Adaptable framework methodology for designing human-robot coproduction

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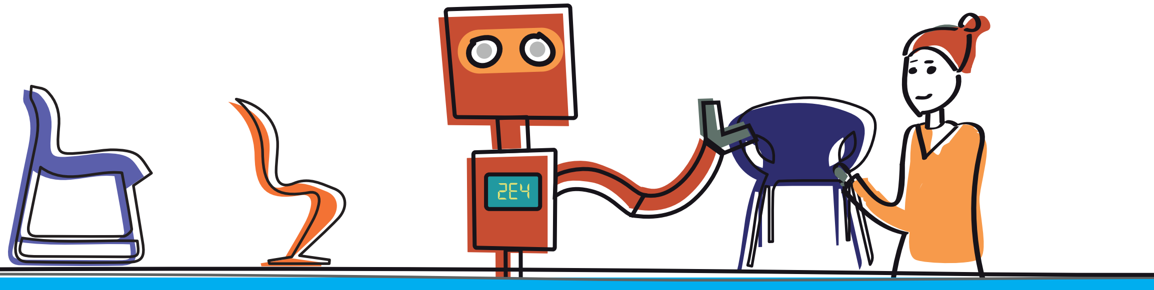

Argun Çençen

Adaptable framework methodology for designing human-robot coproduction

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for the purpose of obtaining the degree of doctor
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For the unconditional love and support of my parents.

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Chapter 1

1 Introduction

The research project presented in this thesis is situated in the domain of design research, and focuses on the designers of production systems. In general, it aims to support the research towards a better understanding of design for human-robot coproduction (HRC).

The specific objective of this research project was the development of support for novice HRC designers for integrating collaborative robots (Cobots) successfully in existing and new human-driven production systems. At the start of the project, it was assumed that novice HRC designers were lacking conceptual design tools for analysing, modelling, simulating and evaluating human-robot coproduction scenarios. Therefore, the design support was realized in the form of an adaptable framework methodology for conceptual design of HRC.

The research for this thesis was executed as a PhD project which was supported by the EU-FP7-'Factory in a day' project, which enabled the generation and exploration of empirical evidence from the targeted context. In addition the research had access to a laboratory environment in which two types of Cobots were present.

This chapter acts as an introduction to the domain in which this research is situated and provides a background on the knowledge gaps in addressing the challenges related to the researched phenomenon. In the final part of this chapter, the research design adopted to achieve the objectives of this research is presented.

1.1 Research domain

1.1.1 Background

This research has been executed at the faculty of Industrial Design Engineering (IDE) of Delft University of Technology in the Netherlands. A summary of the focus of the research at this faculty is as follows;

> *"At the faculty of Industrial Design Engineering (IDE) of the University of Delft we want to improve people's lives and address societal challenges by always combining human desirability, technical feasibility and economic viability. We do this by combining design abilities and scientific knowledge together with conceptualizing and concretizing solutions at local and system level. Our research aims to underpin this with new and validated knowledge and methods. …*
>
> *… In society, design is playing an increasingly prominent role; it is called upon to come up with solutions to societal problems at every scale in domains such as health, mobility and sustainability. Both design practice and academic design research have undergone*

> *rapid development over the past decades. The scope to which design is applied has grown and extended from products to services and now to sociotechnical systems. The complexity of systems increases as technological components are integrated, more constraints are considered, and single-item competition is replaced by collaborations in which an increasing number of stakeholders are involved. On the other hand, this enables multidisciplinary teams including designers to find genuine solutions with distinctive and valuable qualities.*
>
> *This requires from the future designers to be able to combine abstract thinking and concrete implementation, and engage in complex interactions with stakeholders, and new technologies, and forms of organizing business."* (Midterm review - Research at IDE 2018)

Looking at the world from this perspective, one of the focused areas in the faculty of Industrial Design Engineering is the context of manufacturing and the interactions between the novel technologies that are being introduced in this context and their users. Recent projects in this line of research have so far focused on the new design capabilities that are enabled by 3D-Printing (Doubrovski 2016), and the use of Virtual Reality (VR) in production environments (Aschenbrenner 2017).

In recent years, research on topics related to the digitalisation of production systems has been growing rapidly. In particular, the use of robot technology in various forms and capacities to assist human operators in this context has been a major field of focus. While some of this research focuses on the development of better robot-assistants for humans in the manufacturing context (Unhelkar and Shah 2015), on the other end of the spectrum, progress is being made towards a more human-centric way of including humans in highly automated systems (Pacaux-Lemoine et al. 2017). In (roughly) the middle of this spectrum, the development of system and data architectures to enable efficient and safe human-robot task sharing in production environments has been taking shape (Tsarouchi, Michalos, et al. 2017). In this research, this spectrum is called human-robot coproduction (HRC) [1].

On the other hand, the mentioned lines of research often focus on large-scale manufacturing (automotive, aerospace, process industries etc.), which are already highly automated and digitalized. However, research on the application of these new technologies in the context of small and medium-sized enterprises (SMEs) in the manufacturing industry, which

---

[1] In literature, the abbreviation "HRC" is already being used to refer to 'Human-robot collaboration' and 'Human-robot cooperation'. In this research the term 'coproduction' has been used in order to specify the type of collaboration to the production context.

are still mainly human-driven and less digitized, has not been a priority (further discussed in section 1.1.4). Therefore, this research focuses on the application of HRC technologies in the context of SMEs.

1.1.2 Digitalisation and automation of manufacturing

In order to understand how the gap between large-scale manufacturing and SMEs came about, and how production systems have been digitalized over the years, this section presents a historical background that summarizes the first three industrial revolutions.

Humans have developed tools throughout their existence in order to aid them in their daily lives. From tools for hunting to tools for building shelter, these artefacts have had an impact on the well-being and survival capabilities of our ancestors (Basalla 1988). Next to making and using tools, and improving these tools through their use, the organisation of work between humans has also evolved. Throughout human ancestry, individuals have learned to adapt their social skills and exploit teamwork to collaboratively accomplish all sorts of tasks. Over time, by combining specific tools with efficient teamwork schemes, humans began to optimise the production of goods, which gave a greater capacity to produce more complicated goods.

Until the First Industrial Revolution, most manufacturing was done by hand and the tools that were used were seen as an extension of the craftsman’s physical skills (Hounshell 1985). In the period 1760–1840, a transition began during which manufacturing started to involve machines instead of tools alone. The development of interchangeable, standardised machine tools and the steam engine played an important role during this period, and had a big impact on manufacturing productivity. This period has been recorded in history as the first Industrial Revolution.

It did not take long for the next Industrial Revolution to start; about 60 years after the first Industrial Revolution reached its peak, around the turn to the 20th century, the Second Industrial Revolution began. One of the most cited examples for this period is the story of Random E. Olds using an assembly line for the production of his cars, followed by Henry Ford, who applied the same principle on a larger scale to start producing millions of cars each year (Hounshell 1985). Using the assembly line principle, Henry Ford showed that the manufacturing of a product could be divided into smaller steps that could be completed in a pre-determined amount of time, resulting in an output stream of products with predictable quantity, time and quality. In the first three years after being implemented, the assembly line principle gave Ford a 100% annual increase in productivity (Raff 1996).

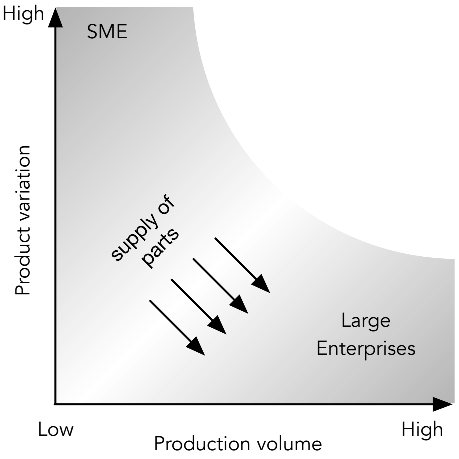


Figure 1 'Product variation' versus 'production volume' between SMEs and large enterprises

Since the invention of the assembly line, the landscape of enterprises in the manufacturing domain has been mostly defined by two factors: (i) the number of products produced (mass production) and (ii) the variation in products produced (mass-customisation) by enterprises.

As flexibility and changeability became the main enablers of staying competitive in global markets (Wiendahl et al. 2007), high-volume low-mix production became the specialism of large enterprises, and low-volume high-mix production became the specialism of SMEs. In this landscape, SMEs have played an essential role in supplying large enterprises with (customised) parts for products/intermediate goods (Figure 1). For example, while it is estimated that the total time spent on the production of (parts of) a car is around 1,020 minutes (Toyota 2018), two cars are produced every minute in a car factory (CAR-Magazine 2016). This is made possible by a myriad of suppliers that produce parts and sub-assemblies for the final assembly of a car. These suppliers are often highly specialized in the production of a certain type of product. However, they possess the flexibility to produce variations of their product for different customers, which is partially made possible by how their products and production systems have been designed.

In the second half of the 20th century, the principles of the assembly line became widespread. At the same time, the development of computers, electronic control systems and industrial automation equipment accelerated the automation and management of such systems. This resulted in a Third Industrial Revolution that gained momentum around 1970. During this time, it is estimated that a productivity gain of 600% has been achieved (Nye

2013). However, this also resulted in an increased level of complexity of these systems and their design processes.

1.1.3 Industry 4.0

In the period that followed the third Industrial Revolution, flexibility of production became increasingly more important. In order to remain competitive, many manufacturing enterprises relocated their production activities and their suppliers to cheaper labour markets as a solution. Therefore today, in the global economy, the choice of where to produce products and product parts is driven mostly by costs and time-to-market, and is no longer dependent of where products are sold (Desyllas 2009). As a result, the manufacturing industry—both in Europe and the U.S.—has seen a production decline over the past decades. However, after several decades of declining interest in manufacturing, its significance as one of the few ways to create wealth is being rediscovered (Zijm 2018).

The latest and most often referenced development in recent years towards the rejuvenation of the industry has been the 'Industry 4.0' initiative. Industry 4.0 puts forward a vision, roadmaps, principles and strategies for operationalizing various emerging technologies, such as; cyber-physical systems (CPS), Internet of Things (IoT) and Artificial Intelligence (AI), which are making their ways into the manufacturing domain and to lay down the foundation for empowering collaborations between manufacturing enterprises in adopting these technologies (Kagermann and Wahlster, 2013). It is expected that through this initiative, manufacturing can be 'reshored' back to Europe and the U.S (Kamer van Koophandel 2016).

The development of the Industry 4.0 concept in Germany around 2013 has also triggered other nations to introduce similar initiatives (Appendix A). These developments have often been mentioned as the start of the Fourth Industrial Revolution. The four main capabilities of systems in the Industry 4.0 are described as: Interoperability, information transparency, technical assistance and decentralised decisions. Together, these capabilities suggest taking new perspectives towards how to design, manufacture and distribute products in the future.

So far, in mainstream automated production systems, work has been arranged in such a way that humans must adhere to work procedures as rigid as the rest of the automated production environment (X. V. Wang et al. 2017). However, when the four capabilities of Industry 4.0 systems are compared to the capabilities of existing production systems, it can be argued that one of the essential changes that will take place during the transformation to Industry 4.0 from the human operator's perspective, concerns the introduction of a mix of new type of resources that possess various forms and types of artificial intelligence

(Gorecky et al. 2014). This is expected to put extra emphasis on the interaction between humans and these intelligent resources in these systems (Pacaux-Lemoine et al. 2017) and therefore calls for a more human-centric approach during their design processes (Romero et al. 2016). These new requirements, which concern the only resource in these systems that cannot be engineered – the human operator –, bring a new level of complexity to the (already complex) design process of these systems.

1.1.4 Implications of Industry 4.0 on SMEs

Even though SMEs are regarded as the backbone of many European countries (Torn and Vaneker 2019), as a result of off-shoring production and the focus on optimising large-scale automated production systems, in the past decennia, less attention has been paid towards the development of knowledge for enabling manufacturing SMEs to structurally adopt and absorb automation and robots (Jäger et al. 2015). This has created a gap in the level of automation maturity of SMEs in comparison with larger enterprises (Spena et al. 2016). To reach the level of maturity needed for Industry 4.0, a digital transformation of production systems of SMEs is essential, including adequate training and further education of their employees (Faller and Feldmúller 2015).

The reasons for SMEs in facing difficulties in adopting the basics of automation and digitalisation are counted as: (i) the lack of skilled employees, (ii) not being able to look beyond their own products and production range, and (iii) limited investment possibilities for implementing new technologies (Sommer 2015). Unfortunately, while the issues related to designing successful Industry 4.0 production systems has been gaining increasingly more attention from academia and the industry in recent years, research on developing methods and tools specifically for allowing SMEs to solve their own Industry 4.0-related issues has received less attention (Erol et al. 2016). The topic of support for SMEs has also been prioritised by the European Union (EU) in the past decade. A review of the EU-supported projects that are targeted towards supporting SMEs shows that there are still many open issues in this domain, which are currently being addressed by the industry and academia.

On the other hand, SMEs are often characterized by a higher ratio of humans to automated systems, compared to larger enterprises. Considering the new human-machine interaction requirements as introduced by Industry 4.0 (Pieskä et al. 2012), the engineers that integrate these technologies will need to take the predominantly human-driven context of SMEs and the implications of this on the performance of the resulting systems into consideration as well. However, the current practice of these engineers – the automation/systems integrator – does not include a focus on these aspects (Siciliano and Khatib 2016, pg1416).

1.1.5 Evolution of robots towards Cobots

An important development in the history of modern production systems has been the industrial robot (also referred to as the articulated robot arm, robot arm, robot manipulator, or robot). By definition, an industrial robot is 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/TC 299-Robotics 2012). The development of industrial robots has enabled manufacturers to automate parts of their production processes that were previously not possible to automate, such as spot welding during automobile production.

Today, most industrial robots are single-purpose automated machines, and in comparison to human resources in a production system, they are limited in the types of task that they can execute in this context. In addition, the costs of engineering currently make up roughly the half of the costs of integrating robots (Siciliano and Khatib 2016). For large series production, the engineering costs of system integration can be spread out to more products. However, for small-scale and flexible production, these costs represent a bigger challenge. Until now, industrial robots have most often been used in the automotive industry (Litzenberger 2018). At the end of 2017, there were 387.000 shipments of industrial robots (an increase of 31% in one year) of which only 64.000 occurred in Europe. In 2017, 125.000 Industrial robots were placed in automotive industry (an increase of 21% in one year) and 116.000 were placed in the electrical/electronics industry (an increase of 27% in one year).

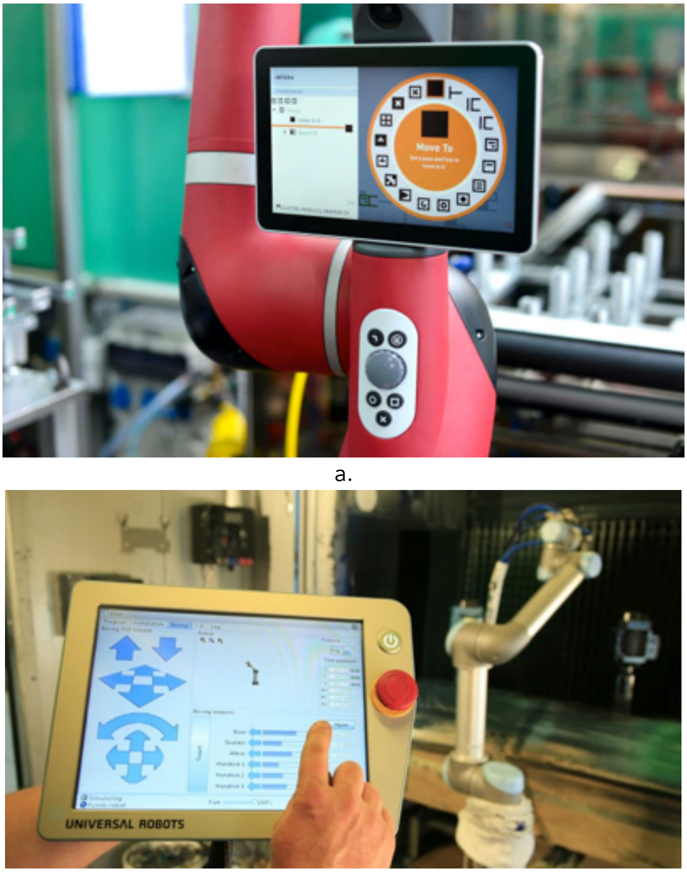
One of the latest developments in the field of industrial robots is kinematic redundancy. New industrial robots that are equipped with this feature do not require safety fences in the locations that they are introduced to due to their intrinsic safety features, consisting of high-frequency safety control systems and under-actuated joints (Siciliano and Khatib 2016). These robots are called “Collaborative Robots” or “Cobots” for short (Figure 2). First coined in 1996, the term ‘Cobot’ refers to a robot that has been specifically designed and built to collaborate with humans (Colgate et al. 1996). In recent years, many manufacturers have introduced their own versions of this new generation of industrial robot to the industrial automation marketplace. Some examples are: KUKA-LBR (KUKA 2010), Universal Robots (Ostergaard 2012), ABB Yumi (ABB 2016). Currently there are 20 manufacturers supplying the Cobot market with around 34 different models (Robotiq 2017).

Cobots are further characterised by their relatively small size and limited payload capacity, and their relatively low price. Some of these robots have been equipped with vision systems and flexible grippers that allow them to perform roles requiring simple cognitive skills. While some Cobots consist of only one articulated robot arm, some consist of two arms, such as the Rethink Robotics – Baxter (Fitzgerald and Ed 2013). These robots can be programmed by non-experienced users in a matter of minutes and are able to fulfil their role without the requirement for long testing and calibration procedures.

The founder of Rethink Robotics captures the concept of collaborative robots and the role of the human in future production systems in the following quote:

> *"… and so our vision is that Mildred who's the line worker becomes Mildred the robot trainer. She lifts her game, like the office workers of the 1980s lifted their game of what they could do. We are not giving them tools that they have to go and study for years and years in order to use. They are tools that they can just learn how to operate in a few minutes. …"* (TED Conference, 2013)

Figure 2 A Collaborative Robot in action. (Rethink Robotics, Sawyer) (Image copyright ©Rethink Robotics)



a.

b.

Figure 3 Examples of Cobot user interfaces (a) A touchscreen is an integral part of the Sawyer Cobot. This image shows a touchscreen-adapted version of the Intera user interface software that allows users to program and operate the Cobot. During operation, the screen displays two eyes, which helps to communicate the actions that the robot is performing to its human operators (Figure 2) (Image copyright ©Rethink Robotics); (b) The teaching pendant that is used to program the Cobots of Universal Robots. Using a teaching pendant is the classical way of programming industrial robots. Besides a dead-man's switch, the pictured pendant includes a joint-lock-button at the back, which when pressed, puts the Cobot in a mode in which the joints of the robot can be moved with minimal physical effort by the human operator. On the robots of Rethink Robotics, this button is located on the robot itself, on the joint that is closest to the gripper. (Image copyright ©Universal Robots)

As explained previously, Cobots are especially promising for solving issues in human-driven production systems where flexibility and re-configurability are important (Dean-Leon et al. 2018). In addition to the relatively low cost of ownership compared to traditional automated systems involving robots, the reduced threshold for programming, operation and troubleshooting make Cobots ideal for SMEs as a stepping stone into Industry 4.0 (Kolfschoten et al. 2015). The development of economically attractive, safe and easy to implement Cobots is promising to be a beneficial development for SMEs (Helms et al. 2002) (Schraft et al. 2005). The aspects that make Cobots ideal for SMEs can be summarized in the following three categories:

Simplified programming: In conventional industrial robots, the programming of movement trajectories is carried out off-line, through a teaching pendant. In contrast, one of the key aspects of Cobots is an increased emphasis on high-level programming (Figure 4) and the high utilisation of 'Learning from demonstration' (LfD) methods. This allows Cobots to be programmed by human operators to execute tasks, in a fashion that resembles how humans teach other humans to perform tasks (Argall et al. 2009). For example, most Cobots can be taught a so-called "pick & place" task using this functionality and start to perform the tending of a machine in a production process in a matter of minutes (excluding installation time). As a result, Cobots can be implemented as stand-alone devices and can be integrated rapidly into existing production systems.

Simplified operation: While the introduction of the first Cobots was motivated by the development of robots with intrinsic safety features, which enabled Cobots to work alongside humans, it also resulted in the development of simplified interfaces based on user-centred design developments. This allowed humans working in close proximity to these robots to interact with them and to monitor their status in an intuitive way (Fitzgerald and Ed 2013). Generally, each manufacturer implements their own proprietary interface on their Cobots (Figure 3a,3b). Some of these interfaces combine tactile buttons and light signals on the robot itself, such as the interface of the Sawyer Cobot (Figure 3a). These features simplify the operational requirements of implementing Cobots.

Simplified troubleshooting: In addition, while conventional robots do not allow dynamic obstacle/collision avoidance (as a standard option), and need to be manually troubleshooted in the occurrence of such events, Cobots do allow slight diversions from pre-programmed actions and can continue operation autonomously after the occurrence of unexpected events. This capability results in less downtime in case of non-happy flows/disturbances.

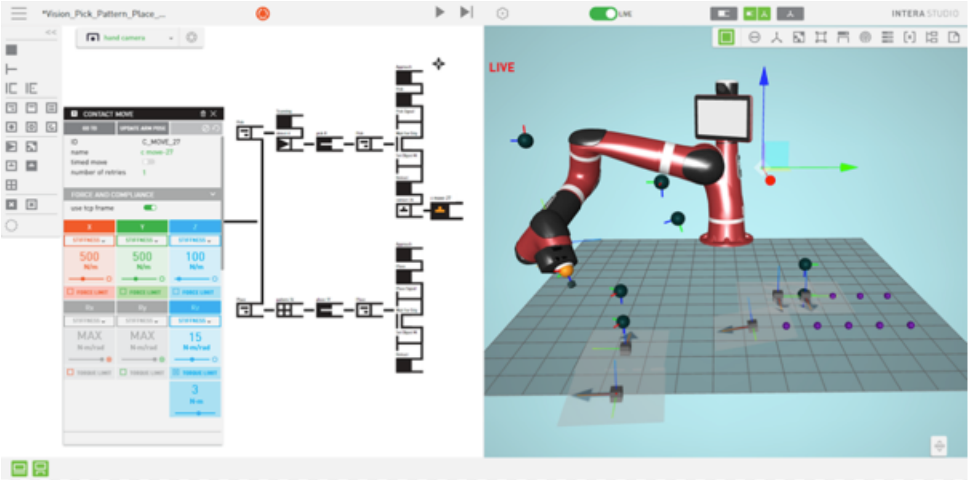


Figure 4 High-level programming of Cobots. A screenshot of the interface of Intera software installed on the Sawyer Cobot that shows an overview of the tasks that the robot is programmed to execute on the left-hand side. On the right-hand side of the screen, a virtual version of Sawyer can be seen, with the locations in space of the tasks and actions that have been programmed so far. Through this interface, all functionalities of the Cobot can be accessed, and operations can be programmed using a proprietary high-level visual programming language developed by Rethink Robotics.

In order to amplify these mentioned advantages, the industry has been taking steps in making the Cobot an attractive means of innovation for SMEs that currently make use of human-driven production systems. For example, Cobot manufacturers and integrators have started to provide trainings and webinars for their existing and potential customers (Bouchard 2017)(Universal Robots 2019)(Smart Robotics 2019). These trainings target both executive-level employees and human operators. It is predicted that this way, it will become easier for employees to install and configure Cobots as assistants for the production processes that they are involved with. This can in return lower the barrier for SMEs to purchase Cobots, but also, increase the acceptance of Cobots as valuable additions to their production processes.

However, it can be seen from recent literature that as of 2018, the design and operation of human-driven production systems involving Cobots still remains a challenge. In comparison to other Industry 4.0-related technologies, Cobots have remained mostly unexplored by the SMEs (Moeuf et al. 2018). One of the reasons for this is assumed to be the lack of knowledge on where, when and how to implement them, and what their return on investment is going to be (Morato et al. 2014). More specifically, understanding existing processes, clear task division between humans and Cobots, and visualising the movement paths and workspaces are counted as key issues that need further attention (Kadir et al. 2018).This is highlighted in the following quote from their work ;

> *"Before investing in Cobots, it is important that the company starts by visualizing the processes of the existing work system in order to gain the necessary understanding of material and workflow and to identify co-dependencies and co-relations within the work system. Having this understanding will lead to better decisions regarding role assignment, work organisation, and work division between Cobots and workers."*

Despite their advantages, Cobots remain a relatively new type of device for its intended users – the SMEs, and in contrast to what their name suggests, the current first generation of Cobots unfortunately do not directly enable/facilitate human-robot co-working (Labrecque et al. 2017) and their potential implications (as social entities) on human operators' perception of safety and their ability to monitor production processes need further exploration(Sauppé and Mutlu 2015). Therefore, most Cobots that have been implemented in production settings so far have been used as weight-compensators (i.e. to improve the ergonomic load of the operation on operators) (Cherubini et al. 2016). To conclude, the implications of Cobots in human-driven production systems need to be better understood by the designers and operators that integrate them in these systems.

1.2 Research problem

The previous section discussed the digitalization and robotization of the manufacturing domain, and the complexities that these developments introduce for their designers and the operators that work with them, especially in the context of SMEs. In the final part of this section, the new technology of Cobot was presented as a valuable asset for SMEs for increasing the physical assistance on the human operators in their production systems and thereby supporting their efforts in further automating their systems.

Considering this information in light of the design(er)-oriented focus of this research as described in section 1.1.1 and the arguments made in section 1.1.4 about the lack of focus towards the development of specific approaches targeted towards SMEs that support and facilitate the adoption of Industry 4.0 related technologies, it can be concluded that action is needed with respect to supporting the designers of these systems. In particular, support is needed with respect to the reduction of the complexity of the integration activity of new automation technologies such as Cobots in existing systems and the facilitation of the integration of these as assistive technologies that enhance the capabilities of the human operators that work with them.

1.3 Research phenomenon

Having described the context of this research and the research problem in this context, in this section the specific research phenomenon that is the focus of the research will be further elaborated.

In order to show the context around the phenomenon, an impression of the 'world' in which this phenomenon is situated is illustrated in Figure 5. One of the sub-levels of this world is the 'production system'. According to the definition of a production system as provided by (Groover 1980), this system consists of;

> *"… a collection of integrated equipment and human resources, whose function is to perform one or more processing and/or assembly operations on a starting raw material, part, or set of parts".*

As seen in Figure 5, a human-driven production system is situated in a world from which it can receive product orders, material, and energy. As an output, it provides the world with finished products. The human-driven production system is further divided into two parts; production resources and a production plan to operationalize these resources. A similar categorisation has also been used by Tsarouchi et al. in the human-robot collaborative assembly context (Tsarouchi, Matthaiakis, et al. 2017). Based on the product order, the production plan may be changed. The production resources may also need to be arranged in

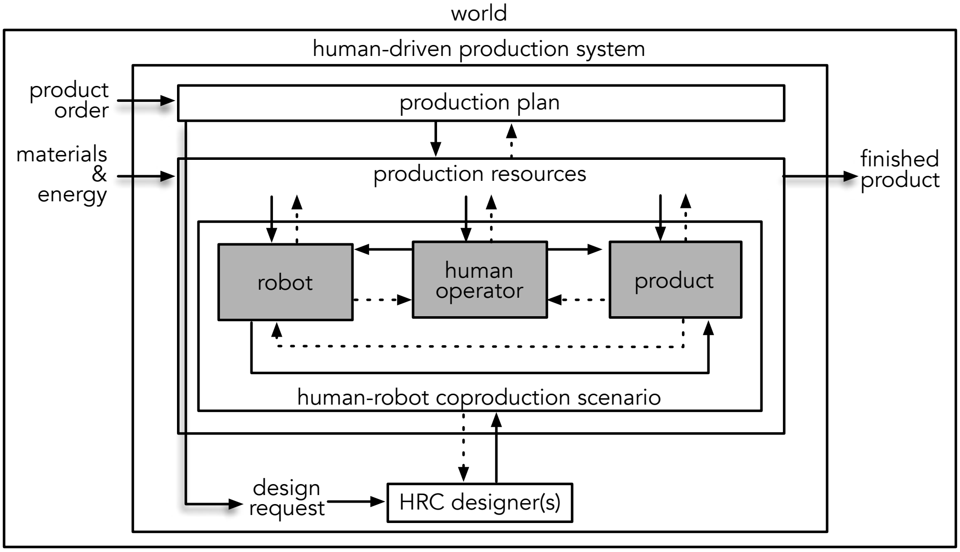


Figure 5 An overview that shows the world in which the research phenomenon and its entities (highlighted in grey) are situated.

different ways in order to execute this production plan. The entities that are part of the production resources are in relationship with each other through which, they are responsible for the production of a product.

The phenomenon that is in the focus of research concerns a designer (HRC designer) and the subject of his/her design activity (HRC scenario). This HRC design activity can be described as;

> *'The design activity of a specific section of a human-driven production system (HRC scenario), which consists of (amongst other components) at least one robot and one human operator. In this specific section, the robot and the human operator perform one or more pre-defined tasks that add value to a product.'*

As it can be seen in Figure 5, there are several entities that need to be considered by HRC designers for the design of HRC scenarios. In a human-driven production system, some of the production resources may be involved in a HRC scenario. Such a scenario consists of a human operator, a robot, and a product. In such a scenario, the human operator determines the capacity in which the robot is involved with the production plan. On this level, the production plan has been broken down into actionable tasks. The robot executes the tasks given to it, and interacts with the human operator when necessary in order to coordinate the execution of production task and support the monitoring of the status of the task. The tasks in the human-robot coproduction scenario are either directly or indirectly related to the product that is being handled.

The HRC designer(s) initiates a HRC design process upon receiving a design request from the production plan of the production system. He/she is responsible for the development of an appropriate HRC scenario based on the requirements that are specified in this request. Such a scenario can then be assessed for its viability, and if evaluated positively, be implemented in the production system.

The HRC designer an the HRC scenario can be further specified by their attributes, some of which that are considered relevant for this research are presented in Figure 6. The presented attributes are meant as illustrations of the type of attributes of each entity, and are neither exhaustive nor definitive. The presented entities of the HRC scenario, together with their attributes, are areas of consideration for the HRC designers during the HRC design activity. On the other hand, the attributes of the HRC designers are of influence during the iterative HRC design process and its outcomes.

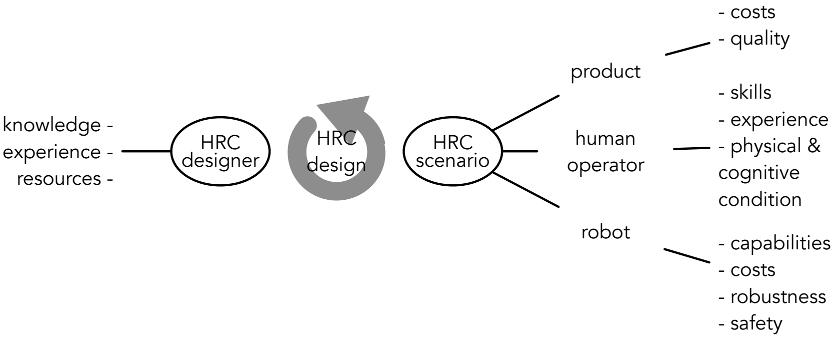


Figure 6 An overview of the attributes of the entities being studied.

In this research, the focus is on the relationships between the knowledge and experience attributes of HRC designers and the effect of these attributes on the ability of the designers for understanding and working with the attributes of the HRC scenario. More specifically, considering the research problem, the abilities of novice HRC designers with limited experience, knowledge and resources have been studied.

1.4 Research objective

The field around HRC has been (and still is) in rapid development, and new technologies, software, tools and methods are being introduced frequently (Kolbeinsson et al. 2018). In addition, the context of SMEs is highly diversified and specialized (Westkamper 2013). Therefore, a one-size-fits-all solution should not be targeted. SMEs should be enabled to develop and modify the methods that they use according to their own context and needs.

On the other hand, the transformation in the industry towards 'plug & work' devices such as Cobots is reducing the need for time and resource-intensive development processes (Onori et al. 2012). Also, as discussed in section 1.2, SMEs are in need of knowledge to support themselves during the justification of investments that they are considering to make, which requires more emphasis on the conceptual design of systems. Therefore, by also considering the knowledge, experience, and resources of the designers (as presented in Figure 6) in this context, the objective of this research is defined as;

> 'To develop an adaptable framework methodology that can be used by novice HRC designers during the conceptual design activities that involve human-robot coproduction scenarios.'

1.5 Research design

In this section, the research design is presented that guided the individual research activities that were undertaken during this research project. The aim of the research design is to organize the research activities in such a way that the objective of the research project can be achieved during the time and using the resources that were allocated for the project. In addition, to guide the research towards the research objective, four research questions were formulated, which were operationalized through four research cycles. Also, two assumptions were made at the beginning of the research by which the research topic was further constrained. These assumptions are presented next, followed by the resources that were available for executing the project. In the final part, the research questions and an overview of the research cycles are presented.

1.5.1 Assumptions

At the beginning of this research, two assumptions were made in order to further define and constrain the scope. The first of this assumptions is related to the type of robot that is in the focus of this research. The second assumption concerns the type of designers that are being focused on. These assumptions are presented next.

Assumption 1: Cobots as robots

When describing the phenomenon that has been studied, the entities of the HRC scenario have been described as the human operator, the robot and the product. However, the term ‘robot’ refers to a large number of devices that can be considered for realizing a HRC scenario. In order to constrain this, the Cobot was chosen as the type of robot and assumed to be the focus throughout this research.

Assumption 2: Expert and novice HRC designers

In the manufacturing industry, automation integration (also called system integration) is the name given to the multi-disciplinary engineering activity of integrating robots (and other automation equipment) into production systems (Siciliano and Khatib 2016). In this research, the engineers that currently execute automation integration will be assumed to be ‘expert HRC designers’. On the other hand, the employees of SMEs that do not have prior experience in integrating robots will be regarded as potential users of the methodology to be developed. These employees are expected to have a technical background, and some knowledge of the context in which they work, however, are expected to lack knowledge and experience about the technical complexities of the automation integration activity. Therefore, in this research, it is assumed that engineering students and recent graduates can be regarded as representatives of ‘novice’ HRC designers.

1.5.2 Resources

In addition to the assumptions that were made, two resources provided substantial ground for the studies that were performed in this PhD project. These are as follows;

Laboratory environment with Cobots and peripheral equipment

For executing some of the empirical parts of the planned research, a laboratory environment was allocated in which two Cobots were present. These were the single-arm Universal Robots – UR5 and the double-arm Rethink robotics – Baxter ("Research" firmware installed). Towards the end of the project, Visual Components software was acquired. In addition, there was access to several types of 3D printers, a laser cutter, various pneumatic actuators/light-gates/vacuum grippers, two non-motorized conveyors, and a CCTV system containing four cameras.

The 'Factory in a day' project

The research that led to this dissertation was supported by the 'Factory in a day' (FiaD) project inside the European Union's FP7 framework programme (Factory in a day 2014). The project consisted of industrial and academic partners located in different countries in Europe. The main objective of the European Union that the FiaD project supported was related to improving the competitiveness of European SMEs through supporting the design of production systems that involve industrial robots.

The specific goal of the project was to remove some of the obstacles for integrating Collaborative Robots (Cobots) in production processes of SMEs. Some of these obstacles are (amongst others): (i) development time, (ii) installation costs and (iii) sub-optimal collaboration possibilities between humans and robots. Figure 7 summarizes the vision/future scenario that guided various research and development activities during the project. This vision stipulates that it should become possible to design and install Cobots at a given location within 24 hours, compared to the usual timeframe of several weeks or months.

The research project presented in this thesis used the resources from the FiaD project mainly as input for empirical studies. In return, this research contributed to several deliverables of the project, as some of the research questions of the project could be answered by input from this research.

1.5.3 Research questions

Considering the assumptions and the resources that were defined for this research, to guide the research towards its objective, four research questions about HRC were formulated. These are;

RQ1- What are the key theories and principles in the bodies of knowledge that underpin HRC design?

RQ2 - What bottlenecks are there for expert designers during HRC design?

RQ3 - What bottlenecks are there for novice designers during HRC design?

RQ4 – How can novice HRC designers be supported during their design activity?

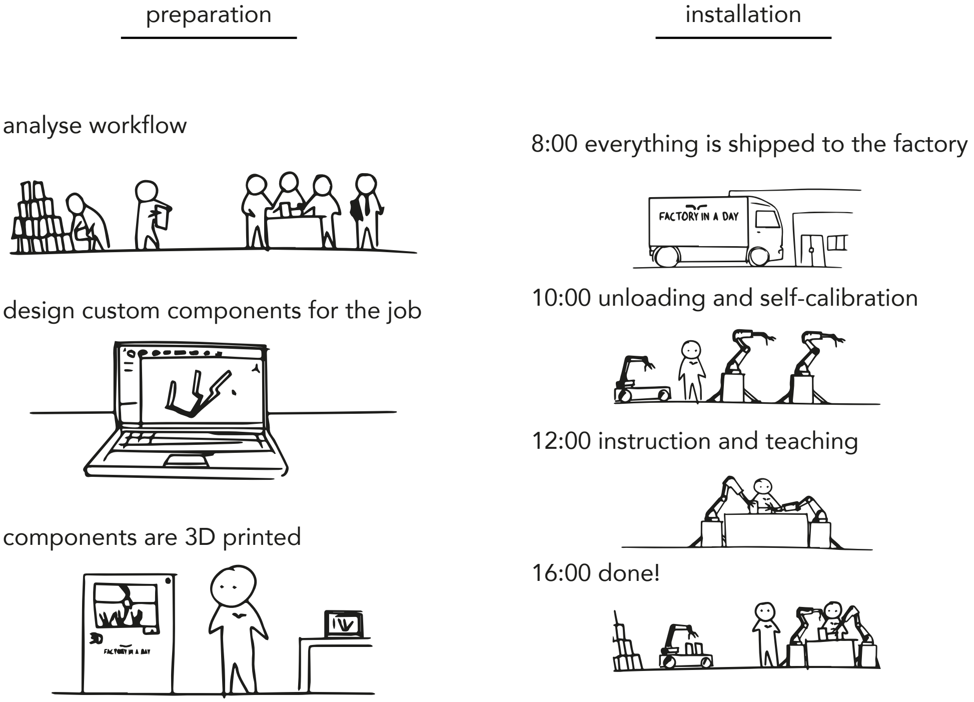


Figure 7 The envisioned “Factory in a day” process steps. (Image courtesy of www.factory-in-a-day.eu)

1.5.4 Research cycles

This research project has been divided into four Research Cycles (RC) each of which can be framed according to the three types of design research as described by Horváth (2013). Research Cycles 1 and 2 are best framed as 'Research in design Context' (RiDC), and target the exploration of the HRC design context. Research Cycle 3 is framed as 'Design Inclusive Research' (DIR), as it involves the development of rough and abstract prototypes for a methodology. The final cycle, Research Cycle 4, is framed as Operational Design Research (ODR), as it involves the exploration of the applicability of the developed methodology in its intended context. The research questions were allocated to three of the RCs (Figure 8). RC1 and RC2 were executed in parallel (mainly during the first two years of this research) and RC3 and RC4 were executed sequentially (during the final two years of the research).

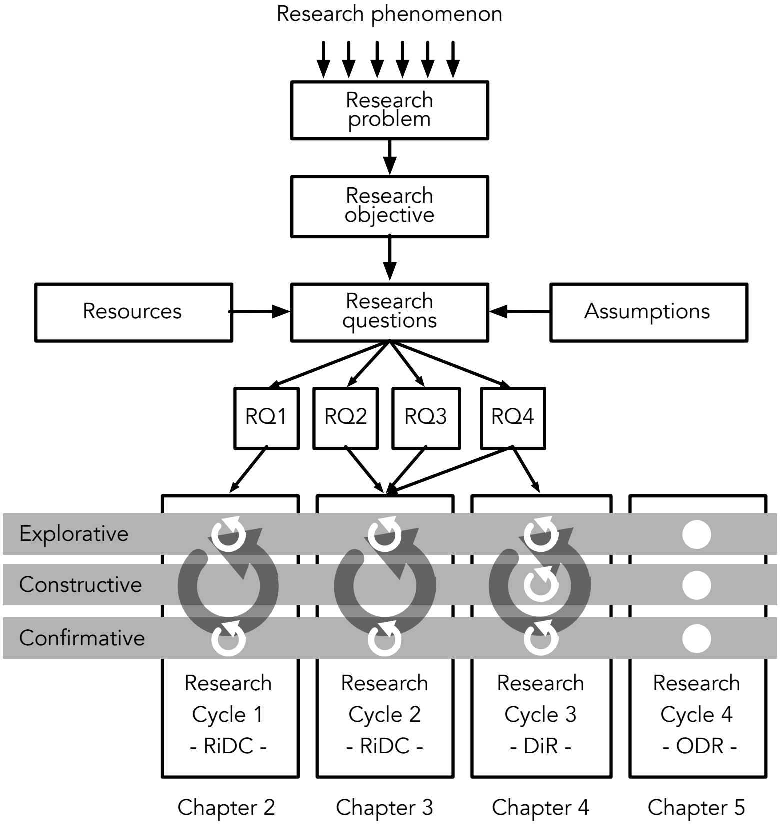


Figure 8 An overview of the research cycles of this research. RQ = Research Question

1.6 Thesis outline

Chapter 1 has presented the overall research domain, the research problem, the phenomena that are being investigated, the objectives of this research, and the research design that was operationalized to achieve these objectives.

In Chapter 2, the process of framing/underpinning HRC design based on three perspectives is presented (Research Cycle 1). A review of literature is presented by which the domains of knowledge and the three perspectives that have been assumed to contribute to HRC design are further elaborated. The chapter is therefore divided into three sections. In each of the sections a separate perspective is discussed and conclusions are drawn with respect to HRC design.

Chapter 3 presents the empirical studies that were performed during this research (Research Cycle 2). These studies are presented in two sections. The first section presents a real-life HRC design activity that was performed by expert designers from a variety of disciplines. This activity has been analysed to learn from it and understand the bottlenecks that are currently being faced. In the second part of this chapter, three HRC design activities are presented that were performed in a laboratory environment by novice HRC designers. This chapter is finalised by an overview of the influential factors for HRC design, and the definition of a set of requirements for a methodology for HRC design.

In Chapter 4, the human-robot coproduction design methodology (HRCDM) is presented, which has been realised as an adaptable framework methodology for the conceptual design of HRC scenarios (Research Cycle 3). The developed methodology is described by presenting details of its main procedures, the four novel instruments that have been developed and the methods.

Chapter 5 presents the applicability validation of HRCDM (Research Cycle 4). In this chapter, the application process of HRCDM by novice HRC designers during a realistic HRC design case is discussed in detail. Based on this discussion, by applying the Validation Square method, an argument is made on the applicability of the developed methodology for other cases.

Finally, Chapter 6 summarises the contributions of this research project and provides recommendations for applying and extending the developed methodology.

Chapter 2

Related publication

Cencen, A., Verlinden, J.C., & Geraedts, J. M. P. (2015). Characterizing the State of the Art of Human-Robot Coproduction. Social Robotics: 7th International Conference (ICSR), Paris, France, October 26-30, 2015, Lecture Notes in Artificial Intelligence: Vol. 9388, p. 135. Springer

2 Framing human-robot coproduction

This chapter presents the results of the research activities of RC1. In RC1, the following research question was addressed;

RQ1 - What are the key theories and principles in the bodies of knowledge that underpin HRC design?

To find answers for this question, a literature review was performed that covered multiple domains of knowledge. The findings are presented in four sub-sections.

In section 2.2, a closer look is taken towards the work between actors of HRC scenarios, and the relationships between them. This is presented based on an analysis of eight examples of experimental HRC setups. These examples have helped to explore the current perspectives and topics in academia on the application of HRC.

In sections 2.3, 2.4 and 2.5 the most prominent theories in the domains that contribute to HRC are explained and the aspects that are relevant for HRC designers are identified. The findings are presented in three categories that represent the three perspectives from which HRC is viewed in this research, namely; (i) Industrial automation, (ii) Human-robot work, and (iii) Design.

The chapter is finalized by a review of the findings from all four sections, and a model to be used as the blueprint for the adaptable framework methodology for HRC design is proposed.

2.1 Introduction

Similar to other areas of engineering that target the development of complex products and systems such as Mechatronics (Bolton 2008), for designing successful production systems in the age of cyber-physical production systems (CPPS), bridges of knowledge need to be built between multiple disciplines (Gerhard 2017). This way, the complexity of problems in these new disciplines can be approached and analysed from the collective perspective of more established disciplines and their know-how.

In order to underpin the research phenomenon of this research in existing knowledge, three perspectives were defined. Throughout this research these perspectives have been regarded as a means for constraining the bodies of knowledge that contribute to the discipline of HRC design and have been used to categorize the investigated literature as such. Figure 9 presents these three perspectives. Next, these perspectives and the contributing bodies of knowledge to these perspectives will be elaborated.

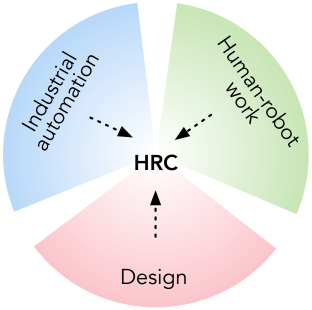


Figure 9 The three perspectives from which HRC has been addressed in this research.

'Industrial automation' refers to the perspective on HRC design from the bodies of knowledge related to the design, commissioning, operation, maintenance and optimisation of systems and their parts that are used to automate production systems. This perspective contains knowledge from domains such as: Information and Communication Technology (ICT), Cyber-physical systems (CPS).

'Human-robot work' refers to the perspective on HRC design from the bodies of knowledge related to the theories and principles that are used to describe various aspects of the interactions between humans and artificial entities (computers, machines, robots) that are required to work in the same physical/digital space. This perspective contains knowledge from domains such as: Human-computer interaction (HCI), Human-machine interaction (HMI), Human-robot interaction (HRI), Human Factors (HF), Computer supported cooperative work (CSCW), and Social Robotics.

'Design' refers to the perspective on HRC design from the bodies of knowledge related to the theories and principles that are used to develop various types of (computer-based) systems and products. This perspective contains knowledge from domains such as: Operations and Production Management, Computer Integrated Manufacturing (CIM), Software engineering, and Product design.

Together, these three perspectives aim to cover the "human-centred', 'technical' and 'societal' perspectives that are the main pillars of the design discipline as practiced at IDE (see section 1.1), and therefore are the three perspectives from which this research considers the context of HRC design.

2.2 Examples of experimental HRC scenarios

As discussed in section 1.1.5, with the introduction of Cobots and other IA equipment such as tactile and optical devices to ensure the safety around industrial robots (For example: Pilz - Safety sensors PSEN, 2018), the safety standards involved with the design of systems involving industrial robots has been changing rapidly in recent years (ISO/TC 299-Robotics 2016). Through the converging of similar developments, physical human-robot interaction (pHRI) in production environments is starting to become a reality (Siciliano and Khatib 2016). However, at the moment of starting this research, commercial Cobots and new-generation safety-enabling IA equipment were only recently introduced, and real-life examples of pHRI were scarce. Therefore, in this section, eight examples of HRC are presented which feature experimental setups built by researchers working in various fields and topics of robotics.

Even though the presented examples may not necessarily be developed to study human-robot coproduction specifically, they were selected as subjects of study in this research based on their inclusion of one or more aspects of a production context, such as handling parts of a product assembly, making direct alterations on a product part. The presented collection of examples were discussed in Cencen et al. (2015). In order to analyse various aspects of these scenarios that are relevant for this research, three guiding questions were formulated. These are as follows;

Tasks: What kind of production tasks currently involve HRC scenarios?

Arrangement of actors: How are humans and robots positioned with respect to each other in HRC scenarios?

Interaction: How do humans and robots interact with each other in HRC scenarios?

2.2.1.1 Example A: Robot assisted table assembly

The researchers that built the HRC setup in this example have developed an experimental setup using a Cobot in order to test a kinaesthetic learning algorithm(Rozo et al. 2013) (Figure 10).

Task: The purpose of the Cobot in the setup is to support the manual assembly of a small side-table. A human assembles the legs of the table one by one while a robot holds the top piece of the table, oriented in such a way that is comfortable for the human. Before the assembly operation, the human demonstrates the portion of the workflow related to the role of the robot by using the kinaesthetic learning function of the robot. The robot records haptic data and movement patterns during this demonstration, using a motion capture system with passive retro reflective markers attached to the

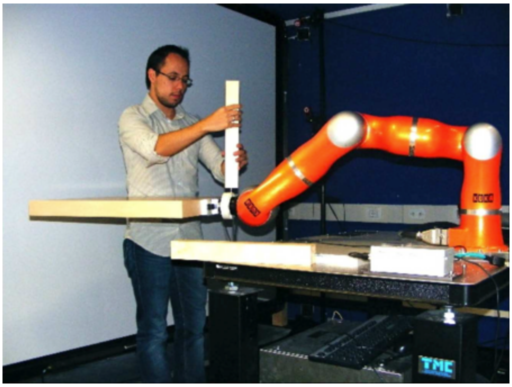


Figure 10 HRC example developed by Rozo et al.

table parts and a six-axis force-torque sensor attached between the wrist of the robot and the table.

Arrangement of actors: There is one human and one robot in the scenario. The human and the robot share the same workspace.

Interaction: During execution of the task, the human communicates with the robot through the exertion of torque or displacement forces that arise during the assembly actions of the parts of the product that he/she is handling.

This example has demonstrated a production-like task in which the robot arm fulfils a physical support role by lifting and repositioning the assembly, while human dexterity and perception coupling (as described by Gibson, (2014) are used to perform the high-precision aspects of the task. It also demonstrates the use of a Cobot in a HRC scenario, and shows that without any additional safety equipment, a human and a robot can execute tasks in the same workspace.

2.2.1.2 Example B: Robot assisted welding

The HRC scenario in this example consists of a robot welding assistant that holds and repositions parts that are being welded together by a human welder (Laine et al. 2007) (Figure 11).

Task: The robot picks and holds the first piece of the assembly in position that is comfortable for the task of the welder. The welder then locates and welds the remaining pieces onto the piece held by the robot, one by one, while the robot changes the orientation of the piece it is holding to allow the human to execute the welding task as effectively and ergonomically as possible. The portion of the workflow related to the task of the robot is pre-programmed before the execution of the task.

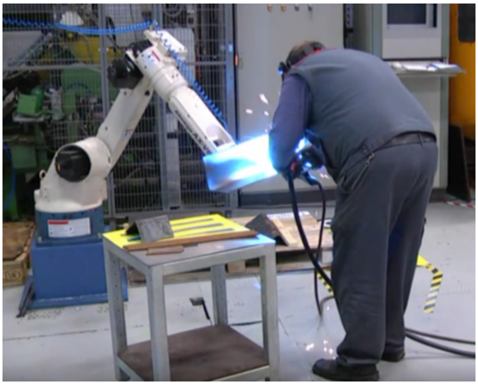


Figure 11 HRC example developed by Laine et al.

Arrangement of actors: There is one human and one robot in the scenario. The human and the robot share the same workspace.

Interaction: The human communicates with the robot by using gestures that can be tracked through a camera that is connected to the control system of the robot.

This example has shown that HRC can be beneficial in situations which humans perform tasks that require high dexterity and therefore can be supported by positioning the work pieces in ideal locations and orientations in each step of the task. It also shows such a HRC setup can be operated through simple hand gestures that can be tracked by a dedicated camera.

2.2.1.3 Example C: Robot assisted hand-over of products

This example involves a series of HRC experiments in a laboratory setting during which the authors aim to investigate human–human hand-over of objects in order to be able to design better robot algorithms for the robot-human handover of objects (Glasauer et al. 2010) (Figure 12).

Task: In the hand-over task, two types of actors are distinguished, namely; a "foreman" and an "assistant". The assistant needs to deliver the parts just in time for the foreman to assemble the parts. The robot has the role of picking of cubes from a table and handing them to a human. The human has the role of receiving the cubes from the robot and using them to build a tower. The workflow is pre-programmed into the robot and communicated to the human before execution of the task.

Arrangement of actors: There is one human and one robot in the scenario. The human and the robot share the same workspace.

Figure 12 HRC example developed by Glasauer et al.

Interaction: The human communicates with the robot through hand motions that can be tracked and interpreted through a camera attached to the robot. This way, the robot is able to monitor the assembly movements of the human and predict the finishing time of the assembly of the current part, so that it can give the following part just at the right moment.

This example has shown that the timing of interactions is an important and crucial aspect, which determines the efficiency, safety and acceptance of robotic systems. The authors show that even though both actors are completely informed and aware of the task, the hand-over was still a dynamic action that is optimized over several repetitions. In addition, the hand-over position and movement profile are described as crucial factors for the efficiency of the hand-over task.

2.2.1.4 Example D: Tele-operated robotic grasping of products

In this example, a HRC setup was used to investigate the performance of a pick & place task when a robot manipulator is tele-operated by a human operator (Bringes et al. 2013) (Figure 13). The authors predicted that a human-in-the-loop would be beneficial to the performance of the system, especially when there is some form of (signal-) noise in the perception/cognition of the robot. The authors test five strategies for studying the influence of a human-in-the-loop during various stages of the pick & place task.

Task: The HRC task in all tested scenarios was the picking of fruit/vegetables from random locations on a table and placing them inside a container. The robot manipulator was equipped with a gripper capable of providing a steady grasp of all the objects that needed to be picked. The human decided on the workflow during operation. The human had the role of targeting each object and communicating their location to the ro-

Figure 13 HRC example developed by Bringes et al.

bot, which was done with a haptic pen device. The system performed best when there was no noise and no human-in-the-loop. However, in the case of the presence of noise, the assistance of a human worker for controlling the coarse approach of the robot towards the objects in the stage resulted in better performance.

Arrangement of actors: There is one human and one robot in the scenario. The human and the robot share the same workspace. Even though the scenario is conceptualised as tele-operation, the human has direct vision on the actions of the robot (but no physical interaction).

Interaction: The human interacts with the robot through a so-called "OMNI haptic device". The force-feedback function was not enabled. The OMNI device allows the human to move the robot arm in an intuitive way. The movements of the OMNI device are translated to input for the movement of the robot and the gripper.

The authors conclude that having a human-in-the-loop is always more beneficial for the performance of the robot than having the robot automatically perform the task. They also suggest that the best phase in the pick & place task to have a human-in-the-loop is the "approach to goal" phase. This example has shown that humans can have assistive roles at various phases of an automated task that are challenging to completely automate without leaving any chances for failure.

2.2.1.5 Example E: Robotic delivery of product parts and assembly instructions

This example revolves around the assembly process of a "LEGO" toy by making use of a HRC scenario (Unhelkar et al. 2014) (Figure 14).

Task: In this example, a robot (ROBOT) and a human operator (HUMAN1) are given the task of delivering the components needed for the assembly of a LEGO toy to another

Figure 14 HRC example developed by Unhelkar et al.

> human operator (HUMAN2), who has the task of assembling the toy using the components and instructions delivered by the human–robot team.
>
> **Arrangement of actors:** The HRC scenario is divided between two separate locations. There are two humans and one robot in the scenario. The robot acts as a transporter and messenger between the two humans.
>
> **Interaction:** The workflow is pre-programmed into the robot and is instructed to HUMAN1. The workflow is communicated through instruction cards to HUMAN2 during the delivery of each new part of the final LEGO assembly. HUMAN2 communicates with the HUMAN1 and the ROBOT by picking up the product parts that are delivered to him/her.

The authors indicate that the performance of the HRC scenario is inferior to when there are only humans involved in all roles of the scenario. In addition, they also make two other observations relating to the perceived value of the robot assistant with respect to a human assistant, namely; (i) that the human assistant's time is valued more than that of the robot, and (ii) personal objectives and comfort take a higher priority during collaboration with the robotic assistant. This example has shown that when a robot is used instead of a human for a task in an assembly process that requires relatively simple skills compared to skills needed for the other tasks in the process, it results in a decrease in the performance of the overall quality of the scenario. It also shows that social issues (acceptance) play a role in the HRC context.

2.2.1.6 Example F: Gesture based operation of pick&place robot

In this HRC example, a robot has the role of picking products from one location and placing them in a stack in another location (Pieskä et al. 2012) (Figure 15).

Figure 15 HRC example developed by Pieskä et al.

Task: The human worker has the role of directing the robot to the location of the product to be picked and where it should be placed. The standard workflow is pre-programmed into the robot, and instructed to the human.

Arrangement of actors: There is one human and one robot in the scenario. The human and the robot share the same workspace. However, the human is located at a distance from the robot, and has no physical interaction with the robot.

Interaction: The worker communicated with the robot using gestures that could be tracked through a camera attached to the robot. The authors claim that through similar interfaces, inexperienced users will be able to program and control robots by making use of gestures.

Similar to Example B, this example has shown that an industrial robot can be operated using hand gestures. The difference in this example is that the task initiative is given to the human instead of the robot. The human is able to show the robot which direction to move to, instead of just indicating that a next action in a pre-defined sequence should be indicated.

2.2.1.7 Example G: Robot-assisted assembly of heavy product parts

This example focuses on a HRC scenario in which a previously manual task that requires a human operator to handle heavy parts for an assembly, have been re-arrangement in new way in which most of the manual tasks are allocated to a robot. The human has the role of guiding the robot in parts of the task where high manual dexterity is required. (Schraft et al. 2005) (Figure 16).

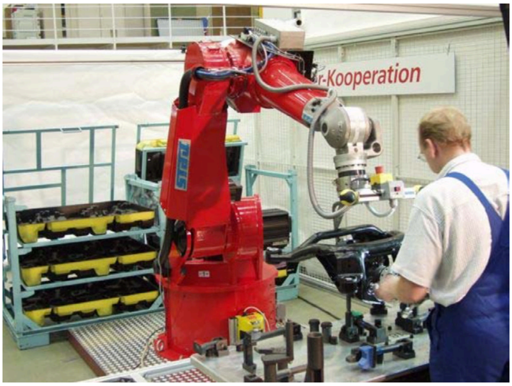


Figure 16 HRC example developed by Schraft et al.

Task: The role of the human is to manipulate the orientation of the part being held by the robot, and insert this into a so-called jig. This task requires several actions that are difficult to perform by the specific robot used in this example, but are easy for the human operator. The workflow is pre-programmed into the robot. The human operator is called for action by the robot when his/her task needs to be executed.

Arrangement of actors: There is one human and one robot in the scenario. The human and the robot share the same workspace.

Interaction: The human can communicate with the robot through kinaesthetic feedback and by pressing buttons.

This example has shown how a regular (non-Cobot) industrial robot has been used for a HRC scenario with the help of additional safety devices. It has also shown how parts of a task that require different skills can be arranged in an efficient workflow in which the human is only needed for a small portion of the tasks that need to be executed.

2.2.1.8 Example H: Human-robot teamwork with semi-autonomous robots

This example shows a HRC scenario that is part of an Extravehicular Activity (EVA) in the context of space exploration. (Fong et al. 2007) (Figure 17). Even though this example is the farthest example to the 'production context' that was referred to at the beginning of this section, it demonstrates how a team of two robots and two humans can perform tasks in a pre-determined workflow in a constrained and safety- critical environment.

Task: A team of robots and astronauts are required to perform a construction task on the lunar surface. The tasks include placing, welding and the inspection of panels. While ROBOT1 has the role of welding, ROBOT2 has the role of quality inspection of the weld

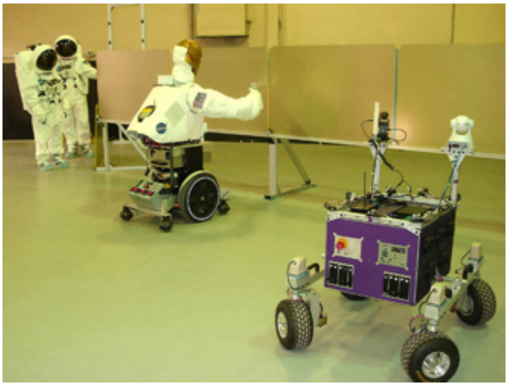


Figure 17 HRC example developed by Fong et al.

being produced. The two human astronauts have various roles within the workflow, ranging from relocating robots to checking the quality of their tasks. A computer based task manager (TM) keeps track of the completion of the tasks.

Arrangement of actors: There are two robots and three humans in this HRC scenario. Two robots and two astronauts share a workspace. The robots can also be teleoperated by the third astronaut when necessary.

Interaction: The astronauts interact with the robots through a speech interface. The robots can initiate interaction with astronauts when they need feedback after performing an action.

The authors indicate that the speech interface is not ideal for communicating with the robots, as errors are quite frequent. In addition, the Task Manager (TM) that monitors the EVA is currently not able to track the details of the tasks performed by humans. It can only interpret whether the task is finished or not. It is indicated that the performance of the task could be improved if more details about the progress of the astronaut's tasks can be communicated to the TM. Finally, the authors mention that the means for astronauts for monitoring the status of the robots during the EVA should be improved, for example by providing another type of interface. This example has also shown some of the issues related to modes of interaction and their design for multi-agent human-robot teams.

2.2.1.9 Discussion

The collection of the examples presented in this review showcase a mix of systems containing HRC scenarios in which humans and robots work together in various capacities and forms to execute simple and complicated production and assembly tasks. In addition, these examples show different possible contexts and modes of interaction between humans and

Table 1 Overview of the analysed aspects in the examples

Example:	A	B	C	D	E	F	G	H
Task Initiative	H&R	R	R	H	R	H	R	H&R
Workplace sharing	•	•	•		•		•	•
Task sharing	•	•	•	•		•	•	
H: Human, R: Robot "•" indicates if a specific type of shared work is present in the example								

robots in these scenarios. With the help of this review, it became clear that systems involving HRC as envisioned in this research project and research towards the design of such systems are still in their infancy.

The examples were initially analysed based on their inclusion of workplace sharing (WS) and task sharing (TS) as defined by Krüger and colleagues (Krüger et al. 2009). The aspect of task initiative (TI) was added to this categorisation for this review in order to be able to see which of the actors has an active/passive role. An overview of the aspects that each of the eight examples contain according to this categorisation is presented in Table 1. Although a limited set of eight examples was analysed, it was notable that dynamic sharing of roles/responsibilities were not integral parts of these systems. However, it was observed that the simultaneous handling of products by both actors is being studied. The examples suggest a preference towards deploying robots in assistive roles to human.

It was also observed that different modalities were used as means of interaction in the presented examples such as; Motion tracking, gestures, voice commands, and haptic technology. This shows that the choice of the human-robot interface in a HRC scenario will depend on the requirements of the context, the task and the human operators.

2.3 Framing HRC from the 'Industrial automation' perspective

In the second half of the 20th century, as production systems started to become increasingly more automated and computerized, the design and management of these systems started to be an important area of focus for research and development in the industry and academia. The domain of knowledge that these activities contribute to is often referred to as Industrial automation (IA). However, IA does not only concern systems in the manufacturing domain, but also the automation of all kinds of electromechanical systems such as transportation and infrastructure systems. In this research, the focus has been on systems used in the manufacturing domain.

Manufacturing currently accounts for 15% of the world's gross domestic product (World Bank 2018). Over the last century, the manufacturing industry has undergone several transformations through which the used systems have become exponentially more productive through the application of automation, but at the same time they have also become exponentially more complex. Therefore, next to the challenges of the further development of the technologies used for automating such systems, the implications of the growing complexity on the design process of such systems has been brought up as one of the challenges that will need more attention by the industry and academia. In this section, these topics will be elaborated further.

2.3.1 ICT for industrial automation

It has been explained in section 1.1.2 that the manufacturing industry has experienced a digital transformation in the past decennia. As the equipment used for production became increasingly more computerized, it also became important to ensure a correct integration of the used technologies, to transfer information between various parts of the systems in a timely and robust manner and to monitor their activities.

Information and communication technology (ICT) is the collection of systems and devices that are used to send, receive, manipulate and store digital information. ICT systems can vary greatly in scale and complexity, and may involve up to thousands of stakeholders. Therefore, in the domain of ICT, the use of a reference 'architecture' for the integration of the elements of systems that are being developed is essential (Aerts et al. 2004).

Similar to the application of ICT in other domains, a domain-specific architecture for the integration of the different types of devices and control systems has been developed for IA as well. Currently, the most commonly referenced architecture for the IA systems consists of five layers, often referred to as the 'automation pyramid' (Sauter 2010) (Figure 18). The layers of 'the automation pyramid' are (from top to bottom): enterprise resource planning (ERP); manufacturing execution system (MES); supervisory control and data acquisition (SCADA); programmable logic controller (PLC); and the 'field level'.

At the management level, a companie's integrated management system is used, also known as 'enterprise resource planning' (ERP). ERP can be seen as a suite of applications that combines information from all underlying layers in the automation pyramid. It allows managers to monitor data from all levels of their business, including the production process (es).

At the planning level, 'manufacturing execution systems' (MES) applications enable the monitoring of the entire production process from raw materials to the end product. This allows the system owner(s) to monitor the current status of production and to make decisions in order to adjust the planning when necessary.

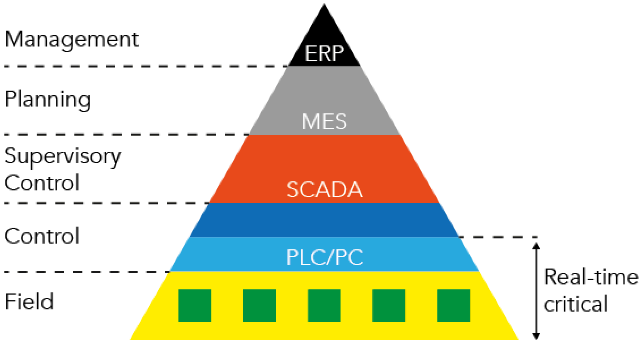


Figure 18 Automation architecture (Automation pyramid) based on five layers of control systems. Green: Field level devices (i.e. sensors, actuators etc.)

The supervisory level utilizes 'supervisory control and data acquisition' (SCADA) systems. These systems provide a combination of the data from the control and field layers, and generally provides a 'graphical user interface' (GUI), or 'human-machine Interface' (HMI) to monitor operations remotely. It allows the control and monitoring of multiple systems from a single location.

At the control level, PC's and 'programmable logic controllers' (PLC) are used to control and drive the devices on the field level that do the actual work. They take information from the sensors and other information devices on the field level to make decisions on what output to produce to complete the programmed task.

The field level consists of those devices, actuators, and sensors that are used on the production floor, that do the actual physical work and the collection of the inputs from the environment.

In the context of production systems, the human operator is one of the main resources of the system (Groover 2007a). The human operators in systems involving IA have various roles at all levels of the automation pyramid. However, they are often seen as boundary objects, instead of integral parts of the system (Bainbridge 1983). This is also visible in the exclusion of the human from the automation pyramid. This issue of technology-orientation and the lack of attention to the integration of the human operators in IA systems need to be taken into account when considering new methods for human-driven production systems.

One of the latest developments in the field of IA systems and robotics is the open-source 'ROS-Industrial' platform, which is based on the successful Robot Operating System (ROS) (Edwards and Lewis 2012). ROS has originally been developed for building robots for research purposes and acts as middleware between sensors, actuators and logical reasoning elements of a robot, enabling communication between these elements in a robust and clear way (Quigley et al. 2009). ROS-Industrial extends the flexibility and capabilities of the original ROS environment to the manufacturing context and thereby presents SMEs with an accessible solution to develop custom solutions for the their own systems in which novel ways of interaction with human operators can be implemented that are currently not possible with traditional IA technologies. However, the safety and robustness aspects of such custom-built systems can present additional challenges.

2.3.2 Cyber-physical systems

In the manufacturing domain, until recently, the main focus and driver of applying IA was to increase product quality and throughput. As previously discussed in section 1.1.2, in the past decades, it became increasingly more important to be able to produce a variety of products in varying quantities using the same production system and the flexibility of production systems became a high priority for some enterprises. As a result, system owners started to look for ways of increasing the flexibility of their production systems using viable mixes of the available resources and emerging technologies. In parallel to this transformation, the criticality of the role of human operators in ensuring the flexibility of production systems has started to receive attention. (ElMaraghy et al. 2009) (Zuehlke 2010). However, as it was discussed in 2.3.1, at the field level of the automation pyramid, until now, relatively less attention has been paid towards the integration of the human operators in automated production systems.

One of the main developments in the field of IA has been the transformation of IA systems towards cyber-physical systems (CPS) (Wang, Törngren, and Onori, 2015), which is also the main underlying principle of Industry 4.0 as discussed in Chapter 1. CPSs utilize cyber and physical technologies with the aid of synergic technologies that bring these two technologies together in order to connect the human domain with the socio-techno-economic environment (Figure 19). *"The objectives of the discipline of CPSs are: (i) blending the knowledge of multiple domains into a consistent body of knowledge so as to underpin it by the basic principles of natural, formal, technical, social and human sciences, and (ii) developing a system-level understanding and conceptual frameworks of this family of systems."* (Horváth and Gerritsen 2012).

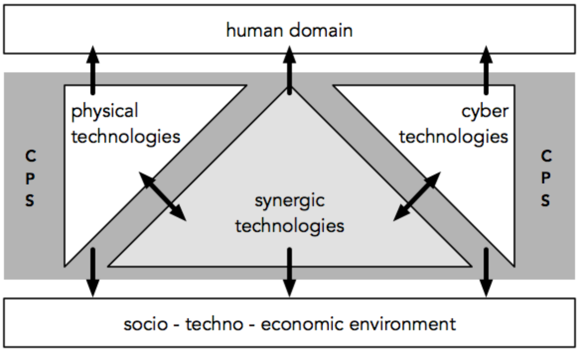


Figure 19 Architectural model of CPS *from* (Horváth and Gerritsen 2012).

2.3.3 Cyber-physical production systems

In the context of manufacturing, production systems involving CPS are named cyber-physical production systems (CPPS) (Monostori, 2014). In this new approach, entities at all levels of the production system are connected with each other by dynamic mesh networks in the Cloud (Monostori et al. 2016) (Figure 20). This allows all entities of the systems to connect and communicate with each other via Internet of Things (IoT), allows to create virtual copies of the real world (Digital-twin) and provide these models with real-time data, allows the systems to support human operators by aggregating information and helping to make informed decisions in order to prevent problems, and finally, it gives the systems the ability to make more autonomous decisions based on the information that is available and learned patterns of action.

This research focuses on the field level of industrial production systems (as defined within the automation pyramid, Figure 18), and on one of the main entities of this domain—the human operator. Human operators are key enablers and controllers in human-driven production systems, especially in the context of SMEs. Considering all of the new capabilities introduced by CPPS, Romero et al. propose the "Operator 4.0" as a new philosophy for looking at the human operator in the CPS. Operator 4.0 is described as; *"a smart and skilled operator who performs work aided by machines if and as needed. It represents a new design and engineering philosophy for adaptive production systems where the focus is on treating automation as a further enhancement of the human's physical, sensorial and cognitive capabilities by means of human cyber-physical system integration"* (Romero et al. 2016). This and similar approaches are more suited for the human-driven systems of SMEs. However, these approaches are fairly new and have not been applied and validated in the real-life context yet.

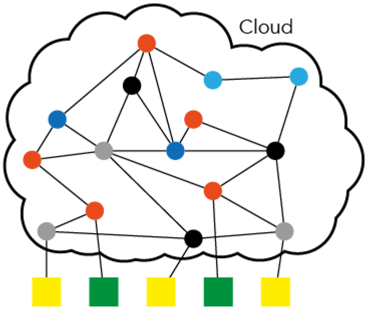


Figure 20 Distribution of the layers of the Industrial Automation pyramid in a CPS-based architecture. (Inside the Cloud: Black: ERP, Grey: MES, Orange: SCADA, Blue: PLC/PC; (Outside the Cloud: Green; Field level devices, Yellow: Human operator). *Adapted from* (Monostori et al. 2016).

2.3.4 Discussion

In this section a review of literature has been presented that summarizes the prevailing theories and approaches related to systems and their parts that are used to automate industrial production systems.

In this review, it was seen that a major transformation is taking place in the manufacturing context towards the implementation of CPSs, which will allow more flexibility for the products being produced, and more interaction and monitoring possibilities between humans and the technical parts of these systems. Also, open-source platforms are being introduced such as ROS-Industrial, which can be particularly beneficial for SMEs. Concepts such as the Operator 4.0 have been proposed to describe the role of the human operator with respect to the automated entities in such systems, and to make a shift from technology-oriented perspective towards a human-oriented perspective. However, these concepts are all relatively new and new guidelines and methods for implementing these concepts need to be developed to support novice designers in designing systems that contain HRC.

2.4 Framing HRC from the 'Human-robot work' perspective

In the previous chapter (section 1.3), the phenomenon of HRC design was defined as;

> 'The design activity of a specific section of a human-driven production system (HRC scenario), which consists of (amongst other components) at least one robot and one human operator. In this specific section, the robot and the human operator perform one or more pre-defined tasks that add value to a product.'

In this section, a review of the literature on the subject of 'human-robot work' is presented in three sub categories. This provides a summary of the current state of affairs with respect to the theories that support the understanding of HRC.

2.4.1 Humans versus machines/computers/robots

In general, robots are designed to resemble the capabilities of humans (Brooks et al. 1998). However, as opposed to the fact that humans are highly unpredictable and irrational in their actions and decision, robots are often modelled as more rational and systematic entities. One of the most often used ways of describing the sequence of steps in how a robot 'reasons' is by the use of the Sense-Think-Act paradigm (Siegel 2003). In an other approach, four steps have been identified for describing how 'automated systems' think, namely; (i) Information Acquisition, (ii) Information Analysis, (iii) Decision selection, and (iv) Action implementation (Parasuraman et al. 2000)

Robots are often used as aids for human in various contexts, and often they are given 'tasks' that are currently being performed by a human. So far, robots have usually been designed as 'benign' entities such as servants, assistants or companions. (Fong et al. 2003). For designing systems in which humans and robots are required to work together, Fitts (Fitts 1951) studied the differences between skills of humans and machines in performing a task, in an attempt to provide support in making trade-offs for task allocation during design of human-machine systems. To this day, the best-known result of his work is the HABA-MABA comparison (Humans Are Better At – Machines Are Better At). However, this way of comparison assumes that the task should be strictly allocated to the best performer. As a solution, the concept of 'adaptive' automation was born (Inagaki 2003). In the concept of adaptive automation, a distinction is made between static and dynamic allocation of functions and tasks between humans and robots, therefore allowing the adaptation of the level of control depending on the situation, which increases the focus on efficient and effective interaction between humans and robots.

2.4.2 Human-robot interaction

Human-robot interaction (HRI) is a rapidly developing domain that builds up on the knowledge that originated in the human-computer interaction (HCI) domain. In contrast to traditional HCI, HRI studies the interaction between human and computers both in the software and hardware domains. In HRI, robots are not limited to an artificial agent on a computer screen, but can take various physical forms in a variety of different contexts. Another aspect that is becoming more relevant in recent years is the artificial intelligence (AI) capabilities of robots, as opposed to monolithic logical structures of traditional computer software. The developments around AI have resulted in many new products and services that are being adopted by large groups of users rapidly, such as virtual assistants with which users can interact using natural language (such as; Apple-Siri, Amazon-Alexa, Microsoft-Cortana), and vehicles that are equipped with an 'autopilot mode' and are able to drive autonomously amongst non-autonomous vehicles on public roads (currently available on various models of the manufacturers Tesla, BMW, Volvo and several others).

These types of automated products and systems that extend from the digital towards the physical domain require intensive and critical interactivity between humans and robots and therefore, have made a big impact on research and developments in the field of HRI. In the next section, various theories relating to the categorisation of human-robot interactive work is presented.

In order to categorise human-robot systems, Sheridan has defined a scale varying between 10 'Levels of Autonomy' (LOA) (Sheridan 1994). Using this scale, systems can be classified according to the extent of which a computer offers assistance to a human. This way of categorising human-robot systems proves to be still relevant. For example, new standards on autonomous vehicles are also based on a similar way of categorisation (SAE - On-road Automated Vehicles Standards Committee 2016). More recently, a robot-specific categorisation was introduced as the 'Levels of Robot Autonomy' (LORA) (Beer et al. 2014). This categorisation uses Sheridan's LOA as its base, and adds the Sense-Think-Act parameters from the robot domain to each level (Figure 21).

As discussed previously, robots can exist either in the digital or physical space. One way of categorising human-robot interactive work in the physical domain is by using the four cate-

LORA	**Sense**	**Plan**	**Act**
Manual	H	H	H
Tele-operation	H/R	H	H/R
Assisted tele-operation	H/R	H	H/R
Batch processing	H/R	H	R
Decision support	H/R	H/R	R
Shared control with human initiative	H/R	H/R	R
Shared control with robot initiative	H/R	H/R	R
Executive control	R	H/R	R
Supervisory control	H/R	R	R
Full autonomy	R	R	R

Figure 21 Levels of Robot Autonomy. (H: Human, R: Robot) Note: 'Manual' means a situation where no robot is involved in performing the task. This level is included for a complete taxonomy (Beer et al. 2014).

gories as defined by Ellis and colleagues. This categorisation divides the work in 'time' as synchronous/asynchronous, and in 'space' as collocated/non-collocated (Ellis et al. 1991). In each of the four categories, different means and interfaces for interaction should be used between the human and the robot. Recently, Krüger and colleagues have used a similar way to categorise interactive work between humans and robots in production environments using the two categories of 'workplace sharing' (WS) and 'task sharing' (TS) (Krüger et al. 2009).

In systems where humans and robots work together, each actor may work as an individual, or as part of a team, resulting in combinations of single and multiple humans and robots, acting as individuals and teams (Figure 22, left) (Yanco and Drury, 2004). Recently, three types of roles between humans and robots in human-robot interaction in production environments have been proposed, namely active, supportive and inactive (Figure 22. right) (Wang, Kemény, Váncza, and Wang, 2017).

Next to the arrangement of the actors in space and time, human-robot interactive work can be further specified based on various aspects such as: (i) task type, (ii) task criticality, (iii) robot morphology, (iv) people to robot ratio, (v) composition of robot teams, (vi) level of shared interaction among teams, (vii) interaction roles and (viii) type of human-robot physical proximity (Yanco and Drury 2004). These categories help to distinguish and compare human-robot work schemes. Factors that help to further define the quality of work between

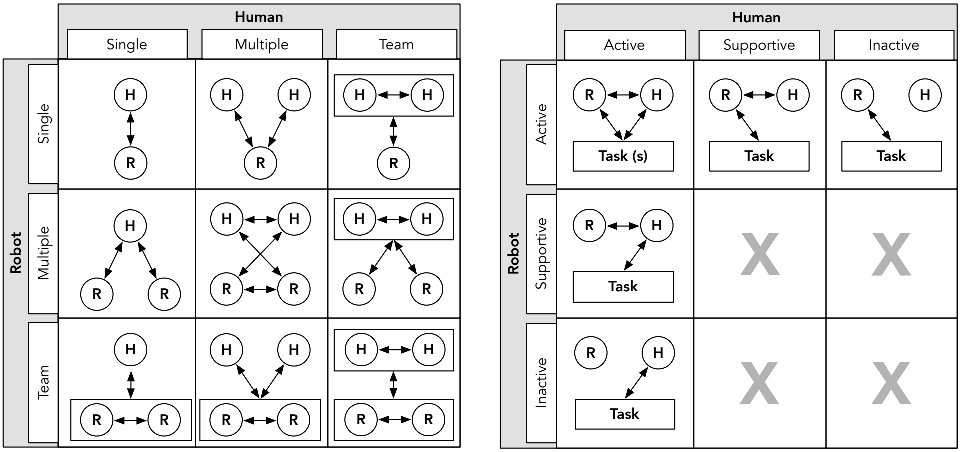


Figure 22 The arrangement of the actors in space and time. Left: Possible arrangements of humans and robots in joint work schemes; Right: Possible roles that humans and robots can take with respect to the execution of a task in a collaborative work scheme.

humans and robots in collaborative work schemes have been identified as joint attention, the link between perception and action, shared task representation, and action coordination (Sebanz et al. 2006).

2.4.3 Industrial human-robot collaboration

Humans can have multiple roles in a production system, as opposed to the purpose-built nature of other entities. Even though robots can be re-programmed to do different tasks when needed, the level of flexibility of robots in the production context is currently not close to that of a human operator. However, they can still be of help in many tasks as supporting entities to humans, and therefore research on this topic is gaining importance (Gorecky et al. 2014) (Michalos et al. 2014). Their increasing level of cognitive ability allows robots to interact with humans in ways that are more natural for humans. It is expected that this will enable collaborative, team-like work scenarios between humans and robots in the near future, which can open the door for achieving the next step in automation in production systems (Knight 2018).

In production systems, the concept of humans and robots working in close proximity, interacting with each other in dynamic work scenarios, forming teams and collaboratively performing tasks is fairly new, especially for SMEs (Helms et al. 2002) (Schraft and Meyer 2006) (Pieskä et al. 2012). A review of the literature on HRI shows that in 2007, Goodrich and Schultz (2007) produced a survey on HRI, providing examples of areas where interaction with robots are to be expected. In their review, manufacturing was not counted in the six main categories, but was included in an "other applications" category. Also, while "*the Springer Handbook of Robotics*" mentioned industrial robots as a minor field of interest in the field of robotics in 2008 (23 pages of 1000) (Siciliano and Khatib 2008), in 2016 (second edition), significantly more attention is paid towards industrial robots, Cobots and physical HRI (70 pages total of 2200) (Siciliano and Khatib 2016). It should be noted that the book itself has grown from 1000 pages to 2200 pages in total in the same period, showing the growing interest in research related to robotics.

Humans and robots should operate together in a way that is efficient, yet cognisant of the skills, preferences and limits of humans (Bosch et al. 2011). In relation to this statement, over the years, different topics related to industrial human-robot interaction have been the subject of various studies. Some of these studies that were encountered during the review in this research will be discussed next.

Stork et al. (2008) developed a foot-pedal interface to communicate with the robot in manual assembly and described positive results in the use of the device by human operators. Krüger et al. (2009) made a review of technologies (Intelligent Assist Devices – IAT) that are being used in human-machine cooperative assembly and concluded that robustness and safety are important issues in such systems. They also concluded that more research is needed on the cognitive load on the human operator and that cooperation between multiple robots and humans should be investigated. (Shah et al. 2011) have studied shared task execution in an assembly task and developed a human-inspired plan execution system for the robot, named 'Chaski'. Their proposed system helped to reduce the human operator's idle time during assembly by 85%. (Pedersen et al. 2016) have studied the interaction of users with robots during the programming phase of tasks to the robot. They concluded that high-level programming based on 'skills' allow non-robot experts to program robots in an intuitive way with only minor training.

Charalambous and colleagues have developed a "Human Factors Roadmap for Industrial Human-Robot Collaboration" (Charalambous et al. 2016). In this roadmap, the importance of the trust between humans and robots is emphasised and a three-phase approach is proposed to improve trust. This approach consists of a 'Operator Training Programme for Initial Trust Calibration' phase, a 'Operator Empowerment for Continuous Trust Calibration' phase and a 'Exposure and continuous trust re-calibration' phase. More recently, Tsarouchi and colleagues have made a review of the literature on industrial human-robot interaction and found that there are three areas that still need attention, namely; task planning and coordination for HRI, HRI for robot programming, and technologies and sensors for HRI (Tsarouchi, Michalos, et al. 2017). These examples show that the topic of industrial human-robot interaction is a complex, and growing field of interest for researchers and increasingly more attention is being paid towards the role and integration of humans in automated production systems.

On the other hand, even though collaboration and working in teams is a natural form of organising work between humans, performance of production systems consisting of a mix of human and robots has several challenges (Krüger et al. 2009). The cognitive and motoric capabilities of humans in relation to the high-paced environment in a production system have been studied. Trentesaux and Millot describe that humans are having difficulties in fitting into the flow of task execution in such environments (Trentesaux and Millot 2016). It is also shown that cognitive load during work involving collaborative (human-human) tasks is higher than in individually executed tasks (Dillenbourg and Betrancourt 2006). Such limitations of human operators should be considered during HRC design, for example by highlighting the areas of the production process in which physical and cognitive load are relatively higher than others.

Moreover, in the context of manufacturing, it has been argued that in the Industry 4.0 age, production systems will be required to take the social skills of humans and social interactions with robots into account in their design (Sadrfaridpour et al. 2016). As also observed in Example E in section 2.2, a human-driven production system contains many social aspects, that may have positive and negative influences on the performance of the tasks that are being performed.

However, the 'social' aspect (sHRI) adds an additional level of complexity to the design of systems that involve robots and the HRI principles that have been developed so far. For example, the acceptance of robots by users has been identified as a key element in this context. The 'GODSPEED' scale was developed in order to measure the acceptability of robots by their potential users. In this scale, the following aspects are used to measure various aspects of acceptance: (i) anthropomorphism, (ii) animacy, (iii) likeability, (iv) perceived intelligence, and (v) perceived safety (Bartneck et al. 2009).

However, it has also been demonstrated that for users, it is more important that a robot does its job correctly than how it looks (Bartneck and Forlizzi 2004). This makes the balance between anthropomorphism an interesting topic to look at in the context of manufacturing, as most machines and robots in this context do not share any anthropomorphic features that resemble humans.

Benchmarks for social interaction between humans and robots have not been set yet. Therefore benchmarking systems that combine various benchmarking techniques from different fields are used in combination to assess social interactions between humans and robots (Feil-seifer et al. 2013).

There has also been critique on the team-like work between humans and robots. It has been argued that while there is sufficient evidence to show that humans and robots can be arranged in teams, it is also assumed that when robots and humans are organised as teammates, that they are ultimately bound to fail due to: (i) autonomy; (ii) agency; and (iii) self-preservation. This will result in the rejection of robots from a team. Therefore, it has been proposed that other forms of organisation should be investigated (Groom and Nass 2007).

2.4.4 Discussion

In this section a review of literature has been presented that summarizes the theories and principles that are currently being used to describe various aspects of the interactions between humans and artificial entities (computers, machines, robots) that are required to work in the same physical/digital space. In this review, it was observed that, instead of strictly dividing tasks between humans and robots based on best-case capabilities, adaptive task allocation schemes are being considered for the next generation of robots. In line with this development, the traditional time/space continuum of categorising human-robot interaction is being expanded to include the various roles that the entities can take such as active/supportive. Finally, thanks to the development in the field of HRI, in recent years, there has been a growing interest in the development of industrial human-robot interaction systems in the manufacturing context. In this context, the topics of pHRI and sHRI and the challenges/complexities that they introduce are currently being explored and proposals for addressing the issues related to them are being made.

2.5 Framing HRC from the 'Design' perspective

Throughout the Industrial Revolutions, the development and implementation of new technologies in production systems have gone hand in hand. While this dynamic resulted in the creation of highly automated, efficient, robust and safe production systems, the systems themselves have become too complex to be understood and addressed by designers from a single discipline. Therefore as mentioned in section 2.1, the design of these systems rely on a successful cooperation of designers from multiple disciplines. In other words, the designers of production systems are no longer concerned with the design of machines that can execute several tasks in sequence without the help of a human operator, nor are they seeking to carefully plan a best-case scenario and production plan for a specific well-understood product. Instead, designers are building systems that are dynamic, responsive, flexible and intelligent. This requires new approaches for supporting their design (Gerhard 2017). According to Monostori et al. (2016), designing CPPS involves a multitude of disciplines that can be grouped in three categories: (i) Computer Science; (ii) Information and Communication Technology; and (iii) Manufacturing Science and Technology. However, until now, little, if any, work has been done to truly understand the multi-disciplinary design practice that involves these disciplines and underpins the development process of such systems. In this section, HRC will be addressed from three different perspectives that each describes various approaches to designing different types of systems and products.

2.5.1 Designing production systems

According to the definition by Bellgran and Säfsten, a production system is a transformation system and should be designed with the technical and physical parts, the humans in the system, and the way to organise the work, taken into consideration. (Bellgran and Säfsten 2010). For designing the technical and physical parts of the system, various handbooks exist that provide a good overview of its different components and what the variations and design considerations of these components are (Groover 2007b) (Groover 2007a) (Chryssolouris 2013). For designing the organisational part of a production system, there are handbooks, such as 'Operations Management' by (Reid and Sanders 2010). These books provide theoretical guidelines and practical examples, often for educational purposes, and often targeting large-scale production. The design of the human part of the system is often included in these documents, however at a far less detailed way, compared to the discussions of the technical parts of the systems.

One of the holistic approaches that consider both the technical and the human part of production systems has been 'Lean Manufacturing'. For decades, enterprises have been following the principles of Lean Manufacturing to optimise high-volume, low-mix production systems for efficiency and effectiveness. (Womak et al. 1990) (Jasti and Kodali 2015). Similar to the production line approach, the approach of Lean Manufacturing has its origins in the automotive industry and was initially developed as a part of the Toyota Production System (Yang and Yang 2013). Yet, it has later found application in the manufacturing of all kinds of products and industries. The main principle of Lean Manufacturing is to systematically reduce waste in a production system without reducing productivity. The seven types of waste that were originally described are: (i) transport; (ii) inventory; (iii) motion; (iv) waiting; (v) overproduction; (vi) over processing; and (vii) defects. Using the principles of Lean Manufacturing, enterprises can analyse their systems in order to identify and eliminate these areas of waste. While Lean Manufacturing has been regarded as one of the most influential approaches to 21st century manufacturing, partially due to their scale of production, research into lean practices in SMEs has been limited and has only recently been performed (Rose et al. 2011). It has been argued that the advantage that can be gained by SMEs by implementing Lean Manufacturing is typically limited, due to the high level of product variety in their production systems.

On the other hand, as the markets requested more flexibility from manufacturing (as discussed in 1.1.2), new methods were needed to improve reaction time to; (i) meet the changing market requirements, (ii) maximize customer service level and (iii) minimize the cost of goods, with an objective of being competitive in a global market and for an increased chance of long-term survival and profit potential This led to the development of the 'Agile Manufacturing' vision (Kidd 1996). According to Gunasekaran and Yusuf (2002), Agile Manufacturing is achieved based on trade-offs between (i)quality, (ii)cost, (iii)flexibility, and (iv) responsiveness. Besides the use of flexible technologies, the responsiveness of the overall system relies on the flexibility of people in these systems. However, it has been reported that the methods and principles introduced by 'Lean Manufacturing' and 'Agile Manufacturing' approaches have both failed to prioritise the ergonomic and psychosocial requirements of human operators (Koukoulaki 2014).

More recently, along with the trends of automation, circular production, and re-shoring, reconfigurability and re-use of system components have become important topics (Esmaeilian et al. 2016) (Zijm 2019). The life cycle of production systems has become short-er due to increasing competition, market globalization, strict quality standards, low costs, short throughput times, availability of new technology, increased environmental problems, and because of the availability of multiple choices of products (Attri and Grover 2012).

As a solution, 'reconfigurable production system design' has become a topic of interest (Rösiö et al. 2013). It has been argued that the complexity level when designing reconfigurable production systems is high and that structural design methodologies are needed that adopt a holistic perspective. It has also been indicated that the use of structured design methodologies in practice is not common. The consideration of 'legacy structures' in an industrial case study has highlighted that production system design methods need to consider legacy equipment, processes and systems in an extended way that can be reused and reconfigured to suit the future need (Wiktorsson 2014).

2.5.2 Designing computer-based systems

The design activity of the 'hardware'' and 'software' for computers requires a multidisciplinary approach. Over the years, there have been many ways to formalize the design process and develop systematic ways of designing, validating and producing computers and computer-based systems. As computers became more standardized, the efficient development of reliable and efficient software became more important and the discipline of 'software engineering' emerged in the late 1960s. The collection of methods for design activities in this domain has since been called software development lifecycle models (SDLCs) (Kelly et al. 1999). The first models that were created, were mainly aimed at guiding the development process. One of the first models was the 'waterfall model', which described a flow of work from 'Analysis', 'Design', 'Coding', 'Implementation', towards the final phase of 'Maintenance' (Boehm 1988). Later on, the 'V-Model' was introduced as an approach to software development (McDermid and Rook 1991). The V-Model allows the efficient organisation and execution of the development process of systems with well-defined design specifications and divides the development process into three phases; (i) Specification, (ii) Integration, and (iii) Implementation. In the 'Specification' phase, components of the system (and their requirements) are defined based on their hierarchy (system-level to component-level), after which the described components are developed and combined with each other during the 'Integration' phase. In the 'Implementation' phase, the performance of the integrated components are tested using the requirements generated during the 'Definition' phase. Over the years, the V-model has been adapted to different context in which complex computer-based systems are developed, such as mechatronic system design (VDI 2004). In this context, the V-model has been used as a template to run multiple development processes (preparation, conception of production, detailed design and implementations planning) in parallel to each other, in order to realise an iterative procedure for the design of production systems for mechatronic products.

On the other hand, today ‘Agile software development’ has become one of the most often used ways of developing software. Agile software development is not a single method, but describes a set of methods. These include; Crystal methodologies, dynamic software development method, feature-driven development, lean software development, Scrum, and Extreme programming. While the ‘Waterfall model’ and ‘V-Model’ emphasize a rationalized and engineering-based approach and considers problems as fully specifiable, and therefore solvable by extensive planning and re-use of code for efficiency, ‘Agile software development’ methods are fundamentally different from the traditional SDLCs in the sense that they rely on the creativity of the people, rather than on robustness of processes, in order to solve problems in an unpredictable world (Dybå and Dingsøyr 2008).

Acknowledging the significance of the complexity of relationships that exist between products and their users, has been a revelation in the field of product design in the past decades. Therefore, many product/system/interaction/service design approaches and methods applied (and developed) in recent years have often been influenced by the user-centred design (UCD) principles, as presented by Norman (2013). At the same time, the importance of addressing humans as integral parts of complex computer-based systems has been recognized by the industry as well. The ISO 9241 standard and its sub-parts currently cover this topic. More specifically:

> *“ISO 9241-210:2010 provides requirements and recommendations for human-centred design principles and activities throughout the life cycle of computer-based interactive systems. It is intended to be used by those managing design processes, and is concerned with ways in which both hardware and software components of interactive systems can enhance human–system interaction.”* (International Organization for Standardization 2010)

Recently, the integration of ‘human-centred design’ and ‘agile software development’ approaches has been proposed as a solution for software development for web-application in the SME context (Ardito et al. 2016). A similar integration that is specific to SMEs in the production context might be worth exploring in the realm of this research.

2.5.3 Designing products

In the domain of design and engineering of consumer products, several theories have been developed and used that support designers in structuring their design processes, such as ‘VDI2221’ and the ‘Pahl & Beitz model’ (VDI 1987) (Pahl et al. 2003). While each model in this domain has its specific niche, most of them are so-called ‘phase-models’ and therefore consist of several phases that are common amongst all models. In order to create a generic product design model that designers can adapt to their own context, Roozenburg & Eekels developed the ‘Basic design cycle’ model as shown in Figure 23 (left) (Roozenburg and Eekels 1995).

This model shows the design process as consisting of four main phases, and documentation that is generated between the phases. Feedback loops are shown between the ‘decision’ phase and the ‘analysis’ and ‘synthesis’ phases. The criteria that are created at the ‘analysis’ phase are used during the ‘evaluation’ phase. In addition, it has also been described that the design process is a sequence of intuitive (reductive) and discursive (deductive) steps between which always a comparison is made of the current results and the desired results (Figure 23, right). In other words, during the design process, one can de-

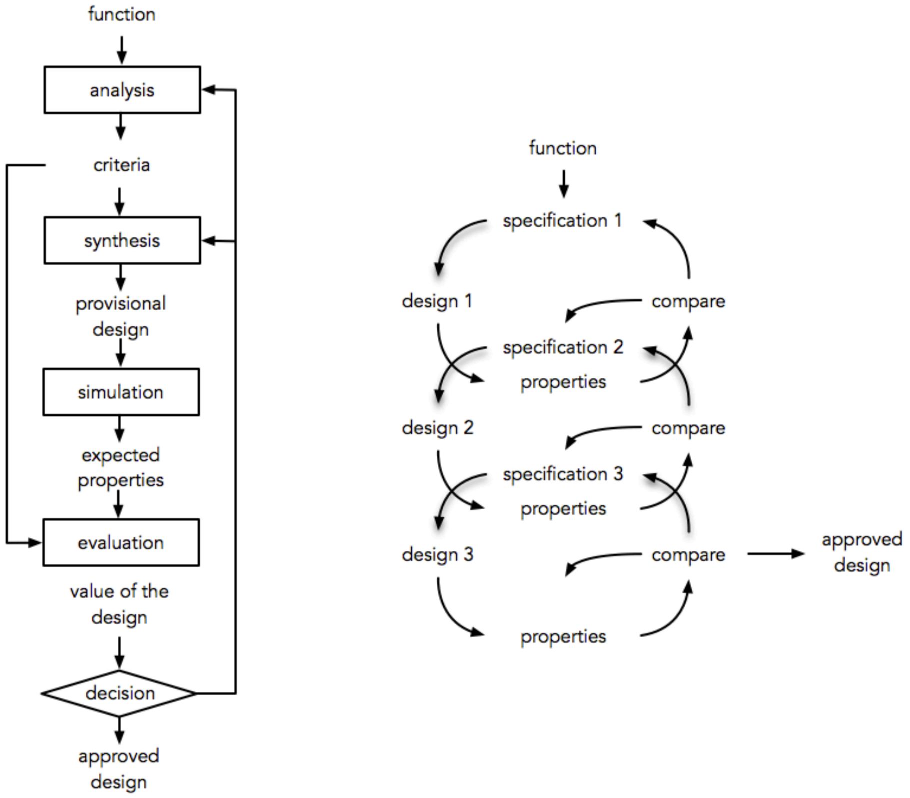


Figure 23 Linear and iterative design methodologies. Left: The basic design cycle, Right: The iterative structure of the design process (Roozenburg and Eekels 1995)

fine/modify/adjust the specifications based on the insights generated during the design process and through the preliminary comparison of results with the specification at hand.

Some further characteristics of phase models can be described as: (i) sharp divisions between the phases cannot be drawn, and stages and phases do not necessarily follow rigidly one after the other, (ii) stages and phases are often carried out iteratively, returning to preceding ones, thus achieving a step-by-step optimisation, (iii) a phase-model does not show the problem solving process, by which solutions for the design problem are generated and refined, (iv) in each phase the designer will go through the basic design cycle, often more than once, (v) in each phase alternative solutions can be thought up, (vi) they pay (too) much attention to the conceptual design phase, (vii) urge a regular evaluation of the project. (Van Boeijen et al. 2014)

Furthermore, in product design, a design-in-the-making can exist in three forms. (i) Function structure, (ii) Solution principle, and (iii) Embodied design.

2.5.4 Discussion

In this section a review of literature has been presented that summarizes three approaches that are currently being used to develop various types of (computer-based) systems and products.

In the review of the approaches towards 'Production design', a relatively low attention to the humans in the system was observed. There is growing attention towards the design of reconfigurable systems and a need for new methodologies and modular design methods is mentioned.

In the review of the approaches towards 'Computer-based system design', a history in the usage of phase models was observed. The human entity in these systems is starting to be recognized as an integral part of the design process. On the other hand, the reviewed methods generally focus on efficient design process management, rather than facilitating creative problem solving. The methods also focus on the development of robust products by means of structural validation.

In the review of the approaches towards 'Product design', also a history in the use of phase models was seen. While the products being targeted in this domain have some fundamental differences compared to the products in the other two categories that were reviewed, such as their type, size and context of use, it can be concluded that much attention has been paid towards the development of 'generic' design models that can be adapted to suit the needs of other engineering design activities. It can also be concluded that the approaches presented in this section showed a high similarity to those presented under

'Computer-based system design' with respect to the use of similar types of phases and iterative loops between phases.

2.6 Conclusion

The aim of this chapter was to present the results of the literature study for this research in a way that helps to frame HRC and HRC design from the three perspectives of 'industrial automation, 'Human-robot work', and 'design'.

The eight examples of experimental HRC scenarios showed that it has become possible to bring industrial robots and human operators in closer physical proximity to each other by using novel safety equipment, gesture-based interfaces and Cobots. This review has also shown that while shared tasks are becoming a reality in this context, robots are generally being deployed in assistive roles to human operators.

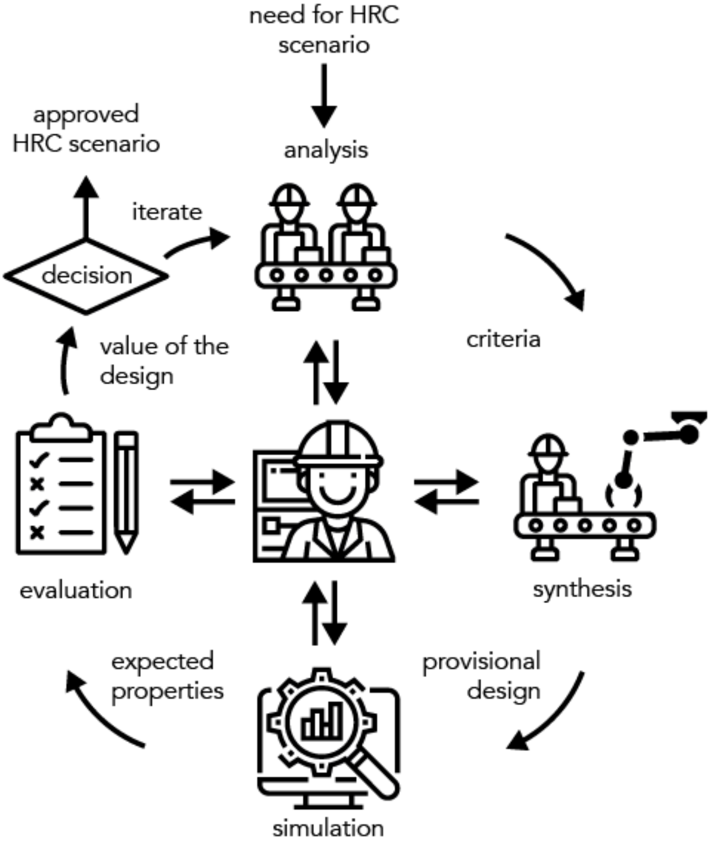


Figure 24 The "*operator-centred production design*" model adapted for HRC design

The review of literature related to the perspective of 'Industrial automation' has shown that a major transformation is taking place in the industry towards CPSs. Concepts such as the Operator 4.0 support the idea that the role of the human operator as controller of these systems should be addressed more and integrated into new design methods for this context.

In the review of literature related to the perspective of 'Human-robot work', it was shown that the field of HRI has extended towards pHRI and sHRI by which the complexities of the interaction between humans and robots in work systems are becoming topics of study. Acceptance of robots by humans is mentioned as a major issue; however, the question remains if this is also valid in the context of human-driven production systems.

The review of literature related to the perspective of 'Design' has shown that the topics of reconfigurability and modular design of production systems are being studied at this moment, in order to increase the efficiency of the design process and to re-use existing components. In the field of 'computer-based system design' much attention is being paid towards efficient design processes as well. Similarities between this field of design and 'product design' was observed with respect to the use of phase-based models and the development of documentation during these phases in order to be used to execute a next phase and for evaluation.

As a result of this review, it is concluded that the reviewed domains of knowledge contain many established and new principles and theories that can be of value for HRC design. However, a common ground for organizing and executing design activities using the available knowledge is missing.

As discussed in section 2.5.2, considering the future production systems of SMEs as complex, computer-based systems in which human operators will have more responsibilities for the successful operation of these systems, Figure 24 presents a model for "*operator-centred production design*", based on an integration of the ISO *9241-210:2010* description on 'human-centred design for interactive systems' and, the terminology and phases of the design approach presented by Roozenburg and Eekels (International Organization for Standardization 2010) (Roozenburg and Eekels 1995). The operator-centred production design model should function as a blueprint for a methodology for HRC design, as targeted in this research. It structures the design activity into four main phases and puts emphasis on the inclusion of operator related information throughout the procedure. It also emphasises an iterative way of working as described in section 2.5.3 and shown in Figure 23.

Chapter3

Related publications

- Cencen, A., van Deurzen, K., Verlinden, J. C., & Geraedts, J. M. P. (2014). Exploring Human-Robot Coproduction. 19th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Barcelona, Spain, September 16-19. Proceedings of the 2014 IEEE Emerging Technologies and Factory Automation.
- Cencen, A., Verlinden, J., & Geraedts, J. (2016). Qualifying the performance of Human-Robot Coproduction at a relabelling station. 11th International Symposium on Tools and Methods of Competitive Engineering (TMCE), Aix-en-Provence, France May 9-13, Proceedings of the Tools and Methods of Competitive Engineering 2016.

3 Learning from human-robot coproduction design

Chapter 2 presented Research Cycle 1 of this research, during which the domains of knowledge that underpin HRC design were explored and discussed. The reviewed literature showed a growing interest on the topic of robotics and human-robot interaction in general, but also in their application in the manufacturing context.

This chapter presents the results of Research Cycle 2, which focused on the empirical exploration of HRC and HRC design, and learning from the process of designing HRC. The research questions that guided this research cycle are;

RQ2 - What bottlenecks are there for expert designers during HRC design?

RQ3 - What bottlenecks are there for novice designers during HRC design?

The chapter is divided into two sections. The first section discusses the work of expert designers, based on a case study in which a group of designers from the FiaD project were studied during a HRC design activity. The second section discusses three cases that were executed by novice HRC designers in a laboratory environment.

The chapter is finalised by the presentation of the key influential factors for HRC design that were gathered through the empirical activities of Research Cycle 2, and the definition of the requirements for the methodology.

3.1 Introduction

As discussed previously in section 1.1.5, in recent years, commercial Cobots have been making their entry into production environments rapidly. While this generation of robots can be integrated into production systems to perform similar tasks as their predecessors, it remains a challenge for engineers to integrate them in novel human-assistive scenarios that leverage the unique capabilities of these robots, such as co-location with human operators and intelligent interaction capabilities. In order to develop support for this design activity, an understanding of its underlying concepts and processes is essential. In section 3.2 and section 3.3, HRC design cases are presented that supported the development of this understanding during this research.

3.2 HRC design by experts

During the FiaD project, several activities were performed that targeted the development of so-called ‘demonstrators’. These demonstrators were developed in order to show the capabilities of the technologies being developed inside the project to the outside world, and to show that the technologies could be applied in real-life production contexts. These demonstrators therefore mainly involved companies that were not part of the project, but rather, the potential users of the technologies being developed inside the project. The case that is presented in this section discusses the design process of engineers involved in the FiaD project during one of these demonstrator projects. In the mentioned case, a company (For non-disclosure reasons, the name of the company and the product can not be disclosed. The company will hereinafter be named 'CompanyX') requested the engineers of the FiaD project to re-design a specific area of their production system in order to accommodate a Cobot, and to have this Cobot perform some of the tasks that are currently being performed manually. The design task given to the engineers was as follows;

> 'Recently, CompanyX set up several 'customisation workstations' (CWs) that allow them to customise a portion of the products they offer to their clients (Figure 26). These CWs are located inside a big distribution centre, from which the products of the company are shipped to all parts of the world. Only a small portion of the products that are currently being shipped are customised using these workstations. However, in the near future, they expect to be shipping more customised products. Therefore, they would like to investigate the possibility to increase the level of automation in these workstations. This way, they can have more number of operational CWs without the need to increase the number of operators. Based on an initial assessment, they believe that Cobots could be an interesting opportunity for their case. They would like you to investigate how Cobots can be integrated in their current setup, and what the potential return on investment scenario would be.'

In order to study the design process of the FiaD engineers during this project, data was collected during the organized 'intake workshop' between CompanyX and the FiaD engineers. The intake workshop took place at the premises of CompanyX, where also the targeted CWs were located. The collected data consisted of audio recordings of the discussions during the design process, video recordings of the targeted HRC scenario, and hand written notes made by the designers. At the end of the workshop, the audio recordings were transcribed and the notes were digitally scanned. Finally, all gathered data were coded and collected in the computer-assisted qualitative data analysis program Atlas.TI, which allows the creation of an overview of the data for the purpose of analysing it.

In the next two sections, the results of the analysis of this data are presented in the two categories, 'the designers' and 'the HRC scenario' respectively.

3.2.1 The designers

The team from the FiaD (hereinafter named 'FiaD team') project that took part in the intake workshop consisted of eight participants, all of whom were employees of organisations that

Table 2 List of the participants from CompanyX

ID	Function	M/F	Experience (years)
1	Manager engineering	M	15+
2	Senior industrial engineer	M	15+
3	Group leader labelling	M	10-15
4	Labelling machine designer	M	15+

Table 3 List of the members of the FiaD team

ID	Function	M/F	Experience (years)
1	Business expert	F	0-5
2	Integration expert	M	10-15
3	Integration expert	M	15+
4	Robot expert	M	0-5
5	Robot expert	M	0-5
6	Robot expert	M	0-5
7	Gripper expert	M	0-5
8	Robot vision expert	M	0-5

were partners of the FiaD project. The members of the team were experts in various disciplines, as indicated in Table 3. At this stage, the members of the team had never worked together before on a design project. As representatives of CompanyX, four participants were present during the workshop. The roles/functions of these individuals inside the company is shown in Table 2. These individuals had the task of providing a demonstration of the CW to the FiaD team and answering any questions to clarify the details that were requested by the team.

3.2.1.1 Design process

The intake workshop during which data was collected is part of a five-step approach that the FiaD team employs for structuring the development process of HRC scenarios (Figure 25). The main steps of the process in this approach are as follows;

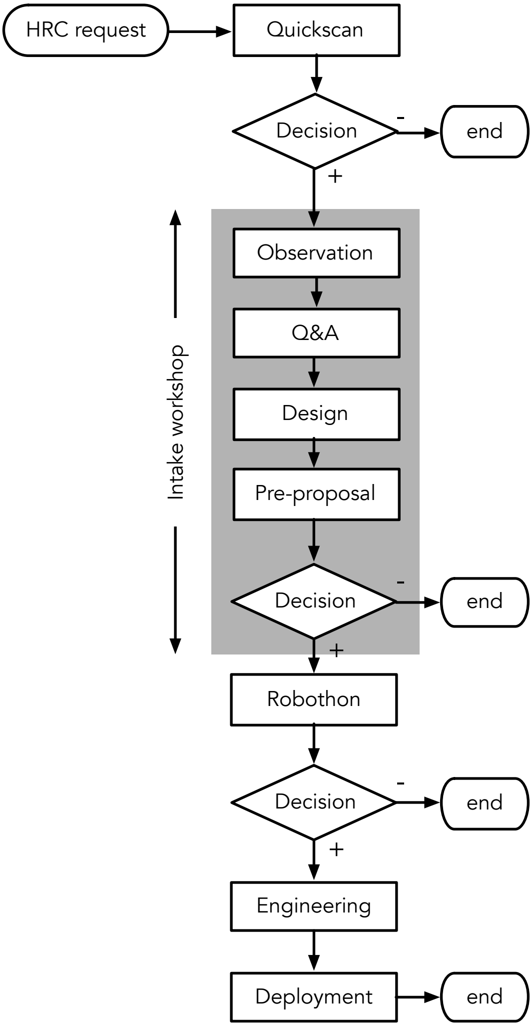


Figure 25 A diagram showing various steps of the FiaD team's HRC design approach.

- **Quickscan:**
  This is an online evaluation tool by which potential clients of the FiaD team can assess whether or not a Cobot can be implemented into one of their processes in a relatively short amount of time and to what extent a robust HRC can be expected as a result (available at: www.factory-in-a-day.nl/quickscan). This tool helps to analyse a pick & place task in a production process based on a set of questions. (an overview of its questions is available in Appendix B). When all questions are answered throughout the tool, it provides the user with an estimation on the level of difficulty of automating the given pick & place task using a Cobot. In case the client is presented with a positive

result and the client is interested in further exploration of the possibility for automation, a request is sent to FiaD team to plan an intake;

- **Intake workshop:**
  The intake step allows the FiaD team to gather the required data about the subject of their upcoming HRC development process, and to discuss with their client what the expectations and requirements are. In this step, based on an initial analysis of the data, some preliminary HRC concepts are presented to the client in order to define the definitive direction of the final solution. This step can result in a decision not to continue with the development process, due to a lack of confidence in the proposed concepts;
- **Robothon:**
  After the selection of a viable HRC concept, a physical prototyping session takes place in which the most crucial components of the system are tested for functionality and robustness. For this session, a proof-of-concept of the proposed solution is built in order to evaluate the essential functions of the solution and if necessary to determine where refinements will be needed during the engineering step. At the end of this step, an evaluation is made together with the client whether or not to continue with the engineering of the current design;
- **Engineering:**
  In this step, all parts of the design (hardware & software) are further refined and the custom parts that need to be produced (such as grippers, jigs, conveyors etc.) are produced;
- **Deployment:**
  The developed HRC solution is deployed at its targeted location. This step mainly involves the installation and configuration of the new peripherals.

Sub-steps of the Intake procedure:

For this case study, the FiaD team was observed during the ‘Intake workshop’ step of the HRC design process only, which contains the design activity, which is of interest for this research, namely the conceptual design of HRC scenarios. This process consists of five substeps as shown in (Figure 25). The intake workshop that involved these five steps was planned to take 8 hours, and took place at the premises of CompanyX as described in section 3.2. The workshop started with a briefing session (±45 minutes) with all of the participants during which everyone introduced themselves and their area of expertise. After the introduction, the official part of the workshop started and followed the following five steps:

- **Observation:**
  The observation session started with a demonstration at the targeted location in the production system where the Cobot needs to be introduced. During this demonstration, all twelve participants that took part in the intake workshop were present. In addition, an operator was present for the purpose of operating the CW. Prior to focusing

on the operation at the CW, a short tour of the facility its different sections and processes was given (±30 minutes), after which all participants gathered around the CW. As the operator operated the workstation, all participants of the FiaD team observed the procedure, while the participants from CompanyX described the details of the operations that were being performed by the operator (±15 minutes);

- **Q&A:**
  After the observation of the CW, all participants moved to a meeting room. The purpose of this session was to clarify the details about the processes at the customisation station, and the requirements for the new system that needed to be developed which involved a Cobot (±90 minutes);
- **Design:**
  During this step, the FiaD team split in two groups in order to generate multiple HRC scenarios in the limited amount of time they had (±150 minutes). Each group was supplemented with two employees to provide additional information and insight in case it was necessary. During this session, a second observation of the CW took place (±15 minutes), with the purpose of analysing it with respect to the considerations being made towards the new design of the workstation;
- **Pre-proposal:**
  After the finalisation of the design process, the concept of a HRC scenario for the CW was presented to CompanyX verbally and a discussion took place between the FiaD team and the representatives of CompanyX about the feasibility of the presented concept (±60minutes);
- **Decision:**
  After the discussion about the presented HRC scenario, CompanyX agreed to continue with the next step in the development, the so-called ‘Robothon’.

3.2.2 The HRC scenario

In the previous section, the designers that were involved in the HRC design activity at CompanyX and their observed design process was presented. In this section, details about the current CW and the future CW including the proposed HRC scenario by the FiaD team will be presented.

3.2.2.1 Current customisation workstation

The scope of the customisation of the products that are processed in the CW is limited to the label that is placed on the products. For different products, ordered by different customers, different labels can be placed on the box of the product. The labelling is performed using a dedicated machine for labelling products. As discussed in section 3.2, the CW is contained within a larger system of automated machines and manual workstations. Currently, CompanyX operates four of these CWs. The CW consists of the entities as shown in Figure 26. At the workstation, there is an area where human operators can stand and process incoming and outgoing products.

On the next page, the entities of the CW and its workflow will be described in detail.

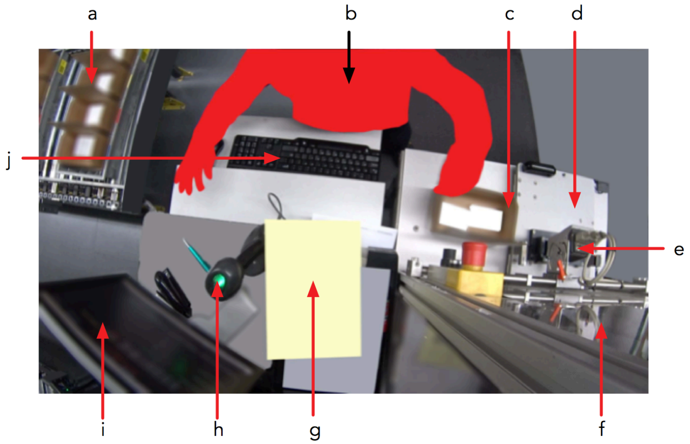


Figure 26 Plan view of the 'CW'

a. shipping boxes in a tray
b. human operator
c. unlabelled packages in a shipping box
d. jig for inserting packages into the labelling machine
e. barcode scanner
f. window for viewing the operation of the labelling machine
g. order sheet
h. manual barcode scanner
i. PC monitor
j. PC keyboard

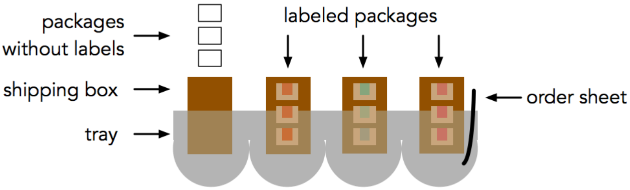


Figure 27 Side view of a tray filled with shipping boxes and packages.

- **Product:**
  The products in this case are white rectangular cardboard 'packages' that contain different quantities of the product made by CompanyX (Figure 27). There are four sizes of packages that can be customised. These packages arrive to the workstation in non-sealed cardboard shipping boxes. These boxes arrive in groups, inside a rigid plastic tray with a capacity of holding four shipping boxes. Each tray always contains four shipping boxes;

- **Human operator:**
  One human operator operates the production workstation at a given time and has two major roles. The first role is to process the labelling task of incoming packages, and the second role is to swap the label rolls in the labelling machine, according to the order being processed;

- **Computer:**
  The computer is used to scan the order sheet and to present information to the human opreator about each product about that is being labeled. This computer consists of a monitor, keyboard, mouse and a barcode scanner. The order sheet in the tray that comes with each shipping box is scanned using the barcode scanner that is connected to this computer;

- **Labelling machine:**
  The labelling machine is used to apply labels on the four types of packages (Table 4) Inside the labelling machine, a self-adhesive paper label is applied to unlabelled boxes. Each label has a different design, and is specific to the specifications of the customer. Each box needed to be inserted into the labelling machine with the correct orientation, and needed to be labelled with a specific label, which was indicated on the order sheet. Labels were provided on rolls, which the human operator installs into the machine. The labelling machine had two barcode scanners; one scanner detected which product had entered the machine and the other detected which label was applied onto the product. This information was immediately sent to the computer and the back-end of the system;

- **Workflow**
  The intended production workflow at the CW is as follows; tray arrives at the workstation that contains four shipping boxes that contain a number of packages that need to be labeled. The tray also contains an order sheet that allows the human operator to register the labelling process in the ERP system of CompanyX and to get the correct labeling information from the system. The human operator then scans the order sheet and compares the label that needs to be used for the order with the label that is currently installed in the labelling machine. In the case the installed label in the machine matches with the label that is needed for the order, the operator proceeds with inserting the packages into the dedicated 'jig' (Figure 26,d.) of the labelling machine in the correct orientation for the machine to label them on the correct side. The operator then pushes this jig towards the inside of the machine.

Table 4 Details of the product parts in the production workstation.

Part name	Description	
Tray	Contains the shipping boxes and the order list	
Shipping box	Contains various amount of packages	
Package	(Type A)	75 mm x 40 mm x 69 mm
	(Type B)	77 mm x 27 mm x 38 mm
	(Type C)	160 mm x 35 mm x 68 mm
	(Type D)	93 mm x 17 mm x 52 mm
Label	(Small)	75 mm x 69 mm
	(Medium)	70 mm x 30 mm
	(Large)	85 mm x 63 mm
	(Extra Large)	153mm x 61 mm

Table 5 Overview of the workflow at the current customisation workstation.

#	Task	Human Operator	Labelling Machine	Computer
0	Tray arrives at workstation			
1	Pick shipping box from tray	X		
2	Place shipping box on the workstation	X		
3	Scan order sheet	X		
4	Check label type in labelling machine	X		
5	Install correct label	X		
6	Pick package from shipping box	X		
7	Insert package in the jig	X		
8	Scan package barcode	X		
9	Check package type			X
10	Apply label on package		X	
11	Indicate completed labelling task		X	
12	Scan applied label		X	
13	Check label type			X
14	Remove labelled package from jig	X		
15	Insert package in shipping box	X		

When the jig is being inserted into the machine, the machine's own barcode scanner (Figure 26,e.) scans the barcode that is on the package and performs the label check that the operator has performed in the pervious step, once more. In case the check is confirmed, the machine applies one label onto the product and signals the operator with an audio signal that the product may be withdrawn from the machine. The operator pulls back the jig. When the product is being pulled back, another barcode scanner on the machine reads the barcode on label that is applied to the package and checks this with the system. In case the check is confirmed, the operator is signalled with an audio signal that the product has been labelled correctly and may be withdrawn from the jig. The operator puts the package with the label back into the shipping box, and performs the labelling operation of the remaining packages. Once all packages inside a shipping box have been labeled, the operator places the shipping box back in the tray and picks a new shipping box with new packages in it, and scans the following barcode on the order sheet, after which the same workflow is repeated again until all packages in the tray have been provided with the correct label. The operator then places the tray on the conveyor that brings them to their next destination in the production process of CompanyX. An overview of the workflow can be seen in Table 5.

The system in which the CW is placed is configured in such a way that the products arrive at the workstation in batches belonging to a single customer. This reduces the number of times that the labels in the machine need to be replaced. The human operator is responsible for changing the labels by fetching the right label that belongs to a specific order from a nearby location (Table 5, step #4), and by performing a series of actions on the machine to swap the two labels. However, this part of the task was outside the scope of CompanyX's request for the FiaD team's HRC design scenario.

3.2.2.2 The proposed customisation workstation

CompanyX had requested the FiaD team to introduce a Cobot next to the operator of the CW. It was assumed that by introducing a Cobot to perform the pick & place tasks in the production workstation, the human operator would be able to operate multiple CWs equipped with Cobots at the same time. The intake workshop aimed to develop a concept for a HRC scenario for the CW during a focussed session during which all involved stakeholders were present.

During the 'Design' step of the intake workshop, the FiaD team considered a variety of ways of operationalizing the Cobot in the CW. In the end, the team created an HRC scenario based on the most viable sub-solutions that were discussed during these considerations, and presented a concept for a HRC scenario for the CW to CompanyX during the 'Pre-Proposal' step. The details of the presented HRC scenario are presented as follows;

- **Product:**
  The product in the HRC workstation remained the same as in the existing workstation;

- **Human:**
  In the original CW, the human operator had 10 tasks that were allocated to him/her in the workflow for labelling products. In the proposed HRC scenario, the human operator's tasks have been reduced to only two. The first of these tasks involve the starting of the labelling operation, which is then executed by the Cobot and the labelling machine. The second task of the human operator is related to checking the label roll that is installed in the machine and the swapping of label rolls for different orders;
- **Robot:**
  The proposed HRC scenario contains a Cobot (Universal Robot UR5) and various peripheral devices. The Cobot is used to replace some of the tasks of the human operator in the labelling workflow (tasks #2,3,6,7,8,14 and 15 in the existing workstation, see Table 5). For this reason, the Cobot needs to be placed in the location where the human operator stands in the current CW;
- **Additional equipment:**
  In addition to the Cobot, a special gripper and other helping peripherals are needed to be developed to enable the Cobot to handle the packages in the correct way. The gripper that needs to be developed must be able to handle all package types a vision system is needed to locate the product inside the shipping box. Finally, because the packages need to be labelled on a specific side, each box has to be inserted into the labelling machine with the correct orientation. To do this using the Cobot, additional equipment is needed. Therefore a re-orientation jig is proposed, which the Cobot can use to re-orient the product so that it can be picked up and correctly inserted into the labelling machine;
- **Workflow**

  Table 6 shows the workflow between the entities of the proposed HRC workstation.

3.2.3 Discussion

The analysis of the HRC design activity of the FiaD team showed in a general sense that while there is an implicit structure in the multi-disciplinary design activity, common ground between the members of the team—acting as experts in their own discipline—was missing. The insights related to HRC design approach of the FiaD team, which emerged from the analysis of the team during the intake workshop at the premises of CompanyX can be summarised under the following five topics:

- **Overall procedure and methods:**
  As shown in Figure 25, the FiaD team had an approach towards how they carry out HRC design. The planning of activities ensured that all stakeholders involved during the workshop were informed about the process steps during the workshop, however, the overall approach of the FiaD team and the follow-up steps were not communicated to CompanyX prior to the workshop.

Table 6 Overview of the workflow at the proposed HRC workstation.

#	Task	Human Operator	Cobot	Labelling Machine	Computer
0	Tray arrives at workstation				
1	Scan order sheet	X			
2	Pick shipping box from tray		X		
3	Place shipping box on the workstation		X		
4	Check label type in labelling machine				X
5	Install correct label	X			
6	Pick package from shipping box		X		
7	Insert package in the jig		X		
8	Scan package barcode		X		
9	Check package type				X
10	Apply label on package			X	
11	Indicate completed labelling task			X	
12	Scan applied label			X	
13	Check label type				X
14	Remove labelled package from jig		X		
15	Insert package in shipping box		X		

In addition, the members of the FiaD team had never worked together before. It was observed that this created situations in which the members had communication issues between each other due to the fact that they did not have sufficient knowledge of the level of expertise and experience of the colleague team members. Also, the majority of the members of the FiaD team had (on paper) less experience in their own fields of expertise, compared to the representatives from CompanyX, and were not familiar with the type of activity at the CW, and the processes around it. This often resulted in extended discussions during which relatively simple details of the targeted systems were clarified. To conclude, during the intake workshop, it was observed that besides a general planning of activities for the workshop, no specific methods or tools could be identified that were used by the members of the team. Performing the 'Intake' step as a planned workshop helped to establish common ground between the stakeholders, but without specific methods that were known to all members, it was not very effective in supporting the team in their design process and communication of the created designs and the argumentation of considerations towards CompanyX. This suggests a necessity for dedicated design methods and tools for this type of design activity;

- **Return on investment calculations:**
  The potential value of the HRC scenario for the labelling workstation needed to be clarified in discussions between CompanyX and the FiaD team. The FiaD team estimated the cost of their proposed system based on the following items: Cobot, vision system, gripper, basic tooling and hardware and software development/engineering for these parts. Even though some parts of the workstation could be re-used and some new parts could be purchased as standard components (such as the Cobot and the vision system), it was difficult for the FiaD team to estimate how many man-hours and material expenses would be necessary for additional hardware and software development. This resulted in a bottleneck in the assessment of the value of the proposed modification involving the Cobot;

  In addition, it was difficult for the FiaD team to make estimations of the number of human operators, number of products produced per hour, and the number of hours a day the workstation can be operated in a day by the current group of human operators present at CompanyX. Yet, these parameters and making calculations with these parameters is an essential part of computing the return on investment of the proposed HRC scenario. In the future, new methods and tools should be developed that simplify this process and allows the computation of estimates based on an conceptual model of a proposed HRC scenario;

- **Technical and economic enquiry:**
  Two lines of enquiry were observed during the Intake procedure of the FiaD team. The first focussed on the technical aspects of the production system. The second line of enquiry focussed on the economic aspects of the production system. These included details on the number of hours per day that the workstation would be operational, amount of product produced per day, and the projected lifetime of the HRC to be built. It was observed that the level of knowledge between all participants regarding these two topics was not always comparable with each other, and considering that only one business expert was included in the team, economic enquiry was in fact not the expertise of most members of the team;

- **Considerations for the human operator(s):**

  It was already decided by CompanyX that the focus of the HRC design activity would be on a pick & place task at one of the customisation workstations. The human operator at such a workstation currently has so-called ‘direct’ (repeated tasks that add value to the product being handled) and ‘indirect’ tasks (intermittent tasks that need to be executed in exceptional cases, or not repeated in every cycle of the workflow). The human operator of the CW has one indirect task, which is to replace label rolls. In the proposed HRC scenario, this task will become one of the primary tasks of the human operator, which he/she will perform for multiple workstations at the same time. This requires the human operator to maintain an overview of multiple labelling machines and Cobots at the same time. It can be expected that this raises the cognitive load on the human operator. However, such topics were not considered by the FiaD team during the intake workshop;

- **Discrepancies in understanding between stakeholders:**
  When the participants visited the CW for analysis, its location in a noisy environment prevented some team members from hearing the explanations and the conversations that took place about the questions that were asked by team members. During the 'Q&A" session that followed the visit, it became apparent that there were discrepancies between the understanding of different team members of the CW. In the future, all insights about the HRC gained during the analysis should be made accessible and understandable to all the involved designers. Therefore, making audio and video recordings of such visits would be a valuable addition to the design process. These recordings can also be made prior to the visit by the company, and demonstrated on a TV screen prior to the visit**.**

3.3 HRC design by novice designers

As discussed previously in section1.2 and section 3.1, the integration of Cobots into existing human-driven production systems is a relatively new task for automation/systems integrators. Therefore, in the previous section, the design process of a team of HRC designers was presented. However, the objective of this research is to provide novice HRC designers with an adaptable methodology. To address this, the following research question was posed;

RQ3 - What bottlenecks are there for novice designers during HRC design?

In order to provide answers for this question, in this section, three HRC design cases are presented and analysed that were executed by novice HRC designers.

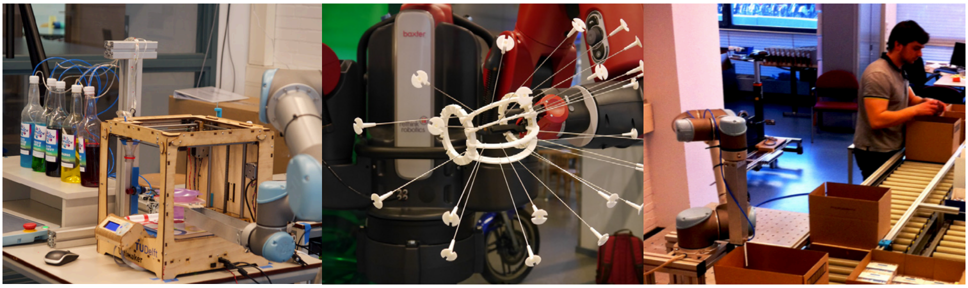
3.3.1 Introduction and goal

While the HRC design activity that was discussed in the previous section talked about a real-life HRC design case, it was performed by a relatively large group of designers that were experts in various topics related to robotics. The targeted group of designers in this research are so-called 'novice' designers. These designers are expected to be experts on the aspects related to the production process of a product, but are not expected to possess any particular knowledge and experience in integrating robots in production systems.

Therefore, in order to learn more about the conceptual design process of HRC scenarios by novice designers, three cases were executed in the laboratory context that was discussed in section 1.5.2. Each case had a different focus, and targeted different types of production tasks. Also, two different types of Cobots were used between the three cases. The final goal in each case was to build a proof-of-concept setup for the proposed HRC scenario. An overview of the three cases is presented in Figure 28 Overview of the three HRC design cases performed as part of RC2

- 'Case A' focused on Robustness and safety. This case required the operation of the HRC scenario during several hours with real-life users.
- 'Case B' focused on Interaction with user. This case required a close interaction between a human operator and a Cobot.
- 'Case C' focused on Performance. This case required the created HRC scenario to have a comparable performance to that of an entirely manual process.

Next, each case will be presented with respect to the HRC scenario that was developed, and the lessons learned during the development and the proof-of-concept building processes.



Case A

Case B

Case C

Purpose of HRC		
Shaved ice production	Lampshade assembly	Packing groceries
Focus of the design activity		
Robustness & Safety	Interaction with user	Performance
Number of designers		
3	5	2
Number of operators		
1	1	1
Type of Cobot		
Universal Robots - UR5	Rethink Robotics - Baxter	Universal Robots - UR5
Degrees of freedom		
6	7	6
Reach		
850mm	1260mm	850mm
Payload		
5kg	4kg	5kg
Safety		
TUV approved	ISO 10218-1 Compliant	TUV approved
Graphical user Interface		
no	yes	no
Tactile user interface		
yes	no	yes

Figure 28 Overview of the three HRC design cases performed as part of RC2.

3.3.2 Case A: Shaved ice production

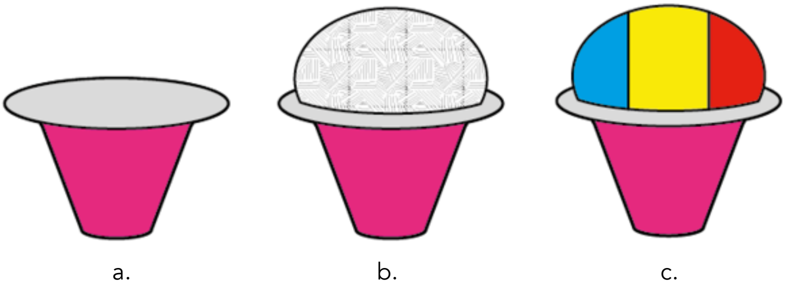


Figure 29 Steps of shaved ice production; (a) empty cup; (b) cup with ice; (c) cup with ice and syrup.

In 2014, for a “family day” at the Faculty of Industrial Design Engineering, Delft University of Technology, the faculty wanted to demonstrate innovative research in an entertaining way for the layperson. Following this, a decision was made to build a Cobot system to serve shaved ice to visitors of the faculty (Figure 29). For one serving of shaved ice, a portion of ice needs to be shaved using an ice shaving machine and dispensed into a cup. The ice shavings are then decorated using coloured and flavoured syrups. This allowed the exploration of the process and challenges involved in designing a HRC scenario in which a digital production machine (syrup printer), a manually operated machine (ice shaver), a Cobot and a human operator was needed.

3.3.2.1 Designers

The author was involved in designing, building and operating the system together with two other novice HRC designers. The system needed to be designed and built within 40 man-hours, and targeted a design problem which is in line with the HRC design objectives as presented in section 1.4. The main objective of the design activity was to create a HRC setup that was robust enough to operate without problems during the event that it was being developed for, and be safe for the visitors of the event.

3.3.2.2 HRC scenario

This HRC design process started without an existing production system that could be used to base the HRC design on. However, the product was defined before starting the design process. Existing peripherals and materials available to the designers helped to define the robot elements. Details of each HRC entity in the resulting HRC scenario were as follows:

Table 7 Parts of shaved ice product and the sequence in which it was produced.

Part name	Sequence	Quantity	Description
Ice cup	1	1	Plastic cups, large enough to hold one serving of shaved ice. In each serving, the recipient inserts a new cup into the gripper of the UR5.
Ice shavings	2	100 g	Ice shavings are produced using the manually operated ice shaving station. The ice shaving station contains a block of ice (1kg). New ice blocks are kept in a freezer until needed.
Syrup toppings	3	Five flavours x 1lt	The syrup printer is able to print with five syrups simultaneously. During each cycle of syrup printing 50 ml of syrup is deposited onto the ice layer.

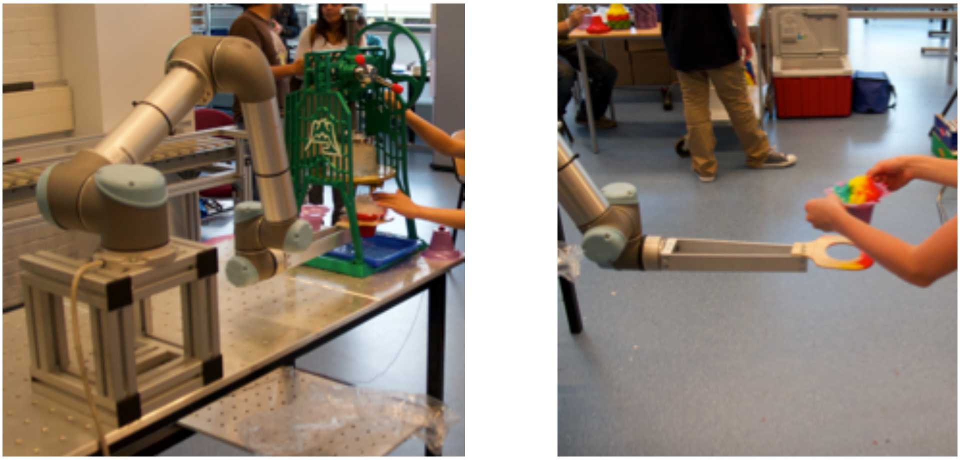
- **Product:**
  The product was a shaved ice dessert (Figure 29). Each serving of shaved ice was served inside a hand-sized plastic cup. The dessert consisted of multiple layers of thinly shaved ice, topped with flavoured and coloured sugar syrup. Each serving of shaved ice was made to order and topped with three selected flavour options (Table 7);

- **Human**:
  The starting point was that one human operator should operate the HRC cell. In this case, the operators were going to be visitors of the faculty. The HRC cell was targeted at both children and adults. The operators were not expected to have any prior experience in robotics or shaved ice production;

- **Robot:**
  The UR5 transported the cup throughout the process. Three separate trajectories were programmed for the robot. During operation, the UR5 followed these trajectories in the same sequence each time. After each trajectory was executed, the UR5 waited for a signal to move to the next location. The first signals were provided by input from the human operator in the system, while the syrup printer provided the third signal. Once the third trajectory was executed, the UR5 waited for the first signal again;

- **Ice shaving station:**
  The shaving station contained a large block of ice that was transformed into thin slices by turning a handle (Figure 30, left). Once the UR5 placed an empty cup under the shaving station, the human turned the handle through and shaved ice was deposited into the cup;

- **Syrup printer:**
  The syrup printer applied syrup topping onto the shaved ice (Figure 28, Case A). Although a specialised syrup printer was not available, it was devised by transforming a standard 3D-printer. This required the integration of pneumatic valves, an air-



a. b.

Figure 30 (a) A human operator operating the ice shaving station and shaping the ice, while the UR5 is holding the plastic cup; (b) UR5 serving the final product.

compressor and a self-made interface between the 3D printer and the UR5. Once the operation of the syrup printer was started, it executed the three pre-programmed syrup-dispensing sequences, as appropriate.

- **Workflow:**
  The task allocation for the HRC cell is shown in Table 8.

Discussion

The aim in this case was to design and test an operational HRC cell in 40 man-hours and the HRC cell was realised within this timeframe. The main objective was to create an HRC setup that was robust enough to operate without problems during the event that is was developed for, and be safe for the visitors of the event to operate it. The resulting system was robust enough to operate during the four hours required. Later, the HRC cell was deployed for a second time, for a further another four hours, for a subsequent public event, during which an estimated 150 servings of shaved ice were served. In addition to theses results, there were three other aspects that should be mentioned about the resulting system and the design process.

Safety: The Cobot that was used enabled the realisation of this HRC cell without the requirement for safety fences or other safety-guarding equipment. Yet, as a precaution, an additional human operator observed the cell during its operation and held a 'dead man's switch', to be pressed in case of a dangerous situation. If this switch was pressed, the system needed to be re-initialised, which could only be performed by this human operator. During operation, this button was used several times due to the unexpected presence of a

Table 8 HRC Workflow for making shaved ice

#	Task	Human Operator	UR5	Shaving station	Syrup printer
1	Pick cup	X			
2	Place cup in end-effector	X			
3	Indicate task completion	X	X		
4	Move to location 1		X		
5	Shave ice	X		X	
6	Indicate task completion	X	X		
7	Move to location 2		X		
8	Choose syrup printing pattern	X			X
9	Print selected pattern				X
10	Indicate task completion		X		X
11	Move to location 3		X		
12	Pick shaved ice	X			

person in the working area of the Cobot. Sensors that are able to sense the presence of a human, and instruct the robot to move more slowly, or pause operation, would have been more convenient to use in this case. This way, an additional human operator would not be needed.

Interaction: A custom gripper was built for the Cobot to hold the shaved ice cup. While the gripper performed successfully, the insertion of the cup needed to be confirmed manually through the interface of the Cobot, by the master operator. This task could have been automated by placing an additional sensor into the gripper to sense when a cup was present. This should be added in a next design iteration.

The other means of interaction with the robot was a button that was placed next to the shaving station. This button was used to indicate when the shaving task was completed by the human operator. While this means of interacting with the Cobot functioned well during the operation of this experimental setup, it was not intuitive for the visitors that this button should be used. In the future, other means of interaction with the Cobot, such as voice command could be used as a more intuitive way of interacting with the Cobot.

3.3.3 Case B: Lampshade assembly

a. b.

Figure 31 (a) Assembled lampshade (Image courtesy of, Inter IKEA Systems B.V.); (b) Detail of one of the lampshade "petals". (Juan Ismael (free3d.com))

In this case, the challenge was to design and build a small production cell in which a Cobot provides both procedural and physical assistance to a human operator during the assembly of a product from IKEA. Most products at IKEA are sold as kits and are assembled by customers after purchasing. This type of product reduces transportation costs, and assembly costs during production, thereby reducing the retail price. However, it is well-known that consumers of flat-packed products often consider the assembly process as cumbersome and unpractical (Petri 2013). Cobots could help to overcome this bias by supporting customers during the assembly of such products. In 2014, for the Minor Program in 'Advanced Prototyping' at Delft University of Technology, an opportunity to develop such a system emerged.

3.3.3.1 Designers

The HRC cell was designed and built as en experimental setup in a laboratory environment by four third-year bachelor degree students from different engineering faculties. The author was involved in supervising the students in their design process, and providing technical support to the students for operating the Cobot. The main objective of the design activity was to create an HRC setup in which the robot and human operator had an intensive interaction during the assembly of a product.

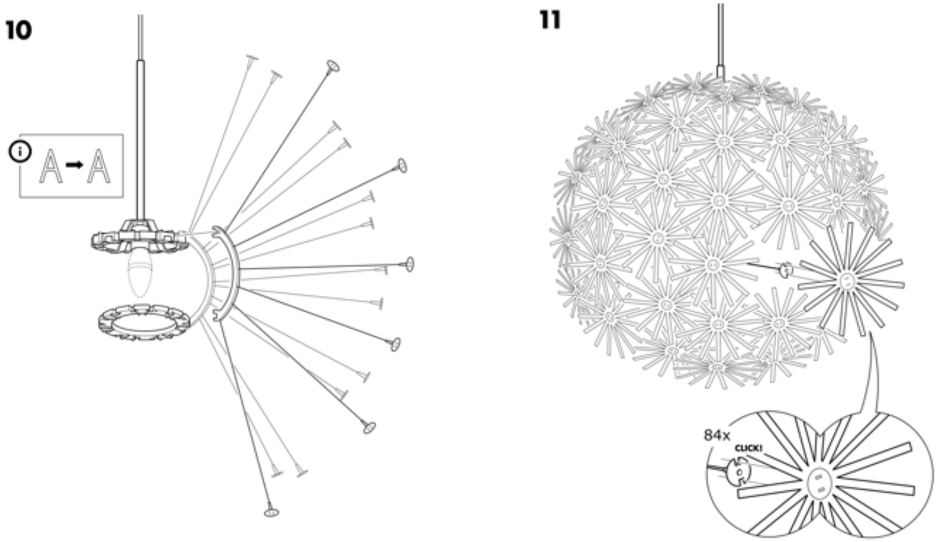


Figure 32 Two assembly steps of the MASKROS lamp as shown in the product assembly manual. (Images courtesy of Inter IKEA Systems B.V.)

3.3.3.2 HRC scenario

This HRC design process started without an existing production cell on which the HRC scenario could be based. However, the HRC entities that needed to be used were already defined in the design brief given to the designers. These were as follows:

- **Product:**
  The subject of the assembly task is a product sold at IKEA, the "MASKROS" lampshade (Figure 31). The execution of the assembly of the product was carried out using an instruction manual, which was provided together with the product. This manual contains all necessary information and a list of the tools needed for assembling the product. The assembly process consists of 10 steps during which the frame of the lampshade is constructed (Figure 32, left), after which 84 so-called 'petals' are assembled onto the main body of the lampshade (Figure 32, right).
- **Human:**
  One human operator operates the HRC cell at a time. In this case, the operators are the visitors of the final exhibition of the 'Advanced Prototyping' Minor (Figure 34a). The design of the cell was therefore targeted at operators aged mainly between 18 and 30 years. The operators were not expected to have any prior experience in operating robots, but were assumed be able to read, understand English and be able to see text that is displayed on the screen of the Cobot;

- **Robot:**
  For realizing the HRC cell, a Baxter Cobot was used, which has two articulated arms, a GUI and a set of control buttons located on its hands and arms. The version of Baxter used in this case needed to be programmed and controlled through the ROS environment. Baxter was equipped at the end of one of its arms with a vacuum gripper, and on the other arm, a linear actuated gripper. The vacuum gripper was designed specifically to handle the petal parts of the lampshade assembly. The linear gripper was used to hold the frame of the lampshade onto which the petals would be assembled.
- **Assembly support tools:**
  The version of Baxter that was used for the HRC cell did not provide an out-of-the-box solution for visual recognition of objects. Unfortunately the involved designers did not have the level of knowledge to create their own programs that would allow Baxter to use its cameras to recognize and monitor objects when handling them. Therefore, special tools were designed and built to provide Baxter with fixed locations to locate and pick parts of the assembly. A 'petal dispenser' was developed in order to provide Baxter with a stable location to pick the petals from (Figure 33a). The dispenser contained a batch of 42 petals. After each petal was picked, a new petal was available for picking at the same location. The second tool was a 'rib rack' that held the 14 petal ribs at the start of the assembly process. When needed, the human could pick a new petal rib from the rack.
- **Workflow**
  At the start of the assembly process, the HRC cell is prepared by an assistant who fills the petal dispenser and the rib rack with the parts needed for the assembly process of the lampshade, and places these in front of Baxter. In this state, any user can start the assembly procedure by interacting with Baxter through its buttons (Figure 34.a). Baxter provides the user with feedback and instructions through its GUI (Figure 34.b).

Table 9 Details of the product parts in the production cell

Part name	Sequence	Quantity	Description
Top assembly	1	1	The fitting for the light bulb, the electrical cable and connection, ceiling mounting pieces etc.
Bottom piece	2	1	This part is attached at the bottom of the lamp.
Petal rib	3	14	These parts connect the top and bottom parts of the frame, and have six connection points for petals.
Petal	4	84	These parts are attached to the ends of the metal wires on each petal rib.


a. b.

Figure 33 (a) Petal ribs assembled onto the top assembly; (b) Two petal dispensers.

Table 10 HRC Workflow for assembling the MASKROS lampshade

#	Task	Human Operator	Baxter	Petal Dispenser	Rib Rack
1	Select product 'MASKROS'	X	X		
2	Teach location of petal dispenser	X	X	X	
3	Pick top assembly	X			
4	Attach top assembly to right gripper	X	X		
5	Indicate completion of task #4	X	X		
6	Pick rib from rib rack	X			X
7	Pick bottom piece	X			
8	Attach rib to top assembly	X	X		X
9	Attach bottom piece assembly to the top assembly	X	X		
10	Indicate completion of tasks #6, 7, 8 and 9	X	X		
11	Pick petal		X	X	
12	Hand over petal to operator	X	X		
13	Attach petal to rib	X	X		
14	Indicate completion of task #9	X	X		
11	Count six repetitions of task #14		X		
12	Turn top assembly		X		
13	Instruct to execute task #6 and #8	X	X		
14	Count 13 repetitions of task #12		X		
15	Indicate completion of assembly task	X	X		

> Once the user selects the correct product that he/she wants to assemble, Baxter provides the human operator with detailed instructions for each assembly step according to the state transition diagram as shown in Figure 35. The workflow for assembling the MASKROS lampshade using the HRC cell is shown in Table 10.

Discussion

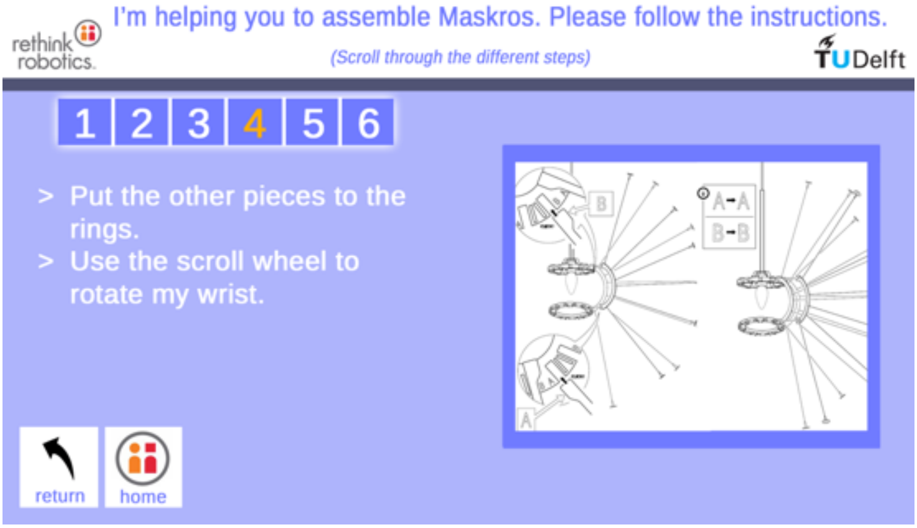
In this case, the aim was to design a robot-assisted assembly cell in which a Cobot not only provides physical, but also procedural assistance to a human operator, by guiding him/her through the assembly steps of a product through its embedded GUI and by performing some of the physical assembly steps automatically. Using a Baxter Cobot, an experimental HRC cell was built for assembling a lampshade. The HRC cell was designed and built by four third-year bachelor degree students during 160 man-hours spread across 10 weeks. The developed setup was demonstrated to the audience of the final exhibition of the Minor Program in 'Advanced Prototyping' at Delft University of Technology. During this event, several visitors performed the assembly of the MASKROS lamp, of which some details were captured in the following quote,

> *"… During the exhibition in the central hall of the Industrial Design Faculty, the robot is helping the visitors to assemble a MASKROS from IKEA, the dandelion lamp with paper fluff. The robot picks up the fluff and rotates the lamp holder a bit further, so that the worker can easily insert the fluff into the lamp. However, the system does not work very well yet… Baxter needs to train more" Bart van de Weijer, de Volkskrant (van de Weijer 2014)*

This shows that while the developed setup can be seen as a proof-of-concept of the proposed HRC scenario, its performance was not up to the standards that would make this a viable setup in a real-life case.

To conclude, having two articulated arms, an integrated operator-facing screen, several integrated tactile buttons and a pedestal with wheels, Baxter proved a valuable, rapid prototyping and development device for simple automation tasks. However, the programming of the robot using Python and ROS proved challenging for the (industrial design bachelor-level) designers. Even though libraries for different functionalities of the robot were provided along with example code, the designers needed to spend several days to program basic functionalities and to access its GUI. These kinds of bottlenecks during the development of the HRC scenario prevented the designers from performing multiple design iterations and refine the interaction capabilities of their proposed HRC scenario.

a.



I'm helping you to assemble Maskros. Please follow the instructions.

(Scroll through the different steps)

- > Put the other pieces to the rings.
- > Use the scroll wheel to rotate my wrist.

b.

Figure 34 Image and screenshot of the system. (a) a visitor to the exhibition, assembling a MASKROS lamp with the help of Baxter. The user can interact with Baxter using buttons placed on its wrists and arms; (b) a screenshot of the graphical user interface that is shown on the screen of Baxter during the assembly activity.

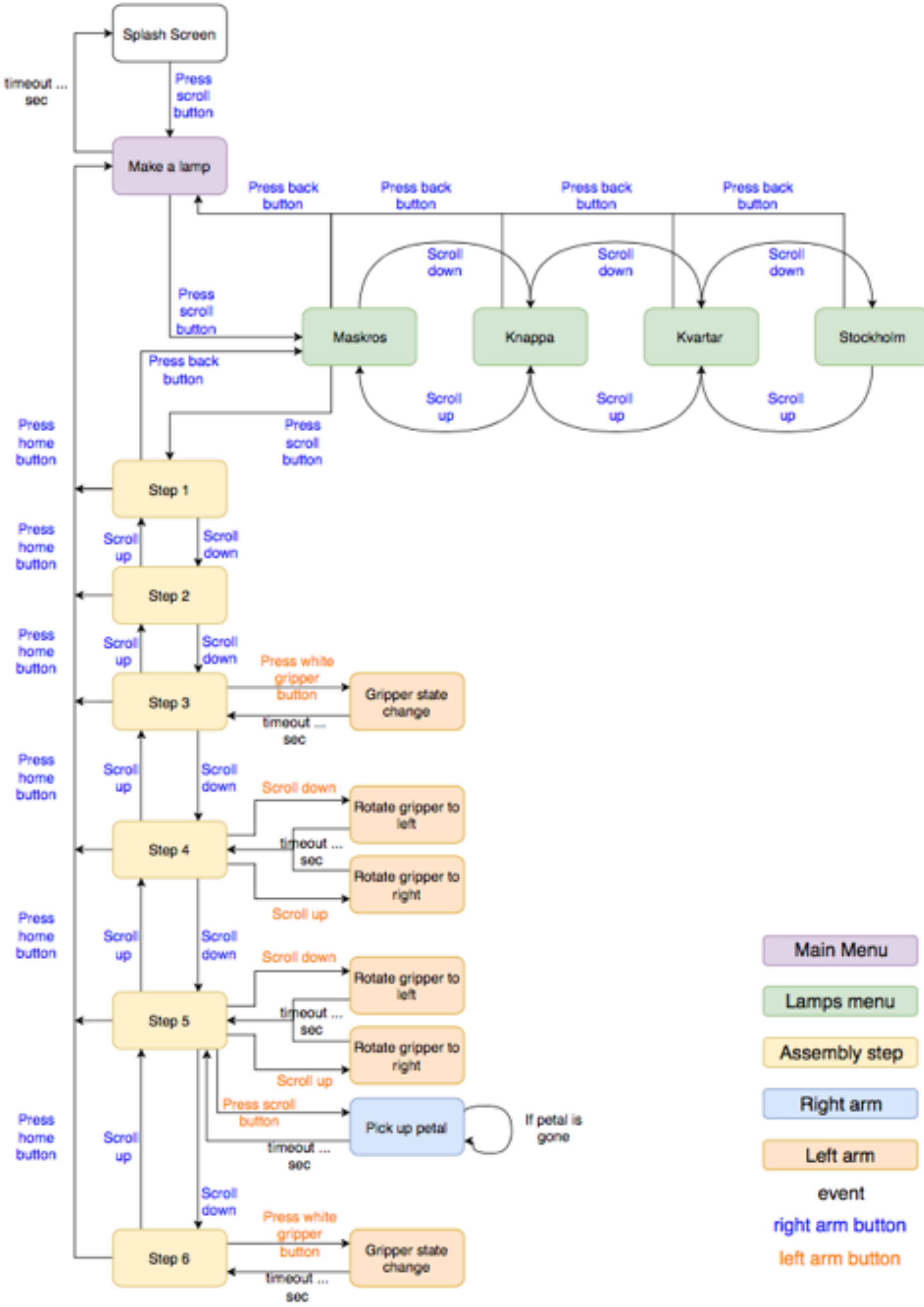


Figure 35 State-transition diagram that was created for implementing the interactive functions of Baxter

3.3.4 Case C: Packing groceries

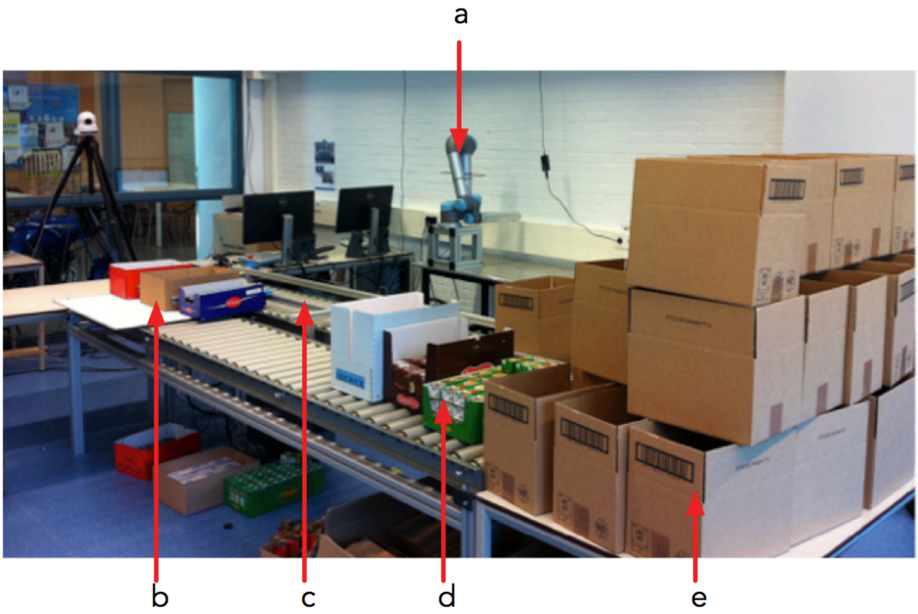


Figure 36 A view of the setup used for Case C, a: Cobot, b: products (5-7), c: conveyor, d: products (2-4), e: shipping container

In production facilities, a generic type of product-handling task is a so-called "pick & place" task. Automating these tasks using robots has become increasingly more accessible and affordable with the introduction of Cobots. Through this, it has also become possible to create HRC scenarios in which human operators can work in close proximity to Cobots, and where Cobots can be re-located easily when needed. A similar scenario was also the subject of the design activity of expert HRC designers as discussed in section 3.2.

This HRC design case is based on an experimental manual pick & place production line (Figure 36), which was located in a laboratory environment at the Faculty of Industrial Design Engineering, Delft University of Technology. Using this production line, six different products can be packed into a shipping container that is moved along a conveyor by human operators (Figure 37). More details of this process are provided in the next section.

3.3.4.1 Designers

Two designers were involved in designing this HRC scenario. Both of which were PhD. students and had background in engineering. Both designers had no prior experience in developing HRC scenarios and had never worked together before.

Table 11 Details of the product parts in the production line

Part name	Sequence	Quantity	Size (Height x Length x Width)
Shipping container	1	1	300 mm x 280 mm x 200 mm
Boxed juice	2	1	120 mm x 50 mm x 38 mm
Chocolate waffles	3	1	95 mm x 57 mm x 37 mm
Boxed sweets	4	1	61 mm x 43 mm x 18 mm
Coffee milk cups	5	1	78 mm x 40 mm x 19 mm
Cotton buds (boxed)	6	1	110 mm x 90 mm x 45 mm
Canned tomato paste	7	1	55 mm (diameter) x 77 mm (height)

The main objective of the design activity in this case was to create an HRC scenario in which the tasks of one of the human operators in the manual production process can be allocated to a Cobot when necessary (i.e. when the human operator is not available). This requires the Cobot to be placed next to the human operator in the production line and be made operational in a short amount of time. In such a case, the performance of the resulting production line should be at a comparable level to that of the manual assembly line.

3.3.4.2 *Existing production cell*

The experimental production line setup shown in Figure 36 was originally built for experiments relating to situational awareness of human operators during production scenarios. This setup consisted of the following components;

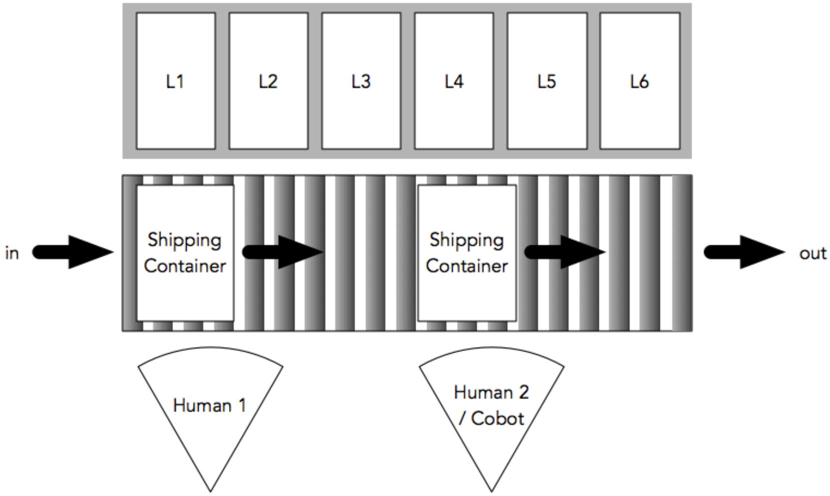


Figure 37 Plan view of the manual pick & place production line.

- **Product:**
  The product that is produced on this production line is a cardboard box containing a selection of grocery products. The grocery products are picked by human operators from product container. These containers contain multiple items of the same product (Figure 37.L1-6). These products are placed into the cardboard box. Each product tray has a different size, and the shape/size/rigidity/centre of gravity of each product is different. In addition, each product is stacked in a different way within their respective trays. Details of the products are provided in Table 11;
- **Human:**
  There are two human operators (Human1, Human2) that work on the production line who execute their tasks simultaneously. The two human operators stand on one side of the setup, next to each other (Figure 37). The task of the Human 1 is to pick products from product locations L1-L3 and place these products into the shipping container in front of him/her. After this he/she pushes the shipping container towards Human2. The task of the Human 2 is to pick products from product locations L4-L7 and place these products into the shipping container in front of him/her. He/she then pushes the shipping container towards the end of the conveyor. Human1 is also responsible for picking the shipping boxes from a stack and placing these on the conveyor.
- **Conveyor:**
  The conveyor used in this case is a so-called roller-conveyor. This conveyor allows easy transportation of products that are placed on it from one side of the conveyor to the other. ;
- **Workflow:**
  The workflow in the existing cell is shown in Table 12.

3.3.4.3 HRC scenario

The HRC design task was to transform the existing manual production line in such a way that it would be possible to introduce a Cobot at the place of Human 2 when necessary. This was achieved by mounting a Cobot onto a moveable platform (Figure 36, a). In addition, several modification needed to be made to the conveyor in order to make sure that the location of the shipping boxes stayed fixed during the pick & place task of the Cobot. Further details of the HRC scenario are as follows;

- **Product:**
  In the HRC cell, the product remained the same to a large extent. However, one product (P4) needed to be removed from the assembly sequence due to the reaching envelope of the used Cobot;

Table 12 Workflow in the existing production cell

#	Task	Human 1	Human 2
1	Pick empty container	X	
2	Place box on the conveyor	X	
3	Pick P1 from location L1	X	
4	Place P1 in container	X	
5	Pick P2 from L2	X	
6	Place P2 in container	X	
7	Pick P3 from L3	X	
8	Place P3 in container	X	
9	Move box to next location	X	
10	Pick P4 from L4		X
11	Place P4 in container		X
12	Pick P5 from L5		X
13	Place P5 in container		X
14	Pick P6 from L6		X
15	Place P6 in container		X
16	Move box off the conveyor		X
"P" refers to "picked item", "L" refers to pick/place location			

- **Human:**
  In the HRC scenario, there is one human operator in the HRC cell who executes the tasks of Human1 in the existing cell. The tasks of Human2 are allocated to the Cobot and the mechanised conveyor;

- **Robot:**
  A Cobot (Universal Robots- UR5) was used take over the tasks of Human 2 in the workflow. Therefore, it was positioned in the location of Human2. However, the reach of the Cobot was not the same as Human2. For this reason, P4 was removed from production sequence. The Cobot was equipped with a vacuum gripper suitable for picking P5 and P6;

- **Mechanised conveyor:**
  The mechanised conveyor in the HRC scenario was used as an aid in handling the flow of boxes between the human operator and the Cobot. The conveyor also acted as a buffer between the two. The existing conveyor was mechanised using pneumatic plungers that could block the flow of boxes, and retro-reflective sensors that detected the presence of boxes at certain locations on the conveyor. The controller of the Cobot controlled the pneumatic plungers and light gates, and the task sequence was also programmed into this controller. This allowed seamless integration of the tasks of the Cobot and the mechanised conveyor.

- **Workflow:**
  The task allocation in the HRC scenario is shown in Table 13.

Discussion

The aim in this case was to create an HRC scenario in which the tasks of one of the human operators in the manual production process can be allocated to a Cobot when necessary (i.e. when the human operator is not available). This was achieved by developing a plug & play solution that could be placed at the location of one of the human operators of in the production line (Cencen et al. 2014). The lessons learned in this case can be grouped in two categories;

Plug & play: The input/output module and programmable logic controlling functionalities of the used Cobot allowed sensors and actuators to be connected to the conveyor, integrating them into the workflow of the robot in a straightforward fashion. The waypoint teaching functionality allowed the programming of the pick & place paths without complicated programming. These helped to realise the plug & play functionality of the HRC scenario. However, next to these advantages provided by the Cobot, there were two shortcomings that were related to the use of a Cobot for automating a manual process.

Table 13 Workflow for the HRC pick & place cell

#	Task	Human 1	Cobot	Mechanised Conveyor
1	Pick empty container	X		
2	Place box on conveyor	X		
3	Pick P1 from location L1	X		
4	Place P1 in container	X		
5	Pick P2 from L2	X		
6	Place P2 in container	X		
7	Pick P3 from L3	X		
8	Place P3 in container	X		
9	Move box to next location	X		X
10	Move box to position		X	X
11	Pick P5 from L5		X	
12	Place P5 in container		X	
13	Pick P6 from L6		X	
14	Place P6 in container		X	
15	Move box off the conveyor		X	X
"P" refers to "picked item", "L" refers to pick/place location				

Matching the performance of manual operation: When using the plug & play solution, the production line was able to process fewer types of products (five instead of the original six) due to the restricted reach of the Cobot that was used. Even though the used Cobot had a reach of 850mm (which is comparable to the arm-length of a human operator), and 6 degrees of freedom, it was not possible to reach the products at the location that was farthest to the robot. This was due to the fact that while a human can extend his/her reach by leaning forward from the waist when needed, the used Cobot was not able to perform such an action. Therefore, when selecting a Cobot for replacing a manual task, the indicated reaching envelope of a Cobot should not be taken as a guideline. A 3D modelling and simulation environment in which the reaching envelopes of various Cobots can be evaluated with respect to the manual production task would be a valuable asset in such a case.

In addition, when the Cobot was pushed in its speed limit and was made to operate at the limits of its envelope of reach, the robot failed more often. Cobots are designed to operate at lower speeds compared to regular industrial robots, so that they can be placed safely alongside humans in production cells. Therefore, it should be taken as a rule of thumb during conceptual design of HRC that, replacing a manual task with a Cobot will result in a higher cycle time for that task.

3.3.5 Discussion

In this section, three HRC design cases were presented that were performed by novice HRC designers. Each case had a different focus, and targeted different types of production tasks. Also, two different types of Cobots were used between the three cases. The final goal in each case was to build a proof-of-concept setup for the proposed HRC scenario. These cases have shown that while small teams of novice designers are able to design and build functional HRC scenarios in a limited amount of time, the use of Cobots does not directly enable a straight-forward design and implementation process for HRC scenarios and that the aspects of safety, robustness, interaction and performance remain a topic that the designers are unable to address and resolve during their design processes.

3.3.6 Influential factors for designing HRC

Through the analysis of the HRC design case of experts presented in section 3.2, and the three HRC design cases by novice designers presented in section 3.3, a better understanding of HRC design has been achieved. This understanding spans over various aspects relating to the design process, the design subject, and the designers of HRC design. These aspects are presented in an overview of 'influential factors' in Figure 38.

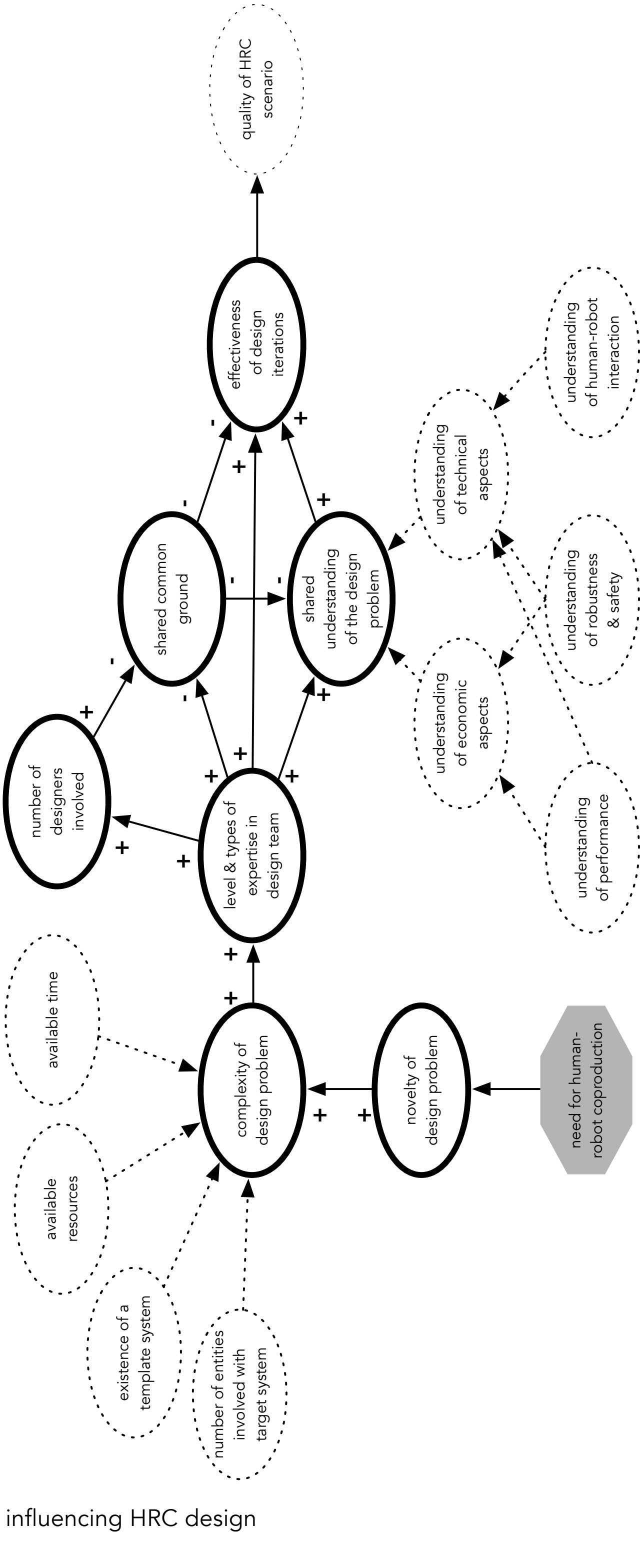


Figure 38 Factors influencing HRC design

In this figure, the positive and negative influences of seven key factors (indicated by thicker borders) are shown, each of which play a role in defining the quality of HRC scenarios. Next, these factors will be further elaborated.

3.3.6.1 Novelty of design problem

The novelty of a problem that is presented to the designers, with respect to the state-of-the-art, influences the complexity of the design problem. In this research, the main factor influencing 'novelty' is the need for human-robot collaboration in the targeted system. The design of HRC scenarios is a relatively new phenomenon, and designers have little to no experience of successful HRC scenarios from which they can draw inspiration or deduce relevant principles for the problem being addressed. This contributes as an influence to the complexity of the design problem.

3.3.6.2 Complexity of design problem

Based on the findings in this chapter, next to the influence of the novelty of the phenomenon of HRC design, there are four factors that influence the complexity of HRC design problems. These are:

- **Available time:**
  The time that is available to complete a HRC design activity. This time is determined by the time of starting the design activity and the final deadline on which the HRC scenario should be operational;
- **Available resources:**
  In addition to available time to complete the design, the amount of time that can be effectively spent on the design process is dictated by the allocated funds. Furthermore, any equipment and human resources (i.e. machines, human operators etc.) that are required in the design should also be considered as factors that influence the complexity of the HRC design problem being addressed;
- **Existence of a template system:**
  During the studies in this chapter, it was seen that a HRC design process can target either a system that needs to be designed from scratch, or which involves some alterations to an existing system. Both situations require different approaches and have their particular bottlenecks. Therefore, these parameters influence the complexity of the design problem. ;
- **Number of entities involved with target system:**
  The number and variety of types of entities (i.e. Human, Robot and Product) have an influence on the complexity of the design problem. When this number increases, or when more types of the same entity are present, designers have to put more effort into capturing and conceptualising their details;

Being influenced by the abovementioned factors, the complexity of the design problem influences the level and type of expertise that is needed for the HRC design activity.

3.3.6.3 Level and types of expertise in design team

In the studied cases throughout this chapter, it was observed that an increased complexity of HRC design problems requires designers with different types of expertise to be involved with the design activity. The previous experience(s) of the designer(s) involved in the design process has an influence on the collective understanding of the design problem, as inferences can be made based on previous experiences. As a result, the required level and type of expertise in the HRC design team influences four other factors; (i) Number of designers involved, (ii) Shared common ground, (iii) Shared understanding of the design problem, and (iv) Effectiveness of design iterations.

3.3.6.4 Number of designers involved

In order to reach a higher level of expertise in the HRC design process, and to involve more types of expertise, more designers need to be involved in the process. Considering that these people are selected based on their expertise in a field that the other members that are involved with the design process do not have, it has an influence on the shared common ground between these designers.

3.3.6.5 Shared common ground

When individuals from different backgrounds and perspectives work together they need to: (i) define a problem; (ii) establish an agenda; and (iii) implement a solution (Gray 1989). Considering the collaborative work of designers who are experienced in their own disciplines, but who do not share a common understanding of HRC, a certain level of common ground needs to be established. However, this requires time and structure to ensure an effective and efficient way of collaborating.

3.3.6.6 Shared understanding of the design problem

Increasing the number of designers that are involved with the design process is assumed to support a better understanding of the design problem, as designers from different disciplines can address various parts of the problem. In the cases that are presented in this chapter, it was observed that the understanding of a HRC design problem is further influenced by several factors that can be grouped in two categories, namely:

- **Understanding of technical aspects:**
  A HRC scenario is a socio-technical solution in the context of a human-driven production system. Therefore, its design process involves both economic and technical considerations. The understanding of the technical aspects of the HRC scenario contributes to a large portion of the total understanding of the design problem.
- **Understanding of economic aspects:**
  A HRC scenario should not only fulfil its technical requirements, but it should also match the economic requirements of the production system that it is in. However, in the study of expert HRC designers that was presented at the beginning of this chapter, it was observed that designers of production systems are less experienced in making such trade-offs, and can benefit from additional support. The understanding of the economic aspects of the HRC scenario contributes to a relatively smaller, but nonetheless essential part of the total understanding of the design problem;

Abovementioned categories contain the following factors;

- **Understanding of performance:**
  The performance of a HRC scenario concerns its productivity. Considering that productivity is defined by the ratio between output and input, HRC designers should have an overview of the costs related to a HRC scenario (economic aspects) and the number of products that it can produce (technical aspects).
- **Understanding of robustness & safety:**
  The robustness of a HRC scenario relates to its potential to be available for production, and the time between failures. The safety aspect relates to the compliance of the resulting system with safety regulations that govern human-driven production systems, and the capability of designers to assess their designs with respect to these regulations.
- **Understanding of human-robot interaction:**
  In order to develop a HRC scenario that is accepted by the human operators and can be operated according to the set standards, its designers need an understanding of human-robot interaction mechanisms that are relevant for HRC. Therefore, this aspect is of influence to the understanding of the technical aspects of an HRC scenario;

3.3.6.7 Effectivity of design iterations

As discussed in section 2.5, HRC design is an iterative activity. The level & type of expertise in the design team, shared common ground, and the shared understanding of the design problem are all of influence on the effectiveness of design iterations. In each of the iterations, an HRC scenario is refined. Therefore, improving the effectiveness of design iterations will in the end contribute to a better overall quality at the end of a HRC design activity.

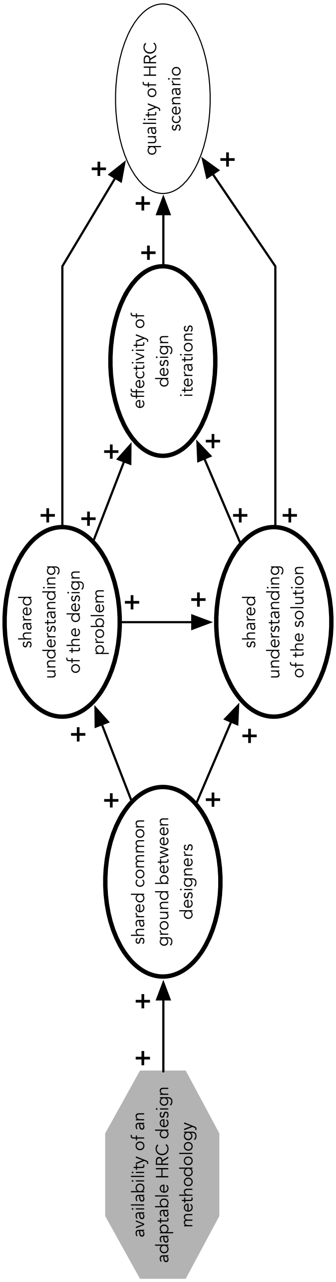


Figure 39 Impact model for a methodology for HRC Design

3.4 Requirements for a methodology for designing HRC

In Chapter 1, the objective of this research was defined as;

> 'To develop an adaptable framework methodology that can be used by novice HRC designers during the conceptual design activities that involve human-robot coproduction scenarios.'

In Chapter 2, HRC design was framed from three perspectives and at the end of this chapter, an "*operator-centred production design*" model was presented which underpins the main procedure of this methodology in four main phases and emphasises an iterative way of working.

In this chapter, based on the HRC design activities of expert and novice HRC designers, an overview of the influential factors in this design activity has been developed. Based on the factors presented in this overview, an impact model for a methodology for supporting HRC design has been presented in Figure 39.

Considering all of the abovementioned insights, the following requirements for a HRC design methodology (for SMEs) are formulated that should further guide the development of the adaptable framework methodology for HRC design. The expectations are;

- Facilitate the establishment and support of common ground between the involved designers.
- Provide a systematic structure for the HRC design process and emphasises an iterative way of working.
- Be applicable by novice HRC designers.
- Allow flexibility in the use of its constructs in order to be adaptable to requirements presented by the contexts that it is being applied in.

Based on the abovementioned insights and requirements, in the next chapter, a conceptualisation of the constituents of the adaptable framework methodology for human-robot coproduction will be presented.

Chapter 4

Related publications

- Dukalski, R., Cencen, A., Aschenbrenner D., & Verlinden, J. C. (2017). Portable rapid visual workflow simulation tool for Human-Robot Coproduction. 27th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM), Modena, Italy, June 27-30, Procedia Manufacturing, vol. 11, pp. 185–197. Elsevier
- Cencen, A., Verlinden, J.C., & Geraedts, J. M. P. (2018). A Design Methodology to Improve Human-Robot Coproduction in Small and Medium Sized Enterprises. IEEE/ASME Transactions on Mechatronics, Vol. 23, No. 3, June 2018

4 Conceptualising an 'adaptable framework methodology for designing human-robot coproduction'

Based on the framing of HRC at the end of RC1 and the established factors influencing HRC design in RC2, four requirements for a human-robot coproduction design methodology (HRCDM) were presented at the end of Chapter 3. Based on these requirements, in RC3 a new HRCDM was conceptualised which comprises various procedures, methods and instruments, which are presented in this chapter.

4.1 Introduction

This chapter presents the 'human-robot coproduction design methodology' (HRCDM), which is an adaptable framework methodology for designing human-robot coproduction. The targeted users of this methodology are those individuals that work in the context of SMEs that make use of human-driven production systems. More specifically, HRCDM is targeted towards engineers and designers in this context who have limited experience in designing parts of production systems, and need support in the conceptual design phase of new HRC scenarios that make use of novel industrial robot technologies, such as Cobots. HRCDM has been developed in order to support the HRC design activity of these individuals and is intended to be used as a set of guidelines, rather than as set of systematic rules that replaces the creative process of design.

A methodology is defined as "a body of methods, rules, and postulates employed by a discipline: a particular procedure or a set of procedures". (Merriam-Webster Dictionary 2019). Therefore, HRCDM contains different types of constituents, which will be elaborated in this chapter. First, the overall procedure, consisting of four phases, is explained. Next, the instruments that were developed or conceptualised for the methodology are described. Finally, the requirements for the methods to be used in the specific phases of the methodology are presented.

For illustrating the various elements of HRCDM throughout this chapter, the product labelling case from chapter 3.2 has been used as an example HRC scenario.

4.2 Overall procedure of HRCDM

To support efficient and effective execution of the HRC design process, and to facilitate the establishment of common ground between designers, HRCDM provides a procedural structure in the form of four consecutive design phases: (i) analysis; (ii) synthesis; (iii) simulation; and (iv) evaluation. These phases are based on the 'operator-centred production design model', as presented in section 2.6. The overall procedure of HRCDM supports an iterative way of working, by which designers are allowed flexibility in emphasising different

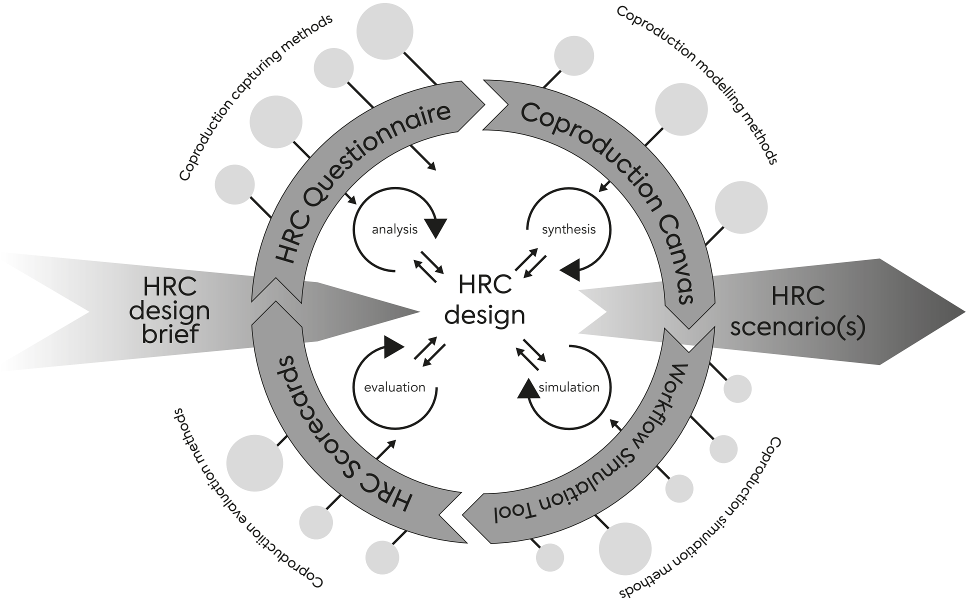


Figure 40 The human-robot coproduction design methodology framework

phases of the design process in HRC design contexts that require either more conceptual or more detailed designs. Figure 40 shows the main framework of HRCDM. An overview of the inputs and outputs of each design phase, together with the used methods, the persons involved, and the location of the design activity is provided in Table 14.

The HRC design brief is the input to the HRC design procedure. A design brief is a document that describes the aim of the design process. The design procedure ends with a decision to perform a new iteration of one or more design phases, or to continue with the implementation of one of the HRC designs that has been generated. Next, the details of each phase and the involved methods and instruments are explained.

4.2.1 HRC Design brief

The first phase of HRCDM (Analysis) is initiated by a design brief. This document contains a description of the design problem, and the requirements for the HRC scenario that needs to be developed. The complexity of the design problem that is described in the design brief (e.g. the type and number of steps in the involved production process, any difficulties related to the environment in which the future HRC scenario is situated, and the resources that are available etc.) will affect the difficulty of the design process. Therefore, based on the design brief, the designers that will be involved in the design process can be selected/invited accordingly.

Table 14 Overview of the inputs, outputs, methods, and stakeholders of each HRC design phase

Phase	Analysis	Synthesis	Simulation	Evaluation
Input	HRC Design brief	HRC requirements & Captured data	Coproduction scenario(s)	HRC Scorecards
Output	HRC requirements	Coproduction scenario(s)	HRC Scorecards	Selected HRC scenario for next development phase
Methods	Coproduction capturing	Coproduction modelling	Coproduction simulation	Coproduction evaluation
Instrument	HRC Questionnaire	HRC Canvas	Workflow Simulation Tool	HRC Scorecards
Who	System owner(s) & HRC designer(s)	HRC designer(s)	HRC designer(s) & Simulation expert(s)	System owner(s) & HRC designer(s)
Where	On-site & Off-site	Off-site	Off-site	On-site & Off-site

HRC design starts either with a request to modify an existing system, or to create a new system from scratch based on a product specification. Each of these cases requires a different approach to analysis and a different course of action throughout the HRC design process. Examples of the two possible types of design briefs are as follows:

- **Existing system**
  A production scenario in which a product is already being produced. The production cell might include (semi) automated machines and one or more human(s). However, a

transformation to the process is needed in order to accommodate a new production plan. This can have (amongst others) two main reasons;

  - System owners wish that the new system includes more automation than the current system (supporting the human operators, or increasing productivity);
  - System owners wish to know if they can produce the new product in the same way and achieve a comparable productivity rate.

- **Proposed system**
  In some cases, the design of an HRC scenario can be initiated by a detailed product design in which the production process for (parts of) the product are described, but specific details of machines and work instructions do not exist yet.

Initially, a design brief should not be expected to be a complete list of details and specifications of the entities that are (and will be) part of the system being developed. Therefore, the design brief should be revised using the emerging details throughout the HRC design process.

4.2.2 Analysis

The Analysis phase is geared towards establishing a good understanding of the requirements of the HRC scenario and its place in the encompassing human-driven production process. During the analysis phase, designers apply Coproduction Capturing methods. These methods allow designers to view their design problem from various angles. The information gathered through these activities should contain details about the current situation and the desired situation. In HRCDM, this information can be formalised using Coproduction Cards, which are symbolic representations of the HRC assets.

4.2.3 Synthesis

The creative processes are initiated when designers have a good understanding of the current and future situations and of all of the required HRC assets in these situations. In HRCDM, during the synthesis phase, Coproduction Modelling methods are applied. These methods mainly revolve around the use of the HRC Canvas, an instrument to develop the information contained on the Coproduction Cards into HRC scenarios. Coproduction cards are symbolic representations of the HRC assets. Multiple scenarios should be developed that describes a different arrangement of these assets. In every iteration step of the synthesis phase, the HRC scenarios are further detailed/expanded/refined, providing new data for the Simulation phase.

4.2.4 Simulation

During the simulation phase, each HRC scenario should be tested for performance through Coproduction Simulation methods. While a formal simulation using specific methods might not be needed for each cycle of the HRC design process, HRCDM prescribes the use of a Workflow Simulation Tool (WST) as a means for the integrated simulation of all assets in HRC scenarios. The WST prescribes the combination of various types of simulations (Computer Aided Design (CAD), event-based etc.) in order to visualise and evaluate the different layers of information, processes and interactions

4.2.5 Evaluation

During the Evaluation phase, the results produced in the simulation are viewed and analysed by the designers and (if needed) with other stakeholders that are (or will be) involved with the HRC scenario being proposed. In HRCDM this phase is supported by HRC Scorecards. The performance of each HRC scenario that has been created during the synthesis phase should be presented on a separate HRC Scorecard. The presented performance indicators should include a summary of quantitative and qualitative measures that relate to each scenario, which should be based on Key Performance Indicators (KPIs) commonly used by HRC designer(s) and system owner(s). Based on the assessment of each HRC Scorecard, designers should take a decision to perform any new design iterations to refine the scenario, or to go forward with the current HRC scenarios to the HRC Deployment phase. Therefore, the possible outcomes of the Evaluation phase are;

- **Improve**
  Perform a new iteration of the complete procedure, or one of the phases. Not all generated HRC scenarios need to be included in the new iteration, and new scenarios may be generated in the new iteration;
- **Continue**
  Select one of the HRC scenarios to continue the development process. In this case, deployment documents should be generated for use in the development process of the chosen HRC scenario.

4.2.6 HRC definition

When a HRC scenario is moved to the HRC deployment phase it should be accompanied by the following information/documents:

- **Deployment schedule**
  A schedule for the deployment process and milestones of the proposed HRC scenario should be documented, for example by using a ‘Gantt chart’. This schedule should

contain information about the installation of the technical equipment for the HRC, its configuration and testing, training schedule for the human operators.

- **Bill of materials**
  Information on all assets of the system, including information about the supply of parts and their availability should be generated. Where applicable and necessary, a parts list and the respective digital models of any custom-made (grippers, jigs, tooling etc.) parts should be provided.
- **Safety assessment**
  The final design of the HRC scenario should comply with the safety standards and regulations that are set for the particular context that the scenario will be deployed in. Therefore, time and resources should be allocated for performing a safety assessment of the final scenario prior to installation and after installation, by certified experts.

4.3 Instruments of HRCDM

In this section, the instruments that have currently been conceptualised for HRCDM are described. These instruments consist of documentation formats and software tools that HRC designers can use throughout the different phases of the design process as prescribed by HRCDM.

4.3.1 HRC Questionnaire

HRC Questionnaire is a document that should be used in the 'Analysis' phase of HRCDM. Such a document is particularly supportive in case the system owner and the designers are not already in a working relationship, and the HRC designers are brought-in to solve a HRC design problem. In its current form, the HRC Questionnaire supports the written and verbal inquiries of HRC analysts, and helps to further develop and refine the Design brief. The current version of the HRC Questionnaire (Appendix C) is developed in cooperation with a panel of interdisciplinary experts from fields including industrial robotics, computer vision, facility layout planning, human resources, operations, end-effector design, business development and project management. The aim of the questionnaire is to address the key questions of each discipline expert, and to integrate common questions between them.

In addition to questions concerning technical and economic details of the design brief, the questionnaire also includes sections that aim to manage the expectancies of the involved stakeholders. In these sections, system owners are informed about the design process, its steps, and what to expect at the end of the process. The expected effort required from system owners with regard to supplying information about the design brief and arranging access to the production system is also documented in the questionnaire.

4.3.2 Coproduction Canvas and Coproduction Cards

For supporting the 'Synthesis' phase of the HRC design activity, a dedicated abstract prototyping instrument has been developed, called the 'Coproduction Canvas'. Abstract prototyping has three main objectives, namely; (i) create an enactable model of the system under development, (ii) create an environment in which the system model will operate, and (iii) create a validation suite comprised of operational scenarios (Wood and Kang 1992). These were used as guidelines for developing this instrument. During each new iteration step of the HRC design process, new Coproduction Canvasses can be created, or a single canvas can be refined. The concept of the Coproduction Canvas has been inspired by the successful Business Model Canvas (BMC), which has proven to be a successful instrument for providing a common language for discussing business models in practice (Osterwalder and Pigneur 2010).

The Coproduction Canvas makes use of a set of dedicated 'Coproduction Cards' to help HRC designers in describing various aspects of HRC scenarios. By doing so, it ensures that designers focus on critically thinking about the entities and their relationships in the HRC

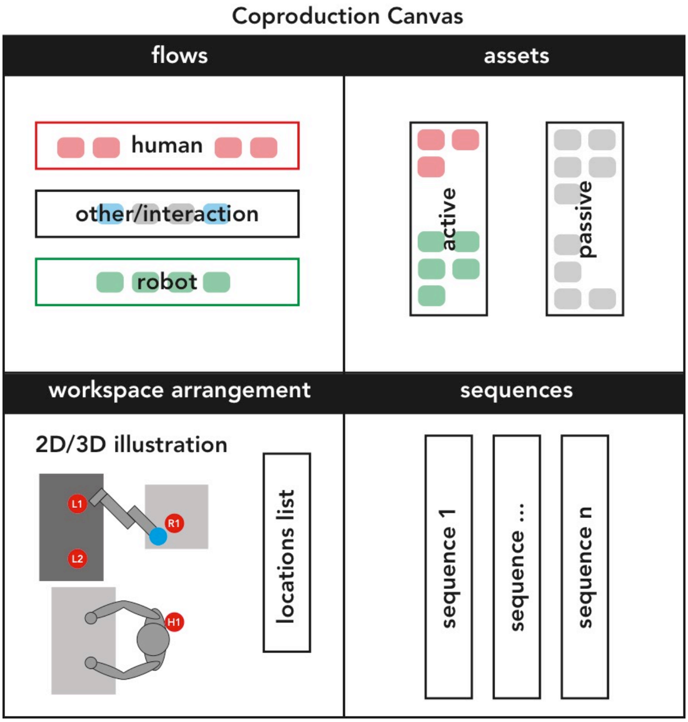


Figure 41 Layout of the Coproduction Canvas and its four fields

scenario, rather than describing each operation and entity in detail in an arbitrary way.

There are eight types of Coproduction Cards. Each card features dedicated sections on which the most important details of each type of HRC entity can be described. The designers fill in the cards based on the information generated during the analysis phase, and the information related to the details of the new scenarios that they are creating. In order to include additional information about each entity, each card provides a dedicated area for taking notes.

The cards are then arranged on the Coproduction Canvas. This contains four fields, namely; (i) Flows, (ii) Assets, (iii) Workplace arrangement, and (iv) Sequences (Figure 41). The details of each of these fields will be elaborated next.

- **Flows**
  In the 'Flows' section, the workflow of the production activity is described. In this section, the 'Human' cards and the 'Robot' cards, (which describe a task that is given to that entity) are laid out horizontally in their own 'lanes'. The cards used in the 'Flows' section are colour-coded with different colors. By definition, a task is "…a goal together with some ordered set of actions" (Benyon 2010). The designers are given flexibility in their choice of the level of detail that they define the flow in. This means that the definition of the how detailed a task is described is up to the designers. Yet, the same level of detail should be maintained throughout the same flow. More or less detailed flows of certain processes can be made separately of each other. In additon, the 'Human' and 'Robot' lanes are separated with a third lane between them on which 'support' or 'interaction' cards can be placed in order to indicate the transitions between the tasks of the human and the robot. Finally, product cards are used to indicate the steps in the process during which a product or part enters or leaves the flow.
- **Assets**
  In the 'Assets' section, all of the entities that are part of the HRC scenario are listed. In order to be used on the Coproduction Canvas, the 'Human', 'Robot', 'Product', and 'Support' cards exist in two variants. These are the 'Flow' and the 'Asset' variants, to be used in their respective areas of the Coproduction Canvas. While on the Asset area, each entity is represented using only one card, in the Flow area of the Coproduction Canvas, multiple instances of the cards should be used. The link between the two variants of the cards in the two areas is established by providing identification numbers on the top-left side of each card (Figure 42) This way, designers can always refer to the details about a card in the 'Flow' area by finding its corresponding card in the 'Assets' area of the canvas. The 'Assets' Field is divided into the two categories, 'Active' and 'Passive'. By definition, the 'Human' and 'Robot' cards should be laid out in the 'Active' and all other cards should go under the 'Passive' category.

- **Workplace arrangement**
  The 'Workplace arrangement' section shows a 2D or 3D illustration of the HRC scenario in which (almost) all entities and specific locations that are of relevance to the active entities in the HRC scenario should be visible. The locations and entities are labeled on the illustration in correspondance with the identifier codes (ID-code) that have been given to them on the 'Asset' cards. The illustration of the HRC scenario is accompanied with a 'Location' card. More details on this card is provided in the 'Location card' section.
- **Sequences**
  The 'Sequences' section is the area in which the different sequences that the entities in the HRC scenario are involved in are listed. There are different sequence cards for describing human-only sequences and robot sequences. These sequences act as an added level of detail to what is shown in the 'Flows' area of the Coproduction Canvas. More details are provided in the 'Sequence cards' section.

Having described the four fields of the Coproduction Canvas, next, each Coproduction Card will be described in detail.

- **Human card**
  For each human operator that will be involved with the HRC, a separate human card should be used (Figure 42). On this card, an 'ID-code' is given to the human operator, by which he/she can be identified in the other fields of the Coproduction Canvas. In addition, the sequences that the human operator is involved in are indicated on the card as well. Furthermore, the card should contain other relevant details about the human operator such as; name, job title, and if this individual is already hired or not.

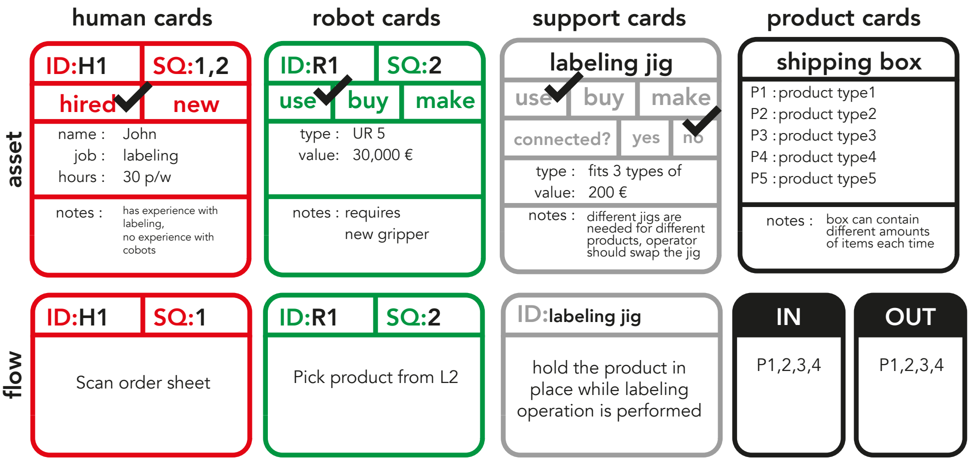


Figure 42 Example human, robot, support and product cards

On the 'Flow' variant of this card, a short description of the task that the human operator should perform must be provided.

- **Robot card**

  For the non-human entities of the HRC scenario that have an 'Active' presence in the scenario, a 'Robot' card should be used (Figure 42). These entities can include; Cobots (or regular robot arms), computers, (computerized) machines, and peripherals that are attached to these entities such as; sensors, actuators, cameras, interfaces etc. On the Robot card, an 'ID-code' is given to the robot entity, by which it can be identified in the other fields of the Coproduction Canvas. In addition, the sequences that the robot entity is involved in are indicated on the card as well. Furthermore, the card should contain information about whether the parts for this entity are already in possession, need to be acquired, or need to be manufactured. On the 'Flow' variant of this card, a short description of the task that the robot entity should perform must be provided.

- **Product card**

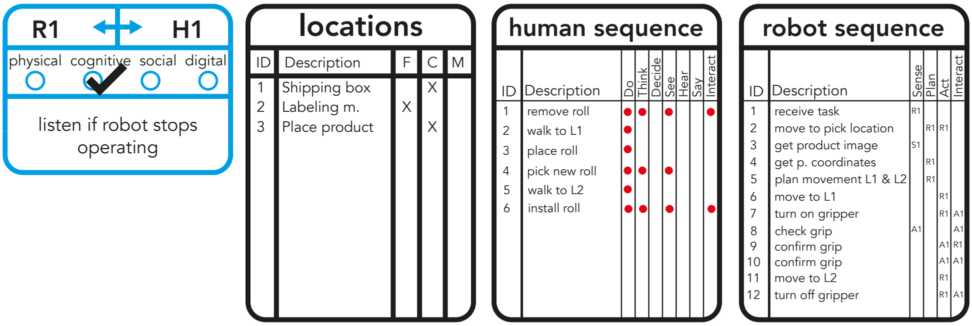
  Each part of the product that is involved in the HRC scenario should be listed using a 'Product card' (Figure 42). On this card, besides the name of the product, information should be included about the physical aspects of the product. The 'Flow' variant of this card indicates if the product part is an incoming or an outgoing part to the workflow. On these cards, the 'ID-codes' of products need to be indicated.

- **Support card**

  All non-human and 'passive' parts of the system should be represented by a 'Support' card. The card should contain information about whether the parts for this entity are already in possession, need to be acquired, or need to be manufactured. On the 'Flow' variant of this card, a short description of the function of this entity in the HRC scenario must be provided (Figure 42).

- **Interaction card**

  The interaction card should be used when communication needs to take place between two entities in the workflow. On the top part of this card, information is provided between which entities the interaction should take place. The card also provides information about whether the interaction is physical, cognitive, social or digital. A physical interaction requires both entities to be at the same place at the same time and to be in physical contact with each other. An interaction should be categorised as cognitive when the senses of the human operator are triggered, and that he/she needs to respond to these stimuli. In addition, a short description of the interaction should be provided.



locations

ID	Description	F	C	M
1	Shipping box		X	
2	Labeling m.	X		
3	Place product		X	

human sequence

ID	Description	Do	Think	Decide	See	Hear	Say	Interact
1	remove roll	●	●		●			●
2	walk to L1	●						
3	place roll	●						
4	pick new roll	●	●		●			
5	walk to L2	●						
6	install roll	●	●		●			●

robot sequence

ID	Description	Sense	Plan	Act	Interact
1	receive task	R1			
2	move to pick location		R1	R1	
3	get product image	S1			
4	get p. coordinates		R1		
5	plan movement L1 & L2		R1		
6	move to L1			R1	
7	turn on gripper			R1	A1
8	check grip	A1			A1
9	confirm grip			A1	R1
10	confirm grip			A1	A1
11	move to L2			R1	
12	turn off gripper			R1	A1

Figure 43 Example interaction, location, human sequence and robot sequence cards

- **Location card**
  The location card contains a list of the locations that are shown on the 2D/3D illustration in the workplace arrangement section of the Coproduction Canvas. The card helps to categorise these locations in three categories. The 'Fixed' category should be used for locations of which the coordinates in space do not change during the workflow. The 'Changing' category should be used for locations that are expected to show variance during the workflow and should be monitored each time the location is used/approached. The 'Moving' category should be used for those locations in the workflow that are expected not to be stationary when they need to be used/approached during the workflow.

- **Sequence cards**
  The entities in the HRC scenario may be involved in more than one sequence of activities that may or may not overlap with each other during the workflow. In order to provide an overview of the steps in these sequences, separate sequence cards should be created. A sequence card should be a list of a specific set of actions that are performed by a specific set of entities. In the 'Flows' field, workflows can be distinguished as being either human-based or robot-based. Therefore, different cards should be used for describing each type of sequence. In the human-based cards, the listed actions can further be categorised according to the following aspects; (i) Do, (ii) Think (iii) Decide, (iv) See, (v) Hear, (vi) Say, and (vii) Interact. On the robot-based sequence cards, the listed actions can further be categorised according to the following aspects; (i) Sense, (i) Plan, (iii) Act, and (iv) Interact. On the robot-based sequence cards, The 'Interact' category allows the indication of the point in the sequence on both types of cards in which an explicit interaction between the 'Human' and the 'Robot' entities should take place. Furthermore, a reference to another sequence card can be made by listing it as an action. This way, overlapping sequences can be made visible.

- **Start, Finish, Repeat cards**
  To indicate the starting and finishing points of a workflow, dedicated cards are used. These cards help to indicate which of the Human and Robot entities has the

responsibility for starting and ending a process. In addition, ‘Repeat’ cards can be used to indicate processes in the workflow that are repetitive.

4.3.3 Workflow Simulation Tool

Compared to the static nature of the models that have been created in the Synthesis phase, in the simulation phase, models should be created that are animated and dynamic. This way the operational and spatial aspects of the proposed HRC scenarios can be elaborated further and discussed. Therefore, for supporting the activities in the ‘Simulation’ phase a dedicated Workflow Simulation Tool (WST) is proposed.

> *“… WST is developed to support in the conceptual design stage, with specific focus on iteration and co-creation. The tool is supposed to be used by specially trained integrators in the context of rapid automation projects, such as envisioned by the Factory in a Day project. Before a production line can be installed and programmed, the integrator visits the site, observes the current workflow, acquires the requirements and makes a general layout for the new envisioned production line, all within a single visit. The WST intends to facilitate the discussion, by providing means to quickly and effectively visualise and document the simulation, allowing for faster iterations, thus arriving at an appropriate solution to an integration problem sooner.”* (Dukalski et al. 2017).

The tool comprises of off-the-shelf software (Visual Components 2018) that enables modelling, simulation and 3D scanning within a handheld portable system.

“Visual Components is a highly extendable CAD solution, offering drag-and-drop 3D

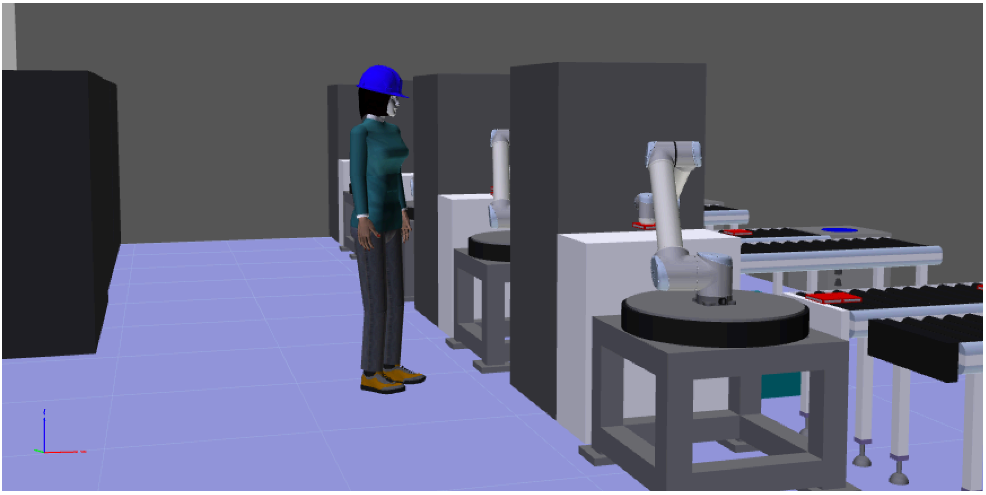


Figure 44 A screenshot from the Workflow Simulation Tool. The presented scenario is the ‘customisation workstation’ case from section 3.2 of this thesis.

> visualisation of animated material flow and offline robot simulation within a single package. In being manufacturer-agnostic and allowing the user to easily expand the library of components (e.g. robot manipulators, conveyors), the software facilitates in simulating a material flow without finalizing the exact technical specification. This was theorized to lend itself highly towards an iterative design process. ”

The tool also features an online repository of automation templates, production machines, Cobots and human models. The 3D-CAD and robotics simulation allows the physical attributes of HRC to be simulated, such as the reaching envelopes of robots and human operators, and make use of Programmable-Logic Controller programs installed in the system.

By using the WST, HRC designers can create digital models of the HRC scenarios that they have created in the Synthesis phase of the HRC design process.

> “A built-in feature of interest was the PDF export, which converts the simulation into an animated 3D environment within the popular portable file format, allowing for a richer documentation, and theoretically more fruitful communication, without requiring from the recipient any additional software”

A pilot implementation of WST has been developed and tested in close collaboration with partners from the FiaD project, and was evaluated as being appropriate to be used in for design considerations of HRC scenarios.(Dukalski et al. 2017)

4.3.4 HRC Scorecards

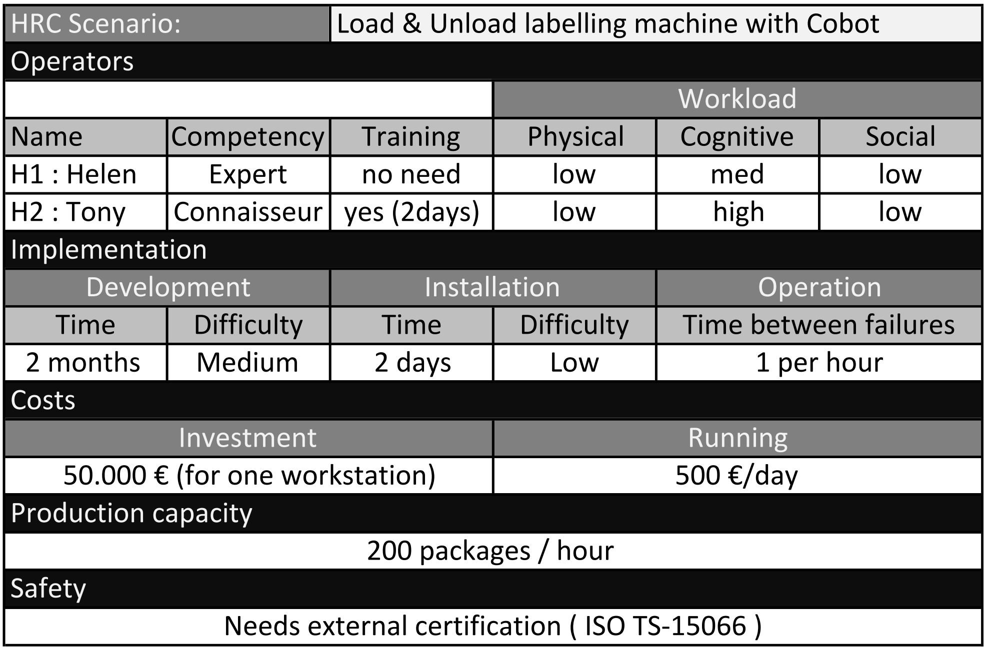
For the ‘Evaluation’ phase of HRCDM, an instrument to support the evaluation of a HRC scenario, and to make comparisons between multiple scenarios is needed. This instrument should also support HRC designers in communicating the created scenarios with other stakeholders that are not involved in the design process, yet will be involved in the decision to implement the HRC scenario or not. Therefore in HRCDM, the use of HRC Scorecards as support during this phase is proposed (Figure 45).

HRC Scorecards are used to summarise KPIs related to each HRC scenario in a clear and comprehensible manner. In the age of product-service systems (PSS), key performance indicators (KPIs) remain valuable measures for the evaluation of system designs that have complicated and intertwined requirements (Mourtzis et al. 2016). Yet, in the context of HRC design, specific KPI’s to evaluate human-robot systems have only recently been taking shape (Ranz et al. 2018). Currently, the KPIs for human-robot collaboration systems are categorized in five categories, namely; (i) Objective & economics, (ii) Product, (iii) Process, (iv) System, and (v) Safety. Each category contains multiple (between 5-11) aspects based on which different HRC scenarios can be compared with each other. However, a specific category for human operators has not been included in these categories.

In the context of HRCDM, the used KPIs should be presented in a concise manner that supports the overall objectives of HRCDM. Therefore, the HRC Scorecard concept has been inspired by the "balanced scorecard", which is often used in organizations to obtain a holistic judgment of operations. In addition, its application for evaluations in production systems has been successful (R. S. Kaplan and Norton 1996). In addition, it has been reported that SMEs are able to refocus daily production operations based on set targets using scorecards (R. Kaplan et al. 2006). HRC Scorecards should be used to summarize KPIs related to each HRC scenario in a clear and comprehensible manner.

The proposed HRC Scorecards consist of the following five categories based on which a HRC scenario should be evaluated

- **Operators**
  In this section, an overview of the human operators that will be part of the proposed HRC scenario should be provided. This overview should indicate several aspects that are expected from the human operator, and the expected effect of the work that he/she will perform in this HRC scenario. These aspects can be discussed in three sub-



HRC Scenario:		Load & Unload labelling machine with Cobot			
Operators					
			Workload		
Name	Competency	Training	Physical	Cognitive	Social
H1 : Helen	Expert	no need	low	med	low
H2 : Tony	Connaisseur	yes (2days)	low	high	low
Implementation					
Development		Installation		Operation	
Time	Difficulty	Time	Difficulty	Time between failures	
2 months	Medium	2 days	Low	1 per hour	
Costs					
Investment			Running		
50.000 € (for one workstation)			500 €/day		
Production capacity					
200 packages / hour					
Safety					
Needs external certification (ISO TS-15066)					

Figure 45 An illustration of the types of information that should be presented on a HRC Scorecard

categories, (i) expertise, (ii) training, and (iii) workload. In the expertise field, an indication should be made whether the tasks given to the human operator require any specific competency that the operator might not have at that moment. Such an assessment can for example be performed based on the "competency measurement instrument" as developed by (Letmathe and Schinner 2017). In this instrument, the competencies of human operators are indicated in three levels: (i) connoisseur, (ii) experienced and advanced, and (iii) expert and creative problem solver. The level, on which an operator is placed, is made based on seven topics that discuss the skills of the operator and the requirements of the task in parallel. In the training field, an indication should be made whether the task that is given to the human operator in the new HRC scenario requires him/her to receive additional training. In the workload section, an indication should be made on the following three aspects that are expected to result from the workflow that the human operator(s) are involved in, in the proposed HRC scenario. These aspects are: (i) physical, (ii) cognitive, and (iii) social. By considering these aspects, an indication (i.e. low, medium, high) should be provided about the overall workload on each human operator in the HRC scenario.

- **Implementation**
  In this section, an indication should be provided on the expected engineering efforts that will be needed for the realisation of the HRC scenario. This indication can be divided into three sub-categories, referring to three phases that will follow after the decision to implement the HRC scenario. These phases are: (i) development, (ii) installation, and (iii) operation. The development field should indicate the software and hardware engineering effort that is expected for the scenario. The installation field should indicate the effort that will be required to install and configure the entities of the scenario. The operation field should indicate the expected robustness of the system and consider the frequency at which failures can happen in the resulting system, based on an estimation of the interactions and compatibilities between the used components.
- **Costs**
  In this section, the financial aspects of the proposed HRC scenario should be included, such as the required capital investment, and the daily running costs of the system (excluding product costs, including human resource costs).
- **Production capacity**
  In this section, the expected production capacity of the proposed HRC scenario should be indicated (based on hours/day and output quantity).
- **Safety**
  In this section an indication should be made whether safety certification is needed or not for the proposed system, and if this certification should be done by the system owner or an external expert (Ranz et al. 2017).

4.4 Methods of HRCDM

The objective for developing HRCDM was to provide HRC designers with a framework methodology that allows them to adapt it according to their needs and the requirements of the context in which the HRC design activity is taking place. So far, a main procedure and four instruments have been presented that support HRC designers in structuring and performing the development process of HRC scenarios. During the various phases as prescribed by HRCDM, designers are expected to benefit from the use of methods that help them to address more specific and well-defined issues in a systematic way. In this section, four categories of methods are presented under which the methods that are applied during HRC design can be grouped. Each of these categories describe guidelines and requirements for methods that can be applied independently or together, and with or without the support of the instruments presented in Section 4.3.

4.4.1 Coproduction capturing

The analysis phase is the starting point of a design project, and generally involves activities targeted towards obtaining an understanding of what is being designed (current situation) and what the requirements are for the projected future situation. This phase precedes the synthesis phase of designing, and is therefore essential for defining the solution space of the generated designs. Yet, in contrast to the creative nature of the synthesis phase, the analysis phase involves the collection of data and therefore can be more conveniently supported by specific methods. Next, an overview of six categories of methods are presented that should support HRC designers in performing the analysis for HRC scenarios.

- **Pre-inquiry**
  During the FiaD project, it was demonstrated that many details of a production process can be collected before visiting a production process (Factory in a day 2014) (Cencen et al. 2016). These details have proven valuable to HRC designers and increase the performance and efficiency of the process observation and verbal inquiry activities. Therefore, the use of similar approaches is suggested especially in cases where a client-designer relationship exists. When a pre-inquiry document is sent to the system owner(s) in advance, sufficient time needs to be allowed for the system owner(s) to fill the document and return it. In addition, time needs to be allocated to view and study the completed document by the HRC designers. (Examples are provided in Appendix B and Appendix C).
- **In-situ inquiry**
  During the Analysis and Synthesis phase of HRC design, the aim is to describe a homogenous process that involves humans and production machines as a heterogeneous process, consisting of discrete steps. This abstracts many details that can be relevant when re-designing the system. Technical documentation of a produc-

tion process can provide valuable information about these steps for HRC designers. These documents include process layouts, machine/robot specifications and process flowcharts. However, observing the same production process first hand, during operation, adds a new dimension to the understanding that can be gained from these documents alone. Production process observation forms a cornerstone of the HRC design process and is therefore considered a compulsory step.

- **Expert inquiry**
  Most production processes are unique and/or specifically configured for the requirements of a product and/or production equipment. Therefore, various parts of the production process will be more difficult to address and fully understand using written documents and in-situ observations of the production process in action may still leave some unanswered questions.

  Therefore, a verbal expert inquiry session between system owner(s) and HRC Designer(s) should take place during which questions can be asked to clarify any aspects of the production process that are still unclear or that need further explanation. This can be performed on-site or off-site. The advantage of performing an on-site verbal expert inquiry is that it can be combined with a re-observation of the production processes and equipment. Recording the verbal inquiry is advised, as this allows designers to hear answers to specific questions after the session is finished.

- **Inquiry recording.**
  Making audio and video recordings during the in-situ inquiry process can bring additional information to the design process due to the fact that these recording can be replayed multiple times, whereas additional in-situ inquiries require additional time and resources to be allocated. In addition, generally multiple experts take part in in-situ inquiries. The use of pre-inquiry documents and audio & video recordings of the observation eliminates the necessity for the HRC designer(s) to be present in person. This approach has additional advantages, such as: (i) Operational production processes have mostly restricted space around them for accommodating multiple people, (ii) A large expert group is distracting for the human operators that are working in the production process, (iii) Some production processes are not safe and require special permissions, making it difficult to arrange visits by multiple people, and (iv) Operational production processes can be noisy, making it difficult for large expert groups of people to hear the accompanying explanations.

  On the other hand, one of the challenges of making recording is that in some cases, recording may be initially prohibited. In such a case, it needs to be made clear that the video will only be used for analysis purposes within the HRC design project, and will be destroyed after the project finishes. In addition, system owners need to be assured that any media (photographic images and video recordings) will be processed in such a way as to make individuals appearing in them unrecognisable.

  Finally, if a video recording of a production process has been made it can be used to identify operation micro-tasks and any irregularities not mentioned in the expert inquiries. These micro-tasks can then be timed. When multiple cycles of a production process are timed, minimum, maximum and average processing times can be calculated, which eliminates the need to time the production process during process observations.

- **Task analysis**
  After data about the targeted systems has been collected using the various inquiry methods, this data can be used to analyse the tasks that are involved in the processes that have been observed. For performing such analysis, there are a variety of well-known task analysis methods that are is use for analysing tasks in complex computer-based systems. Two of these most used methods are the Hierachical Taks Analysis (HTA) and GOMS (Goal, Operators, Methods, Selection rules). An overview of similar methods and how to apply them can be found in (Benyon 2010) and (Holtzblatt et al. 2004).
- **Precedence analysis (for proposed systems)**
  In the case of a design brief in which a HRC scenario is requested that is not based on an existing production system, HRC designers need a way of conceptualising the overall production workflow. This can be made based on an analysis of the product that should be produced using the system. This analysis lists all parts of the product and the sequence in which they are handled during the production process. This analysis is performed using the following steps, and should ideally be performed together with system owners:
    - List all parts;
    - Indicate interfaces between each part and other parts;
    - List parts with the fewest number of interfaces;
    - Indicate which of these interfaces should be created first. In case of there being no existing relationship, list all interfaces;
    - Having completed these activities, designers have a shared overview of the steps involved—and their sequence—in the production process.

4.4.2 Coproduction modelling

The Synthesis phase of HRCDM targets the creative actions in the HRC design process, during which the data generated in the Analysis phase should be operationalized and be used to generate a variety of solutions. Therefore, the goal of the methods used for Coproduction modelling should not be geared towards the development of one "perfect" design. Rather, they should facilitate the synergy between HRC designers and support them in formalizing the solutions that they create.

As a result of the findings discussed in section 2.5, HRC Canvas and Coproduction Cards have been specifically developed for HRCDM and are provided as support for the formalisation of multiple Coproduction scenarios during the Synthesis phase. These instruments convey a specific method of performing the modelling activity during the design process. In addition, Coproduction cards have been designed to enable the rapid translation of the scenarios into digital models. Therefore, in a similar way, any other modelling method that is used in the synthesis phase should take into consideration that the developed models at this stage should be easy to transform into formats that are compatible with the instruments that will be used in the Simulation phase.

4.4.3 Coproduction simulation

The Simulation phase of HRCDM is aimed at testing the Coproduction scenarios generated during the Synthesis phase. In the current conceptualisation of HRCDM, the WST has been proposed as an instrument to be used in this phase. In its current form, WST mainly focuses on the 3D visualisation of HRC scenarios and the animation of the created scenarios for initial assessments related to the spatial requirements of HRC scenarios. However, there are other aspects of HRC Scenarios that should be simulated using different methods. Yet, generally, each of these aspects require the use of a different software package (Kühn 2006). Therefore, for applying different simulation methods, the expertise of simulation experts (as discussed in Table 14) might be needed. Next, an overview of the most relevant simulation methods for HRC design is presented.

For simulating the workload on human operators, simulation software should be used, that is capable of interpreting ergonomic parameters of human operators in a 3D environment (Polášek et al. 2015). Siemens Tecnomatix Jack (Siemens PLM 2018) and 3DS Delmia 3DExperience (”Delmia 3D Experience” 2018) are examples of such software. Methods for measuring and simulating cognitive load of manufacturing tasks on humans has only recently been explored (Thorvald et al. 2019), and therefore are not available in the previously mentioned software packages.

Furthermore, for the simulation of computer vision-based handling of specific types of products by different type of robots, the Gazebo simulation environment can be used (Chenf et al. 2016). For the visualisation of proposed HRC scenarios inside an existing production system, augmented reality (AR) techniques can be used. Recently, the use of portable AR devices in the manufacturing context and the assessment of the introduction of HRC scenarios in existing production system have been explored by (Aschenbrenner et al. 2018), and it has been reported that this method is also suitable for collaborative design activities between two designers that are not co-located.

On the other hand, for the simulation of workflow-related aspects that may not require accurate 3D-models of HRC scenarios, discrete-event simulation (DES) can be performed (Smith 2003). DES can be used as a complementary means of simulation to 3D simulation by which the productivity of various scenarios can be compared with each other. These simulations can perform computations with the operational parameters of a given scenario, and provide HRC designers with insights into potential bottlenecks in the system. Recently, the integration of human factors and AR into DES has been proposed by (Dode et al. 2016) and (Turner et al. 2016), which can be advantageous in the context of Coproduction simulation as well.

The presented overview of different types of simulations that are relevant for HRC design should be used as a guideline when considering the use of other methods when adapting HRCDM to different contexts.

4.4.4 Coproduction evaluation

The Evaluation phase of HRCDM requires the created HRC scenarios to be evaluated with respect to the requirements that were set for the HRC scenario by the design brief at the beginning of the HRC design process. Based on this evaluation, a decision needs to be made in the presence of all of the stakeholders about the next step in the design process. In HRCDM, the use of HRC Scorecards has been proposed as a means of supporting this decision-making step. In the current conceptualisation of HRCDM, no additional evaluation methods have been specified. However, HRC designers are suggested to consider qualitative as well as quantitative evaluation measures when adapting HRCDM to their needs.

4.5 Conclusion

Based on the requirements set for a methodology for supporting HRC design in Chapter 3, in this chapter, an adaptable framework methodology for designing human-robot coproduction has been presented. This methodology is supposed to be used as a guideline for HRC designers that have little to no experience in HRC design. Using this methodology these designers should be able to structure their design processes and select and apply the best instruments and methods for their own HRC design context. The chapter has presented the overall design procedure that the methodology prescribes and the novel instruments that were developed and are proposed for supporting HRC designers during the different phases of this design procedure. In the final part of this chapter, the requirements for the methods to be included in the different phases of the HRC design procedure have been elaborated.

Chapter 5

Related publication

- Cencen, A., Verlinden, J.C., & Geraedts, J. M. P. (2018). A Design Methodology to Improve Human-Robot Coproduction in Small and Medium Sized Enterprises. IEEE/ASME Transactions on Mechatronics, Vol. 23, No. 3, June 2018

5 Exploring the applicability of the human-robot coproduction design methodology

In the previous chapter, HRCDM was introduced as a new framework methodology that HRC designers can adapt and apply for their own specific context. This chapter presents the results of Research Cycle 4, which has the aim to explore the applicability of HRCDM.

Similar to new technologies and technical solutions, new approaches and methodologies should be tested for use in their intended context and the bottlenecks should be identified for the different contexts that these methodologies are applied in. This way, their users can better assess the advantages and shortcomings of these methodologies for their own specific application domain. Therefore, as an initial step in testing the applicability of the new HRCDM methodology, in this chapter its application during an HRC design case is presented.

5.1 Introduction

Validation of a new design methodology is a challenging task that requires the application of the methodology in a variety of cases. In addition, the designers that apply the methodology and the contexts in which the methodology is applied remain important variables that affect the argumentation of the validity of the methodology. Given enough time and resources, sufficient data can be gathered after which a robust argumentation can be built on the actual validity of a methodology.

One can look at the process of validation from the two different perspectives of ‘applicability’ and ‘performance’. ‘Applicability’ concerns the fit between the methodology and the design problems that it is applied to. On the other hand, ‘performance’ concerns the quality of the methodology with respect to other methodologies. In performance validation, the results produced through the application of different methodologies to the same design problem are compared with each other in order to build arguments on the value of a methodology. When data is available on both the ‘applicability’ and ‘performance’ of a methodology on a variety and number of cases, better arguments can be made on the general validity of a methodology with respect to its purpose.

In the literature review (presented in Chapter 2) that was performed for gathering data for the development of HRCDM, no existing methodologies were found that provide a design approach specifically towards HRC design in a similar way to what is being targeted by HRCDM. This makes the comparison of HRCDM with existing design methods and methodologies complicated. Therefore, a ‘performance’ validation of HRCDM was not considered during at this stage in the development of HRCDM. Instead, the focus was set on testing the applicability validation of HRCDM.

5.1.1 Goal

The goal in this applicability validation is to gain insights from the initial application of HRCDM during a HRC design case by its intended users. This process can then be analysed in order to elaborate on the application of various constructs of HRCDM, which are then used to build an argumentation on the applicability of HRCDM in its general application context.

5.1.2 Scope

Considering the goal of the mentioned applicability validation, the scope of the application of HRCDM has been defined by constraining the type of designers that apply it and the type of design problem that it is applied to. A group of designers that have no prior experience in designing HRC were chosen as subjects for applying the HRCDM. In addition, the design problem that was given to the designers involved the design of a HRC scenario for a non-existing production process.

5.1.3 Method

Especially in the case of solving design problems, in which the quality of the created solutions relies heavily on the experience and creativity of the designers that are involved, comparisons between different design cases are difficult to make in an objective and rational way. This requires the application of dedicated validation methods to build arguments on the applicability and performance of methodologies.

The Validation Square provides guidelines for the validation of design methods and supports the argumentation of the applicability and usefulness of these methods based on their application to a limited number of ‘exemplary’ design problems (Seepersad et al. 2006).

The Validation Square was originally developed for the validation of design ‘methods’. Methodologies are more complex and contain more constructs that can be adapted during their application. Nevertheless, the Validation Square method has been successfully applied in the validation of other novel design methodologies, namely ‘a methodology for interactive augmented prototyping’, and ‘a design methodology for additive manufacturing’ (Verlinden 2014)(Doubrovski 2016). Therefore, its application during the applicability validation in this research was considered appropriate.

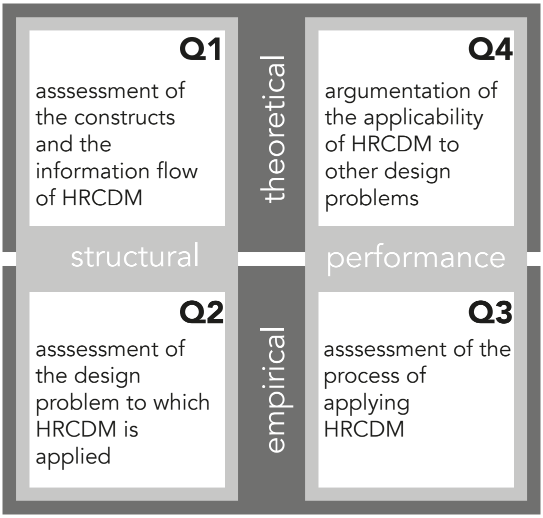


Figure 46 The four quadrants of the applicability validation process. (Adapted from Seepersad et al. 2006)

When applying the Validation Square method, the validation procedure is divided into four 'quadrants'. Each quadrant provides a different perspective and requirements for testing the methodology and the case(s) that it is applied to. By completing all four quadrants in the given sequence, both theoretical and empirical aspects of the test are covered, after which arguments can be built regarding the applicability of the methodology in other cases. An overview of the quadrants and their focus is presented in Figure 46. An overview of the relationships between the methodology, the used case and the used validation method is presented in Figure 47.

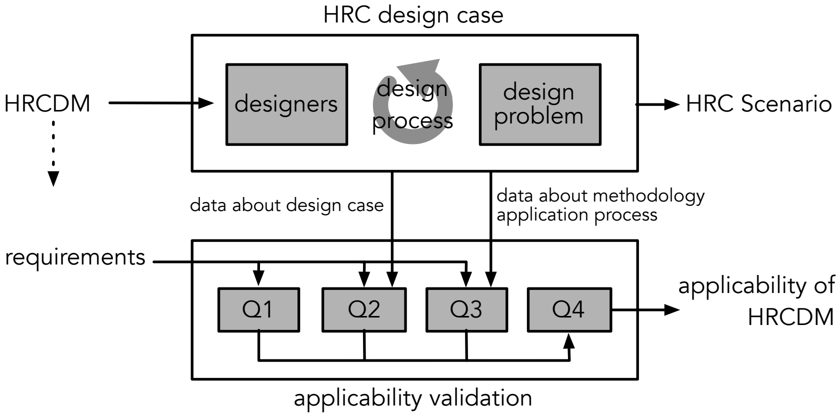


Figure 47 Overview of the validation process Q= Quadrant

5.1.4 Requirements

As stated by the Validation Square method, a set of requirements need to be specified that should be used throughout the first three steps of the quadrant-based validation process. The argumentations that will be made in each quadrant will be used as evidence for each requirement. The used requirements and their corresponding quadrants are presented next.

For the 'theoretical structural validation' quadrant, a requirement is needed which concerns the constructs of the methodology. The following requirement that was formulated for developing HRCDM will be used for this purpose;

- A methodology for designing HRC provides a systematic structure for the HRC design process and emphasises an iterative way of working.

For the 'empirical structural validation' quadrant, a requirement is needed that concerns the type of design problem that HRCDM has been targeted at. The objective that was formulated in section 1.4 defines the type of targeted design problem for HRCDM as follows;

- 'To develop an adaptable framework methodology that can be used by novice HRC designers during the conceptual design activities that involve human-robot coproduction scenarios.'

This objective contains the requirements for the type of designers and the type of design activity that is targeted by the methodology and will therefore be used as a requirement for the second quadrant of the Validation Square method.

For the 'empirical performance validation' quadrant, requirements are needed which concern the application process of the methodology. The following requirements that were formulated for developing HRCDM will therefore be used for this purpose;

- A methodology for designing HRC should facilitate the establishment and support of common ground between the involved designers.
- A methodology for designing HRC should allow flexibility in the use of its constructs in order to be adaptable to requirements presented by the contexts that it is being applied in.
- A methodology for designing HRC should be applicable by novice HRC designers.

5.2 Applying the Validation Square method

5.2.1 Theoretical structural validation

Theoretical structural validation concerns the assessment of the constructs of the methodology and the information flow between them. Therefore, this step is performed disregarding the case that the methodology is applied to.

5.2.1.1 The methodology's constructs

In its current conceptualized form, HRCDM prescribes the application of a combination of constructs during HRC design; an overall procedure which consists of four phases, a collection of coproduction design methods, and four instruments that support the execution of the overall procedure and methods.

The methods and instruments that are currently included in HRCDM originate either from existing models and theories that were encountered during the review of the literature relating to HRC (Chapter 2), or the analysis of design activities of expert and novice HRC designers as presented in Chapter 3. The literature review covered three perspectives on HRC and highlighted the main theories and developments in the domains of knowledge that contribute to HRC design. In addition, several sub-domains were identified that are helpful in categorizing theories that may become available in the future. The empirical data that was generated about the HRC design cases by experts and novice designers helped to understand the influential factors for designing HRC scenarios. These findings were used as input for the creative process that drove the development of HRCDM and resulted in its current conceptualization presented in this thesis.

5.2.1.2 The flow of information between the constructs

While the internal integrity of each construct in a methodology is essential to its contribution to the design process, the information flow between these constructs should allow a good interaction between the constructs. The HRCDM has been based on the generic 'operator-centred production design' model which was introduced at the end of Chapter1. This model describes a concise process flow and emphasizes an iterative way of working. In addition, to maintain a holistic perspective on the HRC scenario being designed, one of the goals of HRCDM is to enable a way of reasoning based on three basic entities, namely; Human, Robot and Product. These entities are used as reference points throughout all four phases of the design process. For example, the HRC Canvas includes different Coproduction Cards for each entity type. During the final phase of HRC design, HRC Scorecards address all entities explicitly to quantify and evaluate each HRC scenario. The phases are linked with each other through instruments developed specifically for HRCDM and therefore use the same three entities. This way, the information flow between the various phases and constructs is ensured.

Considering the abovementioned arguments about the constructs of the methodology and the information flow between these constructs, it can be argued that the methodology has been based on theoretical and empirical evidence which were integrated through a creative process with the goal of developing a framing methodology for HRC design, and that the constructs have been brought together in a way that should allow HRC designers to perform the various activities during the design process in a structured and iterative way.

5.2.2 Empirical structural validation

Empirical structural validity concerns the HRC design case in which novice HRC designers addressed a HRC design problem, with the support of HRCDM. For this purpose, a HRC design case was formulated in which a group of engineers were asked to collaboratively solve a HRC design problem in a limited amount of time, by using the limited resources provided to them. In this section, the designers that are involved and the HRC design problem that they addressed are explained in detail. These descriptions will be used to argue the appropriateness of the used HRC design case for this applicability validation.

5.2.2.1 Designers

The designers that were involved in the HRC design case were a group of four engineers that had never worked together before. In addition, none of the involved individuals had experience with robotics, manufacturing design, or any domain that is closely related to HRC design.

5.2.2.2 Design problem

The HRC design problem involved the request to develop a HRC scenario within the human-driven production process of a small consumer product that can be customized by its customers. This problem will be described by touching upon the details of the three entities that should be considered during the design process of the HRC scenario.

Human operator
The HRC scenario can involve only one human operator. The human operator has never worked with a Cobot before. He/she also does not have prior experience with the product in the scenario. This human operator is classified as a ‘novice’ HRC operator. The human operator is able to perform all of the tasks in the production process of the product.

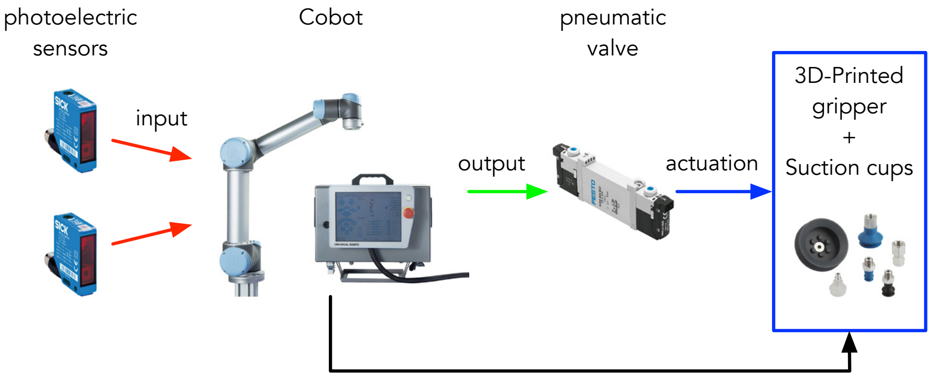


Figure 48 An overview of the used Cobot and the peripherals attached to it

Robot

The robot that is available for the HRC scenario is a Cobot of the type UR5 made by the manufacturer Universal Robots. In addition, the Cobot is equipped with two photoelectric sensors to provide input for its functions and a digitally controlled pneumatic valve as an output. The Cobot can be programmed using its teaching pendant and the functionalities that are provided by its embedded software (Figure 48). There is access to a 3D-Printer for creating a gripper for the Cobot and various suction cups are available that should allow the robot to perform a grip of the parts of the product in the HRC scenario.

Product

The product in this scenario involves a so-called customizable product, which has been developed for the purpose of this HRC design case, the ‘customisable marker box’ (Figure 49). The product is a wooden box containing three felt-tipped marker pens. The box itself is made up of a base and a lid part, which are held together by magnets that are embedded inside their edges. On the lid of the box, an engraving is made using a laser-engraving machine according to its customers’ specifications. The customers of the product choose the colours of each of the pens in the box when placing an order. This type of product therefore demands that the product should be produced once an order is placed.

The designers are asked to first make a decision on which step of the production process of the marker box to design the HRC scenario for, and then, to work out the details of this scenario.

Considering the presented descriptions of the designers and the design problem, it can be concluded that the HRC design case that was used for this validation is representative of a conceptual design activity of a new human-driven production system, and that involves a human-robot coproduction scenario. Therefore, it is assumed to provide an appropriate ground for testing the applicability of HRCDM.

5.2.3 Empirical performance validation

Empirical performance validation concerns the application process of HRCDM during the design case that was described in the previous section. This process will be presented by highlighting five snapshots from the design process that together provide evidence for the applicability of HRCDM. These snapshots are presented next.

5.2.3.1 Introduction to HRCDM

The HRC design process started by providing the designers with a ‘design brief’ that contained information about the upcoming design process and its subject, the methodology that was available as support in this process, and what is expected as final deliverable at the end of the design process (Appendix D). As a next step, the designers were introduced to HRCDM and its constructs in more detail during a presentation. During this presentation, HRCDM was introduced to the designers as a framing methodology that can be used for conceptual design of HRC scenarios, and that its methods and instruments are targeted at novice HRC designers.

5.2.3.2 Starting the HRC design process from scratch

According to the design brief given to the designers, the design process of the HRC scenario needed to start from scratch. In other words, the scenario did not involve an existing human-driven production scenario that needed to be modified to involve HRC. Therefore, the designers had to explore various parts of the future production process (which they had

Figure 49 A picture of the customisable marker box, showing the marker pens, the engraving and the magnet that holds the two parts of the box together

to conceptualise themselves) in order to find a sub-process that they would be able to create an HRC scenario for.

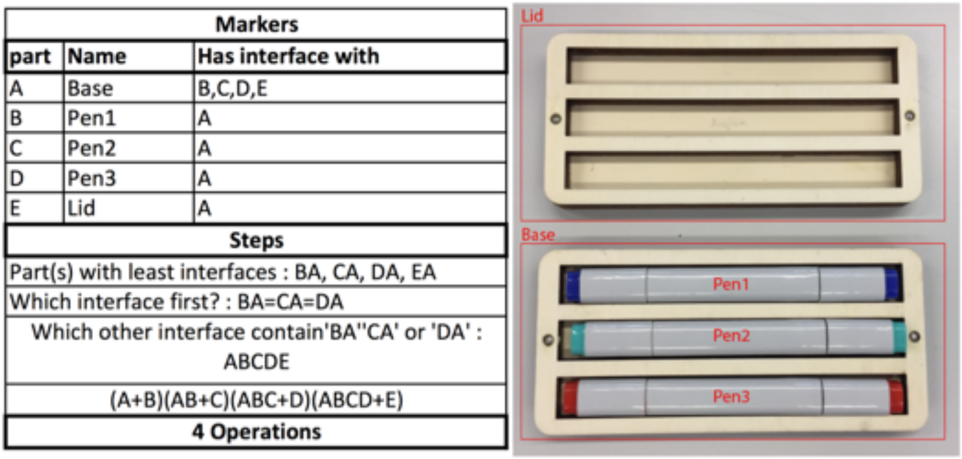
The HRCDM does not prescribe a specific method for such an exploration. However, the designers were able to identify three operations that were potentially attainable for the scope of the HRC design activity they were involved in. First, the designers identified three areas of interest (Table 15). These were: (i) loading & unloading parts to/from the laser-engraver, (ii) supplying engraved parts to the assembly station, (iii) placing finished products in a shipping container. In order to decide which area to focus on, the designers created a typical pro/con chart by which they could evaluate which option would be the best choice for them to develop a HRC scenario for. Based on this overview, the designers decided to explore the possibility of assembling the marker box using the Cobot, primarily for the challenge it provided for designing a good gripper.

At the beginning of the design process, all parts of the marker box were made available for the designers. Therefore, the designers decided to start their HRC design process by exploring the possibility of performing the assembly of the product using a Cobot. The designers applied the ‘precedence analysis method’ – which is described in HRCDM – in order to come up with a basic blueprint for the steps involved with the assembly process of the parts of the marker box. After applying the “precedence analysis method’, the designers had identified that the assembly process for the marker box would need 4 operations (Figure 50).

On the other hand, the team established that the assembly of the product using the Cobot would require the handling of two different types of parts, which would make the gripper

Table 15 Overview of the considered areas with HRC potential

Process	Pros	Cons
Assembly of product	- provides a good gripper design challenge	- robot forms bottleneck - does not require human operator to be present
Load & unload laser engraver	- human does not have to be in the same space as the engraver (noise & smell)	- challenging to establish communication with the engraver - does not require human operator to be present
Placement of finished product in shipping container	- robot is the final step in the workflow (does not form bottleneck) - robot and human operator can be placed next to each other	- assembly could be too heavy for the gripper (product could fall)



Markers

part	Name	Has interface with
A	Base	B,C,D,E
B	Pen1	A
C	Pen2	A
D	Pen3	A
E	Lid	A

Steps

Part(s) with least interfaces : BA, CA, DA, EA

Which interface first? : BA=CA=DA

Which other interface contain'BA''CA' or 'DA' : ABCDE

(A+B)(AB+C)(ABC+D)(ABCD+E)

4 Operations

Figure 50 The precedence analysis of the base, lid and marker(s) assembly

design more complicated. Therefore, the team decided to use a rapid prototyping method (3D-Printing) to test the possibility of using one gripper to handle both the lid/base of the product and the pens. The team had a limited supply of different types of suction cups, and therefore had to design and build a gripper based on the material that was available to them. During the test of prototype of the first gripper design, the gripper (which made use of four suction cups attached to it) failed to form a steady grip on both parts (lid/base and the pens) using the same type of suction cup (Figure 51, left). With this conclusion, and reconsidering the remaining time in their design process of the HRC scenario, the designers decided to go further with another sub-process of the production process of the marker box, the placement of the finished products in a shipping container.

During this starting phase of the HRC design process of the novice HRC designers, it was observed that the designers performed design activities and evaluations that were not prescribed/suggested by the methodology. These actions were performed for rapid, informal evaluations in order to give direction to the design process and to explore new directions for finding solutions to the HRC design scenario that they were requested to develop. These actions show that HRC designers work in an ad-hoc and iterative way, and that they can refer back to the main procedure as prescribed by HRCDM when needed. On the other hand, the time that the team spent on exploring the assembly of the marker box using the Cobot (which can be executed much faster by a human), could be associated with the fact that the designers had no prior experience in HRC design.

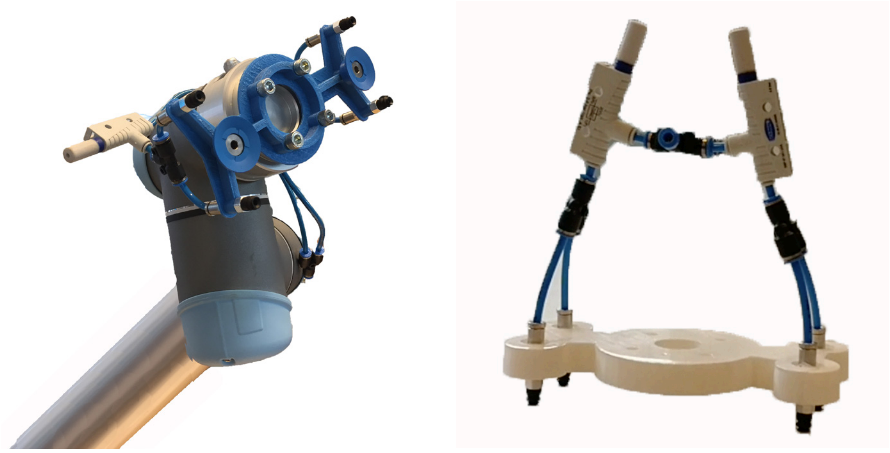


Figure 51 Two versions of the gripper that was designed by the HRC designers. Left: First version, equipped with two types of suction cups for gripping two types of different parts, Right: Second version, equipped with a single type of suction cup.

5.2.3.3 Using the coproduction cards

After their decision on focusing on the development of a HRC scenario for the 'placement of the finished product in a shipping container'-step in the production process of the marker box, the designers created a detailed overview of this process using the Coproduction Cards. An overview of the workflow between the human and the robot that was created using the cards is presented in Figure 52. The human operator in this scenario (H1) is involved in two sequences. SQ1 is the assembly of the marker box, which ends with delivering the finished product to be handles by the Cobot. SQ2 is the sequence that is performed by the Cobot, which consists of six repetitions of the same pick & place process. H1 is also involved in this process, namely for replacing the shipping container when its full.

The Coproduction cards are aimed at modelling the flow of activities in a HRC scenario. In order to describe the arrangement of the workplace in the HRC scenario, the designers created a drawing and a 'location card', which accompanies the drawing as shown in Figure 53. As shown in Figure 52 and Figure 53, the proposed workflow involves various assets. An overview of the used asset cards and the details of these assets is presented in Figure 54.

The application of the Coproduction Cards was intuitive for designers and the designers were able to use it as a means of grounding their discussions about the scenario while giving shape to their design.

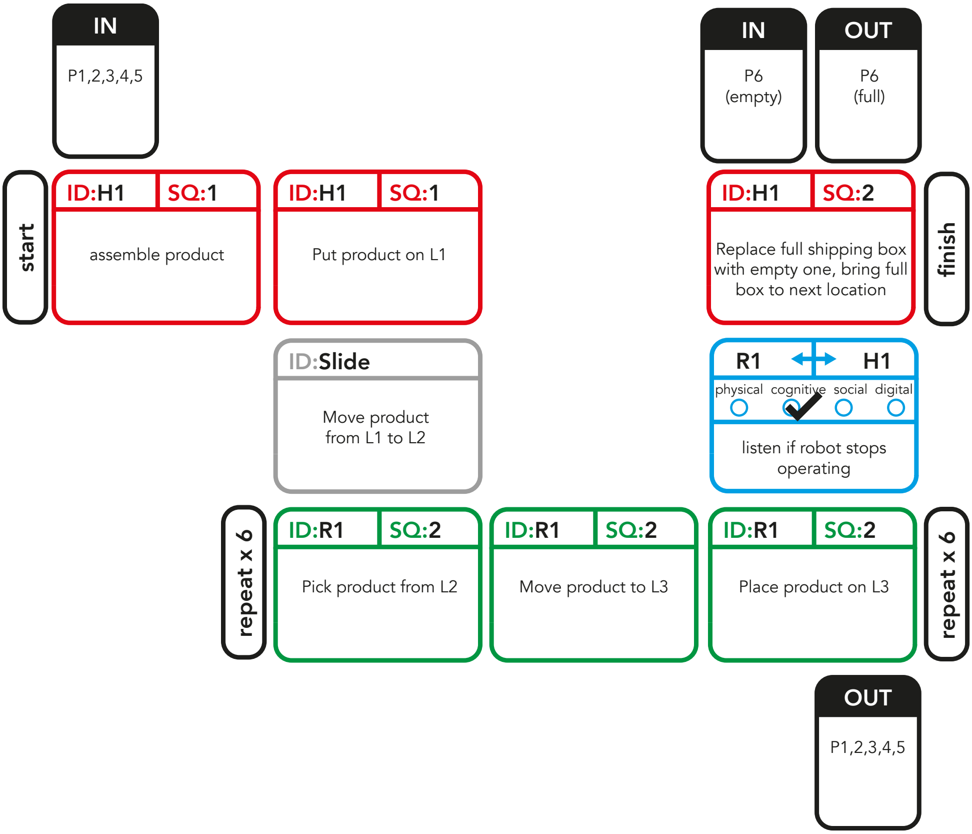
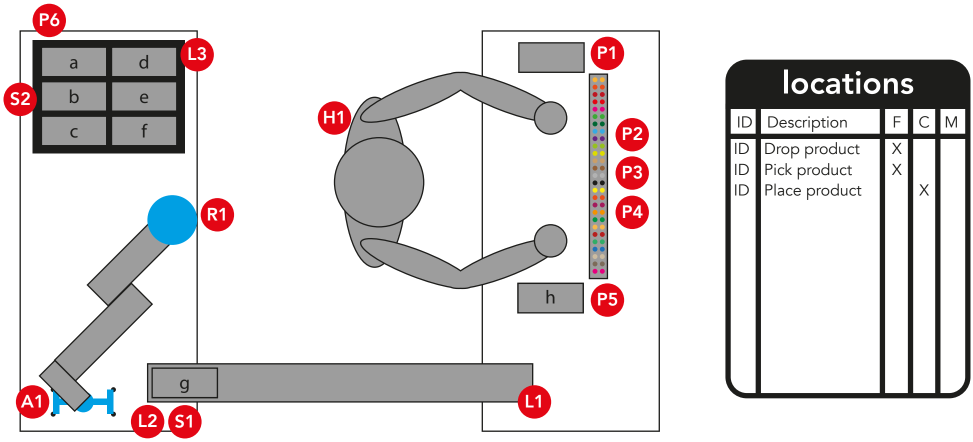


Figure 52 An overview of the workflow of the HRC scenario of the 'placement of finished product in shipping container' step in the production process of the marker box.



ID	Description	F	C	M
ID	Drop product	X		
ID	Pick product	X		
ID	Place product		X	

Figure 53 The workplace arrangement illustration of the created HRC scenario, together with the corresponding 'locations' card.

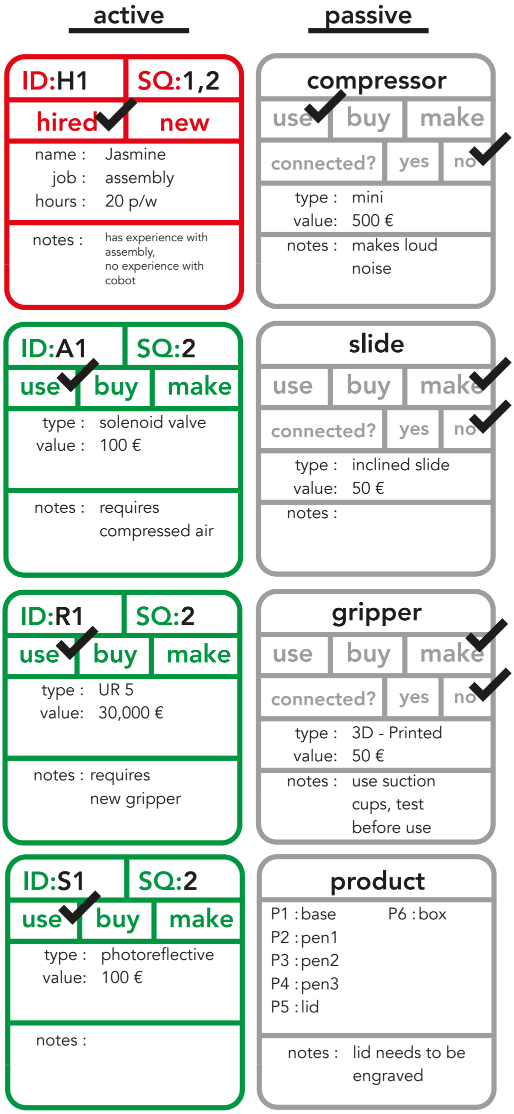


Figure 54 Overview of the active and passive assets for the proposed HRC Scenario

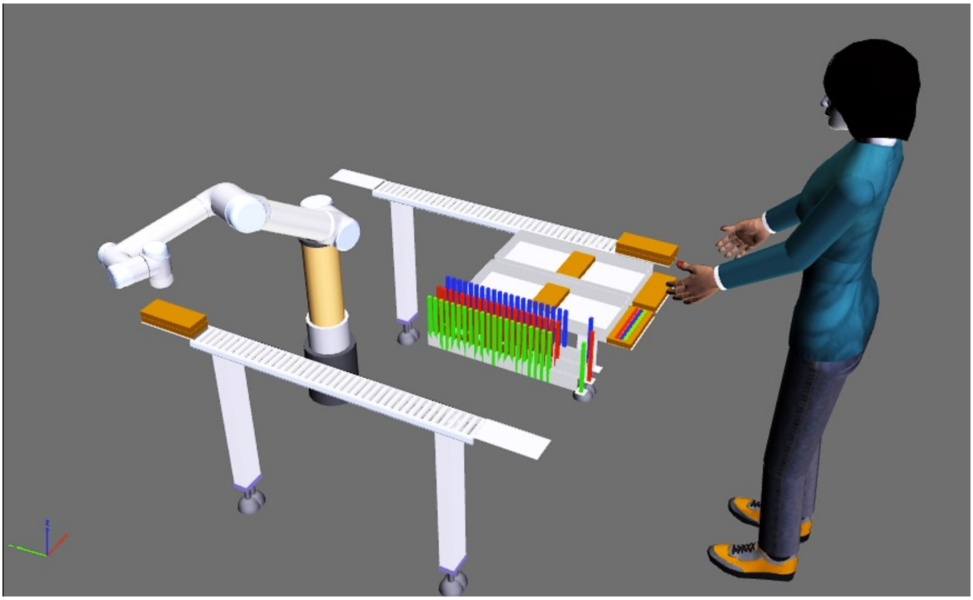


Figure 55 A screenshot from the WST showing the HRC scenario proposed by the designers. The human operator assembles the boxes and places them on a conveyor, the Cobot picks up the boxes at the other end of the conveyor.

5.2.3.4 Using the WST

After the session during which the Coproduction Cards were used, the designers decided to visualize the HRC scenario that they created using the WST. The WST gave the designers the opportunity to further investigate the spatial aspects of the scenario that they had created in a 3D environment, which included an animated version of the Cobot that they wanted to use (Figure 55). Even though the WST did not include detailed models of all of the parts required for the HRC scenario, the designers were able to gain more insights in the sequence of tasks and placement of various components in the workspace around the human operator, which helped them to further refine their designs.

5.2.3.5 Finalizing the process by physical prototyping

At the final stage of the design process, according to the design brief that was given to the designers, a physical prototype of the proposed HRC scenario needed to be built by using the resources that were indicated in the design brief. This would be the step during which the designers could evaluate their final designs.

Figure 56 Picture of the prototype evaluation

The physical prototype of the HRC scenario was built using the resources that are shown in Figure 48 and the final version of the developed gripper as shown in Figure 51 (right). A picture of the operational state of the final prototype is shown in Figure 55. The team had built the slide that was needed for their setup prior to the start of the prototyping session. The team was able to configure the setup in ~60 minutes, including the programming of the locations for the Cobot. One of the team members was placed at the location of the human operator. The goal of the prototype evaluation was to fill the shipping container with a batch of products.

The shipping container could fit six of the customised marker boxes. Therefore, the human operator had an order sheet that contained six orders. After the configuration process ended, the setup was ready for testing its functionality. The human operator and the Cobot assembled six products and packed these products in the shipping container without any issues. After the placement of the sixth product in the shipping container, the Cobot stopped operation and waited for the human operator to replace the shipping container with an empty container. Through this prototype evaluation, the designers were able to evaluate the operational and deployment related aspects of their proposed HRC scenario, such as the importance of the approaching angles of the Cobot to the product and the challenges of establishing a robust and repeatable grip without the use of additional sensing equipment.

These five snapshots provide evidence that (i) HRCDM facilitated the establishment and support of common ground between the involved designers during a HRC design case, (ii) it allowed flexibility in the use of its constructs in order to be adaptable to requirements presented by the context, and (iii) that it was applicable by novice HRC designers.

The application of HRCDM to a HRC design problem was repeated with two other teams of novice HRC designers, bringing the total of the application cases of HRCDM to three. The design briefs given to these teams are presented in Appendix D (Case A, B, C), and an overview of their attributes that are relevant for comparison are presented in Table 16. While the problems given to these teams concerned the development of HRC scenarios for different products, the resulting application process of HRCDM for these teams were analogous with the presented case in this section (Case A). These teams were also asked to finalize their HRC design processes by building physical prototypes of their proposed HRC scenarios, which they successfully completed by having a human operator and a Cobot perform several repetitions of tasks in the HRC scenarios that they proposed.

5.2.4 Theoretical performance validation

The Validation Square method states that, based on the arguments that have been made in the first three quadrants, a conclusive argument should be made in the final quadrant about the applicability of the methodology in the broader context that it is developed for. This is referred to as a “leap of faith”.

Table 16 Overview of the three HRC design cases that were performed

Case:	A	B	C
Designers:			
HRC experience	0 HRC designs	0 HRC designs	0 HRC designs
Participants in team	4	4	4
Design problem:			
Product	marker set	candies	chocolate letter set
Product type	made to order	made to order	made to order
Product parts	5	6	4
Existing system?	No	No	No
Operators	1	1	1
Cobots	1	1	1
Sensors	2x photo-reflective	2x photo-reflective	2x photo-reflective
Actuators	pneumatic valve	pneumatic valve	pneumatic valve
Gripper	3D printing & vacuum	3D printing & vacuum	3D printing & vacuum

In the first quadrant, it was shown that the constructs of HRCDM have been based on a combination of theoretical and empirical evidence that has been discussed in this thesis (Chapter 2 and Chapter 3), and that its constructs have been brought together in a way that facilitates a systematic and iterative way of working for novice HRC designers during their HRC design processes.

In the second quadrant, it was shown that the HRC design problem, consisting of novice HRC designers and the design of a new HRC scenario for a customizable product, constitutes those elements that make it an appropriate surrogate for testing the applicability of HRCDM.

In the third quadrant, it was shown based on the snapshots of the HRC design process of novice designers that the designers were able to structure their design activity with the support of the phase-based structure as prescribed by HRCDM. In addition, the contribution of the instruments of HRCDM to the establishment of common ground between the designers was shown. On the other hand, it was also shown that a (HRC) design process is not a rigid and straight-forward endeavour, and that the methods and instruments as described in HRCDM provide the flexibility that is requested by HRC designers when addressing issues and requirements that emerge along the design process.

Based on the evidence provided through quadrants 1, 2, and 3, it can be stated that the application process of HRCDM during a HRC design activity involving novice HRC designers and a small-scale human-driven production system shows evidence that it provides the support that is required from the methodology as described in the requirements that were set for developing it. In addition, during the design process, it was observed that the methodology could be adapted to the type of design problem (make to order & non-existing) by designers that had no experience in HRC design, who used its constructs in an explorative way rather than a definitive and prescriptive way. Therefore, the application of HRCDM during HRC design cases that target production processes of similar typologies and involve designers with similar HRC design backgrounds should be expected to have a positive influence on the designers and their design process. When considering the applicability of HRCDM for addressing their own HRC design problems, HRC designers are suggested to make an assessment with respect to the qualities of the designers involved in the process, and the type of HRC design problem that is being addressed. The aspects displayed in Table 16, can provide an underpinning for such assessments.

5.3 Discussion

The presented applicability validation showed how the general applicability of HRCDM could be argued. Nevertheless, those who apply the methodology to other HRC design

Table 17 Applied constructs of HRCDM during the applicability validation

Analysis	Modelling	Simulation	Evaluation
Precedence analysis	Coproduction cards	Workflow Simulation Tool	Physical prototyping

cases should consider the limitations of what is presented in this section. The limitations of this validation can be discussed under the following two topics.

The used production scenario: For this applicability validation, a scenario was created for a production process in which a customizable product is produced. Such a product requires the product to be produced in batches of one product, which introduces many challenges that are not relevant for most of the standard production processes. Therefore the application of HRCDM for more common processes should take this into consideration. On the other hand, the presented HRC design case required the design of an HRC scenario from scratch. Therefore, the designers needed a strategy at the beginning of their design process that allowed them to create an overview of all involved steps in an imaginary future production process, which has proven to be challenging for novice designers, with no prior experience in designing such systems. Therefore, the application of the methodology by more experienced designers is expected to result in a more insightful analysis and synthesis procedure compared to what is shown in this validation.

The context in which HRCDM was introduced: In the HRC design case used for this applicability validation, designers were introduced to HRCDM as part of a well-defined design project, which needed to be completed in a limited amount of time and by using limited resources. It can be expected that in a real-life case, eliminating these limitations will allow more design freedom. In addition, during their HRC design process the designers followed all phases as described in HRCDM, but not all of the methods were (needed) used (Table 17). This was mainly due to the limited time that was available for the HRC design project, and the state of development of HRCDM at that time.

5.4 Conclusion

In this chapter, the exploration of the applicability of HRCDM as support for novice HRC designers has been discussed based on its application to three HRC design cases. The results suggest that novice designers use HRCDM and its constructs as guidelines, rather than a set of rules. This is in line with the objectives of this research. Further applicability and performance validation of HRCDM should be performed primarily in order to establish application data that has a wider range with respect to the type of application contexts and background of the designers that apply the methodology.

Chapter 6

6 Conclusion

In the previous chapters, the results of the four research cycles of this research have been presented. In this chapter, the main contributions of this research are summarised. In addition, the implications of the developed methodology are discussed. The chapter finishes with a reflection on the methods used in the research, and the implications of its operational aspects.

6.1 Contributions

The research that has been presented in this thesis is situated in the domain of design research, and aims to support the research towards a better understanding of 'design for HRC'. In this context, the specific objective of this research was to develop support for novice HRC designers for integrating collaborative robots (Cobots) successfully in existing and new human-driven production systems. At the start of the project, it was assumed that novice HRC designers were lacking conceptual design tools for analysing, modelling, simulating and evaluating human-robot coproduction scenarios. Therefore, the design support was realized in the form of an adaptable framework methodology for conceptual design of HRC. This objective has been operationalized through various research activities that were divided into four research cycles.

Considering the abovementioned objectives of this research, its main contributions can be discussed under two topics, as presented next.

6.1.1 Framing of HRC and its design

At the start of this research, a better understanding of what HRC is – and the theories that it relates to – was needed. For this purpose, the following research question was posed;

RQ1- What are the key theories and principles in the bodies of knowledge that underpin HRC design?

The conclusions resulting from this question were presented in three categories (Industrial automation, Human-robot work, Design), which represent the three perspectives from which HRC can be framed (page 24). It was concluded that the reviewed domains of knowledge contain many established and new principles and theories that can be of value for HRC design. However, a common ground for organizing and executing design activities using the available knowledge was missing.

Therefore, considering future production systems of SMEs as complex, computer-based systems in which human operators will have more responsibilities for the successful operation of these systems an 'operator-centred production design model' has been presented that should function as a blueprint for a methodology for HRC design (page 53). This model should help to structure the design activity into specific phases and show the emphasis on the inclusion of operator related information throughout the procedure. It should also emphasise an iterative way of working.

As the second part of understanding HRC and its design, two separate questions were formulated, one targeted at designers of HRC that are experienced in designing systems that involve robots, and the other question, aiming to understand the HRC design activities of inexperienced designers. These questions were as follows;

RQ2 - What bottlenecks are there for expert designers during HRC design?

RQ3 - What bottlenecks are there for novice designers during HRC design?

In order to address these questions, two separate research activities were performed. The first of these activities involved the investigation of the design process of a group of 'expert' HRC designers in a real-life HRC design case (page 56). The second question was addressed by performing three HRC design activities with novice HRC designers in a laboratory setting (page 70).

Based on the investigations of the HRC design activities of expert and novice HRC designers, an overview of the influential factors in HRC design was developed (page 88). Based on the factors presented in this overview, an impact model for a methodology for supporting HRC design has been presented.

6.1.2 Developing support for HRC design

After the explorative part of this research, in the second part, the goal was to create a new methodology for HRC design. This objective was captured by the following research question;

RQ4 – How can novice HRC designers be supported during their design activity?

As a first step in addressing this research question, a set of requirements for the proposed support needed to be formulated. Considering the insights that have been generated through the addressing of the first three research questions, the following requirements were formulated for the development of a methodology for HRC design (page94);

- A methodology for designing HRC should facilitate the establishment and support of common ground between the involved designers.
- A methodology for designing HRC provides a systematic structure for the HRC design process and emphasises an iterative way of working.
- A methodology for designing HRC should be applicable by novice HRC designers.

- A methodology for designing HRC should allow flexibility in the use of its constructs in order to be adaptable to requirements presented by the contexts that it is being applied in.

In response to these requirements, an adaptable framework methodology for designing human-robot coproduction was conceptualised (page 96). The main procedure for HRC design as proposed by the methodology is based on the 'operator-centred production design model', and describes a HRC design cycle based on four phases which designers can use as a guideline when incrementally developing HRC scenarios. In this respect, similar to the 'Agile software development' approach, it relies on the creativity of the people that apply it, rather than the robustness of the design process when HRC design problems are being approached. Furthermore, the methodology comprises of four novel instruments that have been envisioned specifically for HRC design by novice designers (HRC Questionnaire, Coproduction Canvas, Workflow Simulation Tool, HRC Scorecards). In the description of the developed methodology, additional methods (and requirements for additional methods) that can be used in the various phases of the design process have been described. These instruments help to address the 'shared common ground' and 'shared understanding of the design problem' factors of HRC design as displayed in Figure 38.

As a final step in the conceptualisation of the developed methodology, it has been subjected to an applicability validation, during which the application process of HRCDM by novice HRC designers has been explored. For this, HRCDM was applied during three similar HRC design cases. The applicability validation process has been supported by the Validation Square method, which allowed the discussion of the theoretical as well as the empirical aspects of validity of the developed methodology. The results have shown that novice designers use HRCDM and its constructs as guidelines, rather than a set of rules, and that they are able to adapt it according to their own context and needs.

6.2 Implications of HRCDM

HRCDM is expected to have implications for various groups of users in the future. A summary of these groups and thee implications are outlined in this section.

- **SMEs:**
  During the course of this research, interaction with the industry and reflections on the developed theories and instruments from these organisations were key. As a result of one of these interactions, the 'Coproduction Canvas' instrument, which is included in HRCDM has been a point of inspiration for facilitating the workshops given to SMEs at

the RoboHouse [2]. It facilitates organisations to discover the possibilities that novel robotics technologies have to offer and to perform tests in an industrial setting. In order to be used during workshops given to their clients that are involved in manufacturing, RoboHouse has developed a "RoboCanvas" (RoboValley 2019), which is a paper-based abstract prototyping tool, similar to Coproduction Cards and the Coproduction Canvas. During an informal interview in April 2019, it was indicated that the RoboCanvas has so far been successfully used to model the production processes of 50 different organisations, and that there are plans to extend its functionalities towards the generation of concrete HRC scenario proposals based on the models created using the RoboCanvas;

- **Human resources consulting:**
  Currently, in the field of human resources consulting, the aspects through which the fit between a human operator and a production task can be discussed are limited to prior experience of the operator. However, HRCDM can play a role in enabling these non-technical experts to evaluate HRC scenarios based on a greater range of factors than is currently possible. It will also allow them to monitor performance based on human-centric performance indicators. During the FiaD project, the concepts of the Coproduction Canvas and HRC Scorecards were presented to experts from Randstad[3]. The reflection of these experts on the presented material showed a positive stance towards the use of similar tools in the future during their own practice, as they believed that in the near future, with the increase of teaming possibilities between humans and robots, the assessment of the fit between humans and robots for production tasks will become more relevant for human resources consulting;
- **HRC research:**
  This research has helped to clarify the relationships between the different domains of knowledge related to HRC design, and more importantly, where the gaps of knowledge exist. The development of an adaptable framework methodology for designing HRC is an initial step towards a new approach in the field of production system design in which more emphasis is placed on human-related aspects of the system compared to current practices. This presents new scientific challenges for integrating knowledge from alpha and gamma sciences into the predominantly beta science-based production system design practices. On the other hand, the concept of HRCDM

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[2] RoboHouse is a 'Smart Industry Fieldlab', which is associated with Delft University of Technology's Robotics Institute. At RoboHouse organisations and individuals can discover the possibilities cognitive robotics has to offer, develop their own applications and test them in an industrial setting. It also offers a specific set of courses to train new robotic talent.

[3] Randstad is a human-resources consulting organisation based in the Netherlands, and was a partner of the FiaD project.

can be used as a framework during the development of future academic projects and collaborations with industrial partners on topics relating to the use of robot technology in various forms and capacities in the context of manufacturing, and the development of better robot-assistants for humans in the same context;

- **Product design education:**
  Similar to the advantages of understanding the principles of Design for Manufacture and Assembly (DfMA), understanding the dynamics and influential factors in HRC will enable better evaluation of production scenarios and, as a result, will play a role in product design education. Students and educators will benefit from using HRCDM for assessing the manufacturability, and the economic and societal impact of the products that they design.

6.3 Recommendations

HRCDM has been developed as a set of instruments, methods and procedures that HRC designers should adapt to their needs. Next, some recommendations are provided for those who apply the methodology and those who wish to extend it in the future.

6.3.1 Recommendations for applying HRCDM

When considering the application of HRCDM, it should be taken into account that the methodology is the product of an initial attempt to address the design of production systems from a new perspective, and has so far been only elaborated on a conceptual level. Therefore, it currently provides predominantly theoretical support rather than practical support for HRC designers. Its procedures, methods and instruments should be further refined and validated before HRCDM can be used as an efficient and effective methodology for HRC design. It is therefore recommended that, in its current state, HRCDM should primarily be used as a means to support the establishment of common ground in the conceptual design phases of HRC design projects involving multiple designers with backgrounds and experience in different disciplines, rather than detailed design phases of such projects. HRC design remains a complex activity and therefore, it is highly recommended that the underlying theories as discussed in this thesis should be studied in more detail before attempting to make changes to existing human-driven production systems.

6.3.2 Recommendations for extending HRCDM

So far, methods for abstract modelling and prototyping of systems that make use of HRC have not been the focus of the industry. In addition, little distinction has been made between designing a new system and making modifications to an existing system. For this reason, HRCDM provides a new approach towards production system design. In its current state, the methodology provides a theoretical basis for further inclusion of, and extension by additional HRC design methods and instruments. Therefore, it is recommended that future attention should be paid towards extending HRCDM's instruments and methods so that they can be more practically applied.

Currently, software tools that allow multi-aspect modelling of production systems are limited, such as tools that allow the modelling and simulation of ergonomic aspects of production processes. In addition, such existing tools are relatively expensive for SMEs and require expertise to model and interpret results in an effective way. Therefore, it is recommended that in particular, the WST be extended and further developed into an "all-in-one" software suite specifically targeted at providing HRC design support for SMEs, ideally facilitating the application of all of the methods and tools of HRCDM in one place.

6.4 Reflection

6.4.1 Reflection on the methods used in this research

The research design that has been introduced in Section 1.5 provided a balanced combination of theoretical and empirical inquiry, which was operationalized in four research cycles.

Research Cycle 1 included a literature study. The literature study required the exploration of scientific contributions from multiple knowledge domains. This has made the study challenging, as great effort has been put into to establishing a central framework through which these fields of knowledge could be viewed. This also delayed the interpretation of the results of the field study, as the field study was performed before finishing the literature study. In an ideal situation, these elements would have been performed in sequence.

Research Cycle 2 was mainly practice based, involving the researcher participating in four HRC design cases in various roles. Each of these cases provided input for conceptualising different aspects of the methodology and enabled broad coverage of the practice of HRC design, best practice and bottlenecks. Due to the time constraints of the research, some of the cases had to be performed at the very beginning of the research, before finalising the literature study and before becoming acquainted with all aspects of HRC. In an ideal situation, these cases would have been completed after a fuller understanding of the research context had been established.

Research Cycle 3 required the combination of knowledge and insight from the first two research cycles, to consolidate this knowledge into a format that laid the foundation for the methodology. This was achieved by creating diagrams of influential factors in HRC design and by establishing a set of core requirements for the methodology. However, the lack of a surrogate methodology, which HRCDM could be based upon, has proven to be a challenge. As a result, several iterations were needed to ensure that the overall procedure was logical, and that the methods and instruments aligned with each other.

In Research Cycle 4, the Validation Square method provided a structure for the validation process, and helped to build an objective argumentation for the applicability of HRCDM by novice designers. As the Validation Square was originally developed for the validation of design methods, its applicability to the validation of methodologies containing a collection of methods, as well as other constructs, remains a point of discussion. On the other hand, it should be noted that the chosen validation cases were only an approximation of the target context. Application of the methodology in real-life HRC design cases will instill greater confidence in the results.

6.4.2 Reflection on the operational aspects of this research

Several operational factors that had effect on this research project are also worth mentioning.

- **Involvement with the Factory-in-a-Day project:**
  This research was partly funded by the EU-FP7 FiaD project. At the beginning of the project, the main objective of this research was to develop one of the tools of HRCDM, namely the WST, embedded within the FiaD project. However, at the end of RC1, and after the study involving automation integrators (Section 3.2), the conclusion was reached that this objective would not be suitable to provide support in an area that has so far been neglected, i.e. the design process and methods used in designing HRC production systems. This resulted in the decision to focus the research more on developing a holistic methodology for novice HRC designers, rather than a single tool in this context. In addition, the decision was made to focus the methodology on the conceptual design of HRC, rather than detailing and deployment of HRC (as envisioned by the FiaD project). By being embedded within the FiaD project, a network of interested parties was readily available to participate in the research activities. In addition, the project also functioned as a strong foundation on which topics related to robotics and industrial automation could be learnt and discussed with experts in the field. However, being a project that involves academic as well as industrial parties located in multiple European countries has at times resulted in a shift of focus and pace of the planned activities.
- **Performing this research from the perspective of Industrial Design Engineering:**
  This research project was undertaken at the Faculty of Industrial Design Engineering, within a research group that focuses on Mechatronics Design, Cyber-Physical Systems Design, Augmented Prototyping, and Additive Manufacturing. While these fields of study touch upon aspects that are relevant for understanding HRC and its design, a relatively larger gap existed on the understanding of topics that were outside the scope of these fields. Therefore, the greatest challenge during this research related to the need to gain extensive knowledge in disciplines that were less familiar to the research team. Nevertheless, this challenge enabled to establish a new approach to-

wards production system design, and HRC design in particular, from the perspective of Industrial Design Engineering.

- **Performing research in a rapidly developing field:**
  It is well known that the fields of robotics and industrial automation have been going through major changes in recent years. As mentioned in the previous paragraph, much effort was spent at the beginning of this research in the exploration of a range of fields of research. Although this was needed to establish the underlying assumptions and directions of the project, research into HRC design has been gaining pace while this was being done (Kadir et al. 2018). While this increases the relevance of this research, it should be noted that only a limited portion of the most recent work (published after 2014) could be integrated into the discussions in this thesis.

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Abbreviations

AI	Artificial intelligence
AR	Augmented reality
CAD	Computer aided design
CIM	Computer integrated manufacturing
Cobot	Collaborative robot
CPS	Cyber-physical system
CPPS	Cyber-physical production system
CSCW	Computer supported cooperative work
CW	Customisation workstation
DES	Discrete event simulation
ERP	Enterprise resource planning
FiaD	Factory in a day
GUI	Graphical user interface
HF	Human factors
HMI	Human machine interaction
HRC	Human-robot coproduction
HRCDM	Human-robot coproduction design methodology
HRI	Human robot interaction
IA	Industrial automation
ICT	Information and communication technology
IDE	Industrial design engineering
IoT	Internet of things
IIoT	Industrial internet of things
KPI	Key performance indicator
LfD	Learning from demonstration
LoA	Level of autonomy
LORA	Level of robot autonomy
MES	Manufacturing execution systems
pHRI	Physical human-robot interaction
PLC	Programmable logic controller
RC	Research cycle
ROS	Robot operating system
RQ	Research question
SCADA	Supervisory control and data acquisition
SDLCs	Software development lifecycle models
sHRI	Social human-robot interaction
SMEs	Small and medium sized enterprises
TS	Task sharing
UCD	User centred design
VR	Virtual reality
WS	Workplace sharing
WST	Workflow simulation tool

Appendix A

Existing initiatives targeting SMEs

While HRC as defined in this research is a new concept, there are relevant initiatives and researchers around the globe who are working on similar subjects. In this section, a short review of these initiatives is presented with an emphasis on the initiatives in Europe.

Global initiatives

The introduction of the Industry 4.0 initiative has drawn much attention from the rest of the world. Many countries and regions have initiated their own programmes in order to show their willingness and ambition to stay in competition with—and reach the level of—other nations. In the Unites States, a similar initiative has been named "Smart Manufacturing" (National Institute of Standards and Technology 2018); in China a comparable strategy is "Made in China 2025" (Wübbeke et al. 2016); in Japan "Society 5.0" (The Government of Japan 2018); and in the United Kingdom "4IR" (Engineering Employers Federation 2018).

European initiatives

The European Union (EU) has initiated specific funding programmes in order to systematically support the development of knowledge for SMEs. Table 18 shows the number of projects that address SMEs specifically, which the EU has supported through various subprogrammes of its Framework 5 (FP5), Framework 6 (FP6), Framework 7 (FP7) and Horizon 2020 (H2020) programmes between 1998 and 2020. An increase in the number of projects that are SMEs-specific has been observed throughout this period. Looking more closely at projects that target manufacturing SMEs, robots and automation, a similar rising trend is seen (Table 19); during the FP7 programme, for which submissions could be made between the years 2007 and 2013, the numbers of projects addressing SMEs, robots and/or automation showed a considerable increase compared to FP6.

Table 18 Number of projects targeting SMEs

Programme	FP5	FP6	FP7	H2020
Years	1998 - 2002	2002 - 2006	2006 - 2013	2013 - 2020
SMEs projects	N/A	2593	7216	3517 (as of 7/2018)
Data from 18/7/2018. The H2020 programme is currently running, therefore the values indicate periodic figures. All other values indicate final figures.				

Table 19 Number of projects targeting SMEs, robot, and automation

Search terms	Number of report summaries			
Programme	FP5	FP6	FP7	H2020
“SMEs” & “Robot”	4	24	281	27
“SMEs” & “Automation”	8	62	1002	84
Data from 18/7/2018				

Within the FP7 programme, a total of 1,283 projects were funded that address “SMEs, robots and/or automation”. For H2020, which has a submission period of 2013–2020, a total of 111 projects have been funded that address the same topics, at the time of writing. These data show that SMEs are gaining importance in the manufacturing landscape of the future, and that the industry and governments are investing in research and development to support initiatives in this area.

Based on a detailed investigation of 281 project report summaries from the FP7 database using the query “SMEs & Robot”, six projects targeted SMEs and the implementation of robots and automation in general (Table 20). Most of the other projects focussed on technical challenges related to robots and automation in a context of one or more enterprises that classify as SMEs. However, none of these projects specifically focussed on designing collaborative production processes for SMEs.

Initiatives in the Netherlands

In the Netherlands, initiatives relating to Industry 4.0 have been gathered under the umbrella of “Smart Industry” (Huizinga and Walison 2014). Inside Smart Industry, eight subclusters have been described in which new knowledge and technologies are being developed by collaborations between industry, local governments and academia. These clusters are: “Advanced Manufacturing”, “Flexible Manufacturing”, “Smart Products”, “Servitization”, “Digital Factory”, “Connected Factories”, “Sustainable Factory”, and “Smart Working”. The dissemination of knowledge is realised through the initiation of local fieldlabs. Currently there are 34 fieldlabs in the Netherlands that are part of—and are being financed by—Smart Industry (Smart Industry 2018). The Ministry of Social Affairs has also addressed these technological developments in the industry. In a report on the labour market policies, the Minister for Social Affairs indicated the importance of educating the labour force to be ready for the technological transformations of the coming years (Asscher 2016).

Table 20 Selected FP7 projects targeting similar goals with this research

Project Name	Goal/Objective	Method
SMERobotics	The European robotics initiative for strengthening the competitiveness of SMEs in manufacturing by integrating aspects of cognitive systems	Robots with cognitive capabilities
FACTORY-IN-A-DAY	New hybrid production systems in advanced factory environments based on new human-robot interactive cooperation	Robots that are able to interact safely with humans and that can be deployed rapidly
FORTISSIMO	Factories of the future resources, technology, infrastructure and services for simulation and modelling	Providing pay-per-use design and simulation resources for SMEs
ReBORN	Innovative reuse of modular knowledge based devices and technologies for old, renewed and new factories	Re-use of factory machines, and layout design methods
PRIME	Plug and produce intelligent multi-agent environment based on standard technology	System architectures for plug & produce systems
I-RAMP³	Intelligent reconfigurable machines for smart plug & produce production	Intelligent tools and devices for plug & produce systems
Data from 18/7/2018		

Conclusion

This section has presented an overview of the current state-of-the-art of Industry 4.0-related developments from around the world. The gathered data show that there is a trend for supporting SMEs towards a more decentralised structure. In order to realise this in Europe, several projects have been funded (and completed) that address various aspects of the transformation that is needed by SMEs. However, results of these projects show that most have focused on technological- and business-related aspects of transformation, while little or no attention has been given to human-related aspects of the solutions required to support Industry 4.0-compatible SMEs.

Appendix B

QuickScan Tool – Factory in a Day

An overview of the aspects based on which the QuickScan tool makes an assessment on the potential for robotic handling of different types of products. Clients receive the assessment of their proposed robotic pick & place task based on these tables.

Source: www.factory-in-a-day.nl/quickscan

PICKGING	Hard products	Flexible products (i.e. products in bags)	Variable forms(i.e. natural products)	Big, variable form (i.e. Clothes)
Predetermined position and orientation	🟩	🟩	🟩	🟨
Laying on a conveyor belt	🟩	🟩	🟩	🟨
Randomly distributed on a conveyor belt	🟩	🟨	🟨	🟨
Randomly distributed on a conveyor belt, with potential overlaps	🟨	🟨	🟨	🟨
Organized in a pattern in a container	🟨	🟨	🟨	🟨
Randomly distributed in a container	🟨	🟥	🟥	🟥
Randomly distributed and obstructed by neighboring products in a container	🟥	🟥	🟥	🟥

MOVING	weight: <3kg **AND** distance: <1m	weight: >3kg **OR** distance: >1m	weight: >3kg **AND** distance: >1m
Simple lay-down	🟩	🟩	🟩
Orientation in 2D	🟩	🟩	🟩
Orientation in 3D	🟩	🟨	🟨
Follow a trajectory	🟨	🟨	🟨
Assemble	🟨	🟥	🟥

PLACING	Hard products	Flexible products (i.e. products in bags)	Variable forms(i.e. natural products)	Big, variable form (i.e. Clothes)
Predetermined position and orientation	🟩	🟩	🟩	🟨
Obstructed but approximate position	🟩	🟩	🟩	🟨
Moving position (i.e. conveyor)	🟩	🟨	🟨	🟨
Non-obstructed but unknown position	🟨	🟨	🟨	🟨
Obstructed and unknown position	🟨	🟨	🟨	🟨
On a stack of similar products	🟨	🟥	🟥	🟥

🟩 Robotisation possible
🟨 Additional development necessary
🟥 Addition research necessary (longer development time)

Factory in a Day

Appendix C

Example HRC Questionnaire:

Workstation- General

- Describe the workstation that you would like robotize by identifying the following aspects:
    - Purpose of workstation
    - What are the input what are the outputs (what somes in what comes out?)
    - Who is responsible for the production line?
    - Who is responsible for the workstation?
    - What are the tasks that are being executed at the workstation? By the machine and by the operator?

Please indicate these in the sequence of happening.

Time	Act	Who? (human/machine/both)

- How many hours a day operational?
- How many operators?
- Time of cycle (number of items passing workstation)

Workstation – Task and product description

- Describe the products that are being handled at the workstation

Size	
Form	
Weight	
Materials	
Color	
Fragility	
Hard/soft	
Other mentionable details	

- How do products arrive at the workstation? Think of, pallet? Crate? Bulk? Tray? What are the sizes?
- Is there variance between the products coming to the workstation? E.g. in shape round vs square, material soft vs hard.
  Can you describe variance? Is there a recognizable pattern in the varience?
- How do the products leave the workstation?
- Is there a variation between product that leave the workstation?
  Can you describe variance? Is there a recognizable pattern in the varience?

Workstation – process and quality control

- Define errors, when is something rejected?
- What is the current error rate?
- What are the most potential causes of errors
- What is your target error rate?
- Describe how the quality of the workstation is controlled ?
- How often does the quality check happen?
- How often does the workstation need a service/maintenance?
- How often does the workstation actually get serviced?
- Who does this?
- How much time is spend on this? (less than 30 min to ..hours/days)

Production environment

- Describe the environment of the workstation in detail
  Factors that can influence the task, such as; moisture, dust, temperature, vibration, sound, light etc.
- Which persons are involved with the workstation? Describe the character of the involvement
- Are there other workstations in the same area as the workstation in question? If yes, describe these shortly.

Business

- Calculate the costs of labor at the workstation. If possible, make a distinction between temp-workers and permanent workers.
- Provide the hardware costs and the service costs of the workstation.

Appendix D

The three HRC design briefs given to the novice HRC designers at the beginning of the HRC design cases in Chapter 5.

Case A: Customised marker set

Background: With the rise of digital manufacturing technologies (i.e. 3D Printing, digital book printing, laser cutting, CNC milling, etc.), increasingly more products are offered to customers on an on-demand basis, which means that products are produced after they have been ordered/paid for, and they can easily be customized according to the customer's wishes. This also means that smaller enterprises are able to produce and deliver complete products directly to their customers. At the same time, the increasing number of accessible plug & play robotic peripherals, such as Cobots, and grippers is enabling enterprises to realize on-demand production lines that can be setup rapidly.

Assignment: To design the HRC workstation requested in this design brief, you are asked to apply the methods and instruments of HRCDM provided to you. An introduction to the details of the relevant methods, instruments and other details about the design process and time schedule will be given to you at the beginning of the design process. Also, an expert will be available throughout the design process to ask any questions related to HRCDM. You are asked to build a proof-of-concept prototype of your proposed HRC scenario at the end of the design process using the resources that are provided to you.

Subject: You and your team are assigned to design a HRC workstation in which a wooden box containing three felt-tipped marker pens is produced. Customers can order the product through a website. The wooden box is engraved with the customers' choice of text, and the customers are able to choose the colours of each of the pens separately when placing an order. This type of product demands that the product can only be produced once an order is placed. Below, the flow of production activities is shown, followed by details about the human, robot and product entities.

- **Human:** The supply of parts to the engraving machine and the selection of the markers according to customers' wishes are tasks that are relatively difficult to fulfil using automated machines. Therefore, at least one human operator needs to be on the coproduction workstation to fulfil such roles.
- **Robot:** The engraving on the marker box is applied using a laser-engraving machine. The text that needs to be engraved on each box should be transferred from the e-commerce platform directly to the laser-engraver. A Cobot will be used to load and unload this machine, or to put the finished products in shipping boxes.
- **Product:** The wooden box consists of a base and a lid. The box has space for three marker pens. The total number of parts for this product is five. Production orders are automatically transferred to the production workstation after payment.

Case B: Custom colour sorted candies

Background: With the rise of digital manufacturing technologies (i.e. 3D Printing, digital book printing, laser cutting, CNC milling, etc.), increasingly more products are offered to customers on an on-demand basis, which means that products are produced after they have been ordered/paid for, and they can easily be customized according to the customer's wishes. This also means that smaller enterprises are able to produce and deliver complete products directly to their customers. At the same time, the increasing number of accessible plug & play robotic peripherals, such as Cobots, and grippers is enabling enterprises to realize on-demand production lines that can be setup rapidly.

Assignment: To design the HRC workstation requested in this design brief, you are asked to apply the methods and instruments of HRCDM provided to you. An introduction to the details of the relevant methods, instruments and other details about the design process and time schedule will be given to you at the beginning of the design process. Also, an expert will be available throughout the design process to ask any questions related to HRCDM. You are asked to build a proof-of-concept prototype of your proposed HRC scenario at the end of the design process using the resources that are provided to you.

Subject: You and your team are assigned to design a HRC workstation in which coloured candies that are normally are sold in mixed packages are being separately packaged, for customers that would like to eat specific colours. Customers can order the product through a website. On the website, the customers choose the number of candies per package and the colour of candies that they want in each package. Below, the flow of production activities is shown, followed by details about the human, robot and product entities.

- **Human:** The supply of candies to the HRC workstation and the making of the candy sets is an activity that the human operator should fulfil. Due to the fact that each order has a different number of boxes in a set, the human needs to choose the correct packaging material to make the set.
- **Robot:** The sorting and packaging of candies should happen automatically through a purpose-built machine. The candy sets that are produced by the human operator should be placed into a shipping package by a Cobot.
- **Product:** The final product is a set of boxes, each of which contains a number of candies of a specific colours defined by the customer. The sets can consist of three, four or five packages. Each set should consist of specific packaging that has enough space for the number of packages in the set.

Case C: Customizable chocolate letter set

Background: With the rise of digital manufacturing technologies (i.e. 3D Printing, digital book printing, laser cutting, CNC milling, etc.), increasingly more products are offered to customers on an on-demand basis, which means that products are produced after they have been ordered/paid for, and they can easily be customized according to the customer's wishes. This also means that smaller enterprises are able to produce and deliver complete products directly to their customers. At the same time, the increasing number of accessible plug & play robotic peripherals, such as Cobots, and grippers is enabling enterprises to realize on-demand production lines that can be setup rapidly.

Assignment: To design the HRC workstation requested in this design brief, you are asked to apply the methods and instruments of HRCDM provided to you. An introduction to the details of the relevant methods, instruments and other details about the design process and time schedule will be given to you at the beginning of the design process. Also, an expert will be available throughout the design process to ask any questions related to HRCDM. You are asked to build a proof-of-concept prototype of your proposed HRC scenario at the end of the design process using the resources that are provided to you.

Subject: You and your team are assigned to design a HRC workstation for chocolate letters—a seasonal product sold in shops in the Netherlands during the month of November. Normally, each letter is sold separately. In this design brief, customers can purchase a set of three chocolate letters. For example, customer can order two letters and an "&" (and) sign. Below, the flow of production activities is shown, followed by details about the human, robot and product entities.

- **Human:** The supply of chocolate letters to the HRC workstation is fulfilled by a human operator. The human operator also has the role of creating the sets of chocolate letters according to the order that has been placed.
- **Robot:** A purpose-built machine applies packaging around the three chocolate letters. The Cobot should have the role of placing the packaged letter sets into a shipping package.
- **Product:** The final product is a package containing three cardboard boxes, filled with three chocolate letters as specified by the customer. The customers can choose all letters of the alphabet as well as special characters. Order picking is performed before the packaging operation at this HRC workstation.

Summary

In recent years, research on topics related to the digitalisation of production systems has been growing rapidly. In particular, the use of robot technology in various forms and capacities to assist human operators in this context has been a major field of focus. The research presented in this thesis is situated in the domain of design research, and aims to support the research towards a better understanding of design for human-robot coproduction (HRC).

So far in mainstream automated production systems, work has been arranged in such a way that humans must adhere to work procedures as rigid as the rest of the automated production environment. However, one of the essential changes that will take place during the transformation to Industry 4.0 from the human operator's perspective concerns the introduction of a mix of new types of resources that possess various forms and types of artificial intelligence. This is expected to put extra emphasis on the interaction between humans and these intelligent resources in these systems and therefore calls for a more human-centric approach during their design processes. These new requirements, which concern the only resource in these systems that cannot be engineered – the human operator –, bring a new level of complexity to the (already complex) design process of these systems. On the other hand, research on the application of these new technologies in the context of small and medium-sized enterprises (SMEs) in the manufacturing industry, which are still mainly human-driven and less digitized, has not been a priority.

Therefore, the specific objective of this research project was the development of support for novice HRC designers for integrating collaborative robots (Cobots) successfully in existing and new human-driven production systems. The research for this thesis was executed as a PhD project which was supported by the EU-FP7-'Factory in a day' project, which enabled the exploration and generation of empirical evidence in the targeted context. At the start of the project, it was assumed that novice HRC designers were lacking conceptual design tools for analysing, modelling, simulating and evaluating human-robot coproduction scenarios. Therefore, the objective of this research was to realize an adaptable framework methodology for conceptual design of HRC.

For this research, a literature review was performed that covered multiple domains of knowledge. The findings are presented in three categories that represent the three perspectives from which HRC is viewed in this research, namely: (i) Industrial automation, (ii) Human-robot work, and (iii) Design. The findings of this review showed that the reviewed domains of knowledge contain many established and new principles and theories that can be of value for HRC design. However, a common ground for organizing and executing design activities using the available knowledge was missing. Therefore, a model to be used as the blueprint for an adaptable framework methodology for HRC design was proposed.

Next, two empirical studies were performed in order to better understand HRC and HRC design. The first study discusses the work of expert HRC designers during a HRC design activity in the real-life context. The second study discusses the work of novice designers, during three HRC design activities in a laboratory environment. The insights from these studies were used to develop an overview of influential factors for HRC design. This overview shows that the shared understanding of a HRC design problem within a team, and the collective competency of the team are essential factors to be supported during HRC design.

Based on the findings of the literature study and the results of the empirical studies, a set of requirements was established for the development of a HRC design methodology, which led to the conceptualisation of an 'adaptable framework methodology for designing human-robot coproduction' (HRCDM). In this thesis, HRCDM is presented by discussing its main procedures, instruments and methods. HRCDM is supposed to be used as a guideline for HRC designers that have little to no experience in HRC design. Using this methodology these designers should be able to structure their design processes and select and apply the best instruments and methods for their own HRC design context.

Finally, the applicability of HRCDM was explored based on its application by novice HRC designers during an exemplary HRC design case. The findings of this study shows evidence that designers are able to use HRCDM and its constructs as guidelines during HRC design and that it provides support during conceptual design of HRC scenarios.

To conclude, the thesis shows that HRCDM can have (positive) implications on SMEs, human resources consultants, HRC researchers and product design education. In addition, recommendations for applying and extending HRCDM are also presented.

Samenvatting

Tot nu toe is de manier waarop werkzaamheden in de reguliere geautomatiseerde productiesystemen zijn georganiseerd zodanig dat mensen zich moeten houden aan de strikte werkprocedures van een geautomatiseerde productieomgeving. Vanuit het perspectief van de menselijke operator zal een van de essentiële veranderingen tijdens de overgang naar industrie 4.0 de invoering van nieuwe soorten hulpmiddelen met een combinatie van verschillende vormen en soorten van kunstmatige intelligentie betreffen. De verwachting is dat de interactie tussen de mens en de intelligente hulpmiddelen belangrijker gaat worden, dit verlangt een meer mensgerichte aanpak tijdens het ontwerpen van deze productiesystemen. Nieuwe eisen, die betrekking hebben op de enige hulpbron in deze systemen die niet kan worden ontworpen - de menselijke operator -, brengen een nieuw niveau van complexiteit in het (toch al complexe) ontwerpproces van deze systemen met zich mee. Anderzijds is er weinig aandacht geweest voor de toepassing van deze nieuwe technologieën in de context van midden- en kleinbedrijf (MKB) in de maakindustrie, die nog steeds gebaseerd is op mensenwerk en minder gedigitaliseerd is.

De specifieke doelstelling van dit onderzoeksproject was dan ook de ontwikkeling van ondersteuning van onervaren HRC-ontwerpers voor het succesvol integreren van collaboratieve robots (Cobots) in zowel bestaande als nieuwe op mens gebaseerde productiesystemen. Het onderzoek voor dit proefschrift werd uitgevoerd als een PhD project dat werd ondersteund door het EU-FP7-'Factory in a day'-project. Dit heeft de exploratie en het genereren van empirisch bewijsmateriaal in de beoogde context mogelijk gemaakt. Bij de start van het project werd aangenomen dat het onervaren HRC-ontwerpers ontbrak aan conceptuele ontwerpinstrumenten voor het analyseren, modelleren, simuleren en evalueren van mens-robot coproductiescenario's. Het doel van dit onderzoek was dan ook het realiseren van een aanpasbare raamwerkmethodologie voor het conceptueel ontwerp van HRC.

Voor dit onderzoek werd een literatuurstudie uitgevoerd die betrekking had op meerdere kennisgebieden . De resultaten worden gepresenteerd in drie categorieën die de invalshoeken vertegenwoordigen van waaruit HRC in dit onderzoek wordt bekeken, namelijk: (i) Industriële automatisering, (ii) Mens-Robotwerk, en (iii) Ontwerpen. De bevindingen van deze evaluatie toonden aan dat de geëvalueerde kennisdomeinen zowel gangbare als nieuwe principes en theorieën bevatten die van waarde kunnen zijn voor HRC-ontwerp. Een gemeenschappelijke basis voor het organiseren en uitvoeren van ontwerpactiviteiten die gebruik maakten van de beschikbare kennis ontbrak echter. Daarom werd een model dat als blauwdruk voor een aanpasbare raamwerkmethodologie voor HRC-ontwerp kan dienen voorgesteld.

Vervolgens werden twee empirische studies uitgevoerd om een beter inzicht te krijgen in HRC en HRC-ontwerp. De eerste studie bespreekt het werk van deskundige HRC-ontwerpers tijdens een HRC-ontwerpactiviteit in een bestaande situatie. De tweede studie bespreekt het werk van onervaren ontwerpers tijdens drie HRC-ontwerpactiviteiten in een laboratoriumomgeving. De inzichten die voortkwamen uit deze studies werden gebruikt om een overzicht te ontwikkelen van factoren die van invloed zijn op het HRC-ontwerp. Dit overzicht laat zien dat zowel het gedeelde begrip van een HRC-ontwerpprobleem binnen een team als de collectieve competenties van het team, essentiële factoren zijn die tijdens het HRC-ontwerp moeten worden ondersteund.

Op basis van de in de literatuurstudie opgedane kennis en de resultaten van de empirische studies, werd een reeks van eisen opgesteld voor de ontwikkeling van een HRC- ontwerp-methodologie die heeft geleid tot de conceptualisering van een 'aanpasbare methodologie voor het ontwerpen van de coproductie tussen mens en robot' (HRCDM). In dit proefschrift wordt HRCDM gepresenteerd door haar belangrijkste procedures, instrumenten en methoden te bespreken. HRCDM is bedoeld om te worden gebruikt als een richtlijn voor HRC-ontwerpers die weinig tot geen ervaring hebben met HRC- ontwerp. Met behulp van deze methodologie zouden deze ontwerpers in staat moeten zijn om hun ontwerpprocessen te structureren en de beste instrumenten en methoden voor hun eigen HRC-ontwerp context te selecteren en toe te passen.

Vervolgens werd de toepasbaarheid van HRCDM onderzocht met behulp van onervaren HRC-ontwerpers tijdens een exemplarische HRC-ontwerpproces. Het resultaat van deze studie toont aan dat ontwerpers in staat zijn om HRCDM en zijn principes als richtlijnen te gebruiken tijdens HRC-ontwerp en dat het ondersteuning biedt bij het conceptueel ontwerp van HRC-scenario's.

Ten slotte laat het proefschrift zien dat HRCDM (positieve) implicaties kan hebben voor het MKB, human resources consultants, HRC-onderzoekers en productontwerpopleidingen. Daarnaast worden ook aanbevelingen voor de toepassing en uitbreiding van HRCDM gepresenteerd.

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About the author

Argun Cencen was born in 1986 in Istanbul, Turkey. After finishing high school in Istanbul in 2004, he relocated to the Netherlands to continue his higher education. Between 2005-2012 he studied at the Faculty of Industrial Design Engineering of Delft University of Technology where he obtained his BSc degree in Industrial Design Engineering and MSc degree in Integrated Product Design.

During his studies, he became interested in digital manufacturing and 3D-Printing. During his MSc graduation project with the 'Mechatronics Design' group at the Faculty of Industrial Design Engineering, he investigated the technologies related to 3D-Printing of electronic products and developed functional prototypes. He presented the results of this project at the '3D-Printing Event' in 2012.

After graduating, he worked as an Industrial Engineer at Shapeways, which was at the time one of the pioneers in the field of 3D-Printing and offered 3D-Printing services to a worldwide client base. As an Industrial Engineer, he was responsible for optimizing the production process which contained various types of industrial grade 3D-Printers and many manually operated post-processing equipment. During this time his interest in industrial automation and the interaction between automated machines and human operators grew which led him towards learning more about this subject.

As a result of his growing interest in human-robot interaction in production systems, he started his PhD. research project at the Faculty of Industrial Design Engineering of Delft University of Technology at the end of 2013. In this project, he focused on developing new approaches and methods to be applied by novice designers that work with Cobots and want to integrate these robots into production processes. This thesis is a compilation from the results of his PhD. project.