the HIRC workstation considering performance and safety parameters in parallel. The proposed design process is also generic, and any simulation software that quantitatively evaluates HIRC workstations could be used in the process.

3.3 INDUSTRIAL CASES

During the research work a number of industrial workstations have been used to present the HIRC simulation software and its application. All these cases are at existing workstations in an international heavy vehicle manufacturing company, where HIRC solutions could be used. The company produces heavy trucks and buses on mixed-model assembly lines with relatively small automation due to the large variation in products on the same production lines. Table 2 presents a list of the five cases used in the work presented and where these are applied in the appended papers. The cases are described in detail in the following sections.

Table 2 Industrial cases and how they are connected to appended Papers A-E

	A	B	C	D	E
Flywheel cover assembly	X	X	X	X	
Tyre assembly	X		X		
Engine block inspection		X	X		
Material preparation of driveshafts			X		
Gearbox suspension assembly					X

3.3.1 FLYWHEEL COVER ASSEMBLY

This industrial case was identified as a potential HIRC case in which a human needed assistance of a large, traditional industrial robot. The flywheel cover assembly requires a large industrial robot due to the heavy load of the cover (up to 60 kg). The flywheel cover is assembled in the engine assembly plant. The current layout is presented in Figure 6, where three positions are of specific interest:

- Position 1, get flywheel cover from pallet with incoming material
- Position 2, load and unload flywheel cover in an automated press and silicone-applying machine
- Position 3, assemble flywheel cover on an engine block with 12 bolts using manually handled nut runners

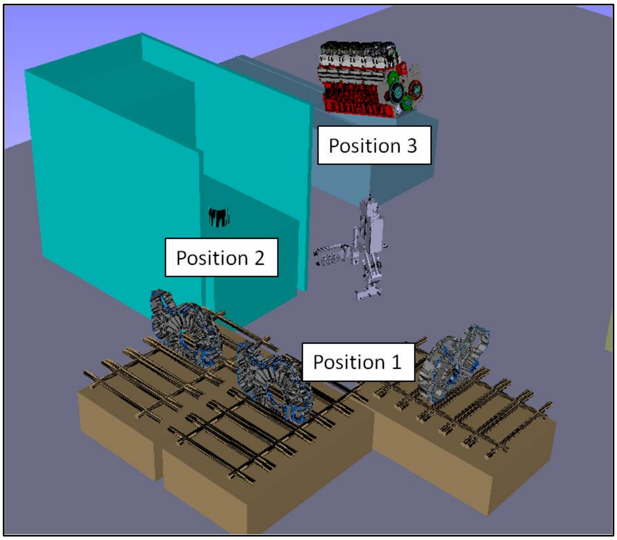


Figure 6 Existing flywheel cover assembly station, with lifting equipment and the product flow of flywheel cover in station (from positions 1 to 3) (Paper A).

This case was selected as a potential HIRC station due to inherent ergonomic difficulties when new and heavier components were to be introduced in the station at the same time as the takt time needed to be reduced. This case was used throughout the whole research process, it has been used with different purposes and methods.

3.3.2 TYRE ASSEMBLY

The truck tyre assembly case was used to demonstrate the software (Paper A) and to identify the automation constraints (Paper C). It was selected since the existing process included a heavy and complex lifting equipment to handle the tyres, where a HIRC layout including might reduce the ergonomic load on the operator. An additional challenge to the heavy load of a tyre (up to 130 kg) is that the assembly line is continuously moving, making automation even more difficult. Figure 7 presents the existing manual layout, where the tyre is handled by a large pneumatic lifting equipment hanging from an overhead rail system controlled by manual force of the operator.

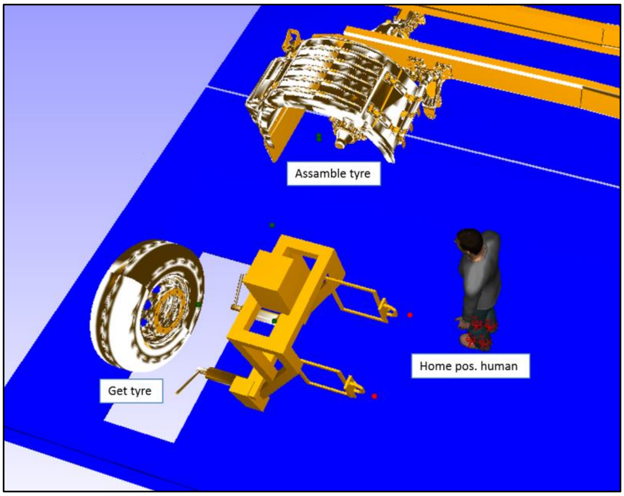


Figure 7 Existing truck tyre assembly station with lifting equipment and pick position of tyre that are transported from the basement.

3.3.3 ENGINE BLOCK INSPECTION

The engine block inspection system is a potential HIRC case from the machining environment. All machined engine blocks have to be visually controlled to detect cracks or other flaws on the machined surfaces. The current process includes a manually controlled rotating device that indexes the engine block to predefined positions, where the inspection is carried out manually with the support of a flashlight. This process involves awkward biomechanical positions and time constraints on the operators. Figure 8 presents the existing system including one bad biomechanical human posture.

Figure 8 Current visual inspection system. The operator inspects the side of the engine block; the circular frame surrounding the block is used to rotate it to enable inspection of the side surfaces (Caliskan and Khalid, 2015).

A HIRC system was in this case of interest as it would enable a large industrial robot to present the engine block at better positions and reduce biomechanical load. This case was used to identify the automation constraints (Paper C) and a prototype of a proposed HIRC workstation was also created in a lab environment and was used to verify human motions in the HIRC simulation software (Paper B).

3.3.4 MATERIAL PREPARATION OF DRIVESHAFTS

This industrial case is located in the logistics area in the heavy vehicle manufacturing company. It includes preparing the correct sequence of driveshafts in pallets to improve the productivity of the assembly line. Driveshafts from eight pallets are moved through manual lifting equipment hanging from an overhead rail system controlled by manual force of the operator to one pallet that is to be transported to the assembly line; see Figure 9.

Figure 9 Existing material preparation of driveshafts (Caliskan and Khalid, 2015).

This process includes a high number of repetitions and back bending to reach the driveshaft at the bottom of the pallet, and thus a HIRC system might reduce the biomechanical load of the workstation. This industrial case was used in Paper C to identify automation constraints.

3.3.5 GEARBOX SUSPENSION ASSEMBLY

The final industrial case presented in this thesis is the assembly of a gearbox suspension on the truck frame. These suspensions are today handled fully manually even though they are quite heavy, 8 kg. Thus a HIRC workstation that could handle the heavy part would improve the biomechanical load on the operator. The existing workstation and the assembly process is shown in Figure 10, with these positions:

- A, pick position of gearbox suspension in the material rack
- B, preassembly fixture for gearbox suspension
- C, frame where gearbox suspension is assembled

Figure 10 Existing gearbox suspension assembly station. The suspension is moved from incoming material rack (A) to preassembly station (B) to be assembled on the frame (C) (Paper E).

This industrial case was used in Paper E, where it demonstrates a HIRC workstation design that considers time, biomechanical load and human safety characteristics simultaneously.

3.4 METHODS APPLIED IN THE RESEARCH

A more detailed presentation of the methods applied in the research for data collection, software and method development and result analysis is given in the following section. Table 3 presents the methods and how they are applied in the appended Papers A–E. Literature search and HIRC simulation are used in many of the publications, thus these are described separately in the following text. The other methods are more closely connected to one publication; these are described in subsections connected to the papers.

Table 3 Methods applied in the research and how they are connected to appended Papers A–E

	A	B	C	D	E
Literature search	X	X	X	X	X
HIRC simulation	X	X		X	X
Set and evaluate software requirements	X				
Motion capture experiments		X			
Statistical analysis		X			
Identify constraints through HIRC analysis			X		
Develop design processes				X	X

3.4.1 LITERATURE SEARCH

Systematic and iterative literature searches have been carried out throughout the research process, starting from the gap identification process, Figure 5. It was initially focused on the broad HIRC field through search terms such as “Robot AND (human OR man) AND (collaboration OR cooperation OR interaction) AND (manufacturing OR assembly)”. These search terms were applied in several databases: IEEE Xplore, ScienceDirect, Scopus and Web of Science. This search was done throughout the whole research process and was complemented by specific searches made for the individual studies conducted. Papers A and B include addition of “simulation”, “evaluation”, “motion capture” and “statistical analysis”. Paper C added “task allocation”, and Papers D and E complement the search with “design method” and “design process”. Chain search (Rienecker and Stray Jørgensen, 2008) was applied in the identified publications to find other relevant literature. The results from all these literature searches are visible in the theories used as well as in the frame of reference sections in all appended publications.

3.4.2 HIRC SIMULATION

The HRC simulation software was used in four out of the five appended papers. It was presented in Paper A, validated in Paper B and used to demonstrate research results in Papers D and E. Regardless of the purpose of the simulation a similar process has been applied when creating the simulations. This generic HIRC simulation process is described in Figure 11. In each of these process steps decisions are taken and these differ in all papers, but these steps have been taken in all papers to create a simulation model, execute it and get quantitative data to evaluate. The following text describes these process steps and the utilisation of the HIRC simulation software in detail.

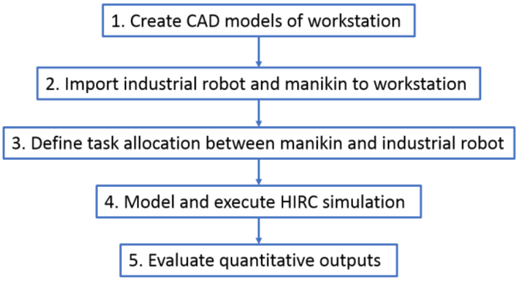


Figure 11 Generic HIRC simulation process.

1. Create CAD models of workstation

The first activity is to generate CAD models of the workstation. These models could be created in any CAD tool and are extracted to the HIRC simulation software in JT or WRML format. The software can also handle 3D-scanned point clouds of an existing workstation as the basis to create a new layout (Lindskog et al., 2016). These CAD models also have to include all the relevant products and fixtures needed in the workstation design.

2. Import industrial robot and manikin to workstation

When the layout is imported into the HIRC simulation software, the industrial robot and the digital manikins shall also be defined and imported. Any type of serial industrial robots can be created in the software. The industrial robots are described as skeleton models that are dressed with the individual robot’s own 3D wireframes available from the homepages of the robot supplier to render a visual accurate representation of the robot. In addition to this, a number of the newly developed power- and force-limiting robots (e.g., KUKA lbr iiwa and UR10e) can also be simulated (Castro et al., 2018). The digital manikins are created in the software and can consist of a single manikin or a family of manikins. The anthropometrics of these manikins can be set based on the demands on the design; often only one medium manikin is used, in other cases one large male and one small female are selected (Bertilsson et al., 2010). It is easy to recognise that there is a need to include a broader variety of the manikins to evaluate the workstation to fit all potential operators. Thus applying manikin families that cover the whole span of individuals is an important feature in the HIRC simulation software. It is also of importance to have access to anthropometric data for the population of interest in order to have appropriate manikin representations. All anthropometric data in the simulations presented in this thesis use measurements from Sweden (Hanson et al., 2009).

3. *Define task allocation between manikin and industrial robot*

The actual task allocation between human and robot must also be decided. There are different methods to create this; Paper C describes one way to identify automation constraints in a task allocation process. Regardless of the exact method, a task allocation is vital to be able to execute a simulation. If there is an interest in investigating multiple task allocations, the HIRC simulation process must be iterated from this activity.

4. *Model and execute HIRC simulation*

This step in the process includes creating the defined tasks in the simulation environment. This involves determining the exact positions of the human and the industrial robot to grasp an object, setting all the start and end positions of all objects and establishing the final layout with exact positions for all equipment, products and resources. A high-level language is used to connect the resources with the objects handled through the exact geometric positions of the objects and their respective grasp points (Mårdberg et al., 2014). The input is the motion of the objects from point A to point B. The software then calculates a collision-free path for all moving objects (the human, the robot and the object being handled).

5. *Evaluate quantitative outputs*

The final common step in all HIRC simulations performed is the quantitative evaluation of total operation time (s) and biomechanical load (RULA value) from the human and robotic motions.

3.4.3 PAPER A – SET AND EVALUATE SOFTWARE REQUIREMENTS

Paper A (Ore et al., 2015) is the appended paper that has the development of the HIRC simulation software in full focus; thus the method to set and evaluate software requirements on its development is only suitable here. This work was done early in the Ph.D. student project after an initial literature study. The focus was on the actual performance of the simulation software. Close collaboration with FCC, which already had developed the DMH tool IPS IMMA and the industrial robot simulation software IPS robot optimization, offered the opportunity to set demands on the performance of a HIRC simulation software.

The existing simulation tools also put constraints on the software development. The DHM tool IPS IMMA had been developed since 2009 with the aim of being a design tool to support ergonomic designs of workstations. It is a tool “that uses advanced path planning techniques to generate collision free and biomechanically acceptable motions for digital humans (as well as parts) in complex assembly situations” (Hanson et al., 2011, p.1). The robotic part of the software was initially developed to optimise the paths between multiple robots (Spensieri et al., 2013). Hence it was natural to focus on the workstation design problem and not on other types of HIRC simulation challenges (such as collision force calculation between human and industrial robot).

Through the initial literature review the general objectives of HIRC were concluded to increase productivity, reduce ergonomic load and improve quality. Thus the HIRC simulation software should be able to analyse some of these issues in order to quantitatively evaluate a future HIRC workstation.

The author of this thesis communicated demands on the HIRC simulation software. These demands can be summarised as follows:

> “It should be possible to simulate and visualise a human and an industrial 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”.

This included multiple iterations where the author used existing industrial cases to evaluate the development. The final evaluation of operating time and biomechanical load was carried out by the author. This included applying existing PMTS (predetermined motion time systems) standards to estimate human operation time and RULA (rapid upper limb assessment) to assess biomechanical load on the human. Both these methods were included in the HIRC simulation software later in the process (after 2015). The final results from this initial work is presented in Paper A.

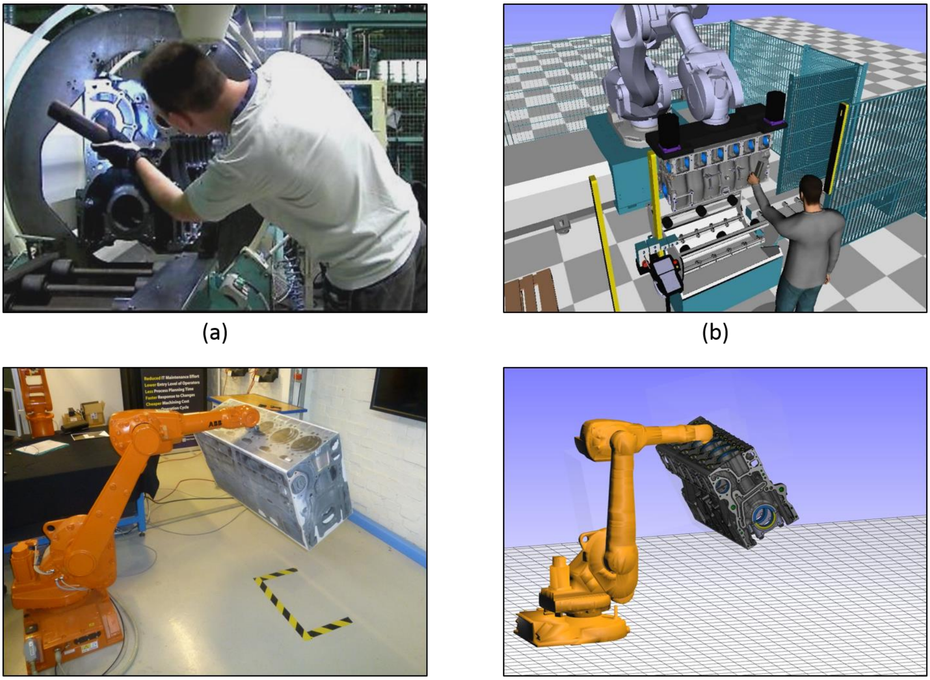
This method to iterate software development with industrial cases had been used in the whole HIRC simulation software process, but had not been the focus of any of the other appended publications. In these the software has been used as a tool to demonstrate the research results, not being the results in itself.

3.4.4 PAPER B – MOTION CAPTURE EXPERIMENTS AND STATISTICAL ANALYSIS

Paper B (Ore et al., 2019b) presents verification of the manikin motions in the HIRC simulation software developed. This is done through comparing motions from real humans with the proposed HIRC design, using the software. Thus motion capture experiments on humans and statistical analysis of the results were applied.

Two cases of existing industrial workstations were used for these verification experiments, engine block inspection and flywheel cover assembly. Potential HIRC workstations for these tasks were created in lab environments.

The engine block inspection includes manual visual inspection of a machined engine block on all its six surfaces. This is currently done through a manually controlled rotating device, where the inspection is done with a flashlight as shown in Figure 12 (a). A HIRC layout was proposed (Khalid et al., 2015), where a large industrial robot handles the engine block and presents it to the operator at suitable positions; see Figure 12 (b). A similar workstation was created in the HIRC lab at KTH, the Royal Institute of Technology in Stockholm, where their largest robot with a payload of 10 kg was used to mimic the station. Thus a lightweight prototype (with the correct outer dimensions) of the engine block made of styrofoam was created as shown in Figure 12 (c). The sides of the styrofoam model were equipped with pictures of an engine block and small holes were drilled that the operator should count, in order to mimic the actual inspection. A virtual model of the same lab installation was created; see Figure 12 (d).

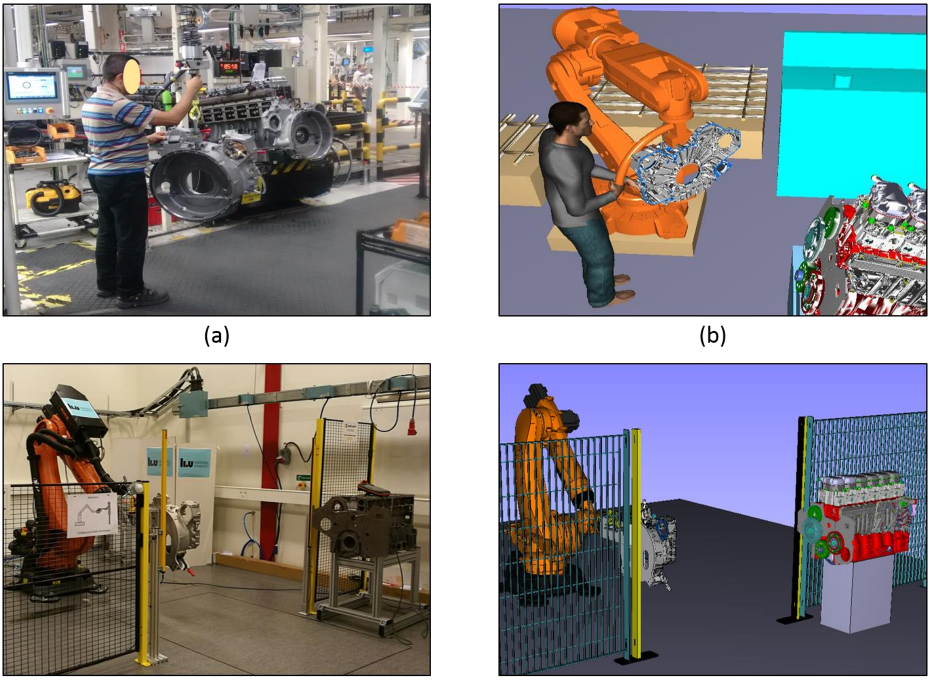


(a) (b)

(c) (d)

Figure 12 (a) Existing visual engine block inspection at company (Caliskan and Khalid, 2015), (b) proposed HIRC layout (Khalid et al., 2015), (c) physical mock-up in lab environment (Paper B), (d) simulated environment representing physical mock-up (Paper B).

The second case was the flywheel cover assembly station. The industrial robot may assist the operator in transporting the flywheel cover, while the final assembly has to be made with a human hand guiding the object. Figure 13 (a) presents the current layout where the flywheel cover is manually handled through an overhead rail system. In Paper A solution where the final assembly was hand-guided was proposed, Figure 13 (b). Figure 13 (c) presents the lab installation (at Linköping University) that was used for the physical tests, and Figure 13 (d) represents the simulated environment used in the verification.



(a) (b)

(c) (d)

Figure 13 (a) Existing flywheel cover assembly at company (Paper B), (b) proposed HIRC layout (Paper A), (c) physical mock-up in lab environment (Paper B), (d) simulated environment representing physical mock-up (Paper B).

Figure 14 presents the enabling device that was developed in the lab in order to hand-guide the robot motions. It consists of two controls (A) with a three-position push button at the top and a force and torque sensor (B). The buttons have to be pushed in the middle position in order to hand-guide the robot. Small forces by the human are detected by the power and torque sensor and move the robot accordingly.

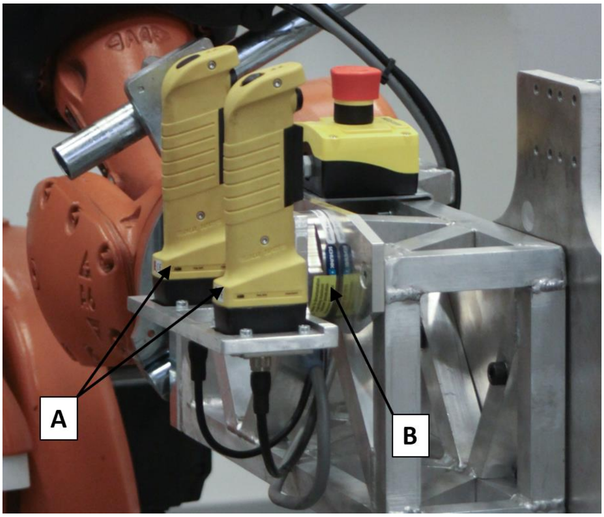


Figure 14 Enabling device used to hand-guide the robot in the lab environment. It consists of two controls (A) and one power and torque sensor (B).

The HIRC simulation software was used to simulate both these industrial cases. To replicate the human variation in anthropometrics of physical test persons, a family of manikins was used. An average family was created in the software consisting of ten manikins, five males and five females. The manikins were created with weight and stature as key measurement parameters, with a 95 % confidence interval for each sex (Bertilsson et al., 2011). Swedish anthropometric data presented by Hanson et al. (2009) were used for the manikin creation, Figure 15.

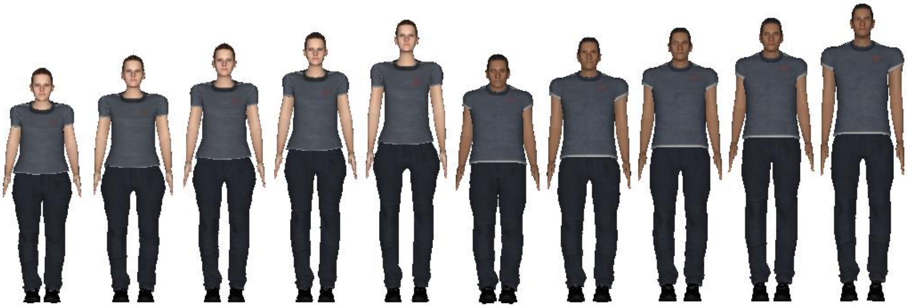


Figure 15 Manikin family used in both verification simulations (Paper B).

Each manikin performed the inspection and assembly tasks, and the corresponding time-weighted average RULA score and time values were extracted, Figure 16.

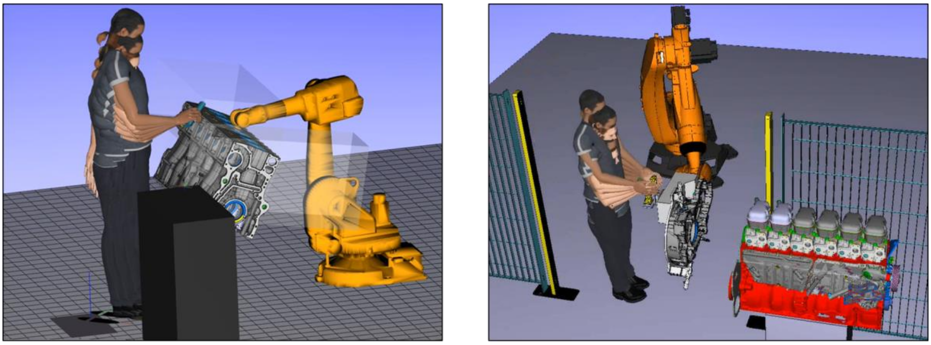


Figure 16 Images from simulation of verification cases, with QR codes linking to videos of the simulation.

The physical experiments included 13 and 12 participants, respectively, who were equipped with Xsens motion capture system MVN Awinda. This system consists of 17 wireless sensors placed at predefined locations on the body and secured with straps. In the flywheel cover assembly experiments, four of the twelve persons were skilled assembly employees from the same engine assembly factory where the current flywheel cover assembly is done (none had previously worked at this assembly station). The other test subjects were all recruited from the student network of the authors and had limited practical manufacturing experience. The participants had an opportunity to practise the task and then performed it in two (flywheel cover assembly) or three (engine block inspection) cycles when the system recorded data; the last one was selected for further analysis, Figure 17.

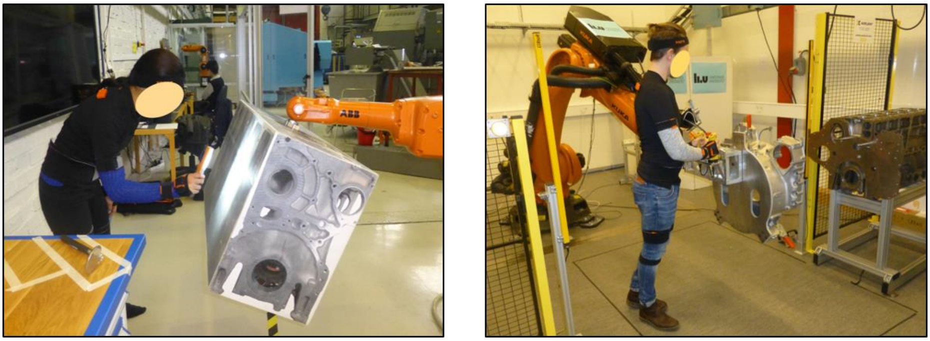


Figure 17 Physical experiments in which the motion capture system collects joint data (Paper B).

The system extracted 22 joint data from the human motions, which were divided into X, Y and Z rotations summing up 66 measurement values that represent the human motions. Operation times for performing the complete work cycles were also extracted from the motion capture system. During the data capture, problems with the wireless sensors were experienced due to electromagnetic disturbances in the physical test environment. Consequently, a number of collected data could not be used for verification. In engine block inspection 7 and in flywheel cover assembly, ten of the participants' data could be used for further analysis. The joint data were then analysed and corresponding time-weighted average RULA score and time values were extracted.

In order to evaluate and compare the results, a statistical analysis was performed. The Mann-Whitney U test was performed on the verification data. This statistical test method was selected since this is performed when the test samples were few and normal distributions could not be assumed as the RULA values are limited to being integers from 1 to 7 (Marusteri and Bacarea, 2010; Nachar, 2008).

3.4.5 PAPER C – IDENTIFY CONSTRAINTS THROUGH HIRC ANALYSIS

Paper C (Ore et al., 2016) aims to investigate automation constraints in HIRC workstations, since these limit potential HIRC designs. In order to identify these constraints, the designs of three HIRC cases from the same international manufacturing company as in the previous cases were analysed.

These three HIRC design cases were evaluated in detail in order to find their automation limitations. The first step in this evaluation was to study the cases through a hierarchical task analysis (HTA). An HTA breaks down the workstation into smaller tasks in order to find goals and sub-goals of a system (Stanton, 2006). For each of the tasks identified, the work process was analysed and factors describing the task were recognised. These factors cover all activities in the station, including transformation of material, human communication needs and environmental considerations. A few of these factors were identified as automation limitations in the task. These were then generalised to common automation constraints. The application of these automation constraints was demonstrated in a fourth industrial case.

3.4.6 PAPER D – DEVELOP DESIGN PROCESSES

Paper D (Ore et al., 2019a) aims to propose a HIRC workstation design process that can be applied in early phases of production development.

The proposed design process is highly influenced by the systematic design methodology that has become a best practice for product and engineering design (Stauffer and Pawar, 2007), more specifically the engineering design method presented by Pahl and Beitz (Pahl and Beitz, 1977). The latest English edition (3rd) of their work (Pahl et al., 2007) (co-authored by Feldhusen and Grote) was used in developing the HIRC design process proposed in this paper. Their design method is named "the Pahl and Beitz engineering design framework" in this thesis. This method was combined with experience from design of four industrial HIRC cases in the development of the HIRC demonstrator simulation software. All this together led to the development of the HIRC design process proposed.

The Pahl and Beitz engineering design framework has four main phases. In these phases a number of working steps are proposed. In the development of the HIRC design process the phases were selected as a backbone structure and each of the working steps was assessed regarding how it could be utilised in HIRC workstation design. Some of these working steps are retained in the developed HIRC workstation design process, while others were combined into new ones and still others were concluded to be redundant in a HIRC workstation design context. All of this is combined into a proposed HIRC workstation design process.

3.4.7 PAPER E – DEVELOP DESIGN PROCESSES

Paper E (Ore et al., 2019c) also proposes a design process for HIRC workstations. The novelty of this process is its possibility to evaluate safety as well as performance criteria simulations in one process.

The proposed HIRC workstation design process presented in Paper E is founded on the basic ASE (analysis, synthesis and evaluation) design method (Luckman, 1967), but with the focus on the third step, evaluation.

The safety evaluation is made considering a power- and force-limiting robotic system, a robot that stops at initial impact with the human. Such robots enable contact between the human and the industrial robot. This safety evaluation is made through collision modelling of a compliant contact force (CCF) approach between the human and the industrial robot. The collision is described as a linear spring-damper system, where different body regions have individual spring constants and effective masses in the mathematic equation. The performance criteria simulation is done based on the capability of the available simulation software. The criteria could be any production system design parameter (e.g., cost, ergonomic load, time, floor utilisation). In the industrial example presented in Paper E the developed HIRC simulation software was used, and thus biomechanical load and operation time were evaluated.

3.5 RESEARCH QUALITY – SEVEN DSR GUIDELINES

This chapter describes how each of the seven guidelines defined by Hevner et al. (2004) has been considered in order to ensure the quality of the research process. These seven guidelines cover the validity and reliability of the research conducted.

Guideline 1: Design as an artefact

This first guideline states that “[d]esign science research must produce a viable artefact in the form of a construct, a model, a method, or an instantiation” (Hevner et al., 2004, p. 83). One resulting artefact from the research presented is a HIRC simulation software developed to virtually evaluate HIRC workstations and to get quantitative numbers of the biomechanical load and operation time of different designs. Papers D and E present application processes in the use of a HIRC simulation software, and these are also considered as artefacts.

Guideline 2: Problem relevance

The relevance of the problem for an organisation is the necessary ignition of a DSR process (Hevner et al., 2004). As described in Section 1, the demonstrator software met previously unsolved problems in the design of HIRC workstations, not just in the company where the author of this thesis is employed, but in the wider industrial and academic world. The HIRC simulation software makes it possible to analyse human and robot that simultaneously work in a collaborative environment, including hand-guiding tasks. The software enables design of both traditional, large industrial robots and the more recently developed power- and force-limiting robots (e.g., KUKA lbr iiwa and UR10e). The application of a simulation software in a workstation design process is a solution proposed to meet the currently challenging task to design a HIRC station that relies on the competence and experience of the designer (Fechter et al., 2018). This need to establish systematic engineering design methods in HIRC workstation design is also highlighted by Pini et al. (2015) and Michalos et al. (2018).

Guideline 3: Design evaluation

The third guideline states that “[t]he utility, quality, and efficacy of a design artefact must be rigorously demonstrated via well-executed evaluation methods” (Hevner et al., 2004, p. 83). The demonstrator software is evaluated in industrial cases where HIRC workstations are designed and evaluated. However, this design evaluation guideline also covers how efficiently the software can be used to meet its goal. This design evaluation can be done in several ways; Paper B presents one evaluation that aims to verify the motions of the digital manikin with actual motions performed by humans. The application processes presented in Papers D and E both include existing industrial HIRC design problems that show the processes in practical applications. The software is evaluated in four industrial cases in Papers A, B, D and E; these are described in their respective sub-sections in Section 3.3.

Guideline 4: Research contribution

This guideline states the need of “clear and verifiable contributions in the areas of the design artefact, design foundations, and/or design methodologies” (Hevner et al., 2004, p. 83). This research contributes with two artefacts, the HIRC simulation software and the process of how to apply it in a design task. The four industrial cases show the contribution of both these artefacts to existing HIRC design tasks in the manufacturing company.

Guideline 5: Research rigour

Hevner et al. (2004, p. 83) define this guideline: “[d]esign-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artefact”. To follow this guideline and 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 MTM for time predetermination of work tasks (Laring et al., 2002). The application part of the research is divided into two papers. Paper D uses Pahl and Beitz’s engineering design framework (Pahl et al., 2007) as a basis to create a HIRC design process, and Paper E includes collision models to calculate potential collision forces between the human and industrial robots (Vemula et al., 2018) in order to ensure safe HIRC designs.

The evaluation of the design artefact is done in Paper B, where the resulting motions from the HIRC simulation software are verified, and the processes in Papers D and E are validated through the industrial application.

Guideline 6: Design as a search process

This guideline states that “[t]he search for an effective artefact requires utilizing available means to reach desired ends while satisfying laws in the problem environment” (Hevner et al., 2004, p. 83). The iterative nature of the design process is a natural part of the research performed. The simulation software has evolved from a number of iterations where different versions of the software have been applied to industrial cases. The resulting simulations, which are available in Section 4, showcase the software development, where cases from Paper A show an early version and cases in Papers B, D and E are performed with the latest version. The suggested design processes answering the second RQ (Papers D and E) are both search processes in themselves as they iterate design alternatives to find the best layout of a HIRC workstation.

Guideline 7: Communication of research

This last guideline highlights the need to present the research in an effective manner “both to technology-oriented as well as management-oriented audiences” (Hevner et al., 2004, p. 83). The research has been presented in various forms to different groups; to academia in the form of peer-reviewed journal papers and conference presentations, to industrial partners in the real case evaluations and seminars and to research colleagues in a number of internal presentations.

4 RESULTS

This chapter presents the empirical and theoretical results from the research conducted. The results are associated with the two research questions in two separate sections.

4.1 SIMULATION OF HIRC WORKSTATIONS

RQ1: How can simulation, visualisation and evaluation of HIRC workstations be performed?

The HIRC simulation software has been developed and matured during the whole Ph.D. process. Paper A presents the identified research gap as a lack of simulation, visualisation and evaluation tool to design HIRC workstations and proposes a new software to bridge this gap, and Paper B aims to verify the proposed human motions through physical experiments.

4.1.1 HIRC SIMULATION SOFTWARE, PAPER A

Paper A presents the HIRC simulation software as a combination of the DHM software IPS IMMA (IPS, 2019a) and the robotic simulation software IPS robot optimization (IPS, 2019b) into one to enable visualisation, simulation and evaluation of HIRC workstations, Figure 18.

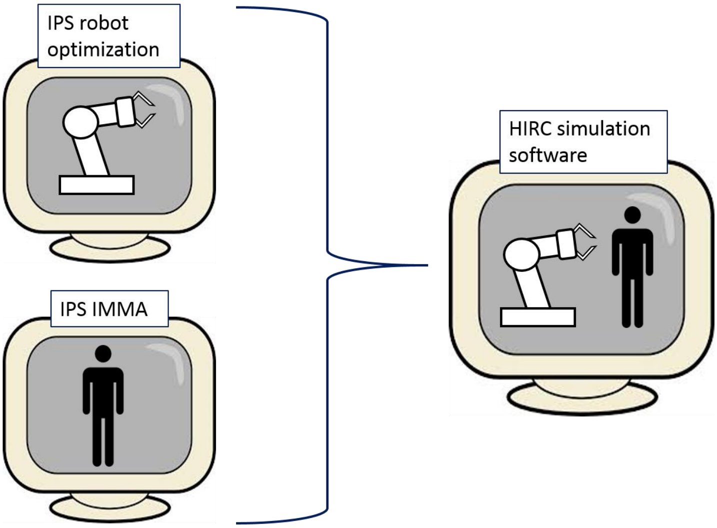


Figure 18 Image showing the merging of robot and DHM software into the new HIRC simulation software.

This software is named HIRC simulation software in this thesis, but it has been given different names throughout its development in the research process and in papers (it has primarily been called "HIRC demonstrator software" and "IPS-HIRC").

The developed HIRC simulation software enables 3D visualisation of a HIRC workstation. Such a visualisation enables evaluation of multiple workstation layout factors. A simple analysis of robotic and human reach envelopes reveals whether the position of the robot, the human or surrounding material and equipment is within corresponding range. This enables early evaluation of robot sizes needed as well as position of material to be within human reach and thus a possibility to design a suitable layout of a workstation. The visualisation can also be used to discuss different technical solutions including safety system, and be the base of early risk assessments in HIRC workstation design. However, sole visualisation is not enough to create an optimal layout. The software also enables quantitative evaluation of production system design parameters. As the main objectives of HIRC workstations are to increase productivity, improve quality and improve the ergonomics for the human operator (Krüger et al., 2009; Reinhart et al., 2012), quantitative evaluation of these will make it possible to evaluate the success of a HIRC design. The HIRC simulation software has focused on evaluation of productivity and ergonomics. It evaluates total operation time of the work task as a measure of the productivity and the biomechanical load on the human operator performing a task as a measure of its ergonomic value.

The total operation time for a task in a HIRC environment is a combination of human, robotic and collaborative times. In order to estimate human operation time, the PMTS system Methods-Time Measurement (MTM) was used. In Paper A the simplified version SAM is used that groups multiple small MTM motions into one common time (Laring et al., 2002). However, in the later versions of the HIRC simulation software the original MTM-1 times are used, as the full geometry of the workstation in the simulation tool enables this (except motions that are too detailed to be included in the software, such as finger motions). These MTM times are used in Papers B, D and E in this thesis. The time for the industrial robot to perform a motion is extracted from the IPS robot optimization part of the HIRC simulation software. The collaborative times are either calculated as human or robotic time, depending on who is in control of the motion.

The biomechanical load on the digital manikins is calculated through RULA. The connection to discrete joint values that the RULA systems use is easily achieved as numerical values in a DHM software like IPS IMMA and thus included in the HIRC simulation software. RULA was initially developed to analyse individual postures, "… the posture held for the greatest amount of the work cycle or where highest loads occur" (McAtamney and Corlett, 1993, p. 93), and not whole motions. However, the HIRC simulation software enables RULA analyses of motions since each motion is divided into a high number of poses (median sampling frequency of 140 Hz) that can be analysed individually. From all these poses, a time-weighted average RULA score is calculated and used in the evaluation to analyse and compare different workstation designs.

The software is presented with two industrial cases in Paper A, flywheel cover assembly and truck tyre assembly. Both originate from existing assembly stations in the heavy vehicle company and are extensively described in Section 3.3. The collaborative HIRC tasks are presented in Figure 19 and Figure 20. These simulations and images were developed in 2015, and the software has since then been further developed.

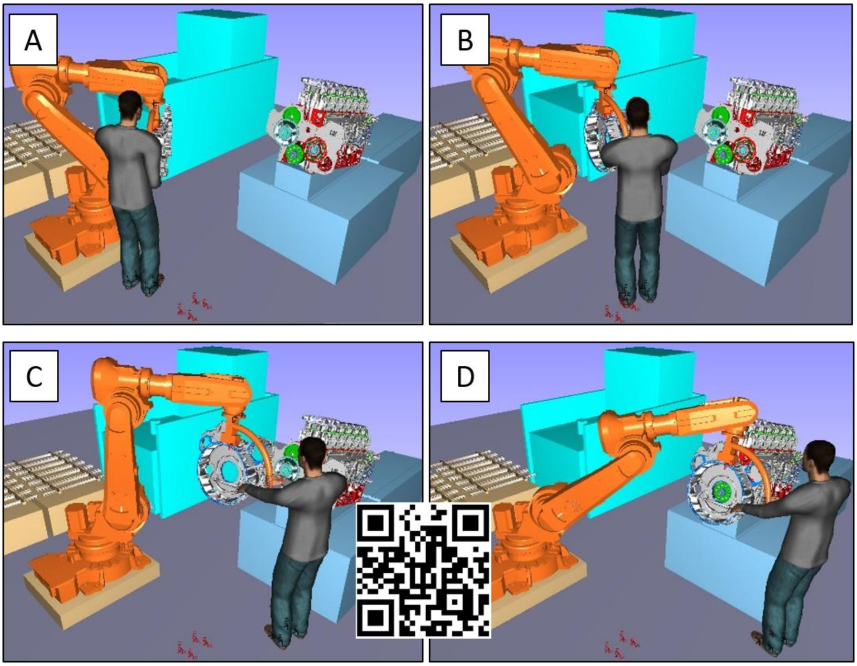


Figure 19 Sequence of the collaborative task of the flywheel cover assembly, with QR code linking to a video of the simulation.

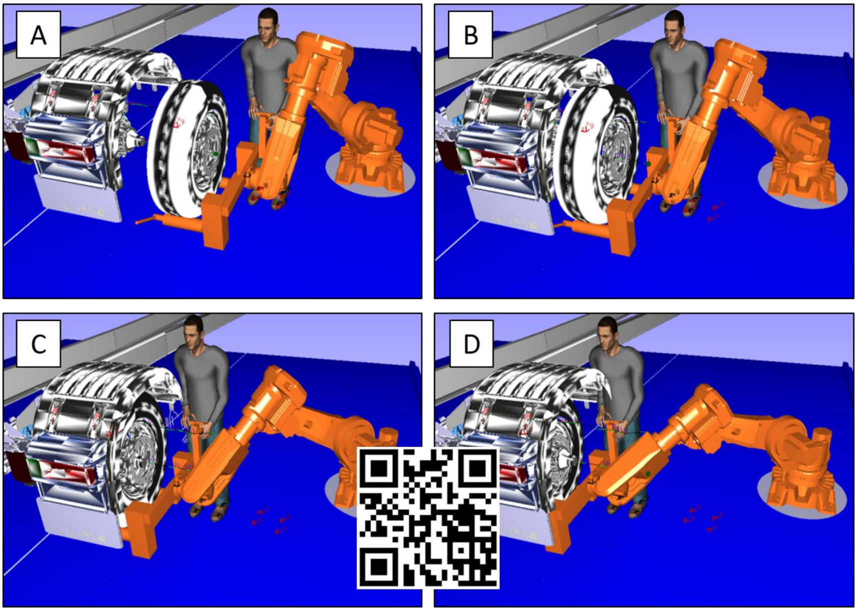


Figure 20 Sequence of the collaborative task of the truck tyre assembly, with QR code linking to a video of the simulation.

In order to demonstrate the quantitative evaluation of operation time and biomechanical load (RULA) in the cases presented, the results from manual, HIRC and robotic workstations were compared. The results verify the proposed benefits of HIRC compared with manual assembly: shorter operation time and improved ergonomics in these specific industrial cases. Table 4 and Table 5 present a summary of these results.

Table 4 Results comparing human, HIRC and robotic workstations of the flywheel cover assembly

Flywheel cover assembly	**Operation time (s)**	**RULA score**
Human	25.7	4.5
HIRC	14.5	4.1
Robot	11.6	0

Table 5 Results comparing human, HIRC and robotic workstations of the truck tyre assembly

Truck tyre assembly	**Operation time (s)**	**RULA score**
Human	14.8	3.3
HIRC	9.8	3.0
Robot	5.7	0

4.1.2 VERIFICATION OF HIRC SIMULATION MOTIONS, PAPER B

It is of high interest to investigate how well the simulation results represent actual human motions in order to build reliability in the simulation software. Thus Paper B aims to verify the manikin motions predicted by the mathematical algorithm in the software with results obtained from motions performed by humans in experiments. Thus a family of digital manikins were used to represent the anthropometric variation in a population. The results from the verification study are presented in Figure 21.

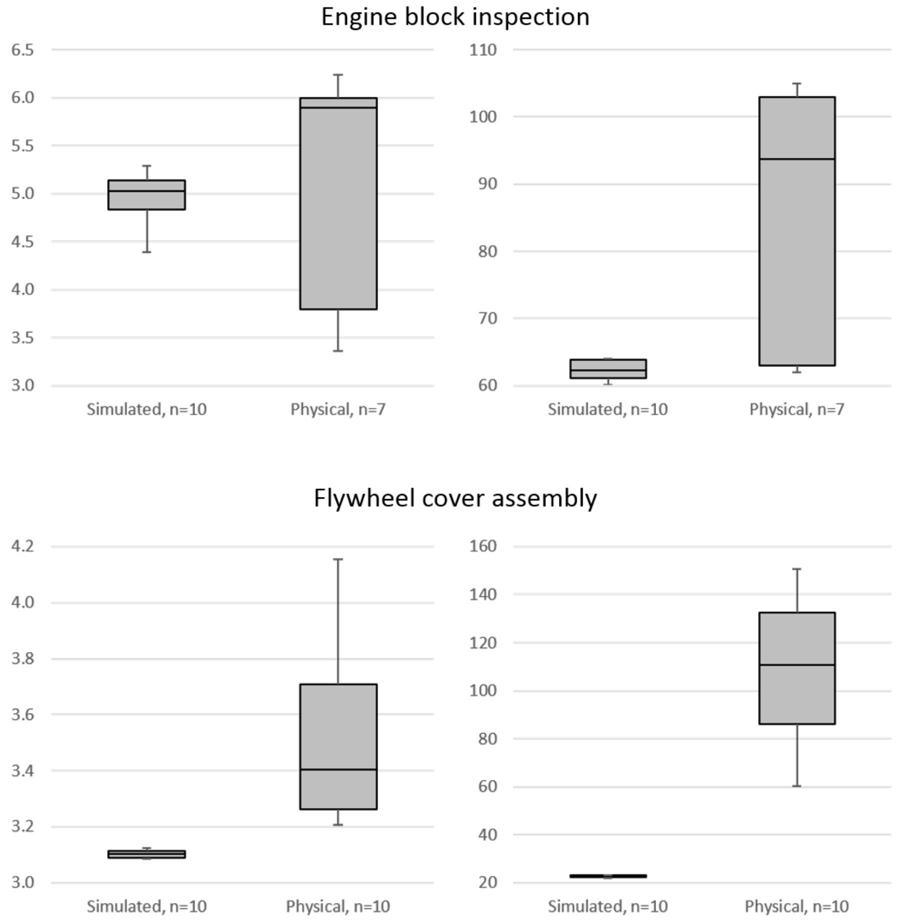


Figure 21 Results from the verification study (Paper B).

The resulting p-values from the Mann-Whitney U test are presented in Table 6. 5 % was chosen as the significant level.

Table 6 P-values comparing RULA and time of the two cases investigated.

	Engine block inspection		Flywheel cover assembly	
	RULA	Time	RULA	Time
P-value	0.143	0.079	0.0002	0.0002

4.2 APPLICATION OF THE HIRC SIMULATION SOFTWARE

RQ2: *How can a software for simulation, visualisation and evaluation of HIRC be applied in the workstation design process?*

As the HIRC simulation software has been developed, the need to present a structured process for its application has arisen. Paper C presents automation constraints to consider in the task allocation, Paper D introduces a HIRC design process and Paper E includes human safety in the design process; the results from each of these papers are presented below. The processes in Papers D and E are both based on existing generic systematic design processes that are applied in the HIRC workstation design context.

In the last section a generic HIRC workstation design process is presented, where findings from Papers C, D and E are combined into one process.

4.2.1 AUTOMATION CONSTRAINTS IN HIRC WORKSTATION DESIGN, PAPER C

An investigation of three HIRC workstations from the heavy vehicle company resulted in identification of four automation constraints: human cooperation, dual operation, manual quality control and inaccurate positioning of objects. Table 7 defines these constraints.

Table 7 Identified automation constraints

Automation constraint	**Description**
Human cooperation	Any kind of human cooperation in a task.
Dual operation	Any situation when multiple tasks have to be performed simultaneously, where there is a need of two or more manipulators. A human could assist.
Manual quality control	A situation that requires the human to inspect the quality of the product, thus entailing close proximity to the object.
Inaccurate positioning of objects	Inaccurately positioned objects are difficult to identify and grasp by industrial robots. Human intervention might be needed.

If any subtask of the workstation includes any of these factors, there is a need of some kind of manual involvement in the process. It is important to mention that these automation constraints are relevant to the manufacturing company investigated. Depending on products and volumes, the potential to automate processes is different; here we deal with discrete manufacturing of heavy vehicle products with takt times between two and seven minutes and between 60 and 400 units produced per day. This is done in a mixed model assembly line with a large part of customised products.

These automation constraints are to be used to identify which resources are capable of performing which tasks; this is called resource allocation. From the resource allocation the best combination of resources shall be identified, resulting in a final task allocation (Fasth et al., 2012).

4.2.2 HIRC DESIGN PROCESS BASED ON PAHL AND BEITZ, PAPER D

This proposed design process is highly influenced by Pahl and Beitz's engineering design framework (Pahl et al., 2007). Their design method comprises four phases: planning and clarifying the work task, conceptual design, embodiment design and detail design, and the activities in each of these phase have been adapted into a HIRC design process, presented in Figure 22. Despite the apparent linear flow of the HIRC design process, the upgrade and improve loop back to previous phases and also in each phase is of high importance to identify optimal solutions. The smallest possible iteration loop is desired in order to keep an efficient process with a low amount of rework (Pahl et al., 2007).

This HIRC design process requires a simulation tool enabling quantitative evaluation of HIRC workstation layouts. This could be any software that allows numerical evaluation of production system design parameters in HIRC workstations.

Each of these phases and their most important activities are briefly described below.

The goal of the first phase, *planning and clarifying the work task*, is to gather information regarding the workstation to be able to create an optimal solution in the following phases. The key activity in this phase is to formulate evaluation criteria and potential variables. Typical evaluation criteria in HIRC workstation design could be operation time, total cost and ergonomic load, and the ones of importance for the specific HIRC design are selected. The potential variables are numerous and include everything in the workstation that might influence the evaluation criteria. Later a few of these might be considered as design variables, while others are set to fixed parameters. In this work, a total of six potential variables are proposed in the future workstation design: industrial robot variant, industrial robot position, industrial robot gripper design, material position, workstation equipment position and anthropometric database. The outcome from this phase is a requirements list that specifies the workstation design problem, including its evaluation criteria and potential variables.

The second phase, *conceptual design*, aims to produce the most appropriate principal solution to the HIRC workstation design problem. The first activity is to identify the essential problem, the second to develop multiple conceptual solutions to meet the essential problem. This requires searching beyond traditional methods and techniques to consider new ideas and novel solutions and puts high demands on the creativity of the designers. Thus, it is recommended to include a group of individuals with various competences in order to challenge previous assumptions and focus on the essential problem in order to identify potential concept solutions. The final activity includes selecting the best concept solution for further development in the following phases.

The third phase is the *embodiment design* phase. It includes the creation of a workstation layout based on the principal solution from the previous phase. The task allocation between human and robot is proposed to be done first in this phase. After task division all the potential variables from the first phase are set to fixed parameters or design variables and their numerical solution spaces are determined. At the same time the demands on the evaluation criteria are defined. Finally a HIRC simulation software is used to simulate a selection of design alternatives within the solution spaces, and the resulting quantitative results are evaluated. Depending on the results, additional design iterations are performed where the values of the design variables are further changed within their solution spaces. It should be noted that the task allocation could be iterated and changed as well, resulting in new layouts and simulations.

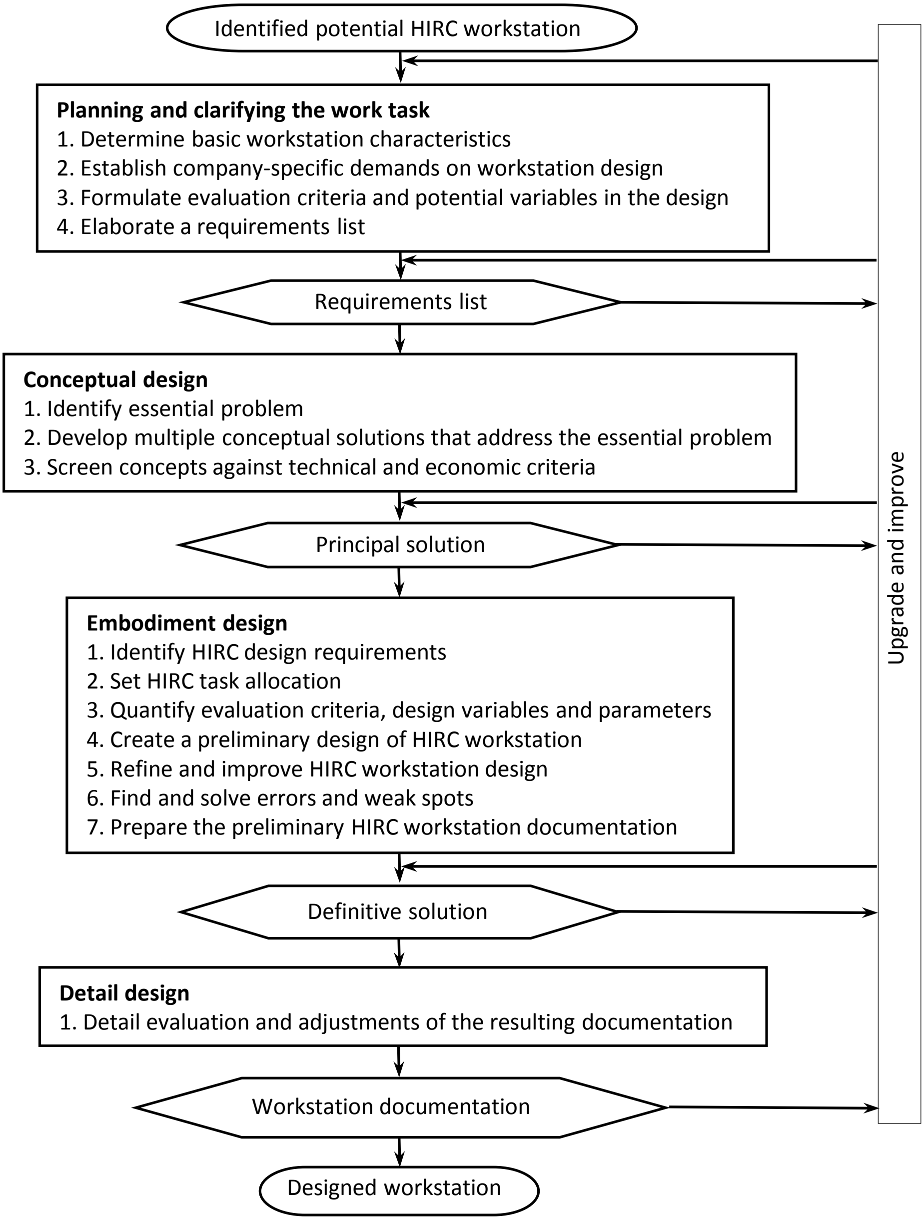


Figure 22 Proposed HIRC design process based on Pahl and Beitz's engineering design framework (Pahl et al., 2007) (Paper D).

The activities in the last phase, *detail design*, includes detail evaluation and adjustments of the resulting documentation from the design task. This includes layout drawings, robot programs and human work instructions, depending on the need of the individual workstation design problem.

This proposed design process is applied in an industrial example case in Paper D. In this application the HIRC simulation software has been used to design the workstation. An optimal layout of the flywheel cover assembly station has been designed. The exact positions of the robot, the incoming material rack and the silicone applying machine as well as the handover position have been identified (within set limits for all these design variables). With the proposed design process and a possibility of automating multiple layout alternatives, 96 different layouts have been evaluated; the best solution is presented in Figure 23.

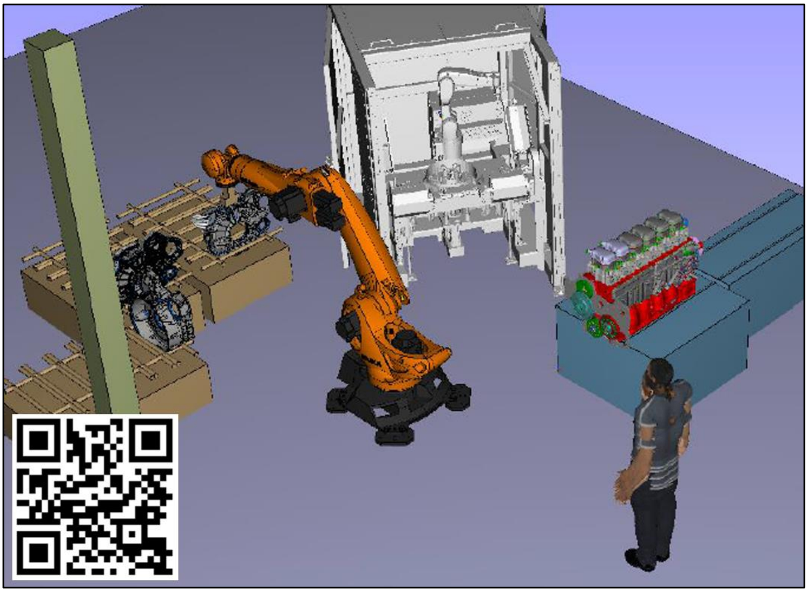


Figure 23 Optimal layout of flywheel cover assembly station through applying the HIRC design process proposed in Paper D, with a QR code linking to a video of the simulation (Paper D).

4.2.3 HIRC PERFORMANCE AND SAFETY EVALUATION PROCESS, PAPER E

When designing a HIRC workstation, personal safety must also be considered. In HIRC installations the maximum allowed collision forces on human body regions in ISO/TS 15066, Appendix A.3, are often used to ensure a safe design (ISO, 2016). These are not possible to extract through the proposed HIRC simulation software and thus an additional evaluation model that considers a human–industrial robot collision is needed. The aim of Paper E is to present a simulation-based HIRC workstation design process that evaluates the HIRC workstation design alternatives by considering both safety and performance characteristics.

The proposed HIRC performance and safety evaluation process is based on the general ASE process (Luckman, 1967; Braha and Maimon, 1997). The three ASE stages are defined as follows: *analysis* contains collection and classification of all the relevant information, including objective and constraints of the design problem, *synthesis* comprises the formulation of potential solutions and *evaluation* covers the assessment of the potential solutions to select the most appropriate one (Luckman, 1967). The HIRC performance and safety evaluation process is presented in Figure 24, where the main novelty is in the evaluation stage.

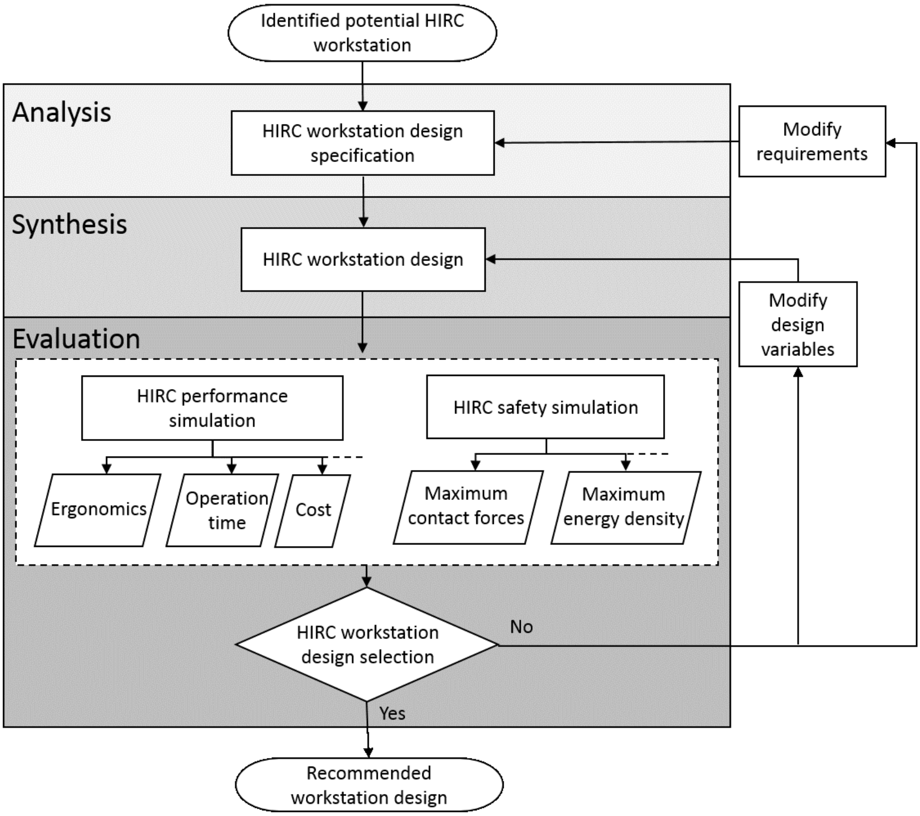


Figure 24 Proposed HIRC performance and safety evaluation process considering performance and safety characteristics (Paper E).

The HIRC performance simulation could be done with any simulation software that quantitatively evaluates HIRC workstations. Figure 24 presents three of the most common criteria, ergonomics, operation time and cost, but other evaluation criteria could be of interest, all depending on the evaluation possibilities in the simulation software. The safety simulation could also be performed in multiple ways; contact forces and energy density are two examples.

The application of this process is exemplified through an industrial case, assembly of a gearbox suspension on the frame of a truck. In this example the proposed HIRC simulation software is used to present the application of the process. In the analysis stage a detailed requirements specification, a set task division and a list of relevant workstation design parameters are set. The performance requirements were a maximum of seven minutes operation time and maximum 4.5 as a grand RULA score. The safety requirements were set at 110 N since Appendix A.3 in TS15066 specifies this as maximum contact force with the abdomen region. In this example a traditional robot was selected (ABB IRB 4600) to represent the collaborative robot application. It does not have the power and force characteristics as demanded to be able to consider the limits from TS 15066, but it is still used to present a theoretical application example as it has sufficient reach and payload.

In the following synthesis stage the design parameters are set either to parameters with a fixed value or to a variable that will be changed to create an optimal layout. Robot speed, the sex of the operator and the robot position were selected as variables. Both parameters and variables are given values (either as a fixed value or as an interval that the variable can be given).

In the evaluation stage a virtual model of the workstation is created in the HIRC simulation software, Figure 25.

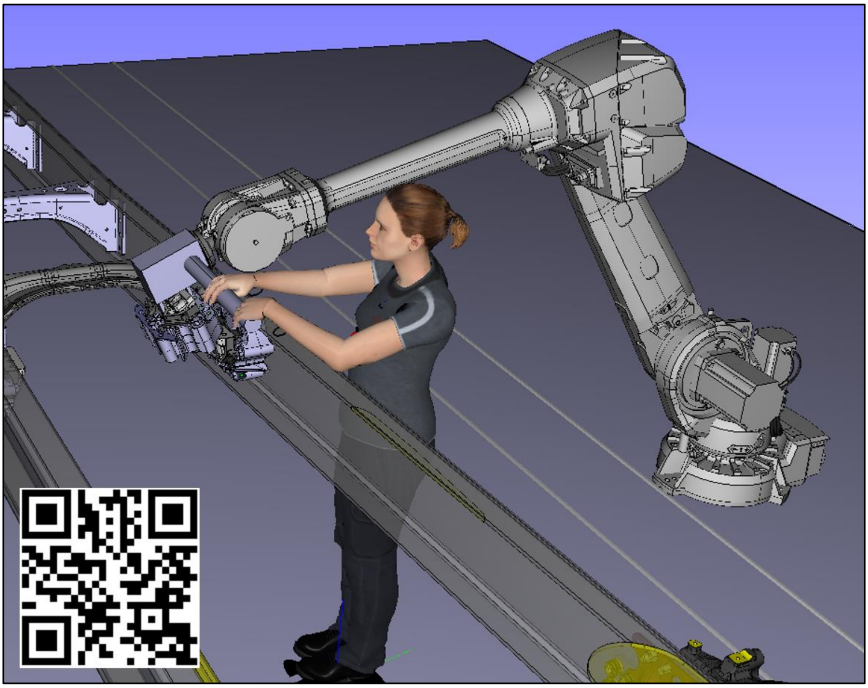


Figure 25 HIRC assembly of gearbox suspension, the industrial case in Paper E, with QR code linking to a video of the simulation (Paper E).

Since the purpose of the industrial case in Paper E is to demonstrate the proposed process, only four design alternatives are evaluated, Table 8.

Table 8 Design alternatives in the industrial case in Paper E

Design alternative	**Robot speed (m/s)**	**Anthropometrics of the operator**	**Robot position in X-direction (m)**
A	0.2	Female	1.8
B	0.3	Female	1.8
C	0.2	Male	1.8
D	0.2	Male	1.4

The software presents values of total operation time and biomechanical load (as a grand RULA score). The trajectories and speeds from the industrial robot are used to calculate the maximum contact force on the human operator, Table 9.

Table 9 Resulting evaluation of design alternatives in the industrial case in Paper E

Design alternative	Operational time (s)	Average RULA score	Maximum contact force (N)
A	62.9	3.45	134.6
B	50.7	3.49	247.7
C	62.9	3.88	136.8
D	60.9	3.88	136.6

The resulting times and RULA values are below the limits set in the analysis stage (maximum 420 and 4.5, respectively), but the contact forces are too high (maximum 110 N) and consequently changes of the design space are needed. Reducing the industrial robot speed will most likely give an acceptable solution. The variables shall be iterated back to the synthesis phase as "modify design variables" in Figure 24. However, this has not been done, since the industrial case only presents an application of the process, not the optimal HIRC workstation.

4.2.4 INTEGRATED HIRC WORKSTATION DESIGN PROCESS

Papers D and E present design processes to use in HIRC workstation designs. Combining them with Paper C results in a more extensive HIRC workstation design process. Figure 26 presents this integrated HIRC workstation design process, of which the process inspired by Pahl and Beitz from Paper D is the backbone and the other two publications supplement it. Both these additions are in the embodiment design phase, where the automation constraints identified in Paper C are to be considered in activity two, *set task allocation*. The combined evaluation of performance and safety from Paper E is a part of activities four, *make a preliminary design of HIRC workstations*, and five, *refine and improve HIRC workstation design*, which both include the development of workstation layouts including a quantitative evaluation.

This integrated HIRC workstation design process is software independent, thus any simulation software that quantitatively evaluates HIRC workstations can be used in this process.

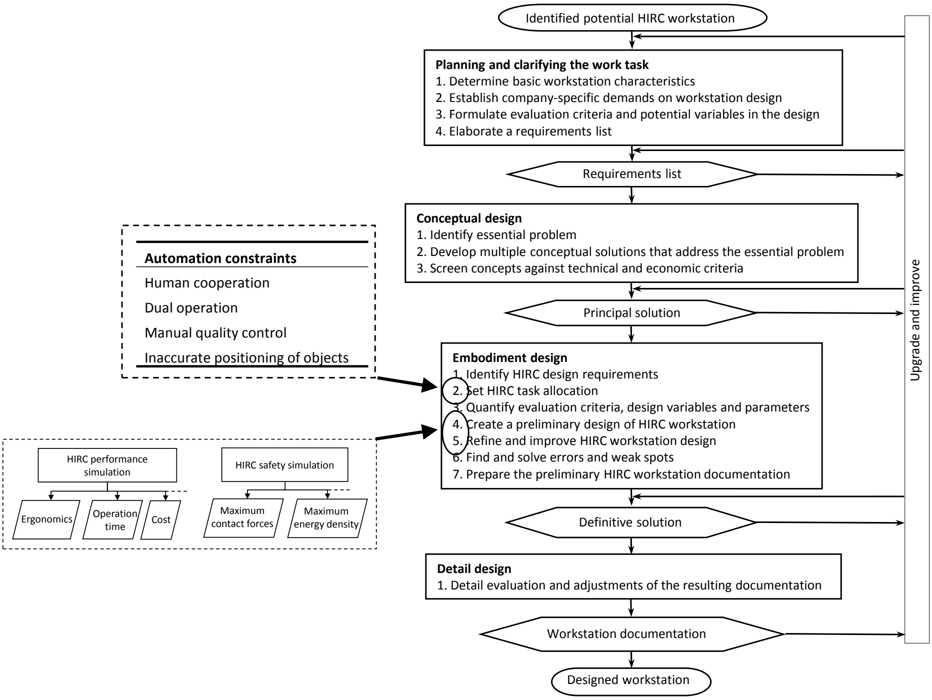


Figure 26 Integrated HIRC workstation design process combining results from Papers C, D and E.

5 DISCUSSION

This chapter discusses the results of the research based on the two research questions. This is followed by a discussion covering HIRC in a wider context. The chapter ends with a text discussing the research method chosen.

5.1 SIMULATION OF HIRC WORKSTATION

The aim of the research work is to contribute to more mature knowledge about human–industrial robot collaboration (HIRC) by focusing on digital tools for validation and methods supporting industrial application development. The first objective was to develop a demonstrator software, leading to the first research question:

RQ1: How can simulation, visualisation and evaluation of HIRC workstations be performed?

There are multiple aspects to consider in order to answer this research question. The areas that have been covered in the research are:

- modelling of workstations (including humans, industrial robots, products and surrounding equipment's and fixtures)
- creating motions for human and industrial robots
- visualising the workstation and the motions
- defining and applying evaluation criteria
- verifying simulated human and robotic motions

All of these aspects (except verification) are covered in the proposed HIRC simulation software, Paper A, and the last verification part is covered in Paper B. The results are discussed below, where the geometric HIRC simulation software and its evaluation methods are presented in the first sections and the verification of its predicted motions is discussed in the last.

5.1.1 GEOMETRIC HIRC SIMULATION AND VISUALISATION SOFTWARE, PAPER A

The geometric simulation part of the HIRC simulation software is the centre from which all evaluations are made. It is developed to design HIRC workstations before a physical installation exists. The simulation software predicts human and industrial robotic motions through mathematical algorithms. The robot motions are calculated given the robot characteristics from its datasheet together with the required motion, linear (point to point) or joint (move individual joints). With these inputs one optimal motion can be executed by the industrial robot. Human motions are more difficult to predict. The human body has several options to perform a motion from posture A to posture B. This much more unpredictable behaviour compared to that of the industrial robot originates from various individual characteristics (e.g., education, strength and strains in the body and previous experience), which all affect how we choose to perform a task (Baines et al., 2004). This problem of selecting one of the possible human motions is met in the HIRC simulation software by applying mathematical comfort functions on the manikin. This is based on results from Rasmussen et al. (2003), who show that real humans tend to minimise muscle strain, i.e., minimise the proportion of load compared to the maximum possible load. Thus the manikin normalises the load on each joint by muscle strength to achieve a human-like motion (Bohlin et al., 2012). The software present a possible motion to carry out the work task (Högberg et al., 2016). If no motion is found, or if the motion is evaluated to be too difficult for a human to make, a new HIRC workstation design must be created.

The visualisation of the simulation improves the possibilities of presenting future workstations to decision makers, operators and all other parties that are interested. The visualisation can also assist in performing risk analysis early in the production development process to meet the great challenge of personal safety in HIRC. Through 3D visualisation these risk assessments can be made more efficiently than from drawings and sketches. The desktop visualisation and the possibility of changing the view position and taking direct measurements in the model facilitate understanding of the future design and communication of actual risks, and measures are easier to discuss in a risk assessment procedure. These possibilities might be even stronger if the desktop solution in the future is upgraded to a virtual reality (VR) environment.

As described in Section 3.2.2, the HIRC simulation software has been further developed after Paper A was published in 2015. Its main new features include improved functionality to manoeuvre the manikin and robot in the workstation, enabling the digital manikins to take actual steps, offering a possibility to set maximum TCP speeds of the industrial robot and having a more natural-looking texture on the manikins in the simulations. These developments have been used in the later simulations in publications in the thesis (Papers B, D and E). The possibility of including the newly developed power- and force-limiting robots in the simulation is another very important improvement in the software (Castro et al., 2018). The HIRC simulation software is to be developed further in future research projects.

The novelty of the HIRC simulation software lies in its possibility of simulating HIRC workstations where a human operator and an industrial robot simultaneously work on the same product and in situations where the human hand-guides the robot. These simulations shall then be used to evaluate workstations and compare them against each other. Currently operation time and biomechanical load are evaluated with quantitative values. An investigation of the quantitative results of the industrial cases in Table 4 and Table 5 shows that the fully automated solution is superior to both manual and HIRC solutions, with shorter operation times and without any biomechanical risks. The fully automatic or manual station might outperform the HIRC station in other workstations and scenarios. The goal of the research presented is not to promote HIRC workstations but to present an evaluation tool, that combine visualisation and quantitative numbers to be used in decision making for production investments. With current evaluation criteria (time and biomechanical load), the industrial robot is often faster than a human and always carries less musculoskeletal injury risks. However, many other constraints (e.g., need of human interaction, Paper C) and parameters (e.g., cost) affect design and decision.

Evaluation of operation time and biomechanical load is discussed further in the following sections and then additional evaluation criteria in HIRC workstation design are discussed.

5.1.2 PRODUCTIVITY EVALUATION, PAPER A

Productivity is evaluated in terms of operation time in the HIRC research software. However, since productivity is defined as output divided by input, a productivity improvement could also be measured in costs. A cost reduction with the same output is a productivity increase. Section 5.1.4 discusses cost evaluation further; in the following, operational time is discussed.

Human operational time in the HIRC simulation software is generated from the predetermined time standard MTM-1 with slight simplifications. MTM-1 covers a huge variety of body motions, while its usage in the HIRC simulation software is limited to the motions and programming language in the HIRC simulation software. In an initial work the more simplified SAM method was included; this is the time evaluation in Paper A, in later evaluation in Paper B, D and E, are MTM-1 times used, Paper B, D and E.

The speed of an industrial robot is calculated directly in the robotic part of the HIRC simulation software with the datasheets from the robot supplier as a basis. The maximum speeds are, however, seldom used in practice, in order to reduce stress on the robots and limit wear of the equipment. Discussions with experienced robot programmers revealed that the programmed maximum speed is often set in the interval 50 to 80 % of the theoretical maximum. The speed of the robotic motions can be set in two ways, joint by joint and by tool centre point (TCP). The TCP functionality is an important feature as control of the TCP speed enables using power- and force-limiting robot systems, since the speed of the TCP often correlates with the impact force between the industrial robot and the human. In risk assessments the approach speed of the robot is used as an input; this equals the TCP speed in many situations. In many publications a TCP speed of 250 mm/s is set as some kind of safe speed for collaborative applications (e.g., (Michalos et al., 2015)). However, there is no general safe speed for impact between human and industrial robot; this has to be identified case by case through risk analysis (ISO, 2016).

5.1.3 ERGONOMIC EVALUATION, PAPER A

As described in Section 2.4.2, biomechanical load is selected to represent the ergonomics of the HIRC workstation. An observational method was selected to evaluate the biomechanical load on the operators since the quantitative values that can be extracted from the software are easily accessed through the scoresheets in the methods. The specific RULA method was selected since it is a widespread, easily accessible method focusing on upper body motions (similar to the HIRC simulation software).

RULA has (together with all other observational methods) the weakness that it does not include time as a factor. Its calculations are based on analysing a static human pose, “the posture held for the greatest amount of the work cycle or where highest loads occur” (McAtamney and Corlett, 1993, p. 93). 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). The HIRC simulation software does consider time; the manikin motions are created through adding a high number of poses with a small time duration (median sampling frequency of 140 Hz) into a continuous flow. Each of these poses is then held for a fraction of time. This makes it possible to calculate a time-weighted average RULA score for the complete motion, similar to Vignais et al. (2017) who analysed RULA of a human motion through calculating percentage of time spent in each RULA range. A consequence of evaluating a time-weighted average RULA value instead of just one posture, as stated by McAtamney and Corlett (1993), is that the interpretation of the RULA grand score value (1 to 7) cannot be interpreted according to Table 1. A time-weighted average RULA score is often lower than the result of a single posture analysis since the time-averaged score considers all poses in a motion, thus the time-weighted average RULA score can not be compared to RULA scores from traditional evaluations. But the time-weighted average RULA score can be used to compare different motions in order to select the one with the least biomechanically negative impact on the human operator. However, this method of including time does not take the injury risk of repetitive lightweight motions into consideration.

Another common weakness of the observational methods mentioned above is that they were developed to assess human joint angles though manual observations. Thus small variations in the joint values of body regions are difficult to assess visually. In the HIRC simulation software the joint angles are defined by deterministic numbers with multiple decimals, and these values are used to calculate a RULA score. This offers an opportunity to distinguish between the thresholds where small differences in the joint angles give big differences in the RULA score, as also identified by (Högberg et al., 2016). The largest influence of this is extension of the neck (leaning backwards), where any extension of the neck results in the highest available neck position score = 4 compared to a natural or slightly flexed position (leaning forward), which gives the lowest neck position score = 1. Figure 27 demonstrates the difficulty to visually identify a bent neck. Can the reader identify which of the two manikins has her neck bent two degrees? And is it in extension (bent backwards) or in flexion (bent forwards)? The answer is found in a footnote on this page.[1]

Figure 27 One of these manikins has her neck bent two degrees. Which one, and is it in extension (bent backwards) or in flexion (bent forwards)? The answer is in footnote 1 on this page.

In the manikin prediction in the software the neck angle is often in the interval -1˚ to 1˚. In order to meet the challenges, the RULA limits are slightly adjusted to fit a DHM evaluation of the joint angles. These adjusted values are found in Appendix A; for example, the neutral neck position is set at -2˚ to 2˚. These adjustments were developed late in the research and are only incorporated in the evaluation in Paper B. However, in all future RULA evaluations in the HIRC simulation software, a similar adjustment will be made in order to get relevant results.

Operation time and biomechanical load are measures of two of the three proposed benefits in HIRC systems; productivity and ergonomics. The third benefit is improved quality. Since the manufacturing artefact is not simulated in the HIRC software, it is difficult to draw any conclusions regarding product quality. However, Falck and Rosenqvist (2014) present a strong correlation between bad ergonomics and quality errors in automobile assembly (high-risk ergonomic tasks

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[1] The left manikin neck is in extension (bent backwards) by two degrees.

showed 5–8 times as many quality errors as low-risk tasks). Thus, by evaluating ergonomics and striving towards a design with good ergonomics, the quality produced will also most likely be improved.

5.1.4 ADDITIONAL HIRC WORKSTATION EVALUATION CRITERIA

The HIRC simulation software facilitates HIRC workstation design through evaluation of classical production system design parameters that are used to make engineering design decisions, operation time and biomechanical load. However, there are other characteristics that could be of interest to also evaluate the design process, e.g., investment costs, operation costs and floor utilisation (Argyrou et al., 2016).

As mentioned in Section 5.1.2, productivity can also include cost. Combining investment and operation costs into one criterion could be an additional parameter in HIRC workstation design. Investment costs are the individual costs for all resources (e.g, industrial robots, robot grippers, fixtures and material equipment), while operation costs include man-hours for manufacturing personnel. These costs can be calculated at different HIRC workstations and also be compared between fully manual and fully automatic layouts. One additional feature to consider is the availability of all resources. Automatic robots and machines can run without the breaks that a human has to take; however, the mean time between failures of a technical equipment states how often a machine is expected to fail and thus stop the complete manufacturing. Investing in some kind of fall-back solution might be needed to be able to continue production during repair of the robotic system.

5.1.5 VERIFICATION OF HIRC MOTIONS, PAPER B

The results from the verification study presented in Section 4.1.2 show some correlation in the biomechanical load between manikin and physical test. The correlation is weaker regarding operation time, where the simulation underestimates the experiments in these two cases. This indicates that the simulation software does not represent motions performed by the test subjects in a sufficient way. However, another verification study of the same software in a HIRC workstation presents a better correlation between the simulation and the physical test (Castro et al., 2018).

A closer investigation of the design of the verification studies can explain some of the differences. One important feature is the background of the test subjects; a majority of them were university students with very limited practical manufacturing experiences. This together with the limited training to perform the task (two or three cycles) makes it difficult for test subjects to perform the most efficient motions. Four of the test subjects in case B were skilled assembly operators and these four had lower RULA results that was closer to the simulated ones. This show that training and also motion strategies that experienced assembly operators learn are efficient and that the HIRC simulation software mimic these motion of skilled operators.

Another reason is the workstations selected for the verification studies. These workstations originate from the available physical demonstrator stations and both include tasks that are difficult to estimate with MTM-1 times. One of the stations included visual inspection that is a vague and not well-defined process (e.g., How long do you inspect? How closely do you keep your body while inspecting?) and the other includes an enabling device controlling the robot motions that was difficult to handle for the manual test subjects. It demanded much more training than the single test run that the test subjects made; the experience of the researchers building the station indicated that it took many days to acquire the skill needed to handle it smoothly. Both these problems led to inaccurate biomechanical motions and operation times.

These results showcase that, even though the human motions in a virtual tool seem to represent motions from an actual human, it is still challenging to generate them as accurately as desired. However, it is worthwhile to continue the development and verification work since the DHM software is state of the art in representing human motions.

In future evaluations the verifications of the human and the robotic motions could be performed separately. The human verification should be investigated in separate IPS IMMA experiments in cases more suitable for manikin verification. These experiments could be designed to include tasks that represent human motions and avoid tasks including reading and fumbling risks. The robotic verification part could be investigated separately.

It might also be possible to compare the simulated motions with the physical ones through other methods than RULA. The task was to compare 134 joint values from the digital manikin in the HIRC simulation software with 66 joint values from the human in the Xsens Awinda system. It is difficult to compare values joint by joint since the individual skeletons are different, and thus the RULA system was selected as a neutral method to compare postures. Other observational systems could also have been used (e.g., OWAS or REBA), but RULA was selected since it was already integrated into the HIRC simulation software.

Concluding the verification study, despite the low correlation, new verification studies with more appropriate cases are needed before any clear statements can be made on the validity of the HIRC simulation software.

5.2 APPLICATION OF THE HIRC SIMULATION SOFTWARE

The second objective of this research work was to propose a design process on how to apply a simulation software in an industrial context, leading to the second research question:

RQ2: *How can a software for simulation, visualisation and evaluation of HIRC be applied in the workstation design process?*

There are multiple aspects to consider in order to answer this research question. The areas that have been covered in the research are:

- describe a general HIRC workstation design process
- identify where the simulation and visualisation software assists the process
- define feasible HIRC workstation designs
- manage task allocation vs. layout evaluation
- provide quantitative results of performance and safety to support decision making

These have been covered in the appended papers. Paper C focuses to define feasible HIRC workstation designs, while Paper D and E both cover the other aspects. The results are discussed below, divided into the automation constraints identified and the proposed design processes, and concluded in the generic HIRC workstation design process. Both presented HIRC design processes require a simulation software enabling quantitative evaluation of HIRC workstation designs; however, it does not need to be the proposed HIRC simulation software that answers research question 1.

5.2.1 AUTOMATION CONSTRAINTS, PAPER C

In order to define feasible HIRC workstation designs Paper C identified automation constraints. In total was four constraints identified: human cooperation, dual operation, manual quality control and inaccurate positioning of objects. They are listed in Table 7 in section 4.2.1. These constraints are used to identify tasks that limit the automation possibilities in the task allocation phase of HIRC workstation design.

These factors are only relevant for the manufacturing company investigated, that is, manufacturing of discrete heavy vehicle products with takt times between two and seven minutes and between 60 and 400 units produced per day. This is done in a mixed-model assembly line with a large part of customised products. Depending on products made and their volumes, the potential to automate the process varies. Thus there are technical solutions available to challenge the constraints and automate a process which include some of these factors. For instance, some degree of *inaccurate positioning of objects* might be solved with a camera system identifying the objects to pick or another camera system might assist to automate *manual quality control* through computer vision systems. However, such systems are considered to be too expensive to invest in by the manufacturing company investigated. But as the technology develops and the price gets lower, these solutions are likely to be feasible even in this company. Thus there is a need to be aware of the development and question these constraints, also in the company investigated. This exact trade-off when a factor is a constraint should be discussed and questioned as the technologies develop.

These constraints are valid for the manufacturing company investigated, but companies with similar production volumes and products might utilise the same automation constraints.

Two HIRC workstation design processes are developed in this work. Paper D presents the HIRC design process based on Pahl and Beitz's engineering design framework and Paper E a HIRC performance and safety evaluation process. They are discussed in this section, starting with the HIRC design process.

5.2.2 HIRC DESIGN PROCESS, PAPER D

Two HIRC workstation design processes are developed in this work. Paper D presents the HIRC design process based on Pahl and Beitz's engineering design framework and Paper E a HIRC performance and safety evaluation process. First is the HIRC design process discussed.

The need to describe how to utilise the HIRC simulation software emerged as the tool developed. The potential of virtual simulation is huge, but users also need methods and processes to assist in better utilisation of its potential. Existing production system development processes were presented in Section 2. However, these describe the design of production systems on a higher level, how to design a whole production line including positioning of machines and their logistic flows. It was more suitable to consider the HIRC workstation design problem as the design of any mechanical engineering artefact, thus applying established systematic design methodologies to it.

The proposed HIRC design process in Paper D is a HIRC adaptation of Pahl and Beitz's engineering design framework, including the same phases, but with modifications of the individual activities (or working steps) included in each phase. The proposed HIRC design process, Figure 22, involves an incremental structure of how to design a HIRC workstation. This structure is similar to other design methods, e.g., the basic ASE process (Luckman, 1967), Wu's (1992) general design methodology and Ulrich and Eppinger’s (2016) product development process. It is how the detailed activities are performed that differentiates this process from others. The HIRC design process requires a simulation software enabling quantitative evaluation of product system design parameters, and the HIRC methodology presents how such a software should be used.

Cencen et al. (2018) present a similar HIRC-specific human–robot coproduction design methodology, named HRCDM. This methodology is presented as a control system form where outputs from previous phases are inputs in the next. It is an incremental process with four subprocesses: analysis, modelling, simulation and evaluation similar to Wu’s (1992) general design methodology. Both this HRCDM process and the proposed HIRC design process rely on a simulation tool with evaluation capabilities to compare HIRC workstation designs. The HIRC design process presented in Paper D shows a more detailed focus on the task allocation and evaluation criteria in HIRC workstation design. In the application examples the capabilities of the HIRC simulation software are also superior to the ones presented in HRCDM (Visual Components). However, the control system analogy and the HRC scorecard that presents the results from each workstation design are two very interesting approaches in the HRCDM process.

One general challenge in HIRC workstation design is to consider both the workstation layout and the task allocation simultaneously. One of these could be optimised, but both have to be considered in order to identify a successful design. The proposed process includes multiple iterations; the challenge is met through iterations in the embodiment design phase, from the design activity back to the task division, since another task division could give improved workstation performance characteristics.

5.2.3 HIRC PERFORMANCE AND SAFETY EVALUATION PROCESS, PAPER E

The second HIRC workstation design processes, the HIRC performance and safety evaluation process are discussed below.

It is necessary to include personal safety in the HIRC workstation design process as this is a prerequisite in enabling HIRC workstations to be installed (Haddadin and Croft, 2016). Limiting the speed and load on the industrial robot generates a less dangerous robotic system. However, too strong performance limitations can reduce productivity to an extent where the very purpose of implementing the HIRC workstation becomes questionable. Thus it is very important to evaluate both the performance and the inherent safety characteristics associated with the HIRC workstation during the design and development stages.

Personal safety has been evaluated while keeping the collision forces between human and the industrial robot under the maximum limits stated in the technical specification ISO/TS 15066. How well these limits actually warrant safe collisions is still under debate. Rosenstrauch and Krüger (2017) perform an experiment in which they demonstrate residual hazards in a HIRC design even though the collision forces are within the limitations stated in ISO/TS 15066. Vemula et al. (2018) propose a power flux design metric that considers impact quantities such as magnitude of energy transfer, contact area and contact duration in order to identify an improved indicator of safe human–robot collisions.

However, since the limits have been set by the International Organization for Standardization, they are often considered and used as a standard in HIRC workstation design as they present quantitative numbers to define safe interactions. But ISO/TS 15066 is still not a standard and it is clearly stated in its introduction that “[c]ollaborative operation is a developing field. The values for power and force limiting stated in this Technical Specification are expected to evolve in future editions" (ISO, 2016, p. v). The aim is to include this TS as a part of the future revision of the robotic standard ISO 10218-2 (Hägele et al., 2016).

In the industrial example the HIRC simulation software is used to present the application of the design process. It this example the robot is a traditional industrial robot (ABB IRB 4600). This is not a power- and force-limiting robot, but its reach and payload is needed in order to perform the operation. Thus, to show the application of the HIRC workstation design process it is assumed that this robot can respond to a collision as a power- and force-limiting robot.

5.2.3 INTEGRATED HIRC WORKSTATION DESIGN PROCESS

The integrated HIRC workstation design process presented in Figure 26 in Section 4.2.4 is a summary of Papers C, D and E into one process. It includes the collision force evaluation in a detailed design process considering the task allocation and its automation constraints. This design process shall be used in early phases of workstation design; it requires a virtual software capable of simulation and quantitative evaluation of HIRC tasks.

The automation constraints from Paper C are, as previously mentioned, only valid for the company investigated and thus they have to be identified depending on industry. However, it is still valid to show them in the process since they help reduce waste in the future simulations. By considering automation constraints in the task division, impossible task divisions can be identified and excluded from future simulation tasks.

5.3 HIRC WORKSTATIONS IN A WIDER CONTEXT

In this section the possibility of realising collaboration between humans and industrial robots is examined. The section also includes a review of the terminology in the area and it concludes with a discussion linking the performed research back to the initial industrial challenges stated in the introduction of this thesis.

5.3.1 HIRC DEFINITION AND OPERATION MODES

As mentioned in Section 2, the terms and definitions regarding interaction between humans and industrial robots are numerous and not clearly defined. One way to distinguish the collaboration with industrial robots from that with other types of robots is the "I" turning HRC into HIRC, which is proposed in this research. This distinguishes industrial robots from other types of robots (e.g., autonomous cars, search and rescue robots and healthcare robots). However, there are other weaknesses in the HIRC term. The most obvious is that the C is an abbreviation for collaboration, while collaboration also is one of the interaction types defined by Fraunhofer IAO, coexistence, synchronisation, cooperation and collaboration, all illustrated in Figure 2 (Bauer et al., 2016), while all these interaction types are included in the HIRC definition. This complex situation reveals the need of an improved term for the whole field.

ISO (the International Organization for Standardization) should be able to assist in definitions of terms. TS/ISO 15066 (ISO, 2016) is named "Robots and robotic devices — Collaborative robots", but nowhere in the technical specification is the term "collaborative robot" defined. However, in ISO 10218-2 (ISO, 2011b) collaborative robot is defined as "a robot designed for direct interaction with a human within a defined collaborative workspace". The use of the term collaborative robot is not optimal since it indicates that it has to be the robot itself that should be designed for human interaction. But collaboration can also be achieved by purposely design of the whole system, including safety sensors outside the robot (e.g., cameras), that enables HIRC workstations with close interaction between human and industrial robots. The now increasingly popular term "cobots" (as a fusion of the words collaboration and robots) has the same problem; it focuses on the robot being collaborative. A broader view includes HIRC with large traditional industrial robots in systems where key characteristics such as big payloads, long reach and fast motions are needed. Recent discussions in research projects have concluded that there are no collaborative robots, only collaborative robot applications. And, according to ISO standardisation committee members, such a statement will be included in the next version of the robotic standards.

5.3.2 Realisation of HIRC workstations

Despite the strong focus on HIRC from academic publications and robot manufacturers installed HIRC workstations in industry are still few (Awad et al., 2017). Current safety legislation that limits the industrial applications are the main restriction (Saenz et al., 2018). The standards that are used to describe industrial robots as well as collaborative applications are derived from traditional robot standards that were built to guarantee separation between human and robot. To move from the explicit demand that no one should be hit by a moving robot to a situation where this kind of impact is possible, perhaps even desirable (for instance, tap on robot arm to signal something to it) is a huge step that has to be considered as the standards are being developed.

The possibility of accepting small collision forces between human and industrial robot is a complex challenge when the whole collaborative robot application is considered. It is not only the robot that has to comply with collision forces and pressures, but also the gripper and the object that is handled by the robot. One sharp edge on these parts increases the danger of the application significantly. A low force on a small surface area results in high pressure. TS/ISO 15066 states that "[o]bjects with sharp, pointed, shearing or cutting edges, such as needles, shears, or knives, and parts which could cause injury shall not be present in the contact area" (ISO, 2016, p. 16). The issue is then to define sharp edge and contact area. Another important feature is the environment where the collaborative application is installed. Are there clamping risks due to surrounding machineries and equipment that reduce the possibilities of avoiding a collision?

Another challenge of using TS/ISO 15066 is that the maximum allowed collision forces in its Appendix A.3 present different values on different body regions. But how can the designer of a HIRC workstation verify which body region is colliding with the robot at an undesired collision? The human operator might pick something from the floor or simply fall. This kind of risk has to be considered in the design of HIRC workstations. All of this is considered in a risk assessment made in "ISO 12100 – Safety of machinery as an iterative process of risk analysis and risk reduction" (ISO, 2010). Gopinath et al. (2018) present a HIRC application of this process with a large traditional robot.

It is recommended to install the first HIRC applications with the smaller power- and force-limiting robots in companies. These robots are designed to be installed in a fenceless environment. Installing them in workstations with limited human interaction, coexistence or synchronisation, further increases the possibilities of creating safe workstations, all in line with recommendations from Fraunhofer IAO (Bauer et al., 2016). Experiences from these installations could later be turned into more advanced interactions, possibly also with larger industrial robots.

5.3.3 INDUSTRIAL NEED OF HIRC SIMULATIONS

As mentioned in the introduction, no software has been identified that simulates, visualises and evaluates HIRC workstations where a human can hand-guide an industrial robot. This kind of software is necessary as a decision tool to be able to make proper and well-grounded investment decisions in future HIRC workstation design. However, currently the hand-guided collaborative installations in industry are extremely limited due to the complex safety challenges in such collaborations. The workstations currently installed focus on coexistence or synchronisation. In these systems separate simulation of industrial robot and human might still result in an sufficient input to decision makers, even though there is a need of two kinds of software. But in future, after additional technological developments, the need to be able to simulate collaborative installations will exist.

An industrial need in HIRC workstation design is to be able to predict collision forces between the human and the industrial robot. There are complex finite element (FE) solvers that consider the non-linear visco-hyperelastic nature of the human's biological soft tissues at impact (Maeno and Hasegawa, 2001; Oberer and Schraft, 2007). However, applying these FE approaches is a computationally intensive process. One simplified way of addressing this issue is through the compliant contact force (CCF) approach, which is applied in Paper E.

One other interesting approach to be able to predict collision forces is still under development at Fraunhofer IFF. They have developed a large database regarding collisions between humans and a pendulum, as well as data regarding the effective mass of power- and force-limiting robots. With these data they are able to determine the maximum allowable robot speed for situations where a possible collision with a human could take place. This allows for the assessment of a future HIRC installation with regard to possible collisions in a virtual environment (Saenz, 2019).

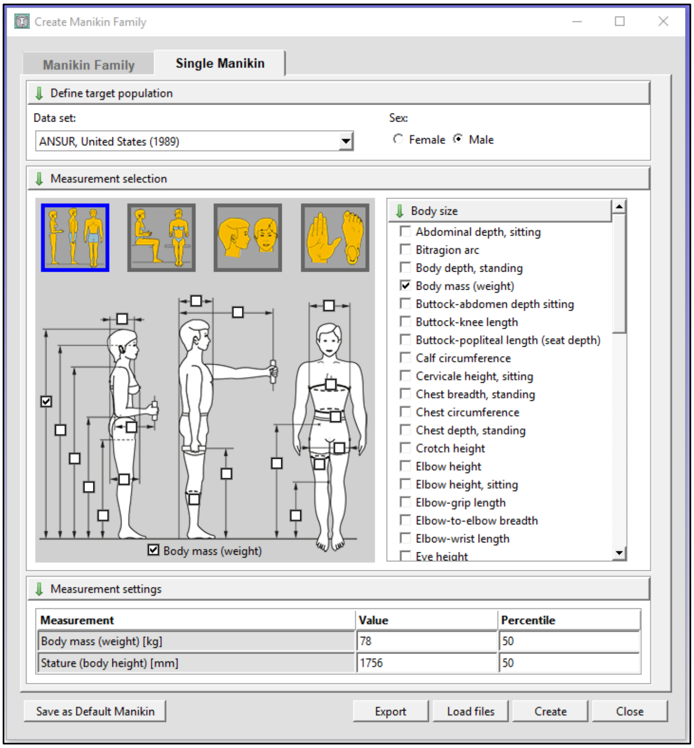
5.3.4 HIRC RELATIVE INDUSTRIAL CHALLENGES

The industrial challenges identified in the introduction of this thesis, productivity demands and a demographic change resulting in an elderly population, are both met through closer collaboration between human and industrial robot.

Productivity has been discussed throughout the thesis; industrial robots have the capability to move objects over 2 m/s, much faster than a human. Thus productivity increases as more handling is performed by an industrial robot. This also means free time for the human from handling an object to more value adding tasks in the final product to the customer. This theoretical reasoning is not simple to bring into practical HIRC applications, as the robots developed to work close to humans, the power- and force-limiting robots, enable this close interaction by reducing their payload and velocity. With slower speeds (often well below 250 mm/s) the competition with human handling is the opposite. Human intuitive decision making and skills to move objects often outperform robots in these environments. This makes it somewhat difficult to identify many HIRC cases at manufacturing companies. However, the capabilities of enabling close interaction with high robot speeds are being developed and will further increase productivity.

There is a correlation between high age and probability of musculoskeletal disorders (Fritzsche, 2010; Zaeh and Prasch, 2007). Thus reducing the biomechanical load on workstations also results in preparing them for a future elderly workforce. A stronger interaction type (cooperation and collaboration) opens up greater possibilities of finding HIRC workstations that improve the biomechanical load on the operators, thus the potential for HIRC to meet the demands of the demographic change is huge.

The possibility of simulating a manikin family with variable characteristics also enables including an older population in the simulation. Figure 28 below presents the interface in the HIRC simulation software that enables selection of multiple parameters to create a manikin family.



Data set: ANSUR, United States (1989)

Sex: ○ Female ● Male

Body size
☐ Abdominal depth, sitting
☐ Bitragion arc
☐ Body depth, standing
☑ Body mass (weight)
☐ Buttock-abdomen depth sitting
☐ Buttock-knee length
☐ Buttock-popliteal length (seat depth)
☐ Calf circumference
☐ Cervicale height, sitting
☐ Chest breadth, standing
☐ Chest circumference
☐ Chest depth, standing
☐ Crotch height
☐ Elbow height
☐ Elbow height, sitting
☐ Elbow-grip length
☐ Elbow-to-elbow breadth
☐ Elbow-wrist length
☐ Eye height

☑ Body mass (weight)

Measurement	Value	Percentile
Body mass (weight) [kg]	78	50
Stature (body height) [mm]	1756	50

Figure 28 Interface in HIRC simulation software with the possibility of creating a manikin family with different anthropometric characteristics (Brolin et al., 2019).

The difficult question here is what anthropometric measures define this elderly population. Constraining range of motion of the joints can be one way, but what other measures represent an elderly population? Strength is not currently included in the software and thus not possible to adjust.

5.4 RESEARCH METHOD DISCUSSION

The design science research (DSR) concept has been used as a methodological approach in the thesis. This approach implies that all development must be grounded in an actual technical need from industry and solved through theoretical academic measures. The solution has been iterated in industry until a satisfactory technical result has been achieved. The academic contribution has been made through scientific publications.

Seven framework guidelines to consider in DSR were presented in Section 3.5 (Hevner et al., 2004), where also their application in the research conducted was presented. However, a critical discussion about each of these guidelines is appropriate.

Guideline 1: Design as an artefact

The HIRC simulation software and design methods for HIRC workstation design processes are the artefacts that has been the focus of this research. This development of actual technical artefacts is within the scope of the DSR methodology (Baskerville et al., 2018). The IPS software family has been vital in the development of the simulation software. This has had a huge impact the resulting software, and it has put constrains on the final results, in a way that the author of this thesis could not control. However, without the close collaboration with Fraunhofer-Chalmers Research Centre (FCC), such a mature simulation tool would never have been developed.

Guideline 2: Problem relevance

The need to be able to design a HIRC workstation is a challenge in the whole industrial and academic world, as stated in the introduction and clarified in the frame of reference section. The problem relevance for the industry is constantly investigated as seen in the HIRC performance and safety evaluation process that includes the need from industry to be able to predict collision forces in HIRC workstation design.

Guideline 3: Design evaluation

The HIRC simulation software is evaluated and put into practice in Papers A, B, D and E. However, the evaluation of the proposed human motion in Paper B shows a weak correlation with physical human motions. This is further discussed in Section 5.1.5, where also countermeasures are proposed. Another weak evaluation is industrial application of the proposed design processes from Papers D and E. Again, these processes are presented with industrial cases in the papers, performed by the author of this thesis, but no broader evaluation of their functionality has been made. This weakness of evaluation of both the software and its application processes should be met through future case studies with simulation engineers. This would most likely give valuable feedback and improve both the HIRC simulation software and the proposed design processes. However, the developed design processes are based on established and well evaluated methods.

Guideline 4: Research contribution

One important contribution is the HIRC simulation software. However the proposed design processes are also vital contributions. Hevner et al. (2004) also point out that the artefacts must be possible to implement within the business; the design processes present a procedure to achieve this. This is exemplified through industrial cases in Papers A, B, D and E.

Guideline 5: Research rigour

The HIRC simulation software relies on rigorous methods for development of human and robotic motions as well as performance evaluation. Even though the presented research has been evaluated within a single heavy vehicle manufacturer, are both the software and its application method generic enough to be used in other manufacturing environments. Evaluation of the rigour of both design artefacts is limited in the research presented. This should be done in case studies with simulation engineers.

Guideline 6: Design as a search process

There are many features of the research presented that answers to this guideline, e.g., the development of the HIRC simulation software through multiple iterations, both iterated design processes that highlight the need to reconsider previous desertions and iterations to find an optimal solution. The selection of this optimal solution is also a relative measure. It could either be discrete maximum values on RULA and operation time or an iterative search to find optimal solutions, but it is then necessary to put emphasis on biomechanical load versus operation time and how these are prioritised relative each other.

Guideline 7: Communication of research

The research work has been presented at numerous forums in multiple ways, internally at the manufacturing company and externally at academic conferences. Currently two journal papers have been published, while two others have been submitted. One group that may have had less focus is the actual management of the manufacturing company. This might also be the reason why cost is not yet included in the evaluation criteria, since total operation cost often is the key issue for management.

Another interesting aspect of the DSR framework presented in Figure 4 is that it also illustrates the process of being an industrial Ph.D. student. By interpreting the design cycle of artefacts a bit wide to be the process of the Ph.D. student research project, the similarities become clear. It shows that the research project has to solve practical problems from the industry by using applicable research methods. The result of the research shall then make both academic and industry contributions.

6 CONCLUSION AND FURTHER RESEARCH

In the last chapter of this thesis, the major conclusions drawn from the research are presented. The outcome of the study is also discussed in terms of its impact on both the academic and the industrial point of view. This chapter concludes with some suggestions for further research.

6.1 CONCLUSIONS FROM THE RESEARCH

The HIRC simulation software developed present one solution on how to perform simulation, visualisation and evaluation of all kinds of HIRC workstations where human and robot simultaneously work in a collaborative environment, including hand-guiding tasks. Simulation includes mathematical algorithms predicting human and robot motions thus enabling design of HIRC workstations before the physical installation on the shop floor. The visualisation of the design in a desktop environment improves communication of the workstation design to management as well as future operators. The software also enables evaluation of multiple layout alternatives with quantitative numbers on total operation time and biomechanical load on the human body. These evaluations could be done among HIRC workstation alternatives, but also in fully manual and robotic solutions. The possibility of quantifying layout alternatives is based on rigours and commonly used methods. Operation time in the simulation software is achieved through the PMTS system Methods-Time Measurement (MTM) and the biomechanical load is evaluated through Rapid Upper Limb Assessment (RULA).

The integrated HIRC workstation design process illustrates how such a simulation software can be applied to create suitable workstations. The process is based on existing generic systematic design processes that are applied in a HIRC workstation design context. This process does not depend on a specific simulation software, but any simulation software that quantitatively evaluates HIRC workstations can be used in this process.

An important part of the workstation design process is its capability to measure the potential collision forces between an industrial robot and a human. This safety evaluation is made through collision modelling of a compliant contact force (CCF) approach between the human and the industrial robot. These forces have to be minimised to go below tolerable limits in order to design safe HIRC workstations.

6.2 ACADEMIC AND INDUSTRIAL CONTRIBUTIONS

Design science research (DSR) highlight the division between academic and industrial contribution and the need of both. The design artefact (in this research the HIRC simulation software and its application processes) with an industrial demand is the key in DSR, but it also requires connection to the foundations in the knowledge base from the academic world.

The central contribution in this thesis is the HIRC simulation software developed. This software bridges a gap in the simulation, visualisation and evaluation possibilities of HIRC workstation design (Tsarouchi et al., 2016a). The HIRC simulation software contributes to both the academic and the industrial community. Its contribution to the academic society is the collection of well-established methods in the software, enabling it to be used for further research in the HIRC workstation design area. The software includes the IPS IMMA software, IPS robot optimization software, the Methods-Time Measurement (MTM) system, Rapid Upper Limb Assessment (RULA), Pahl and Beitz's engineering design framework and compliant contact force (CCF) collision modelling, to mention the most important ones. Including all of these methods in a HIRC simulation software increases the validity of it as a part of its rigour and to expand the utilisation of these previously published methods. The industrial contribution of the HIRC simulation software is the ability to evaluate design alternatives (HIRC, fully manual and fully automatic) in early stages of production development processes. These data could be used as decision making support in industrial settings.

The application processes presented also bridge an identified gap in current research, where there is a need of design methods for HIRC workstations (Pini et al., 2015; Michalos et al., 2018). Since they tackle this uncharted area of HIRC workstation design, the academic contribution is to bridge this gap. But the main contribution of this process is to the industrial practitioner, who can use it to systematically design HIRC workstations. The combined performance and safety evaluation is another important contribution. To be able to design the workstation considering performance and safety criteria simultaneously makes the design process more efficient as it does not demand multiple and resource-demanding (in terms of both time and money) simulation software systems.

6.3 FUTURE RESEARCH

The HIRC simulation software presented in Paper A has been developed since 2016, but it is still a demonstrator software and requires further development before it could be released to any user. This involves including more power- and force-limiting robots, improving the possibilities of extracting robot programming code from the software and enhancing the usability and general stability of the software by reducing existing bugs. All of this is included in current development in newly started research projects.

Another interesting development of the HIRC simulation software is to include evaluation of more production system design parameters. Besides operation time and biomechanical load, could for instance cost criterion also be included. This is a parameter of highest importance for manufacturing management. The cost criterion should include both investment and utilisation costs. Part of the information needed to create these cost figures is also available in the geometric simulation model (e.g., robot type, number of operators, takt time). The individual cost of all resources (industrial robots, fixtures, man hours and maintenance) could be inserted manually.

Including more verification studies is another area where future research is needed. Paper B presents two such studies, but these have to be updated with cases that are more representative of human motions. These should focus on the digital human motion part of the HIRC simulation software. Thus by studying standard assembly tasks such as pick and place and use of nut runner the DHM part of the software is better evaluated. The robotic verification should be investigated separately in robotic manufacturing stations. This procedure facilitates the identification of suitable verification cases since the availability of HIRC cases is limited in industries.

It would also be interesting to investigate user experience from simulation engineers, who are the future users of the HIRC simulation software and its application processes. Users from industry have already partly been included in the software development in research projects after 2016. But the application process from Papers D and E has not been verified with industrial users. This is important in order to ensure that the process is a support for HIRC workstation design and gives the needed assistance.

One additional suggestion is to take the HIRC simulation software from the desktop setting and utilise it in a VR environment. To put operators in a VR model of a future workstation opens up great potentials. It would further increase the visualisation part of the software and improve communication of future workstation designs. It might also be used to put more research into the cognitive reaction from operators working in close collaboration with industrial robots.

The final suggestion is to widen the scope to partly focus on multivariable optimisation in the whole production development area. The HIRC simulation software presented uses two evaluation criteria (operation time and biomechanical load), and these are often conflicting. Adding more parameters, such as cost and floor utilisation, would highly increase the complexity of selecting the most appropriate design. Use of mathematical multivariable optimisation techniques can assist in this kind of difficult decision making. Applying multivariable optimisation of production development software is a field that would also benefit from extended research.

REFERENCES

Abdel-Malek, K., Yang, J., Marler, T., Beck, S., Mathai, A., Zhou, X., Patrick, A. & Arora, J. 2006. Towards a new generation of virtual humans. *International Journal of Human Factors Modelling and Simulation,* 1, 2-39.

Argyrou, A., Giannoulis, C., Papakostas, N. & Chryssolouris, G. 2016. A Uniform Data Model for Representing Symbiotic Assembly Stations. *Procedia CIRP,* 44, 85-90.

Awad, R., Fechter, M. & Van Heerden, J. 2017. Integrated risk assessment and safety consideration during design of HRC workplaces. In: *Proceedings of the 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, 1-10.

Badler, N. I., Phillips, C. B. & Webber, B. L. 1993. *Simulating Humans: Computer Graphics Animation and Control.* New York, NY: Oxford University Press.

Baines, T., Mason, S., Siebers, P.-O. & Ladbrook, J. 2004. Humans: the missing link in manufacturing simulation? *Simulation Modelling Practice and Theory,* 12, 515-526.

Baldwin, L. P., Eldabi, T., Hlupic, V. & Irani, Z. 2000. Enhancing simulation software for use in manufacturing. *Logistics Information Management,* 13, 263-270.

Baskerville, R., Baiyere, A., Gregor, S., Hevner, A. & Rossi, M. 2018. Design Science Research Contributions: Finding a Balance between Artifact and Theory. *Journal of the Association for Information Systems,* 19, 358-376.

Bauer, A., Wollherr, D. & Buss, M. 2008. Human–Robot Collaboration: a survey. *International Journal of Humanoid Robotics,* 5, 47-66.

Bauer, W. (Ed.), Bender, M., Braun, M., Rally, P. & Scholtz, O. 2016. *Lightweight robots in manual assembly—best to start simply! Examining companies' initial experiences with lightweight robots*. Stuttgart, Germany: Fraunhofer-Institut für Arbeitswirtschaft und Organisation IAO*.*

Bellgran, M. 1998. *Systematic Design of Assembly Systems: Preconditions and Design Process Planning.* Ph.D. thesis, Linköping, Sweden: Linköping University.

Bennett, D. 1986. *Production Systems Design.* London, UK: Butterworth-Heinemann.

Berlin, C. & Adams, C. 2017. *Production Ergonomics: Designing Work Systems to Support Optimal Human Performance*. London, UK: Ubiquity Press.

Bertilsson, E., Hanson, L., Högberg, D. & Rhén, I.-M. 2011. Creation Of The IMMA Manikin With Consideration Of Anthropometric Diversity. In: Spath, D., Ilg, R. & Krause, T. (Eds.) *Proceedings of the 21st International Conference on Production Research (ICPR 21)*, 416-420.

Bertilsson, E., Svensson, E., Högberg, D. & Hanson, L. 2010. Use of digital human modelling and consideration of anthropometric diversity in Swedish industry. In: *Proceedings of the 42nd annual Nordic Ergonomic Society Conference: Proactive Ergonomics – implementation of ergonomics in planning of jobs, tasks, systems and environments*.

Bischoff, R., Kurth, J., Schreiber, G., Koeppe, R., Albu-Schäffer, A., Beyer, A., Eiberger, O., Haddadin, S., Stemmer, A., Grunwald, G. & Hirzinger, G. 2010. The KUKA-DLR Lightweight Robot arm – a new reference platform for robotics research and manufacturing. In:

Proceedings of ISR 2010 (41st International Symposium on Robotics) and ROBOTIK 2010 (6th German conference on robotics), 1-8.

Bobka, P., Germann, T., Heyn, J. K., Gerbers, R., Dietrich, F. & Dröder, K. 2016. Simulation platform to investigate safe operation of human-robot collaboration systems. *Procedia CIRP,* 44, 187-192.

Bohlin, R., Delfs, N., Hanson, L., Högberg, D. & Carlson, J. S. 2012. Automatic Creation of Virtual Manikin Motions Maximizing Comfort in Manual Assembly Processes. *In:* Hu, S. J. (Ed.) *Proceedings of the 4th CIRP Conference on Assembly Technologies and Systems*, 209-212.

Braha, D. & Maimon, O. 1997. The design process: properties, paradigms, and structure. *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans,* 27, 146-166.

Brolin, E., Högberg, D., Hanson, L. & Örtengren, R. 2019. Development and evaluation of an anthropometric module for digital human modelling systems. *International Journal of Human Factors Modelling and Simulation,* 7, 47-70.

Brown, R. G. 2000. Driving digital manufacturing to reality. In: *2000 Winter Simulation Conference Proceedings, Vol. 1*, 224-228.

Busch, F., Wischniewski, S. & Deuse, J. 2013. Application of a character animation SDK to design ergonomic human-robot-collaboration. In: *Proceedings of the 2nd International Digital Human Modeling Symposium*, 1-7.

Bänziger, T., Kunz, A. & Wegener, K. 2018. Optimizing human–robot task allocation using a simulation tool based on standardized work descriptions. *Journal of Intelligent Manufacturing*, April 2018, 1-14. https://doi.org/10.1007/s10845-018-1411-1.

Caliskan, D. & Khalid, O. 2015. *Simulation of Human-Industrial Robot Collaboration in Machining and Logistics Environments.* M.Sc. thesis. Stockholm, Sweden: KTH.

Cencen, A., Verlinden, J. C. & Geraedts, J. M. P. 2018. Design Methodology to Improve Human-Robot Coproduction in Small- and Medium-Sized Enterprises. *IEEE/ASME Transactions on Mechatronics,* 23, 1092-1102.

Chaffin, D. B. 2007. Human motion simulation for vehicle and workplace design. *Human Factors and Ergonomics in Manufacturing & Service Industries,* 17, 475-484.

Chen, F., Sekiyama, K., Cannella, F. & Fukuda, T. 2014. Optimal Subtask Allocation for Human and Robot Collaboration Within Hybrid Assembly System. *IEEE Transactions on Automation Science and Engineering,* 11, 1065-1075.

Chen, F., Sekiyama, K., Huang, J., Sun, B., Sasaki, H. & Fukuda, T. 2011. An assembly strategy scheduling method for human and robot coordinated cell manufacturing. *International Journal of Intelligent Computing and Cybernetics,* 4, 487-510.

Colgate, J. E., Wannasuphoprasit, W. & Peshkin, M. A. 1996. Cobots: robots for collaboration with human operators. In: *Proceedings of the 1996 ASME International Mechanical Engineering Congress and Exposition*, 433-439.

Dalle Mura, M. & Dini, G. 2019. Designing assembly lines with humans and collaborative robots: A genetic approach. *CIRP Annals*, 68, 1-4.

Delfs, N., Bohlin, R., Hanson, L., Högberg, D. & Carlson, J. S. 2013. Introducing stability of forces to the automatic creation of digital human postures. Paper presented at DHM 2013, Second International Digital Human Modeling Symposium, Ann Arbor, MI, June 2013.

Dong, W., Li, H. & Teng, X. 2007. Off-line programming of Spot-weld Robot for Car-body in White Based on Robcad. In: ICMA 2007 International Conference on Mechatronics and Automation, 763-768.

European Union. 2006. Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006 on machinery, and amending Directive 95/16/EC (recast). *Official Journal of the European Union.* http://data.europa.eu/eli/dir/2006/42/oj [Accessed 9 June 2006].

Falck, A.-C. & Rosenqvist, M. 2014. A model for calculation of the costs of poor assembly ergonomics (part 1). *International Journal of Industrial Ergonomics,* 44, 140-147.

Fasth, Å., Provost, J., Fabian, M., Stahre, J. & Lennartson, B. 2012. From Task Allocation Towards Resource Allocation when Optimising Assembly Systems. *Procedia CIRP, Vol. 3, 45th CIRP Conference on Manufacturing Systems 2012*, 400-405.

Fechter, M., Seeber, C. & Chen, S. 2018. Integrated Process Planning and Resource Allocation for Collaborative Robot Workplace Design. *Procedia CIRP,* 72, *51st CIRP Conference on Manufacturing Systems,* 39-44.

FFI. 2019. *Strategisk färdplan: Hållbar produktion* [in Swedish]. Stockholm, Sweden: Vinnova.

Fortin, C., Gilbert, R., Beuter, A., Laurent, F., Schiettekatte, J., Carrier, R. & Dechamplain, B. 1990. SAFEWORK: a microcomputer-aided workstation design and analysis. New advances and future developments. In: Karkowski, W., Genaidy, A. M. & Asfour, S. S. (Eds.) *Computer-Aided Ergonomics.* London, UK: Taylor & Francis, 157-180.

Franka. 2019. *Franka Emika.* https://www.franka.de/ [Accessed 16 May 2019].

Fritzsche, L. 2010. Ergonomics risk assessment with digital human models in car assembly: Simulation versus real life. *Human Factors and Ergonomics in Manufacturing & Service Industries,* 20, 287-299.

Genaidy, A. M., Al-Shedi, A. A. & Karwowski, W. 1994. Postural stress analysis in industry. *Applied Ergonomics,* 25, 77-87.

Gombolay, M. C., Bair, A., Huang, C. & Shah, J. A. 2017. Computational design of mixed-initiative human-robot teaming that considers human factors: situational awareness, workload, and workflow preferences. *International Journal of Robotics Research,* 36, 597-617.

Gopinath, V., Johansen, K. & Ölvander, J. 2018. Risk Assessment for Collaborative Operation: A Case Study on Hand-Guided Industrial Robots. In: Svalova, V. (Ed.) *Risk Assessment.* Rijeka, Croatia: InTech, 167-187.

Haddadin, S. & Croft, E. 2016. Physical human–robot interaction. In: Siciliano, B. & Khatib, O. (Eds.) *Springer Handbook of Robotics.* Berlin, Heidelberg, Germany: Springer-Verlag, 1835-1874.

Hanson, L., Högberg, D., Bohlin, R. & Carlsson, J. S. 2011. IMMA – Intelligently Moving Manikins – Project Status 2011. In: *Proceedings of the 1st International Symposium on Digital Human Modeling*, 1-5.

Hanson, L., Sperling, L., Gard, G., Ipsen, S. & Olivares Vergara, C. 2009. Swedish anthropometrics for product and workplace design. *Applied Ergonomics,* 40, 797-806.

Helms, E., Schraft, R. D. & Hagele, M. 2002. rob@work: Robot assistant in industrial environments. In: *Proceedings of the 11th IEEE International Workshop on Robot and Human Interactive Communication*, 399-404.

Hevner, A. R. 2007. A Three Cycle View of Design Science Research. *Scandinavian Journal of Information Systems,* 19, 87-92.

Hevner, A. R., March, S. T., Park, J. & Ram, S. 2004. Design Science in Information Systems Research. *MIS Quarterly,* 28, 75-105.

Hignett, S. & McAtamney, L. 2000. Rapid Entire Body Assessment (REBA). *Applied Ergonomics,* 31, 201-205.

Hägele, M., Nilsson, K., Pires, J. N. & Bischoff, R. 2016. Industrial robotics. In: Siciliano, B. & Khatib, O (Eds.) *Springer Handbook of Robotics.* Berlin, Heidelberg, Germany: Springer-Verlag, 1395-1421.

Högberg, D., Hanson, L., Bohlin, R. & Carlson, J. S. 2016. Creating and shaping the DHM tool IMMA for ergonomic product and production design. *International Journal of the Digital Human,* 1, 132-152.

IEA. 2019. *Definition and Domains of Ergonomics*. https://www.iea.cc/whats/ [Accessed 6 June 2019].

IPS. 2019a. *Industrial Path Solutions: IPS IMMA*. https://industrialpathsolutions.se/ips-imma/ [Accessed 15 March 2019].

IPS. 2019b. *Industrial Path Solutions: IPS robot optimization*. https://industrialpathsolutions.se/ips-robot-optimization/ [Accessed 15 March 2019].

ISO. 2010. *ISO 12100:2010 Safety of machinery–General principles for design–Risk assessment and risk reduction*. Geneva, Switzerland: International Organization for Standardization.

ISO. 2011a. *ISO 10218-1:2011 Robots and robotic devices – Safety requirements for industrial robots – Part 1: Robots*. Geneva, Switzerland: International Organization for Standardization.

ISO. 2011b. *ISO 10218-2:2011 Robots and robotic devices – Safety requirements for industrial robots – Part 2: Robot systems and integration*. Switzerland: International Organization for Standardization.

ISO. 2016. *ISO/TS 15066:2016 Robots and robotic devices - Collaborative robots*. Geneva, Switzerland: International Organization for Standardization.

Karhu, O., Kansi, P. & Kuorinka, I. 1977. Correcting working postures in industry: A practical method for analysis. *Applied Ergonomics,* 8, 199-201.

Kee, D. & Karwowski, W. 2007. A Comparison of Three Observational Techniques for Assessing Postural Loads in Industry. *International Journal of Occupational Safety and Ergonomics,* 13, 3-14.

Khalid, O., Caliskan, D., Ore, F. & Hanson, L. 2015. Simulation and evaluation of industrial applications of Human-Industrial Robot Collaboration cases. In: Fostervold, K. I., Kjøs Johnsen, S. Å., Rydstedt, L. & Watten, R. G. (Eds.) *Creating Sustainable Work-*

environments: Proceedings of NES2015 Nordic Ergonomics Society 47th Annual Conference. Lillehammer, Norway: NEHF (Norwegian society for Ergonomics and Human Factors).

Klingstam, P. & Gullander, P. 1999. Overview of simulation tools for computer-aided production engineering. *Computers in Industry,* 38**,** 173-186.

Kock, S., Vittor, T., Matthias, B., Jerregard, H., Källman, M., Lundberg, I., Mellander, R. & Hedelind, M. 2011. Robot concept for scalable, flexible assembly automation: A technology study on a harmless dual-armed robot. In: *Proceeedings of the 2011 IEEE International Symposium on Assembly and Manufacturing (ISAM)*, 1-5.

Krüger, J., Lien, T. K. & Verl, A. 2009. Cooperation of human and machines in assembly lines, Keynote paper. *CIRP Annals – Manufacturing Technology,* 58, 628-646.

Krüger, J., Nickolay, B., Heyer, P. & Seliger, G. 2005. Image based 3D Surveillance for flexible Man-Robot-Cooperation. *CIRP Annals – Manufacturing Technology,* 54(1), 19-22.

KUKA. 2019. *KUKA lbr iiwa*. https://www.kuka.com/en-cn/products/robotics-systems/industrial-robots/lbr-iiwa [Accessed 23 May 2019].

Kunz, A., Zank, M., Nescher, T. & Wegener, K. 2016. Virtual Reality Based Time and Motion Study with Support for Real Walking. *Procedia CIRP,* 57, 303-308.

Laring, J., Forsman, M., Kadefors, R. & Örtengren, R. 2002. MTM-based ergonomic workload analysis. *International Journal of Industrial Ergonomics,* 30, 135-148.

Lasota, P. A., Fong, T. & Shah, J. A. 2017. A Survey of Methods for Safe Human-Robot Interaction. *Foundations and Trends® in Robotics,* 5, 261-349.

Le Masson, P. & Weil, B. 2013. Design theories as languages of the unknown: insights from the German roots of systematic design (1840–1960). *Research in Engineering Design,* 24, 105-126.

Lee, D. M. A. & ElMaraghy, W. 1990. ROBOSIM: a CAD-based off-line programming and analysis system for robotic manipulators. *Computer-Aided Engineering Journal,* 7, 141-148.

Lichtenthäler, C. & Kirsch, A. 2016. Legibility of Robot Behavior: A Literature Review. https://hal.archives-ouvertes.fr/hal-01306977 [Accessed 23 May 2019].

Lindskog, E., Berglund, J., Vallhagen, J. & Johansson, B. 2016. Layout Planning and Geometry Analysis Using 3D Laser Scanning in Production System Redesign. *Procedia CIRP,* 44, 126-131.

Liu, H., Fang, T., Zhou, T., Wang, Y. & Wang, L. 2018. Deep Learning-based Multimodal Control Interface for Human-Robot Collaboration. *Procedia CIRP,* 72, 3-8.

Luckman, J. 1967. An Approach to the Management of Design. *Journal of the Operational Research Society,* 18, 345-358.

Luh, J. Y. S. & Srioon, S. 2000. Animated simulation of human-robot interactions. In: *Proceedings of the 3rd World Congress on Intelligent Control and Automation, Vol. 2*, 1361-1366.

Maeno, T. & Hasegawa, J. 2001. Development of a finite element model of the total human model for safety (THUMS) and application to car-pedestrian impacts. SAE Technical Paper 2001-06-0054. https://www.sae.org/publications/technical-papers/content/2001-06-0054/ [Accessed 23 May 2019].

Manufuture. 2018. *Manufuture –Vision 2030: Competitive, Sustainable And Resilient European Manufacturing.* Report from ManuFUTURE High-Level Group, December 2018.

Marusteri, M. & Bacarea, V. 2010. Comparing groups for statistical differences: how to choose the right statistical test? *Biochemia Medica,* 20, 15-32.

Maurice, P., Padois, V., Measson, Y. & Bidaud, P. 2017. Human-oriented design of collaborative robots. *International Journal of Industrial Ergonomics,* 57, 88-102.

Maynard, H. B., Stegemerten, G. J. & Schwab, J. L. 1948. *Methods Time Measurement,* New York, NY: McGraw-Hill.

McAtamney, L. & Corlett, E. N. 1993. RULA: a survey method for the investigation of work-related upper limb disorders. *Applied Ergonomics,* 24, 91-99.

Michalos, G., Makris, S., Tsarouchi, P., Guasch, T., Kontovrakis, D. & Chryssolouris, G. 2015. Design Considerations for Safe Human-Robot Collaborative Workplaces. *Procedia CIRP,* 37, 248-253.

Michalos, G., Spiliotopoulos, J., Makris, S. & Chryssolouris, G. 2018. A method for planning human robot shared tasks. *CIRP Journal of Manufacturing Science and Technology,* 22, 76-90.

Motte, D., Bjärnemo, R. & Yannou, B. 2011. On the interaction between the engineering design and the development process models—Part I: Elaborations on the generally accepted process models. In: Chakrabarty, A. (Ed.) *Research into Design: Supporting sustainable product development*. Chennai, India: Research Publishing Services, 87-95.

Mourtzis, D., Papakostas, N., Mavrikios, D., Makris, S. & Alexopoulos, K. 2015. The role of simulation in digital manufacturing: applications and outlook. *International Journal of Computer Integrated Manufacturing,* 28, 3-24.

Murphy, C. A. & Perera, T. 2002. The definition of simulation and its role within an aerospace company. *Simulation Practice and Theory,* 9, 273-291.

Mårdberg, P., Carlson, J. S., Bohlin, R., Delfs, N., Gustafsson, S., Högberg, D. & Hanson, L. 2014. Using a formal high-level language and an automated manikin to automatically generate assembly instructions. *International Journal of Human Factors Modelling and Simulation,* 4, 233-249.

Nachar, N. 2008. The Mann-Whitney U: A Test for Assessing Whether Two Independent Samples Come from the Same Distribution. *Tutorials in Quantitative Methods for Psychology,* 4, 13-20.

Ng, A. H. C., Adolfsson, J., Sundberg, M. & De Vin, L. J. 2008. Virtual manufacturing for press line monitoring and diagnostics. *International Journal of Machine Tools and Manufacture,* 48, 565-575.

Oberer, S. & Schraft, R. D. 2007. Robot-Dummy Crash Tests for Robot Safety assessment. In: *Proceedings 2007 IEEE International Conference on Robotics and Automation*, 2934-2939.

Ogorodnikova, O. 2008. Human Weaknesses and strengths in collaboration with robots. *Periodica Polytechnica. Mechanical Engineering,* 52, 25-33.

Ore, F. 2015. *Human − industrial robot collaboration: Simulation, visualisation and optimisation of future assembly workstations.* Lic. thesis, Västerås, Sweden: Mälardalen University.

Ore, F., Hanson, L., Delfs, N. & Wiktorsson, M. 2015. Human industrial robot collaboration - development and application of simulation software. *International Journal of Human Factors Modelling and Simulation,* 5, 164-185.

Ore, F., Hanson, L., Wiktorsson, M. & Eriksson, Y. 2016. Automation constraints in human–industrial robot collaborative workstation design. Paper presented at the 7th International Swedish Production Symposium, 25-27 October 2016,

Lund, Sweden.

Ore, F., Jiménez Sánchez, J. L., Hanson, L. & Wiktorsson, M. 2019a. Design Method of Human–Industrial Robot Collaborative Workstation with industrial Application. *Submitted to journal*.

Ore, F., Ruiz Castro, P., Hanson, L., Wiktorsson, M. & Gustafsson, S. 2019b. Verification of manikin motions in a HIRC simulation. *Submitted to journal*.

Ore, F., Vemula, B., Hanson, L., Wiktorsson, M. & Fagerström, B. 2019c. Simulation methodology for performance and safety evaluation of human–industrial robot collaboration workstation design. *International Journal of Intelligent Robotics and Applications,* 3, 269-282.

Pahl, G. & Beitz, W. 1977. *Konstruktionslehre: Handbuch für Studium und Praxis,* Berlin, Germany: Springer.

Pahl, G., Beitz, W., Feldhusen, J. & Grote, K. H. 2007. *Engineering Design: A Systematic Approach,* London, UK: Springer-Verlag

Pan, Z., Polden, J., Larkin, N., Van Duin, S. & Norrish, J. 2012. Recent progress on programming methods for industrial robots. *Robotics and Computer-Integrated Manufacturing,* 28, 87-94.

Panel on Musculoskeletal Disorders and the Workplace, Commission on Behavioral and Social Sciences and Education, National Research Council & Institiute of Medicine. 2001. *Musculoskeletal Disorders and the Workplace: Low Back and Upper Extremities*. Washington, DC: National Academy Press.

Pidd, M. 1994. An introduction to computer simulation. In: *Proceedings of the 26th Conference on Winter Simulation*, 7-14.

Pini, F., Leali, F. & Ansaloni, M. 2015. A systematic approach to the engineering design of a HRC workcell for bio-medical product assembly. In: *2015 IEEE 20th Conference on Emeerging Technologies & Factory Automation (ETFA)*, 1-8.

Produktion2030. 2018. *Make in Sweden 2030.* Stockholm, Sweden: Vinnova.

Pugh, S. 1991. *Total Design: Integrated Methods for Successful Product Engineering,* Harlow, UK: Addison-Wesley.

Punnett, L. & Wegman, D. H. 2004. Work-related musculoskeletal disorders: the epidemiologic evidence and the debate. *Journal of Electromyography and Kinesiology,* 14, 13-23.

Ranz, F., Hummel, V. & Sihn, W. 2017. Capability-based Task Allocation in Human-robot Collaboration. *Procedia Manufacturing,* 9, 182-189.

Rasmussen, J., Damsgaard, M., Surma, E., Christensen, S. T., de Zee, M. & Vondrak, V. 2003. AnyBody - a software system for ergonomic optimization. Paper presented at the Fifth

World Congress on Structural and Multidisciplinary Optimization, 19-23 May 2003, Lido di Jesolo, Italy.

Rasmussen, J., Vondrak, V., Damsgaard, M., de Zee, M., Christensen, S. T. & Dostal, Z. 2002. The AnyBody Project – Computer analysis of the human body. In: Jelen, K., Kušová, S., Chalupová, M. & Otáhal, J. (Eds.) *Proceedings of International Conference on Biomechanics of Man 2002*, 270-274.

Reinhart, G., Spillner, R. & Shen, Y. 2012. Approaches of Applying Human-Robot-Interaction-Technologies to Assist Workers with Musculoskeletal Disorders in Production. In: *International Conference on Intelligent Robotics and Applications*, 74-84.

Rienecker, L. & Stray Jørgensen, P. 2008. *Att skriva en bra uppsats* [in Swedish], Malmö, Sweden: Liber.

Robla-Gómez, S., Becerra, V. M., Llata, J. R., González-Sarabia, E., Torre-Ferrero, C. & Pérez-Oria, J. 2017. Working Together: A Review on Safe Human-Robot Collaboration in Industrial Environments. *IEEE Access,* 5, 26754-26773.

Rosenstrauch, M. J. & Krüger, J. 2017. Safe human-robot-collaboration-introduction and experiment using ISO/TS 15066. In: *2017 3rd International Conference on Control, Automation and Robotics (ICCAR)*, 740-744.

Ruiz Castro, P., Högberg, D., Ramsen, H., Bjursten, J. & Hanson, L. 2019. Virtual Simulation of Human-Robot Collaboration Workstations. In: Bagnara, S., Tartaglia, R., Albolino, S., Alexander, T. & Fujita, Y. (Eds.) *Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018)*, *Volume V,* 250-261.

Saenz, J. 2019. *Computer-Aided Safety Engineering tools for consideration of safety during design of robotics applications.* Presentation at European Robotics Forum, Bukarest, Romania, 20-22 March 2019.

Saenz, J., Elkmann, N., Gibaru, O. & Neto, P. 2018. Survey of methods for design of collaborative robotics applications-Why safety is a barrier to more widespread robotics uptake. In: *Proceedings of the 2018 4th International Conference on Mechatronics and Robotics Engineering*, 95-101.

Savoy, A. & McLeod, A. 2013. A precursory look at potential interaction objectives affecting flexible robotic cell safety. In: Yamamoto, S. (Ed.) *Human Interface and the Management of Information: Information and Interaction for Health, Safety, Mobility and Complex Environments*, Springer, 198-206.

Scholer, M., Vette, M. & Rainer, M. 2015. A lightweight robot system designed for the optimisation of an automotive end-off line process station. *Industrial Robot,* 42, 296-305.

Schraft, R. D., Schmid, S. & Thiemermann, S. 2002. Man-robot cooperation in a flexible assembly cell. *Assembly Automation,* 22, 136-138.

Segeborn, J., Segerdahl, D., Ekstedt, F., Carlson, J. S., Andersson, M., Carlsson, A. & Söderberg, R. 2014. An Industrially Validated Method for Weld Load Balancing in Multi Station Sheet Metal Assembly Lines. *Journal of Manufacturing Science and Engineering,* 136, 1087-1357.

Seidl, A. 1997. *RAMSIS – A New CAD-Tool for Ergonomic Analysis of Vehicles Developed for the German Automotive Industry. SAE Technical Paper 70088. https://doi.org/10.4271/970088.*

Spensieri, D., Bohlin, R. & Carlson, J. S. 2013. Coordination of robot paths for cycle time minimization. In: *2013 IEEE International Conference on Automation Science and Engineering (CASE)*, 522-527.

Stanton, N. A. 2006. Hierarchical task analysis: Developments, applications, and extensions. *Applied Ergonomics,* 37**,** 55-79.

Stauffer, L. & Pawar, T. 2007. A comparison of Systematic Design and Design for Six Sigma. In: Bocquet, J.-C. (Ed.) *Proceedings of ICED 2007, the 16th International Conference on Engineering Design*, 791-792 (exec. Summary).

Tan, J. T. C., Duan, F., Zhang, Y., Watanabe, K., Kato, R. & Arai, T. 2009. Human-robot collaboration in cellular manufacturing: Design and development. In: *IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2009*, 29-34.

Teknikföretagen 2014. *Made in Sweden 2030: Strategic Agenda for Innovation in Production.* Stockholm, Sweden: IF Metall, Production: A Chalmers Area of Advance, Svenska ProduktionsAkademien, Swerea/IVF, Teknikföretagen and XPRES*.*

Tsarouchi, P., Makris, S. & Chryssolouris, G. 2016a. Human–robot interaction review and challenges on task planning and programming. *International Journal of Computer Integrated Manufacturing,* 29, 916-931.

Tsarouchi, P., Spiliotopoulos, J., Michalos, G., Koukas, S., Athanasatos, A., Makris, S. & Chryssolouris, G. 2016b. A Decision Making Framework for Human Robot Collaborative Workplace Generation. *Procedia CIRP,* 44, 228-232.

Ulrich, K. & Eppinger, S. 2016. *Product Design and Development*. New York, NY: McGraw-Hill Education.

United Nations. 2013. *World Population Prospects: The 2012 Revision, Highlights and Advance Tables. Working Paper No. ESA/P/WP.228.* New York, NY: United Nations.

Universal Robots. 2019. *Collaborative Robots from Universal Robots.* https://www.universal-robots.com/products/ [Accessed 23 May 2019].

Wallén, J. 2008. *The history of the industrial robot*. Linköping, Sweden: Linköping University.

Vemula, B., Matthias, B. & Ahmad, A. 2018. A design metric for safety assessment of industrial robot design suitable for power- and force-limited collaborative operation. *International Journal of Intelligent Robotics and Applications,* 2, 226-234.

Vignais, N., Bernard, F., Touvenot, G. & Sagot, J.-C. 2017. Physical risk factors identification based on body sensor network combined to videotaping. *Applied Ergonomics,* 65, 410-417.

Wiktorsson, M. 2000. *Performance Assessment of Assembly Systems: Linking strategy to Analysis in Early Stage Design of Large Assembly Systems.* Ph.D. thesis. Stockholm, Sweden: Royal Institute of Technology.

Vollmann, K. 2002. A new approach to robot simulation tools with parametric components. In: *Proceedings of the 2002 IEEE International Conference on Industrial Technology, IEEE ICIT '02, Vol. 2*, 881-885.

Wu, B. 1992. *Manufacturing systems design and analysis*. London, UK: Springer Science & Business Media.

Wu, B. 1994. *Manufacturing Systems Design and Analysis: Context and Techniques.* London, UK: Chapman & Hall.

Yaskawa. 2019. *Motoman HC10*. https://www.yaskawa.eu.com/en/products/robotics/motoman-robots/seriesdetail/serie/hc10/ [Accessed 29 May 2019].

Zaeh, M. F. & Prasch, M. 2007. Systematic workplace and assembly redesign for aging workforces. *Production Engineering,* 1, 57-64.

APPENDIX A

In this process there is a need to interpret and adjust some RULA thresholds in the digital models to compute a grand RULA score (all text in italics below is from the RULA employee assessment worksheet (McAtamney and Corlett, 1993)):

- *If shoulder is raised: +1*, interpreted as > 2° in the digital joint data.
- *If upper arm is abducted: +1*, interpreted as > 2° in the digital joint data.
- *If arm is supported or person is leaning: -1*, has to be manually inserted.
- *If arm is working across midline of the body: +1*, interpreted as > 25° elbow angle in the digital joint data.
- *If arm out to side of body: +1*, interpreted as > 2° in the digital joint data.
- *Locate wrist position*, *neutral position* interpreted as values between -2° and 2° in the digital joint data.
- *If wrist is bent from the midline: +1*, interpreted as values beween-2° and 2° in the digital joint data.
- *If wrist is twisted mainly in mid-range =1*, mid-range interpreted as values between-90° and 90° in the digital joint data.
- *Add muscle use score*, has to be manually inserted.
- *Add force/load score*, has to be manually inserted.
- *Locate neck position*, *in extension*, interpreted as > 2° in the digital joint data.
- *If neck is twisted: +1*, interpreted as values between -2° and 2° in the digital joint data.
- *If neck is side-bending: +1*, interpreted as values between -2° and 2° in the digital joint data.
- *Locate trunk position*, *neutral position* interpreted as < 2° in the digital joint data.
- *If trunk is twisted: +1*, interpreted as values between -2° and 2° in the digital joint data.
- *If trunk is side-bending: +1*, interpreted as values between -2° and 2° in the digital joint data.
- *If legs & feet supported and balanced: +1, If not: +2* has to be manually inserted.