CRANFIELD UNIVERSITY

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The development of a human factors tool for the successful implementation of industrial human-robot collaboration

School of Aerospace, Transport and Manufacturing

PhD
Academic Year: 2011 - 2014

Supervisor: Sarah R. Fletcher
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ABSTRACT

Manufacturing organisations have placed significant attention to the potential of industrial human-robot collaboration (HRC) as a means for enhancing productivity and product quality. This concept has predominantly been seen from an engineering and safety aspect, while the human related issues tend to be disregarded. As the key human factors relevant to industrial HRC have not yet been fully investigated, the research presented in this thesis sought to develop a human factors tool to enable the successful implementation of industrial HRC.

First, a theoretical framework was developed which collected the key organisational and individual level human factors by reviewing comparable contexts to HRC. The human factors at each level were investigated separately.

To identify whether the organisational human factors outlined in the theoretical framework were enablers or barriers, an industrial exploratory case study was conducted where traditional manual work was being automated. The implications provided an initial roadmap of the key organisational human factors that need to be considered as well as the critical inter-relations between them.

From the list of individual level human factors identified in the theoretical framework, the focus was given on exploring the development of trust between human workers and industrial robots. A psychometric scale that measures trust specifically in industrial HRC was developed. The scale offers the opportunity to system designers to identify the key system aspects that can be manipulated to optimise trust in industrial HRC.

Finally, the results were gathered together to address the overall aim of the research. A human factors guidance tool was developed which provides practitioners propositions to enable successful implementation of industrial HRC.

Keywords: Organisation, workforce acceptance, trust, scale development, qualitative analysis, quantitative analysis, factor analysis, reliability analysis

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1 INTRODUCTION

1.1 Summary of the research problem

Manufacturing organisations are in need to achieve superior product performance, enhance production rates while reducing costs in order to stay competitive and meet the market demands. One way of achieving this is with the introduction of automated solutions, such as robotic systems. Although automated systems have attracted significant attention over the years, a significant amount of tasks in various manufacturing industries still require the flexibility and adaptability of a human operator. For example, the aerospace manufacturing industry is heavily dependent on skilled manual labour to complete aircraft equipping processes (e.g. attachment of aerodynamic surfaces on the wing). Such processes require high levels of dexterity and judgement from human operators. Therefore, in certain manufacturing processes the traditional vision of full automation is difficult to achieve. In these processes, the desire to appropriately integrate automated systems (e.g. robots) and humans to collaborate in the same workspace has become an attractive solution. The emerging concept being sought is industrial human-robot collaboration (HRC).

The rationale of this concept is not to remove humans, but rather complement human weaknesses with the strengths of a robot and vice versa. For instance, humans lack accuracy, repeatability, speed and strength, while robots are very accurate and do not suffer from fatigue. Also, industrial HRC can enhance the ergonomics of the work place by delegating heavy, repetitive and sometimes dangerous tasks to the robots. Despite the expected benefits of industrial HRC, close collaboration of humans and robots in industry has been prevented largely due to safety concerns. However, recent advances in intelligent automation have allowed true collaborative working with human operators. In light of this, health and safety standards (e.g. International Organisation for Standardisation (ISO) 10218:2-2011) are also being advanced and updated to reflect that in some circumstances it is safe and viable for humans to work more closely to industrial robots. Hence, the introduction of industrial HRC in production lines has become an attractive proposition.

Although more attention has been placed in the development of human-robot teams in industrial environments, the focus has predominantly been on the technical and safety aspects of the collaboration. However, the implementation of industrial HRC should be seen simply as a technological or engineering challenge. The introduction of such a radical technological change will impact the organisation as a whole and subsequently the employees. A plethora of studies over the years have highlighted that the workforce is among the key driving forces for the success of a technological implementation. Simply rolling robots on the shop floor does not guarantee their acceptance and effective use by the workforce. Earlier literature from the domain of advanced manufacturing technologies highlighted that inattention to the human factors has been shown to be a key detrimental factor. Similarly, the introduction of an industrial HRC system will generate comparable challenges. Although the importance of human factors has been previously stressed, to date there is no human factors tool or framework identifying the key human factors that need to be considered by automation specialists to successfully implement industrial HRC. As the concept of industrial HRC is still at its infancy, it is crucial to gain a comprehensive understanding of the key human factors.

1.2 **Research aim, objectives and contribution**

The aim of this research is to develop a human factors tool with the key human factors at an organisational (i.e. factors influencing the organisation) and individual level (i.e. factors influencing the human) that need to be considered for the successful implementation and acceptance of industrial HRC.

To satisfy the aim three principal objectives were set:

The first objective was to develop a theoretical framework with the key human factors at an organisational and individual level by reviewing literature from comparable domains to industrial HRC. This objective is achieved in chapter 3.

The second objective was to investigate whether the organisational human factors identified in the theoretical framework were enablers or barriers through a real industrial case study where traditional manual work was being automated. This objective is achieved in chapter 4.

The third objective was to explore the key individual level factors. From the list of individual level human factors identified in the theoretical framework, the focus of this research was given on the construct of trust in industrial HRC. The rationale for selecting trust is outlined at the end of chapter 3. This objective is achieved in chapter 5.

The completion of these objectives enabled to meet the overall aim of this research. A human factors guidance tool, in the form of propositions, is developed to aid automation specialists and system designers to successfully implement industrial HRC.

The principal contributions of this research are:

- It provides additional support for the significance of considering human factors for the implementation of automated systems on the shop floor and particularly industrial HRC.
- It identifies the key organisational level human factors that need to be addressed and the crucial inter-relations between them.
- It provides an initial understanding of the key system characteristics can influence operators’ perceived trust in an industrial HRC scenario. This knowledge can be utilised to optimise the collaboration between workers and industrial robots.
- The developed human factors guidance tool provides practitioners a framework which: (a) highlights the key human factors at an organisational and individual level that need to be considered and (b) informs practitioners when these key human factors need to be addressed as the project progresses from the conceptual phase to being fully operational. This tool can be utilised to obtain a holistic understanding of the impact these human factors and to successfully implement industrial HRC. Furthermore, the tool is flexible so that it can

be utilised by large manufacturing organisations as well as by small and medium manufacturing enterprises.

1.3 Thesis overview

This thesis has been structured in the following order:

Chapter 2 will present the concept of industrial HRC and its importance for the manufacturing industry. Furthermore, in this chapter, the importance of considering human factors for the successful introduction and implementation of advanced automated technologies will be discussed.

Chapter 3 will present the approach taken to develop a theoretical human factors framework which will identify the key theoretical human factors relevant to industrial HRC. The identified key human factors were segregated at two levels:

- human factors at the organisational level, influencing the organisation
- human factors at the individual level, influencing the human operator: Although a number of individual level human factors were identified in the theoretical framework, the focus of this research was placed on trust. The decision to place focus on trust will be outlined in this chapter.

Chapter 4 presents the work carried out to investigate whether the organisational human factors outlined in the theoretical framework above were enablers or barriers. For this purpose, an industrial exploratory case study was conducted where traditional manual work was being automated.

Chapter 5 discusses the approach taken to investigate the individual level human factors. As discussed previously, the focus was placed on trust. To understand how trust develops in an industrial HRC context, a psychometric scale that measures trust in industrial HRC was developed.

Chapter 6 presents an overall summary of the results emerging from this research.

Chapter 7 addresses the overall research aim. This chapter gathers the findings from chapters 4 and 5 to provide the human factors guidance tool (HFGT). This tool provides guidance to practitioners, in the form of propositions, to enable successful implementation of industrial HRC.

Chapter 8 discusses some of the limitation of the research and provides suggestions for future research.

Figure 1 illustrates the structure of the thesis, presenting how each of the principal objectives and research aim were met.

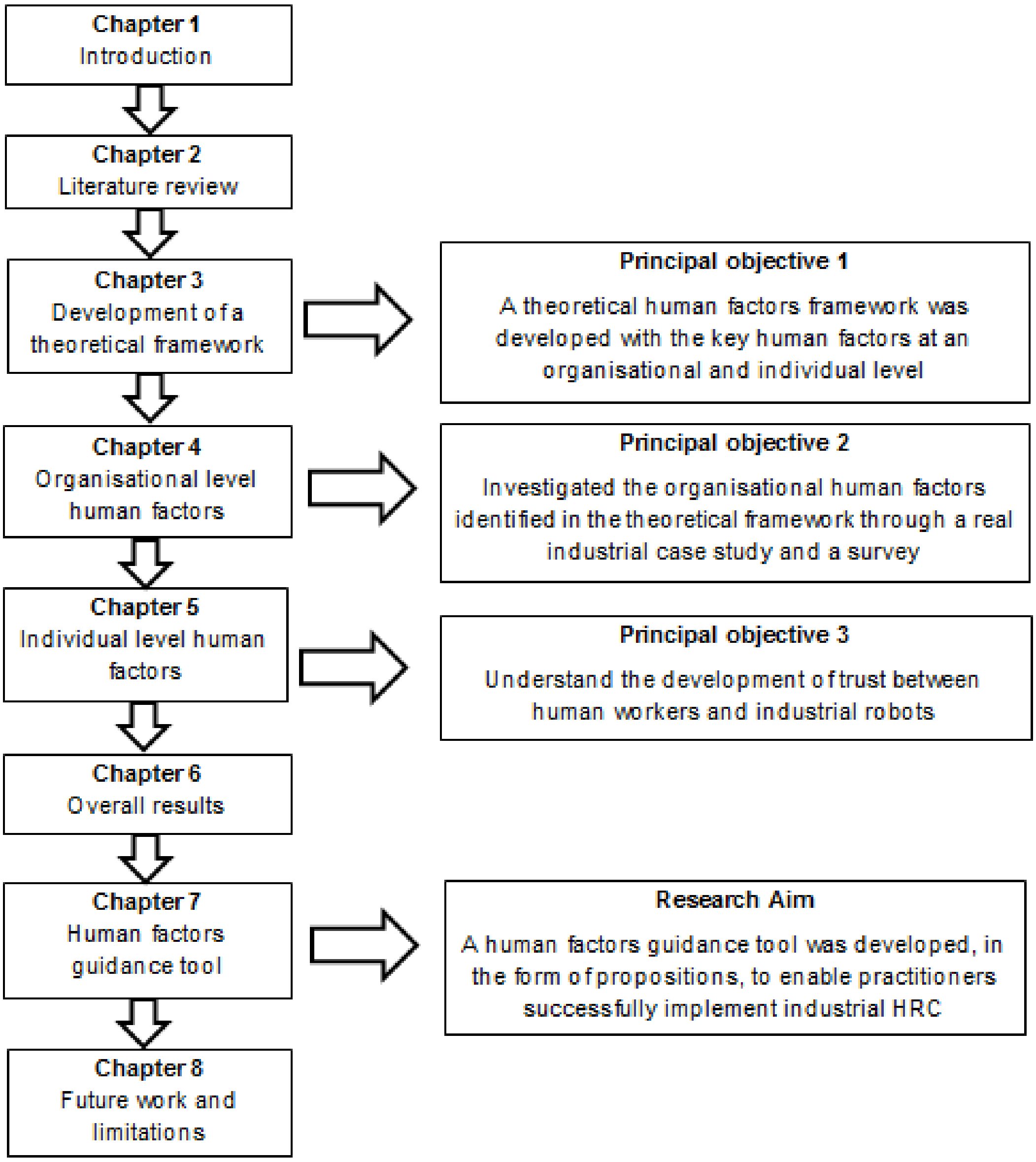

Figure 1-1 Graphical illustration of the structure of the thesis

2 LITERATURE REVIEW

This chapter reviews the relevant literature regarding the implementation of industrial HRC. Section 2.1 provides an overview of automation implementation in the manufacturing industry and the obstacles to the application of full automation. Following this, section 2.2 introduces the concept of industrial HRC. Section 2.3 discusses the importance of attending to the human factors issues for the successful implementation of technological initiatives by reviewing relevant literature from comparable domains.

2.1 Automation in the manufacturing industry

Superior product performance, new product introduction and manufacturing performance such as lower cost, reduced lead times and enhanced product and volume flexibility have been suggested to be the key success elements for manufacturing organisations (Chen and Small, 1996; Gunasekaran, McNeil, McGaughey and Ajasa, 2001). This led to the introduction of automation in the manufacturing industry. Automation has been defined as "*a device or system that accomplishes (partially or fully) a function that was previously, or conceivably could be, carried out (partially or fully) by a human operator*" (Parasuraman, Sheridan, and Wickens, 2000, p. 287). Particularly in the 1960s, manufacturing organisations began the adoption of advanced manufacturing technologies (AMTs). AMTs represent a wide range of technologies aiming to improve operational efficiency hence the competitiveness of the organisation (Small, 2006). AMTs consist of computer aided design (CAD) technologies, computer aided process planning (CAPP), computer numerical control (CNC), robotics, computer-integrated manufacturing (CIM) and flexible manufacturing systems (FMS) (Chen and Small, 1996; Chung, 1996; Small and Yasin, 1997; Udo and Ebiefung, 1999).

Traditionally, the automotive industry has been by far the largest customer of automated solutions as a means to achieve mass production. In 2012 alone, almost 63 000 robotic systems were installed in automotive applications across the globe, suggesting a six percent increase when compared to 2011

(International Federation of Robotics (IFR), 2014). Also, recent studies reported that nearly 50% of a standard automotive assembly process is performed with the aid of automation (Unhelkar, Siu and Shah, 2014). Furthermore, the food and drink industry in the United Kingdom (UK) has been embracing automated solutions on their factory floors as a means for expanding their productivity ((Centre for Food Robotics and Automation (CenFra), 2014)

Automated solutions have also started to become more attractive to other specialised markets such as the aerospace manufacturing industry. Historically, the application of automation in aerospace manufacturing has been limited when compared to the automotive industry. The larger size of the end product, low manufacturing volumes (when compared to the automotive industry) and the inherent dimensional variability between assemblies (Eastwood, Webb and McKeown, 2003) have traditionally been the major barriers for the uptake of automation. To date, the majority of aircraft assemblies use dedicated tooling, such as complex jigs and fixtures to ensure the product meets the design requirements (Jayaweera and Webb, 2007). Jigs and fixtures, however, have long lead-time to manufacture and are costly to make and calibrate. In addition, the manual process requires a considerable amount of fettling which is time consuming and implies lack of quality. Furthermore, most of these tools are only suitable for a specific aircraft type.

In light of this, aircraft manufacturers have started to favour the introduction of automated system on production lines to meet their orders. For instance, Boeing – the major aircraft manufacturer in the United States of America (USA) – is currently experiencing a massive backlog for commercial airliners such as the 737MAX, 777X and 787. More than 5000 aircraft have already been ordered with the estimated value being 440 billion dollars (Assembly Magazine, 2014). At the same time, Airbus – the rival aircraft manufacturer in Europe – is currently being reported to deliver almost 55 aircraft per month, while since the beginning of the 21st century commercial aircraft deliveries have increased by 60%. Just like Boeing, Airbus' order backlog has reached 4950 over the past decade (Aviation Week, 2014). To face these challenges, both aircraft manufacturers have turned towards automated solutions. For example, Airbus' A380 wing manufacturing team has been under particular pressure due to the extraordinary physical dimensions of the components being assembled. In particular, the massive size of the trailing edge required the use of automation. PaR Systems, Inc. and Airbus UK developed a pair of gantry system, each of which is 55 meters long to assist the drilling, fettling and cold working needs for the trailing edge spar (Siegel, Cunov and Doyle, 2003). Also, for the manufacture of the A380 wing, automation has been developed for the gear rib area drilling (Hogan, Hartmann, Thayer, Brown, Moore, Rowe and Burrows, 2003). The manual operation required operators to use multi-step process using numerous pneumatic drill motors and drill templates, while restricted worker access made this process even more demanding. In response to this, Airbus UK and Electroimpact developed a mobile automated system, called Gear Rib Automated Wing Drilling Equipment (GRAWDE) to assist production. Furthermore, the horizontal automated wing drilling equipment (HAWDE) was developed to assist with the drilling of A380's wings (Calawa, Smith, Moore and Jackson 2004). HAWDE operates over the top and bottom surfaces of eight wings.

In summary, automated systems are being utilised across a variety of sectors. Although automation is considered as the passport for achieving superior performance, full automation is not always viable. There are manufacturing processes which cannot be fully automated and human input is still a critical part of the manufacturing chain. This is described in the following section

2.1.1 **Obstacles to the application of full automation**

Despite the rapid expansion of automated systems the human element is still a vital part of the production chain. A significant amount of assembly tasks in various manufacturing processes still require the flexibility and adaptability of a human operator (Ding and Hon, 2013). For instance, although the automotive industry has embraced automation since the early 1960s, the final assembly of cars involves very dexterous tasks performed almost exclusively by human workers (Unhelkar, Siu and Shah, 2014). Also, certain markets require a greater degree of responsiveness and flexibility. For instance, the market for electronic products tends to have short lifetimes making product changeovers highly frequent (Matthias, Kock, Jerregard, Källman, Lundberg and Mellander, 2011). This high rate of product change means that the manufacture of these products requires a high degree of versatility from the human operator, making the traditional vision of a fully automated factory difficult to achieve.

Difficulties are also found in the application of full automation in more specialised manufacturing markets, such as the aerospace manufacturing production lines. The key drivers in the manufacture of aircraft are to increase productions rates while reducing costs and emissions (Buckingham and colleagues 2007). One possible solution has been the implementation of cost-effective automation on the production lines and some examples have been outlines above (e.g. GRAWDE, HAWDE). However, the majority of these automated solutions suffer from several disadvantages. First of all, these systems are highly inflexible. Apart from their massive physical dimensions, they are specifically used for a certain product. Utilising them for any other product has been suggested to be problematic (Kihlman, 2005; Webb, Eastwood, Jayaweera and Ye, 2005). Secondly, these machines have a very high-capital cost. Ming (2012) provides an indicative cost range between 2.5 and 3 million pounds. Therefore, a high-investment is required. In addition, these machines tend to have long lead-time introducing capital bottlenecks (Jayaweera and Webb, 2010). Finally, such monumental machines take up a significant amount of floor space which translates to a high budget for facilities and foundations to accommodate them. Recent views suggest that one way of introducing flexibility while maintaining cost-effectiveness is the incorporation of robots (Jayaweera and Webb, 2007). Industrial robots have been well-established in the automotive industry and their technological maturity makes them an attractive option for aerospace applications (Jamshidi, Kayani, Iravani, Maropoulos and Summers, 2010). Although they have been criticised for their lack of accuracy and stiffness, recent work has been directed to compensate these shortcomings with metrology systems (Ming, 2012). However, in such a highly specialised market merely the application of industrial robots is not the solution. A significant amount of processes require human input. For instance, the majority of aircraft equipping processes is heavily dependent on manual labour. Bolt-up operations during the equipping process require high levels of dexterity and judgement from human operators (Walton, 2013). Therefore, introduction of conventional robots to take over the process from start to finish is neither feasible nor cost-effective. In such processes, efficiency can be improved by integrating intelligent automated systems to collaborate with human operators (Unhelkar, Siu and Shah, 2014). Thus the emerging concept currently being sought is human-robot collaboration (HRC).

2.1.2 Section summary

In summary, although some processes can potentially be automated to some extent, a portion of these processes will require the high levels of dexterity, judgement and sensory possessed by the human operator. In these processes, there is an emerging desire to appropriately integrate automated systems, such as robots with human workers to form a team and collaborate in real time. The concept is termed human-robot collaboration (HRC). The following section introduces the concept of industrial HRC.

2.2 Concept of industrial human-robot collaboration

2.2.1 Overview

As discussed in the previous section, automation has not always been able to successfully replace the human input needed for many complex tasks. A possible solution is the implementation of closer human-robot collaborative working. Before proceeding further into the concept of human-robot collaboration, section 2.2.2 will introduce industrial robots, their development and their key features. Then, section 2.2.3 introduces the concept of industrial HRC and its advantages. Section 2.2.4 provides a review of health and safety legislation regarding industrial human-robot collaboration. Finally, section 2.2.5 provides a review of various research initiatives utilising the concept of industrial HRC.

2.2.2 Industrial robots

Although industrial robot definitions exist in various ways, a standard definition was created by the International Organisation for Standardisation (ISO) (ISO10218-1): "*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, p2). The first industrial robot arm was developed in 1959 by George Devol and Joseph Engelberger. The robotic arm, called Unimate, weighted two tons and was controlled by a program on a magnetic drum and used hydraulic driven actuators (International Federations of Robotics (IFR), 2012). This development commenced the industrial robots era around the globe. In 1969, General Motors (GM) installed the first spot-welding robots at its assembly plant. Traditionally, welding was a manual, dirty and dangerous task requiring the use of large jigs and fixtures. However, the installation of the first welding robot by GM was a breakthrough and increased productivity while allowing more than 90 per cent of welding operations to be automated when compared to only 20 to 40 per cent at traditional non-automated plants (IFR, 2014). Around the same time, industrial robots began to be considered by the Japanese market. In 1969, Kawasaki Heavy Industries considered the implementation of labour-saving machines and systems as a vital part of their development. Later on that year, the company managed to develop the first industrial robot produced in Japan. The continuous uptake of industrial robots led the robotics industry to a rapid growth between 1970s and 1990s (Shibata, 2004). In 2011 and 2012 industrial robot sales reached a peak with 165 719 and 159 346 units sold worldwide respectively, while future forecasts suggest a 6% average increase of robot installations worldwide between 2014 and 2016 (IFR, 2014). Overall, since their development, manufacturing organisations have continuously invested in industrial robots. The next sections, 2.2.2.1 and 2.2.2.2 present the anatomy of an industrial robot and their special features respectively.

2.2.2.1 Anatomy of an industrial robot

A robotic manipulator is a mechanical structure composed on joints and links interconnected (Figure 2-1). Similar to the human body, the joint of an industrial robot provides relative motion between two parts of the body. A joint, or sometimes called an axis, indicates the degrees of freedom (DOFs) of the robot's motion. Usually one DOF is relevant to a joint. In industry, robots tend to be described by the total number of DOFs they possess (e.g. a six DOF robot). Each joint connects together two links, the input link and the output link. Links are the rigid parts of the robot. Therefore, the purpose of the joint is to provide relative movement (e.g. rotation or translation) between the adjacent links.

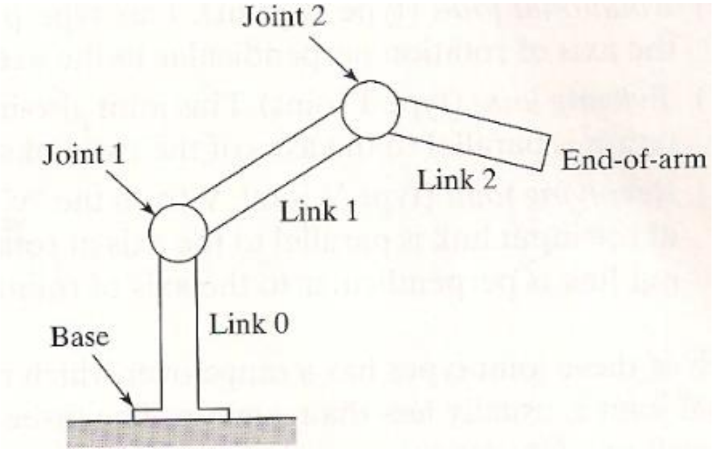

Figure 2-1 Components of an industrial robot (Retrieved from Groover, 2001)

Based on the figure above, link 0, is the input link to joint 1. The output of joint 1 is link 1. With the same logic, link 1 is the input link to joint 2 while link 2 is the output of joint 2. The schematic above is a simplistic illustration of an industrial robotic arm. Using a similar logic, industrial robots can be designed in various shapes and sizes according to the application being utilised. Figure 2-3 below indicates several types of industrial robots utilised by major robot manufacturers.

Figure 2-3 Different types of industrial robots[1]

As it can be seen, industrial robots can be designed as a single or a twin-arm manipulator depending on the application. Also, in some recent developments, human head features such as eyes and eyebrows are added (bottom right) to enhance human-likeness of the robot.

Furthermore, as shown in the figure, industrial robots utilise different types of end-effectors at the end of their arm to allow for interactions within the environment. This is an important feature of industrial robots and is discussed in more detail in the following section.

2.2.2.2 End-effector

An end-effector is attached to the end of robot arm, allowing the robot to perform some interactions with its environment and accomplish its task. End-

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[1] Images retrieved from: http://whatis.techtarget.com/definition/end-effector (Top left); http://www.zacobria.com/robot_photo_video.html (Top right); http://www.plant.ca/production/teaching-robots-new-tricks-9959/ (Bottom left); http://www.roboticstoday.com/news/abb-unveils-collaborative-robot-yumi-3041/ (Bottom centre); Guizzo and Ackerman (2012) (Bottom right)

effectors tend to be segregated in two categories, namely grippers and tools (Groover, 2001):

***Grippers**: Grippers are a particular set of end-effectors utilised to grasp and manipulate objects during a work process. Grippers come in various shapes, sizes and weights depending on the task being used for. Grippers tend to be categorised in the following categories:*

- mechanical grippers: these types of grippers tend to consist of multiple fingered grippers (two or more) and are used to grasp the part under manipulation. Figure 2-4 illustrates examples of a two-finger and a three-finger gripper.

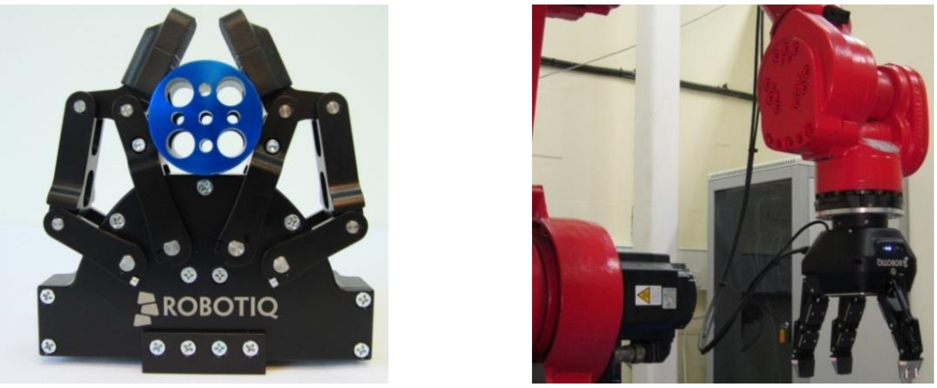

Figure 2-4 A two-finger (left) and a three-finger (right) mechanical grippers[2]

- vacuum grippers: these type of grippers utilise suction cups to lift the objects (Figure 2-5). In this case, objects need to be flat in order for the gripper to successfully lift the object.

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[2] Images retrieved from: http://robotiq.com/en/products/industrial-robot-hand

Figure 2-5 Example of vacuum grippers[3]

- magnetised devices: These types of grippers are utilised for grasping the *ferrous* materials (Figure 2-6). Magnetic grippers can either be electromagnetic grippers or permanent magnets. The former include a *controller unit* and a *DC power* for handling the materials. If the work part gripped is to be released, the polarity level is minimised by the controller unit before the electromagnet is turned off. The latter do not require any sort of external power as like the electromagnets for handling the materials and can be used in hazardous applications like *explosion-proof apparatus* because of no electrical circuit.

Figure 2-6 Example of magnetised grippers[4]

- adhesive devices: An adhesive substance is used to manipulate a flexible material, such as a fabric.

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[3] Images retrieved from: http://www.directindustry.com/prod/schmalz/vacuum-grippers-7112-1195605.html (left); http://www.romheld.com.au/sub_products.php?cat_id=102&cat_name=Vacuum (right)

[4] Images retrieved from: http://www.roboticsbible.com/robot-magnetic-grippers.html

- simple mechanical devices: These type of grippers typically consist of hooks and scoops.

Tools: Tools are used when the robot is performing a specific operation on the part under manipulation. Examples of robot tools are spot welding guns, arc welding tools, spray painting guns, assembly tools, and water jet cutting tools. For instance, in airframe assembly, the end-effector are usually equipped with processing tools and sensors to accomplish tasks such as drilling, fastening and accurate positioning (Devlieg, 2010). Figure below shows an example of a spot welding gun (left) and how it can be utilised on a robot (right).

Figure 2-7 Example of a spot-welding tool (left) attached on an industrial robot (right)[5]

2.2.3 Benefits of human-robot collaboration in industry

The continuous increase of robot installations across different manufacturing disciplines is expected to increase the need for human and robot co-existence and collaboration. Historically, industrial robots have been used in factories as a standalone system and operating autonomously (Weber, 2008; Papadopoulos, Bascetta and Ferretti, 2013). Most of the time, where robots were implemented, they were surrounded by fences and guards for safety purposes. Essentially this allowed no room for real time interaction. The increasing need for flexibility and adaptability along with the prohibitive cost for implementing full automation, the manufacturing industry has shown growing interest in the development of

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[5] Images retrieved from: Retrieved from: http://www.globalrobots.ae/robots_applications/images/abb-spotwelder.jpg

collaborative robots able to work alongside human operators (Hägele, Schaaf and Helms, 2002; Santis, Siciliano, Luca, and Bicchi, 2008).

The rationale of this concept is that the weaknesses of the human operator can be complemented by the strengths of the robot and vice versa (Bortot, Born and Bengler, 2013). As described earlier certain manufacturing processes require the sensory skills and ability of the human worker to react to external influences, such as tolerances or process variations. Thus the application of full automation in these types of processes is not a viable solution allowing the human operator to retain a key role (Krüger, Lien and Verl, 2009). However, human operators lack accuracy, repeatability, speed and strength. Industrial robots on the other hand are very accurate and do not suffer from fatigue. Furthermore, industrial HRC can enhance employee working conditions by delegating heavy, repetitive and sometimes dangerous tasks to the robots. Examples include instances where workers are required to perform a task within a confined space or carry out tasks which pose very high physical load.

Occupational risks of work in confined spaces

Recent work in aerospace manufacturing has been directed for the development of a human-robot cooperative system to assist assembly tasks within confined spaces, such as aircraft wings (Anscombe *et al.,* 2006). The current method requires operators to work, for a specific amount of time, within a confined space while carrying power tools. According to the UK Health and Safety Executive (HSE) a confined space is described as a place substantially enclosed, but not entirely, and where serious injury can occur from hazardous conditions within the space, such as lack oxygen (Veasey, McCormick, Hilver, Oldfield, Hansen and Kraver, 2006), extreme temperature (Aw, Gardiner and Harrington, 2007) and hazardous substances (National Institute of Occupational Safety and Health (NIOSH), 1996). Also, apart from the physical constraints, accessing and working for an amount of time within a confined space has been suggested to impose feelings of claustrophobia, panic or stress (Veasey *et al.,* 2006). With the use of a human-robot cooperative system, the robot will be used for the completing the task in the confined space.

Occupational risks due to difficult tasks

Certain manufacturing processes require operators to perform difficult tasks that impose high physical load on operators. According to Maurice, Schlehuber, Padois, Measson and Bidaud (2014), work-related musculoskeletal disorders are a major health problem in developed countries. Schneider and Irastorza (2010) reported that musculoskeletal disorders affect almost 50% of the workers. Therefore, introducing a robot to collaborate with the operator is likely to enhance operators' working conditions. For example, the welding of tubular and frame-shaped constructions is currently carried out manually, using tools and cranes. Also, the worker is required to carry out additional tasks such as handling and positioning of parts or prepare the welding seam (Thomas, Busch, Kuhlenkoetter and Deuse, 2010). Due to workplace restrictions the worker has to constantly change their position to complete the welding task by bending, twisting, stretching and kneeling down (Thomas, Busch, Kuhlenkoetter and Deuse, 2012). Furthermore, an ergonomic assessment of such a process revealed high physical load on employees (Busch and Deuse, 2011 – In Thomas, Busch, Kuhlenkoetter and Deuse, 2012). In response to this, a human-robot cooperative work system is being developed to assist welding operations (Thomas, Busch, Kuhlenkoetter and Deuse, 2011) which will relieve workers from working in unhealthy conditions.

Summary

The concept of industrial HRC implies that human operators will perform the “value added work” while robots will take over the repetitive and “non-value added work” (Unhelkar, Perez, Boerkoel, Bix, Bartscher and Shah, 2014). Successful implementation of human-robot collaboration can potentially increase production output, enhance quality and reduce product cost (Unhelkar, Perez, Boerkoel, Bix, Bartscher and Shah, 2014; Papadopoulos, Bascetta and Ferretti, 2013; Weidner, Kong and Wulfsberg, 2013).

2.2.4 Health and safety legislation and definitions

Despite the expected benefits of industrial HRC, close integration of human workers and industrial robots has been prevented largely due to safety concerns. Until recently, strict separation of man and machine was only allowed making simultaneous collaboration between humans and robots almost an impossible scenario. Recent technological advancements have seen robots becoming more mobile and human-oriented (Bostelman and Shackleford, 2010; Guizzo, 2008; Rethink Robotics, 2008). Furthermore, collaborative robots are now more compact, lightweight and dexterous (Robotique, 2014), while human safety is a top priority (Weidner, Kong and Wulfsberg, 2013). In the light of these advances, safety regulators, such as the ISO, began adopting a more progressive approach allowing closer collaboration between humans and robots. The ISO updated its documents regarding the integration of humans and robots in July as ISO 10218-1:2011 (Robots and robotic devices – Safety requirements for industrial robots – Part 1: Robots). Simultaneously the second edition of ISO 10218-2:2011 (Robots and robotic devices – Safety requirements for industrial robots – Part 2: Robot systems and integration) was published. The updated ISO standards introduced new concepts of safety regarding human-robot collaboration. Part 1 involves guidance for the assurance of safety in design and construction of the robot while Part 2 refers to the safeguarding of personnel during robot integration, installation, functional testing, programming, operation, maintenance and repair. The modifications in Part 2 allow cooperation with personnel due to prescribed limits for speed, power and additional safeguard installation. ISO defines HRC as a "*special kind of operation between a person and a robot sharing a common workspace*" (ISO 10218:2-2011, p.32). The collaboration can be initiated under the following three conditions:

- used for predetermined tasks;
- possible when all required protective measures are active;
- for robots with features specifically designed for collaborative operation complying with ISO 10218-1.

According to the ISO, a collaborative robot is defined as "*a robot designed for direct interaction with a human within a defined collaborative workspace*" (ISO 10218:2-2011, p. 2). Subsequently, collaborative operation is identified as "*state in which purposely designed robots work in direct cooperation with a human within a defined workspace*" (ISO 10218:1-2011, p.2) and collaborative workspace is defined as a "*workspace within the safeguarded space of the robot work cell, where the robot and human can perform tasks simultaneously during production operation*" (ISO 10218:2-2011, p.3).

In summary, health and safety regulations are being updated and advanced to allow some closer collaboration between industrial robots and human operators. Although we have not reached the desired level of acceptance from safety regulators, the first step has been made towards enabling industrial HRC.

2.2.5 Review of industrial human-robot collaboration initiatives

A number of research activities have been initiated over the years in the field of industrial human-robot collaboration aiming to integrate humans and robots to constitute an effective team. The first introduction of assistive robotic devices in production environments was in 1996 by Edward Colgate and colleagues (Colgate, Wannasuphoprasit and Peshkin, 1996). These assistive robotic devices were mechanical devices, primarily providing guidance through servomotors while a human operator is providing the motive force. Since then additional work has been directed towards developing assistive robotic workmates.

PowerMate

The PowerMate system (Figure 2-8) was developed by Fraunhofer Institute IPA (Schraft, Meyer, Parlitz and Helms, 2005). PowerMate is an intuitive robotic assistant utilised to assist operators in assembly and handling tasks.

Figure 2-8 The PowerMate collaborative system (Retrieved from Schraft, Meyer, Parlitz and Helms, 2005)

The *Power*Mate is stationary and has physical contact with the human operator. The interaction occurs through a force-torque-sensor enabling the robot to move when the operator applies force. The main purpose of this system is to assist the assembly of heavy parts. Initially the robot has to grip the heavy component and bring it to the human worker. Because this part is taking place in an area where the human worker does not have access, the robot is allowed to move at maximum speed. Once the part is brought in the collaborative area the robot changes into collaborative mode. In this mode, the human worker is able to move the robot through a handling device mounted on the robot gripper in combination with the force-torque-sensor. Therefore, during the collaborative part the human worker can ensure the final component has been precisely assembled. When the collaborative task is finished, the robot moves the completed item to a separate area and the next cycle begins.

Flexible Assembly Systems through Workplace-Sharing and Time-Sharing Human-Machine Cooperation (PISA)

The Flexible Assembly Systems through Workplace-Sharing and Time-Sharing Human-Machine Cooperation (PISA) was initiated in 2006 (Bernhardt, Surdilovic, Katschinksi, Schreck and Schroer, 2008; Bernhardt, Surdilovic, Katschinksi and Schroer, 2008). The aim of this project is to support human workers with powerful tools in order to complete a task as well as keep in the loop. The focus of the project is to develop novel intelligent assist systems, provide planning tools for their integration and to achieve reusability of assembly equipment. One of the sub-projects of this initiation is the development of a humanoid service robot to be used in human workplaces (Figure 2-9).

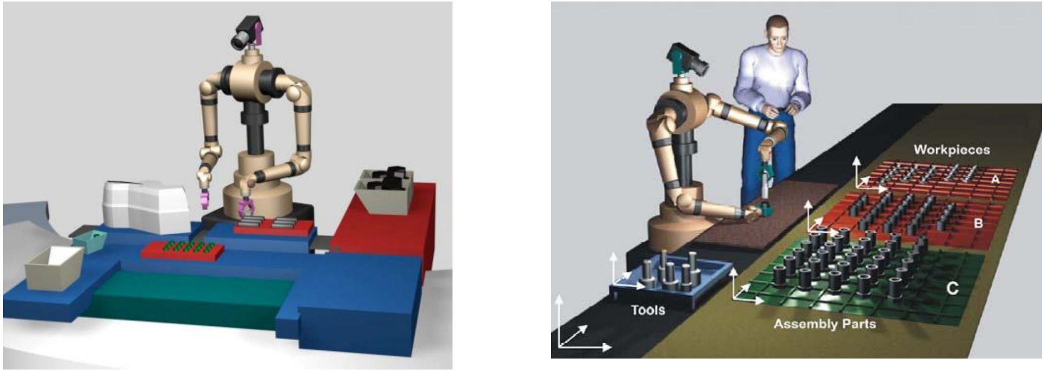

Figure 2-9 The PISA collaborative system (Retrieved from Bernhardt, Surdilovic, Katschinksi, Schreck and Schroer, 2008)

The use of this dual arm robot is to cope with the capacity and flexibility challenges faced with product life cycles and product volume. This robot is intended to be installed on a mobile platform will at the same time sharing the same workspace.

Rob@work projects

The rob@work project was initiated in 2001 by Fraunhofer Institute IPA (Schraft, Helms, Hans and Thiemermann, 2004). Rob@work is a single arm assistive robot, utilising a mobile platform with varying gear drive, energy supply for up to nine hours of work and a control system (Figure 2-10).

Figure 2-10 The Rob@work robot[6]

The aim of rob@work is to assist production workers in fetch and carry tasks, assembly and tool handling tasks as well as participating in manual arc welding. It has the ability to navigate autonomously while the human worker commands and supervises the robot. Further on this work, a second variant of rob@work was developed in 2008. Rob@work 2, on the other hand, is developed as static machining equipment which can be positioned in a variety of workplaces (Figure 2-11).

Figure 2-11 The Rob@work 2 robot[7]

This type of robot can be positioned on a variety of workplaces while it can be changed accordingly allowing for increased flexibility. It consists of a touchscreen and built-in sensors and actuators. A third variant of rob@work

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[6] Image retrieved from: http://www.care-o-bot.de/en/rob-work/history.html

[7] Image retrieved from: http://www.care-o-bot.de/en/rob-work/history/rob-work2.html

was developed. Rob@work 3 combines a mobile base with a modular manipulator system, which enables versatile and effective application in industrial environments. This robot platform is able to perform fetch-and-deliver tasks within a human assembly environment (Unhelkar, Perez, Boerkoel, Bix, Bartscher and Shah 2014).

Figure 2-12 The Rob@work 3 robot[8]

Co-operative Robot Assistant (CORA)

The Co-operative Robot Assistant (CORA) was developed (Iossifidis, Bruckhoff, Theis, Grote, Fauberl and Schoneir, 2005). CORA is a human-like robot assistant whose task is to collaborate with a human operator on simple manipulation or handling tasks (Figure 2-13):

Figure 2-13 The CORA system (Retrieved from Iossifidis, Bruckhoff, Theis, Grote, Fauberl and Schoneir, 2005)

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[8] Image retrieved from: http://www.care-o-bot.de/en/rob-work/download/images.html

CORA can be fixed on a table, and its purpose is to physically interact with a human worker standing across the table. CORA consists of a seven DOFs manipulator arm in combination with a two DOF stereo camera mounted on its head. In addition, it includes an interface for the human worker to interact and provide corrections to its end-effector according to the needs of the task.

Lightweight robotic arm

The Deutsches Zentrum fűr Luft-und Raumfahrt (DLR) developed an anthropomorphic light-weight robotic arm for direct human-robot collaboration (Figure 2-14) (Albu-Schäffer, Haddadin, Ott, Stemmer, Wimböck and Hirzinger 2007).

Figure 2-14 The Lightweight robotic arm system (Retrieved from Albu-Schäffer, Haddadin, Ott, Stemmer, Wimböck and Hirzinger, 2007)

This humanoid arm is designed for co-operation with human workers in unstructured environments. In addition, the humanoid construction of this arm, when compared to an industrial robotic arm, offers intrinsic safety due to its light-weight structure. Potential industrial applications can be assembly processes where accuracy is not of prime importance, applications where the robot operates within the immediate workspace of the human worker and possibly in direct physical co-operation with them and mobile service robotics applications.

Baxter

Recently, Rethink Robotics unveiled Baxter which can be deployed to work alongside human operators in certain manufacturing processes (Figure 2-15).

Figure 2-15 The Baxter robot[9]

Baxter is an easy to use interactive robot and was designed to handle light payloads and operate alongside human operators without being physically safeguarded. Baxter was designed to execute a variety of manufacturing and productions tasks, while at the same time it can be aware of its environment allowing it automatically adjust to changes. Furthermore, It features advanced force sensing technology, back-drivable motors, and a moderate velocity that aim to reduce the likelihood and impact of a collision (Assembly Magazine, 2014).

Rorarob

The ‘rorarob’ project has been initiated at TU Dortmund University and a recent initiative has been undertaken to introduce a human-robot collaborative system for the welding of tubular and framework constructions (Thomas, Busch, Kuhlenkoetter and Deuse 2010). Currently, the welding of such tubular pipe sections is done manually utilising simple tools while at the same time the operator performs other tasks such as, handling and positioning of heavy parts. This is a very labour-intensive process causing employees to receive a considerable amount of physical strain (Thomas, Busch, Kuhlenkoetter and

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[9] Image retrieved from: http://www.pdfsupply.com/blog/boston-based-rethink-robotics-partners-with-three-new-distributors/

Deuse, 2011). To this end, work has been directed to develop a safe and ergonomic human-robot assisted welding operation (Figure 2-16).

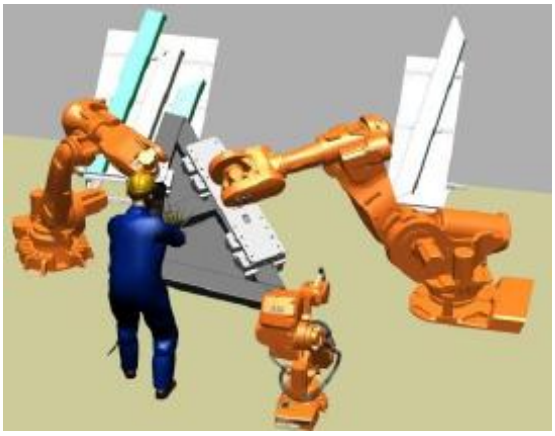


Figure 2-16 The RoraRob project (Retrieved from: Thomas, Busch, Kuhlenkoetter and Deuse, 2011)

This project is an excellent example of how a hybrid system can optimise a manufacturing process by utilising the advantages of each partner. A multi-robot system assists the human operator by positioning and handling the heavy parts. Thus removing a very labour-intensive and unhealthy part of the process from the worker.

HRC in cellular manufacturing

Tan, Duan, Zhang, Watanabe, Kato and Arai (2009) discussed the development of a human-robot collaborative system in cellular manufacturing. The system was chosen to optimise cable harness assembly (Figure 2-17).

Figure 2-17 A human-robot collaborative system for a wiring operation (Retrieved from: Tan, Duan, Zhang, Watanabe, Kato and Arai, 2009)

Interestingly, in this study, authors made a preliminary attempt to include human factors. Authors suggested that in such close proximity collaboration, operators are likely to experience high mental workload due to the robot's speed and the proximity of the robot to the human operator. As expected mental workload appeared to increase when robot speed was higher and when human-robot working distance reduced. The small sample size used (five), however, does not allow for more rigid conclusions to be made. Nevertheless, their attempt provides an indication that in close proximity industrial HRC, human factors need to be considered in order to achieve successful collaboration.

'Snake arm' robots

Industrial human-robot cooperation initiatives have also been conducted in the aerospace manufacturing sector. It was previously discussed that certain aircraft manufacturing processes can benefit from a human-robot collaborative system. Recent work by OC Robotics and Airbus has seen the development of 'snake-arm' robots to assist the assembly tasks within aircraft wing boxes (Buckingham *et al.* 2007). Currently, when the aircraft wing is closed-out in a box, aircraft fitters need to enter the wing box through small access panels while carrying power tools to perform a variety of tasks. The narrow access opening does not allow sufficient room for manual work to be carried out efficiently. This problem is particularly emphasised in wing sections where the wing is too small for a person to enter inside. At the same time, health and safety issues are raised when working within a confined space for a prolonged period of time (Albarracin, 2010). In such situations conventional off-the-shelf automation is impractical. A potential solution is the development of 'snake-arm' robots (Buckingham *et al.,* 2007) (Figure 2-18).

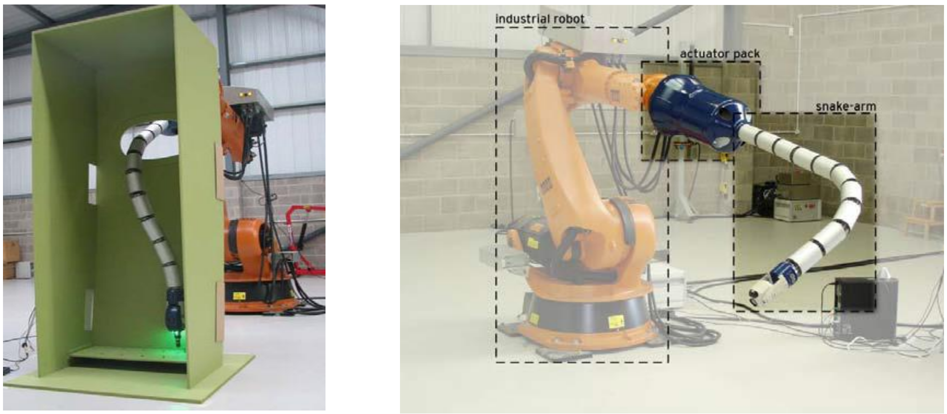


Figure 2-18 The ‘Snake’ arm robot (Retrieved from Buckingham *et al.*, 2007)

This concept utilises a standard single arm industrial robot, while the snake-arm is mounted on the robot and represents a long slender ‘proboscis’. In this way, the slender snake-arm section can advance into the wing box or any restricted section where human operators cannot reach. The snake-arm robot can follow a route into the section under investigation either by joystick control or from a pre-determined of path (OC Robotics, 2014). In addition, the system has been designed to allow automatic operation without the operator being present, semi-automatic where the operator is initiating a program and supervises the robot and manual tele-operation where the robot is controlled via a robot control system (Buckingham *et al.* 2007).

HRC in aircraft equipping processes

Apart from the snake-arm robot, the concept of industrial HRC has also been considered to optimise the equipping of aircraft with internal services such as attachment of aerodynamic surfaces with the use of industrial robots. To date, this area of aircraft manufacture remains exclusively manual (Walton, Webb and Poad 2011). The reason is because these type of processes require lengthy assembly methods, while the tight tolerances utilised in aerospace manufacturing of +/−0.25mm or less, have historically made the application of off-the-shelf automation almost impossible (Devlieg 2010). Walton, Webb and Poad (2011), however, suggested that a potential solution to overcome these challenges would be a metrology assisted human-robot collaborative system.

The aim of this system is to optimise the assembly process by utilising an industrial robot to position the parts whilst the human operator performs the attachment process which requires high level of dexterity. In light of this, a metrology assisted demonstrator cell was developed at Cranfield University where a typical equipping process is performed using realistic parts (Figure 2-19).

Figure 2-19 The human-robot collaborative demonstrator for aircraft equipping processes

The development of this demonstrator proved that a HRC system can be the solution into labour intensive aircraft equipping processes. The robotic partner will execute the “non-value adding” process of accurately positioning the surface while human operators will be utilised to perform the highly dexterous task of fixing the moveable.

As part of the development of this cell, a small scale study was carried out to investigate potential human factors close proximity collaboration between operators and industrial robots, such as situation awareness. Similar to the study by Tan and colleagues (2009), this study highlighted that integrating humans and industrial robots within the same workspace will be a challenging area for human factors practitioners:

2.2.6 Section summary

There is a breadth of prior work aimed at deploying collaborative industrial robots in manufacturing settings. Recent advances in intelligent automation enabled robot designers to develop industrial robots with sufficient technological sophistication to allow closer proximity to, and true collaborative working with, human operators. In light of this health and safety regulations have also been updated to reflect that in some circumstances it is safe and viable for humans to work more closely to industrial robots. Although more work has been directed towards developing effective human-robot teams in industrial environments, the focus has predominantly been on the technical and safety aspects of the collaboration. A key aspect often neglected is the key human factors that will enable successful implementation and adoption of industrial robotic partners within the human working environment. The following section discusses the importance of attending to the human element when introducing new technologies.

2.3 Human factors for the implementation of manufacturing technologies and techniques

2.3.1 Overview

The implementation of industrial HRC will be a major step change for many manufacturing firms. The implementation of such a radical technological change within a plant floor will be a challenge not only from a technical and production point of view but also from a human factors perspective. The introduction of a collaborative industrial robot will take over some of the manual tasks. This will inevitably change the work design and can potentially add significant pressure on shop floor workers. The importance of attending to the human element when such radical technological changes take place can be examined from previous literature. This is described in section 2.3.2.

2.3.2 Human factors in the implementation of a technological change

As early as the 1950s it was highlighted that merely introducing a new technology does not necessarily imply effective use and acceptance by the workforce. For instance, Trist and Bamforth (1951) investigated the social and psychological consequences of a new method for coal mining, namely the “longwall” method. The standard method involved teams of miners utilising tools (e.g. shovels) to extract a seam of coal and placing it on trains. The “longwall” method, which was expected to increase productivity, involved automated blades that sliced off coal and transferred it to the surface with a belt. Miners were no longer now working as a team but rather stationed along the belt ensuring the coal was transferred to the surface without any problems. Although this method reduced physical strain, the change in the way the work was conducted resulted in worker distress and lower productivity. The break-up of the teams along with the inattention paid to the human element during the implementation of the new method had the complete opposite results than expected. Although this study was carried out six decades ago, many of the lessons have not been learned from the manufacturing industry. Literature from comparable contexts, such as the implementation of advanced manufacturing technologies and cellular manufacturing (CM) provides a valuable lesson about how inattention to designing for the human element can be detrimental.

The majority of organisations have failed to grasp the full potential of these practices. Particularly for AMT, some reports indicated that nearly 50–75% of implementations have failed in terms of quality, flexibility, and reliability (Chung 1996). Ironically, the problem does not appear to lie with the machine or the technology itself. Numerous studies have suggested that these practices impose significant organisational challenges and require a fundamental transition in the way business is conducted which in turn is affecting the human element (Zammuto and O'Connor, 1992; McDermott and Stock, 1999; Pun, 2002). An empirical survey of 759 senior executives of manufacturing organisations by Sheridan (1990) concluded that the major barrier towards successful introduction of flexible automated systems is the inattention to human issues (Ghani and Jayabalan, 2000; Waldeck, 2000; Lewis and Boyer, 2002; Castrillon and Cantorna, 2005). As with the coal mining example given earlier, the implementation of a new technology requires the organisation to undergo a series of changes altering the way work is carried out. This implies that significant attention needs to be placed on the human factors that will forge acceptance of the technology. In order for the new technology to be supported by the workforce, their concerns and needs must be considered in advanced otherwise the organisation is flirting with failure. As Schonberger (1986) stated: "*do not put in equipment simply to replace labor. Equipment cannot think or solve problems; humans can. Our past failures to use shop floor people as problem-solvers have shaped the view that labor is a problem*" (p.75).

Similar observations have been made for the implementation of CM. CM is a form of work organisation in a factory whereby working units are grouped together in cells, are equipped with all the facilities they need and complete a particular set of "family" parts without having to move out of the unit (Burbidge, 1991; Wemmerlov and Johnson, 1997; Fraser, Harris and Luong, 2007). The benefits of CM adoption have been suggested to be shorter lead times, reduction in inventories, lower costs and enhanced product quality (Wemmerlov and Johnson, 1997). Despite the benefits of CM make it a sought after strategy, manufacturing firms at large fail to grasp the expected outcome. Many firms adopting CM find the implementation very challenging (Yauch, 2000). Udo and Ehie (1996) reported that CM implementation successes are limited to nearly 50 per cent. Earlier literature on CM identified that tremendous effort has been placed on understanding the technical aspects, such as machine layout, cell formation and family part grouping using mathematical simulation methodologies (Shambu and Suresh, 2000; Albadawi, Bashir and Chen, 2005). CM adoption, however, is not just about re-arranging the factory layout to form manufacturing cells. It is highly dependent on understanding the human element and the amount of social changes occurring rather than just focussing only on the technological factors (Wemmerlov and Johnson, 1997; Fraser, Harris and Luong, 2007). Other empirical studies identified human factors such as, employee training and adequate communication of information as key antecedents for the success of the implementation (Park and Han, 2002; Fraser, Harris and Luong, 2006b).

2.3.3 Section summary

Earlier literature suggests that the implementation of a technological change should not be viewed simply as an engineering problem. The impact of the change will affect the organisation and subsequently the employees. The workforce is a key driving force for the success of the implementation. Failure to attend to the human factors has proven to be detrimental for numerous manufacturing firms adopting new technological strategies. Similarly, the introduction of an industrial HRC system will generate comparable challenges. Merely rolling industrial robots on the shop floor will not ensure acceptance and effective use. These intelligent work systems will inevitably alter workers’ job roles. With the concept of industrial HRC still at its infancy, it is crucial to understand the key human factors that need to be considered for the successful implementation of industrial HRC. To this end, a theoretical framework has been developed collecting the key theoretical human factors appearing in the literature. This is described in the following section.

3 DEVELOPMENT OF A THEORETICAL FRAMEWORK

Having identified the importance of attending to the human element in chapter 2, this chapter discusses the development of a theoretical framework. The theoretical framework identified and collected the key theoretical human factors influencing the successful implementation of industrial HRC. Section 3.1 presents the approach taken for the development of the theoretical framework. Sections 3.2, 3.3 and 3.4 discuss the key theoretical human factors identified from the literature through comparable and/or relevant domains. Finally, section 3.5 summarises the chapter and presents how the identified factors were addressed in this research project.

3.1 Approach to developing the theoretical framework

This section outlines the approach taken for the development of the theoretical framework.

3.1.1 Domains investigated

The concept of industrial HRC in manufacturing is still emerging and real world applications of this concept are limited. In order to identify the key theoretical human factors comparable domains were reviewed. As discussed previously, integrated manufacturing paradigms and strategies such as, AMT and CM implementation have indicated the importance of considering human factors prior to the implementation. Therefore, the domain of integrated manufacturing technologies implementation was chosen. Furthermore, it was previously discussed that the introduction of a new technology is a major change which impacts the workforce. Consequently, it was necessary to adopt a more global perspective. To this end, investigating the organisational change literature can provide a useful tool to identify key human factors to assist the acceptance of industrial HRC. In addition, the collaboration between human workers and robots prompted the review of another major domain, that of human-robot interaction in social and military context.

3.1.1.1 Databases utilised

The following databases and sources were used to conduct the searches:

- PsychInfo
- IEEE
- ScienceDirect
- Sage Journals
- Taylor & Francis
- Emerald
- World Wide Web (WWW) – Google Scholar

3.1.1.2 Criteria for study inclusion

To ensure that human factors were sufficiently explored by articles, all were inspected to ensure they fulfilled the following criteria: (i) each study had to report an empirical examination, (ii) the study had to have some relevance to manufacturing, implementation of manufacturing practices, technology/robot adoption, organisational change and (iii) the study had to incorporate human participants who either viewed or participated directly in interactions with automation/robots through physical, virtual or augmented means

3.1.1.3 The search

To conduct the literature search a set of primary key phrase was developed. A summary of the key areas explored are shown below:

- Human-robot and human-automation interaction
- Successful adoption of automated systems
- Implementation of advanced manufacturing technologies / cellular manufacturing
- Human factors in advanced manufacturing technologies
- Barriers in implementing manufacturing technology
- Critical success factors for implementing technology
- Organisational change

This process yielded a number of articles from a variety of diverse domains (e.g. aviation, domestic service robotics, advanced manufacturing technology, military robots etc.). When a key phrase search generated a large number of references, keywords were added from the above list to limit the search (e.g. human-robot interaction *and* implementation). Conversely, when the combination yielded too few references, keywords were dropped from the combination, or replaced with a related term (e.g. successful adoption of *automated* systems was changed to successful *implementation* of automated systems). Within the articles a set of emergent key themes appeared to provide secondary search terms in further searches. Following this iterative procedure, the collected literature was examined to identify factors of most relevance to implementation of industrial HRC.

3.2 Organisational change and implementation of new technology

3.2.1 Introduction to the section

This section presents the importance of managing organisational change and two key strategies for reducing the negative concequences of organisational change on employees. First, section 3.2.2 discusses the concequences of organisational change on employees (e.g. uncertainty, resistance). Following this, sections 3.2.3 and 3.2.4 discuss two key strategies for managing the negative impacts of organisational change on employees.

3.2.2 Importance of managing organisational change

Organisations operate in a changing socio-political, technological and economic environment (Hoskisson, Eden, Lau and Wright, 2000). To maintain a competitive advantage it is crucial for the organisations to continuously change and reconfigure (Fay and Lührmann, 2004). Failure of an organisation to read the market signs and change in a timely and effective manner will lead to a significant financial cost or even cease to exist (Collins, 2001; Vollman, 1996). The same applies for manufacturing firms aiming to stay competitive and enhance their productivity. New technologies are introduced in order to meet new market and customer demands. According to Armenakis, Bernerth, Pitts and Walker (2007) a significant portion of organisation changes involve new technological initiatives. For instance, traditional shop floor layout has been replaced by cellular manufacturing and manual processes have been optimised with the utilisation of advanced manufacturing technologies. The implementation of these initiatives involved a significant amount of changes taking place. Nowadays, as discussed in chapter 2, the concept of industrial HRC is becoming an attractive proposition among manufacturing organisations in an attempt to stay competitive. This implies that organisations will undergo a change period. A key aspect for business leaders is how to handle and manage this period of organisational change as the financial cost of change implementation can be massive. According to a Harvard Business School review, the change implementation cost for Fortune 100 companies was estimated to an average of 1 billion dollars between 1980 and 1995 (Jacobs, 1998). Therefore, it becomes apparent that successful change implementation is a major priority. However, numerous studies have suggested that change initiative rarely go as planned (Beer and Nohria, 2000; Sturdy and Grey, 2003; Taylor-Bianco and Schermerhorn, 2006) while some indicate that 75 per cent of organisational changes end in failure (Choi and Behling, 1997). More recently, a survey of more than 3000 company executives, Meaney and Pung (2008) found that two-thirds of respondents felt their organisations failed to grasp the performance benefits expected after implementing organisational changes.

What is important to understand is that organisations are made up from the people in them; if the people do not change there will be no organisational change (Schneider, Brief and Guzzo, 1996). Ultimately, the success of a change initiative depends on the workforce. Therefore the implementation of a new technology will only be effective if the workforce is willing to embrace the new technology and make it part of their daily work routine. Neglecting workforces' needs will eventually lead the change initiative to fail (Armenakis, Harris and Mossholder, 1993; Armenakis, Harris and Field, 1999).

The implementation of a new technology leads to fundamental changes in the social environment on the shop floor and imposes a significant degree of uncertainty on employees (Callan, 1993; Terry and Jimmieson, 2003). Milliken (1987) described uncertainty as "*an individual's inability to predict something accurately*" (p136). Uncertainty during an organisational change is likely to raise when limited information is disseminated (Berger and Calabrese, 1975) or when vague and even contradictory information is provided (Putnam and Sorenson, 1982) generating feelings of fear and anxiety among the workforce (Fugate and Kinicki, 2008). Uncertainty has been described as a common psychological state during organisational change with scholar linking it with negative effects on psychological well-being (Pollard, 2001; Rafferty, 2002). For instance, earlier literature found that during company mergers, employees reported experiencing higher levels of uncertainty regarding their work role (DiFonzo and Bordia, 1998; Terry, Callan and Sartori, 1996). Also, uncertainty appears during organisational restructuring because employees are unsure about the new priorities of the organisation and the chance of being made redundant (Bordia, Hobman, Jones, Gallois and Callan, 2004a).

Uncertainty has been linked with various negative consequences. Numerous scholars have found higher stress levels among employees working in environments with increased uncertainty (Schweiger and DeNisi, 1991). In addition, uncertainty has been found to increase turnover intentions (Johnson, Bernhagen, Miller and Allen, 1996), and reduces job satisfaction (Nelson, Cooper and Jackson 1995). Bordia, Hunt, Paulsen, Tourish and DiFonzo (2001) suggested that the negative influence of uncertainty on employees' well-being is due to the feeling of lack of control that develops during an uncertain period. Greenberger and Strasser (1986) have defined control as "*an individual's beliefs, at a given point in time, in his or her ability to effect a change, in a desired direction, on the environment*" (p.165). What that means is that during a period of organisational change, employees are likely to feel there is not much information flow regarding the upcoming change. This directly diminishes the control they have over the change events. Subsequently, the lack of control leads to the development of stress and anxiety (DiFonzo and Bordia, 2002), psychological strain (Terry and Jimmieson, 1999) as well as reduced performance (Orpen, 1994).

In the context of implementing a technological change, the developed uncertainty can turn into resistance. Davis (1994) indicated that employee resistance reaches a maximum during periods of technological change. Over the years, scholars have given various definitions to resistance. Chawla and Kelloway (2004) defined resistance as an attitude or behaviour that impedes the organisation from changing while Zaltman and Duncan (1977) suggested that is the reluctance of employees to maintain the status-quo in the face of upcoming changing threatening the established status-quo. Furthermore, resistance can take the form of a non-violent, passive behaviour (Giangreco, 2002) or can take a more active behaviour such as sabotage, vocal opposition, reduction in output as well as withholding information (Giangreco and Peccei, 2005; Recardo, 1995). Considering the previous established relationship between control and uncertainty, it becomes apparent that employee resistance is a reaction aiming to gain back control and stability. The introduction of a new technology will change the way things are done, therefore employees feel an uncertain environment is being developed. This subsequently reduces their feelings of control thus leading to reluctance over the new technology. Similarly, the implementation of a human-robot collaborative system could generate uncertainty among shop floor employees. First of all, a major adjustment will take place because the workforce will be requested to interact with an intelligent robotic system in close proximity. Also, the manufacturing cell will be restructured since the robot will take over some of the manual tasks. Therefore, workers will need to know their new work roles and what is expected from them. This is particularly important especially for employees who have been at the organisation for decades and are used to do things in a certain way. Levinson (1972) suggested that the upcoming change is seen by employees as a personal loss especially when they have valued and familiar routines. Therefore it is understandable why in the face of these changes employee may choose to resist the change. It would be irrational to expect there will be no resistance, especially when the introduction of robots and automated systems has been associated in the general public's mind with job loss. Therefore, it is possible for employees to feel a loss of control which can turn into resistance.

In light of this, managing uncertainty during an organisational change and being able to support employees during the change is central to determining whether the change will be succeed or fail (Cummings and Worley, 2005). A very important method is to evaluate contextual factors, such as communication of the change and employee participation during the change (Armenakis and Harris, 2002; Elving, 2005; Goodman and Truss, 2004; Lines, 2004). The advantage of investigating contextual factors is that they can be controlled by change managers and implemented as effective as possible. One vital strategy for alleviating uncertainty and reducing resistance during a period of change is communication.

3.2.3 Communicating the change

It was previously discussed that uncertainty is generated due to lack of information flow regarding a change event which makes an individual unable to accurately predict the new status quo in their working environment. This in turn is detrimental to employees' well-being due to feeling of lack of control over the upcoming change which then leads to resistance. Effective communication can serve as a vehicle to provide employees with a degree of information as to why, how and when these changes will take place (Wanberg and Banas, 2000). In the domain of change management, communication has received extensive attention (Robertson Roberts and Porras, 1993; Schneider and DeNisi, 1991; DiFonzo and Bordia, 1998; Bordia, Hobman, Jones, Gallois and Callan, 2004a). However, despite empirical research, some organisations do not realise that lack of effective communication to employees, change is almost impossible (Barrett, 2002). As Robertson, Roberts and Porras (1993) suggested, organisational change is related to the organisation's ability to influence the behaviour and attitude of its employees.

The purpose of communication within an organisation is twofold: (i) to inform its employees regarding their tasks, the policy and other issues of the organisation and (ii) create community within the organisation (Francis, 1989; De Ridder, 2003). While the provision of information will inform employees regarding the rationale behind the change, the second goal aims to foster a community spirit within the organisation enhancing employees' sense of social identity (Tajfel, 1978). Based on this, Elving (2005) proposed a communications model that displays the impact of communication on uncertainty and readiness for change. According to the author, provision of information to employees and fostering a sense of community through communication can reduce uncertainty among employees which in turn will have a positive impact on reading for accepting change.

Empirical research revealed that the existence of a formal communication avenue in organisation undergoing a change period reduced uncertainty and enhanced commitment (Cullen, Edwards, Casper and Gu, 2013; Hobman, Bordia and Gallois, 2004; Bordia Hobman Jones Gallois and Callan, 2004a; Wanberg and Banas, 2000). Bordia and colleagues (2004a) studied the demerging of a government department and their findings suggested that adequate communication regarding the change has the potential to reduce feelings of uncertainty. Similarly, empirical work has shown that open communication as well as employee participation during the introduction of a change initiative can promote employee readiness to accept the change and subsequently reduce resistance (Jones Jimmieson and Griffiths, 2005; Elving, 2005). Furthermore, Jimmieson, Peach and White (2008) proposed a theoretical model suggesting that employee communication and participation in the decision-making can have a positive impact on employees' intentions to accept the proposed change. According to the proposed model, communication and participation in the decision making will foster positive attitude about the change, evoke stronger social pressure and increase one's sense of personal control over the upcoming change which in turn, will generate change-supportive intentions. Similar findings have been found for the successful implementation of manufacturing technologies and techniques on the shop floor. Appropriate communication has been suggested to be a key driver for introducing lean manufacturing and gaining support from shop floor personnel (Puvanasvaran, Megat, Sai Hong, and Mohd Razali, 2009; Scherrer-Rathje, Boyle and Deflorin, 2009). In addition, Worley and Doolean (2006) pointed that communication among shop floor employees can reduce uncertainty regarding their role and responsibilities. Such initiative can enhance employees' acceptance of the new technology particularly during the early stages of the implementation where uncertainty is expected to be high. At the same time, during this stage communication can serve as a vehicle for reducing rumour spreading.

According to Smeltzer (1991) change efforts can significantly be undermined by the presence of rumours during the change period. At the same time, rumour spreading can have a significantly negative impact of employees' morale and commitment to the organisation (Burlew Pederson and Bradley, 1994). Therefore, reducing the potential for rumour spreading is a vital step during the introduction of a major change initiation. Communication has been suggested to be a major source for controlling rumour spreading (Smelzer and Zener, 1992; DiFonzo and Bordia, 1998).

Summary

In relation to the implementation of industrial HRC, communication is identified as a key factor for successful implementation. Establishing a formal communication avenue to the workforce during the change period it is hypothesised to have a positive impact on employees' acceptance. Inadequate provision of information regarding the new system, or even contradicting information is expected to increase uncertainty and the feeling of lack of control among employees. Based on the above employees will initiate informal information seeking activity which can lead to rumour spreading, negativity, and resistance which will be detrimental for the deployment of the system on the shop floor.

3.2.4 Employee participation in the change

Successful implementation of an organisational change is heavily dependent on employees' cooperation while any resistance posed by the workforce can have detrimental effects (Porras and Robertson, 1992; Miller, Johnson and Grau, 1994; Piderit, 2000). Although the importance of considering employee reactions to a planned change has been highlighted as early as the late 1940s (Coch and French, 1948), it was not until the 1990s that research on organisational change studied employees' reactions to change (Fugate, Kinicki, and Scheck, 2002; Oreg, 2006; Stanley, Meyer and Topolnytsky, 2005; Miller, Johnson, Grau, 1994). In the domain of change management, employee participation in the change decision-making is, along with communication described earlier, one of the core practices to enable employee change-supportive behaviours (Jimmieson and White, 2011; Gagne, Koestner and Zuckerman, 2000; Sagie and Koslowski, 1996).

Employee participation in the implementation of a change initiation is the process by which decisions are being shared between superiors and sub-ordinates (Sagie Elizur and Koslowsky, 1995; Zanoni and Janssens, 2007). According to Sashkin (1984), employee participation during a period of organisational change can fulfil three basic work needs: autonomy, meaningfulness and decreased isolation. According to Lines (2004) employee involvement in the change provides employees with a clearer picture regarding the need to change. This aspect is vital when it comes to implementing the change. As discussed earlier, change introduces uncertainty and employee involvement provides personnel with a sense of ownership and control of the upcoming change which in turn increases acceptance and readiness for change (Armenakis Harris and Mossholder, 1993; Strauss, 1998; Wagner, Parker and Christiansen, 2003; Pierce, O'Driscoll and Coghlan, 2004).

Empirical research literature on participative leadership highlighted that employee participation in the decision-making during a change period fosters employee openness and acceptance of the change while reducing resistance (Sagie and Koslowsky, 1996; Wanberg and Banas, 2000; Amiot, Terry, Jimmieson and Callan, 2006; Van Dam, Oreg and Schyns, 2008). At the same time, employee participation has also been found to be a catalyst for the successful implementation of a new technology (Korunka, Weiss, Huemer, and Karetta, 1995; Garcıa-Arca and Prado-Prado, 2007). Furthermore, employee participation has been identified to be a major factor for introducing total quality management (TQM). Rahman (2001) and Salaheldin (2009) suggested that a key success factor for the successful implementation of TQM is to allow increased employee involvement in the implementation process.

Employee participation has been identified as a key success factor for the implementation of manufacturing paradigms such as AMT and CM. These manufacturing technologies and techniques have given rise to certain job features such as cognitive demand and production responsibility (Wall and Jackson, 1995). Therefore it is important for the personnel who will eventually operate, manage and support the system to actively participate in the design and development (Wemmerlov and Johnson, 2000, Bidanda, Ariyawongrat, Needy, Norman and Tharmmaphornphilas, 2005). Various scholars have supported that engaging shop floor personnel and allowing them to participate in the introduction of a new manufacturing initiation is critical for the success (Koufteros, Vonderembse and Doll, 1998; Chung, 1996; Boyer, 1996; Cua, McKonea and Schroeder, 2001; Fullerton and Wempe, 2009). Through participation, employees can obtain a better understanding of the new technology and its expected benefits not only to the organisation but also to their work routines. By seeing the benefits of the new system to their own work environment will help reduce resistance and scepticism. Also, their involvement can serve as a vehicle to make them feel valuable while their extensive knowledge of the working environment can provide change managers with valuable information to help make better decisions when implementing the change (Badore, 1992; Kotter, 1996; Waddell and Sohal, 1998).

Summary

Similar benefits can be expected with the participation of employees in the implementation of a HRC system. As discussed, the concept of industrial HRC is a new manufacturing initiative involving the implementation of intelligent robotic assistants to collaborate with shop floor operators to execute manufacturing processes that currently are predominantly manual. This is a radical shift for a traditional manufacturing production line. Because of the changing nature of the work, it is important for the individuals who will eventually use the system to participate in its implementation. Shop floor employees have a great understanding of the current manual process. This is crucial, especially for specialised processes where off-the-shelf industrial robot application will not be feasible. By allowing employees to be involved in the implementation, change manager will have the advantage of gaining their insights about the process and proactively managing technical issues in order to ensure the new system is process capable. Furthermore as shown in literature, employee involvement can act as a means for reducing resistance and negativity while making employees feel valuable. This in turn can increase the likelihood of acceptance and ownership of the new technology by the shop floor personnel. To this end, shop floor operators have an important role to play during the development and implementation of a HRC system.

3.3 Implementation of manufacturing technologies and techniques

Although new manufacturing technologies and techniques are continuously being implemented to increase competitiveness, the literature above reflects that many organisations have often failed to grasp the expected benefits due to implementation issues attributed to the human element. This has led to numerous studies attempting to capture the key success factors.

3.3.1 Senior management commitment to the new technology

A plethora of studies have indicated that failure of senior management to support and commit to the change will doom the project before it even starts (Kotter, 1996; Somers and Nelson, 2001; Vollman, 1996; Alavi, 2003; Bamber and Dale, 2000; Boyer and Sovilla, 2003; Parks, 2002; Womack and Jones, 1996). As described by Shaw (1995), when a radical change is taking place the chief executive officer (CEO) must hold "… *a deep conviction that the change must occur in order for it to succeed and the senior-management team should collectively assume responsibility for [the change initiative's] success*" (p.70). Management that fails to embrace the implementation may intentionally or unintentionally sabotage the effort (Boyer and Sovilla, 2003).

Empirical research has indicated that senior management can be an important driver for their success. For instance, various scholars have highlighted that people management and strong senior management support is a key factor for the successful introduction of TQM in both large and SMEs (Black and Porter, 1996; Dayton 2003; Hodgetts, Kuratko and Hornsby, 1999; Demirbag, Tatoglu, Tekinkus and Zaim, 2006). Also, senior management support has been identified an important element for the implementation of AMTs (Singh, Garg, Deshmukh and Kumar, 2007). Klein, Conn and Sorra (2001) in their empirical study pointed that establishing senior management commitment and support to the project is as important as the financial support. Visible participation and support from the senior management can provide a strong message to employees regarding the gravity of the initiation undertaken by the organisation (Boyer and Sovilla, 2003; Worley and Doolen, 2006). Employees tend to gauge the importance of the new initiation by the plant managers' statements and behaviours (Klein, Conn and Sorra, 2001). A strong management front committed to and supporting the new technology can indicate the gravity of the initiative for the plant thus enhancing employee acceptance.

The results from these studies suggest that senior management have a crucial role to play when it comes to the introduction of a new technological change and although it appears obvious, their influence on employees should not be underestimated. Senior management can sometimes be viewed as the individuals taking the "go/no-go" decisions and indicate the strategic orientation of the organisation. However, they have a more subtle yet important role to serve. Senior management are role models, intentionally or not, for the rest of the organisation. Their behaviour and statements can act as a strong tool to communicate how other organisational members should behave and what initatives are important for the organisation (Neubert, Kacmar, Carlson, Chonko and Roberts, 2008; Brockner and Higgins, 2001; Kark and Van Dijk, 2007). This can be particularly important during a period of change where uncertainty will be high. A visible support and commitment from senior management can help employees shape their beliefs regarding the upcoming change and potentially reduce resistance. Although it is not expected to have a fully united management, it is vital to have a front supporting the proposed initiative in order to drive it forward (Beer, 1980). An example by Kotter (1996) involving a large domestic bank can highlight how senior management support can determine the success of a project. In this example, senior management failed to put together a powerful guiding coalition to support a proposed change initiative and, because several key managers were not directly involved in the process, the change initiative failed. Going even further, Kotter offered an example of a high-ranking executive in one organisation who actively prevented a proposed change from succeeding simply because the executive did not believe that the change was necessary. Similar thoughts have been supported by Covin and Kilmann (1990). Authors attempted to investigate highly positive and highly negative impact issues during a large-scale change process from individuals who participated. Authors noted that visible senior management support and commitment led to positive perceptions of a change initiative. Conversely, a lack of visible management support and commitment foster negative perceptions and doom the project to failure.

Summary

Similar to the above, the implementation of a HRC system will be a senior management initiation. Therefore the senior management has a very important role to play. Their support and commitment to the new initiation, particularly during the early stages where uncertainty is expected to be high, will be vital for its success. The individuals at the senior levels with their behaviour and statements can highlight the importance of the new technology for the organisation. This in turn can shape the employees' beliefs about the new initiation and assist to embrace and accept it. Lack of support from the senior management to provide a strong support can result in the project failing.

3.3.2 Existence of process champion

The implementation of technological innovations, such as a HRC system on the shop floor will require close governance and supervision throughout the process. Past research investigating the implementation of AMTs on the shop floor highlighted the importance of a process champion (Beatty, 1990; Beatty and Gordon, 1990; Dirnnik and Johnston, 1993).

A champion can be a knowledgeable individual about the new technology who will provide continuous encouragement for embracing the new technology and can foster support across the organisation (Chen and Small, 1996; Hottenstein, Casey and Dunn, 1997). According to Rothwell and Zegveld (1985) a product champion is essentially a business innovator, someone who can provide information and solve problems as and when they arise. Furthermore, Zhao and Co (1997) indicated that champions are those individuals who will enable organisations to grasp the expected benefits of the new technology by bringing all key stakeholders on-board and ensure smooth implementation.

As described earlier during an organisational change, such as the introduction of a new technology, uncertainty is high which in turn can generate resistance from employees. Researchers have indicated that the presence of a high quality leader exchange or more trust in a supervisor, employees are likely see the initiation in a more positive way (Van den Bos, Wilke and Lind, 1998; Martin, 1998). Traditionally, a supervisor tends to be viewed as an individual who has the power to reward behaviour or penalise non-behavior (Warshaw, 1980). For instance, Marler and colleagues (2009) identified that pressure placed on employees by supervisors resulted in more positive adoption of new technology. At the same time, pressure by supervisors should not be viewed as a master-slave relationship. The champion supervising the introduction of the new product will provide encouragement rather than forcefully imposing the new initiation on employees. Change recipients who received supervisory support and encouragement during an organisational change were found to be more willing to support and embrace the change initiative (Organ, 1988; Vanyperen, Van den Berg and Willering, 1999). Therefore the role of the champion gives a new perspective as to the influence they can have on sub-ordinates. As Larkin and Larking (1994) stressed, supervisors assigned to introduce a change initiative are the ambassadors of the change and can have a huge influence on change recipients to embrace the new initiative. According to the authors, during the implementation of a change often enough the senior management assumes that simply delivering the message is sufficient for the employees to understand the rationale behind the new initiative and to accept it. However, as the authors stated, "*programs don't change workers – supervisors do*" (Larkin and Larkin, 1994, p.85). Employees will seek advice and further information once they found about the new initiative in an attempt to gain back control and reduce the developing uncertainty. Therefore, the presence of a process champion during the implementation will serve as a point of reference for employees to seek further information and understand the change. This individual will need to have sufficient knowledge about the change in order to provide quality information to employees.

Earlier empirical research has indicated that the existence of a process champion supervising the implementation of AMTs is a driver for success (Zhao and Co, 1997; Scannell, Calantone and Melnyk, 2012). These studies suggested that the champion can proactively influence the key stakeholders as well as building alliances and partnerships with key individuals to enhance acceptance of the change (Gambatese and Hallowell, 2011). According to Lee, Kim, Rhee and Trimi (2006) process champions can assist the workforce realise the usefulness of the new technology and enhance their acceptance. Furthermore, the presence of a process champion has been found to be a key driver for organisations attempting to introduce lean production systems. Dombrowski, Mielke and Engel (2012) investigated the implementation of lean production system on the shop floor and found that the use of an experienced team of champions supervising the implementation is a key node in the process. As described earlier, authors pointed that their presence can serve for providing advice as well as managing the establishment of the innovation process. Contrary to this body of literature, Lewis and Boyer (2002) in a study investigating the key characteristics between high and low AMT performers, found no significant difference with regarding to the involvement of a technology champion.

Summary

The existence of a process champion during the implementation of a HRC system is considered to be important. The champion would act as a means of getting all key stakeholders at different levels on-board and support the initiation. This is particularly important as the introduction of such a system will most likely take over some of the manual tasks of the process. Therefore, workers insights and knowledge is vital for ensuring a process capable system is introduced. This can be particular important for high value and complex processes where off-the-shelf robotic systems will not be suitable. Therefore, the champion has a pivotal role to encourage workers to support the initiation. At the same time, as shown by literature the champion will play an important role in terms of providing quality information to employees during the early stages where uncertainty is expected to be high.

3.3.3 Organisational flexibility through employee empowerment

According to Quinn (1988) organisations may follow a strategy based on a continuum ranging from a control-oriented strategy to a more flexible-oriented one. A control-oriented strategy concentrates control and decision-making over the automation uncertainties to middle managers and technical specialists. In this type of strategy, worker’s discretion and authority over the system is reduced significantly as the organisation is functioning on a strict hierarchical structure and a clear set of steps as to who needs to be informed when a problem arises (Susman and Chase, 1986). A flexibility-oriented strategy, on the other hand, dissipates control and decision-making over the automation uncertainties to the point which they occur, thus empowering operators to rectify operational issues. Employee empowerment has long been suggested to enhance employee performance, well-being and positive attitudes (Hempel, Zhang and Han 2012; Spreitzer, 2008; Wagner, 1994). Therefore, this strategy implies the organisation is less hierarchical, authority is decentralised and employees have the expertise and knowledge to resolve issues (Khazanchia, Lewis and Boyer, 2007).

It has previously been theorised that in uncertain environments, a flexible-oriented strategy where decisions are decentralised and dissipated to the lower levels of the organisation (e.g. operators) is necessary (Burns and Stalker, 1961). Similarly, a flexible-oriented strategy where operators are empowered to take operational decisions could be useful when an organisation introduces automated manufacturing technologies. The reason for this lies in the fact that automated manufacturing technologies have been suggested to increase operational uncertainty due to the increased complexity and cognitive demands posed on operators (Cummings and Blumberg, 1987). Operation uncertainty can be defined as the "*lack of predictability in work tasks and requirements*" (Wall, Cordery and Clegg, 2002, p. 151). For instance, new technological systems require additional hardware and software to function appropriately which impose more technical requirements. Also, complex automated systems can generate unpredictable problems that are difficult for an operator to diagnose, interpret and resolve, which are adding to the uncertainty (Cavestro, 1989; Perrow, 1984). Furthermore, operational uncertainty is exacerbated by other contextual factors such as, product complexity, variability of raw materials, production tolerances and specifications (Mullarkey, Jackson, Wall, Wilson and Grey-Taylor, 1997). Therefore, additional demands are placed on human operators as they now need to monitor the automation, intervene when necessary and rectify the problem to ensure production continues. However, it has been highlighted in the literature that for employees to have the authority to take action, organisations need to alter their organisational structure and culture.

Zammuto and O'Connor (1992) emphasised that control-oriented strategies can be detrimental to the implementation and use of AMT due to the centralisation in decision-making and the reduced employee discretion. This is because an uncertain system, particularly during the early implementation stages, will make it challenging for operators to anticipate the nature of work demands or the number of exceptional demands. Therefore, a more flexible strategy is appropriate whereby employees have higher discretion in the decision-making (Griffin, Neal and Parker, 2007). At the same time, higher operator control will allow employees to understand the new system and task requirements a lot better (Wall, Cordery and Clegg, 2002). Empirical research has identified that for successful manufacturing technology implementation, organisation should select a more flexible-oriented organisational strategy whereby shop floor employees have a central role, are empowered to take decisions over their work and to continuously seek to expand their expertise are more likely to grasp the benefits of manufacturing technologies and techniques (Rahman, 2001; Cleland, Bidanda and Chung, 1995; Salaheldin, 2009). Through flexibility employees become experts of their system and problem-solvers rather than pushing a button to initiate it and then passively monitoring it.

The message projected by literature favours the adoption of a more flexible-oriented strategy for the implementation of manufacturing technology and techniques. However, Brown and Eisenhardt (1995) suggested that balanced strategy orientation can also enable successful organizational change. A balanced application of a controlling strategy to discipline and clarify responsibilities which is complemented by a flexible approach through empowerment to foster creativity can also be beneficial for organisation. Further on this, a study by McDermott and Stock (1999) regarding the impact of organisational strategy on AMT implementation, proposed a slightly different approach. Authors collected data from 97 manufacturing plants and their findings suggested that successful implementation of AMT could be achieved through a balance of flexible and controlled strategy rather than a heavily flexible or controlling strategy. Similar findings were reported by Lewis and Boyer (2002). The authors studied varied organisational cultures, strategies and implementation practices impact AMT performance among 110 manufacturing plants. Results indicated that a balanced culture which promotes both flexibility and control simultaneously. According to Quinn (1988), control and flexibility are two extremes on the same continuum and could therefore be complementary to each other.

Summary

The aforementioned literature is closely related to the implementation of industrial HRC. The application of this technology will create uncertainty, at least during the early stages of the implementation. Therefore, the organisation will need to align its organisational structure and culture with the technology in order to grasp its benefits. Therefore, it is proposed that a flexible-oriented strategy where system operators are empowered to identify and resolve deviations of the system will result in greater acceptance of the technology. By empowering operators, they will be able to expand their skill set and knowledge. At the same time, it must be not be neglected that the introduction of any type of robotics will be seen with scepticism. Therefore, providing operators with additional control over their job can reduce resistance.

3.3.4 Training and development of the workforce

Earlier research in the domain of advanced manufacturing technologies suggested that although the new systems relieve human operators from physical strains they also introduce additional cognitive demands and responsibilities (Wall and Jackson, 1995). The computerisation introduced by an advanced technological system often leads to radical changes both in terms of the complexity and uncertainty of production. According to Waldeck (2000), the new workplace needs posed by the introduction of a new manufacturing system creates a highly uncertain environment which in turn impacts the adoption of the change. Earlier studies have called manufacturing organisations undertaken a major change initiative (e.g. introduction of a new technology on the shop floor) to update and invest in their business infrastructure by providing workforce training and education to ensure their long-term success (Bratton, 1993; Agnew, Forrester, Hassard and Procter, 1997; Wemmerlov and Johnson, 1997). This can be particularly important for manufacturing organisations where historically processes have been completed manually. Introducing an advanced manufacturing technology to assist operators will be a radical change and a considerable effort has to be issued to prepare the workforce. In order for operators to adopt the new concept it is vital to feel comfortable enough to use the new technology. For this purpose, provision of training and education of the workforce has been viewed in the literature as a key step for effective implementation (Ettlie, 1986; Majchrzak, 1988; Duffy, Danek, and Salvendy, 1995; Chung, 1996; Boyer, Leong, Ward and Krajewski, 1997; Park and Han, 2002).

Several empirical studies have found provision of workforce training to be instrumental for reducing uncertainty and fear regarding the new machinery (Cleland, Bidanda and Chung, 1995; Zhao and Co, 1997; Power and Sohal, 1997). The development of a training programme will enable employees to feel comfortable with the new technology as well as develop their skills and knowledge regarding the new demands introduced by the new manufacturing method (Hottenstein, Casey and Dunn, 1997; Lewis and Boyer, 2002). Similar findings have been highlighted for the implementation of CM. As discussed earlier, CM has traditionally been seen from a technical point of view whereby organisations have placed focus on creating cell arrangements (Kazerooni, 1997). Recently scholars have been raising the need for organisations to attend to human factors for grasping the full benefits of the technique. Empirical investigations from Olorunniwo and Udo (2002) and Fraser, Harris and Lee Luong (2007) highlighted that organisations implementing CM need to invest in training programmes in order to expand their workforce skill set and ability to run various machines.

Summary

Overall, the picture that emerges is that developing a training programme and educating the workforce regarding the new technology can be a driving success factor. Similar to the above, the introduction of an industrial HRC system will be a radical change in the manufacturing method. Operators will be required to utilise a state-of-the-art industrial robot to complete the task This will generate certain degree of uncertainty and if not managed properly, as shown in literature, it can be detrimental for the successful implementation. Proving an appropriate training programme to the workforce is likely to assist building confidence and comfort with the new system. This will help reduce uncertainty and scepticism while enhance adoption of the system.

3.3.5 Impact of union involvement

The introduction of a change initiative inevitably creates uncertainty among employees not only regarding their employment status, but also for the new working conditions. It is often assumed that a unionised organisation will find greater resistance implementing the change (Shah and Ward, 2003). Empirical studies linking unionisation level with implementation of manufacturing practices has been scarce and contradicting. A body of literature has suggested that unions can be cooperative in the implementation processes (Katz, 1985; Cappelli and Scherer, 1989; Pagell and Handfield, 2000). Also, some studies found no support between unionisation and implementation of manufacturing practices (Ahmed, Tunc and Montagno, 1991; Osterman, 1994). At the same time, some evidence suggests that unionisation is negatively associated with organizational performance (Machin, 1995; Meador and Walters, 1994; Jayaram, Ahire and Dreyfus, 2010). In addition some studies have found that the impact of unions (positive or negative) will depend upon the nature of the practice being implemented (Ng and Maki, 1994).

Also, manufacturing organisations have been reported to show a growing interest in the implementation of employee involvement (EI) programmes to increase competitiveness (Gittleman, Horrigan, and Joyce, 1998). EI programmes are a term used to describe Quality Circles (QCs), self-managed work groups (SMGs), Quality of Work Life programmes (QWL), and other types of joint process. Implementation of these programmes, however, has been found to be a challenge (Beer, Eisenstat and Spector, 1990; Pasmore and Fagans, 1992). An important factor, particularly for a unionised environment, has been found to be the position of the labour union (Allen and Van Norman, 1996). According to Kelly and Breinlinger (1995) the degree to which an individual identifies with the labour union may also influence the decision-making process. More recently, Dawkins and Frass (2005) have highlighted that organisations and management intending to implement new EI programmes need to significantly consider how workers' social cohorts influence their decision-making.

Summary

Overall, union influence appears to have an important role for the implementation of a change initiative, however, there is no clear direction. For the implementation of industrial HRC, the impact of labour union is expected to be a significant factor that needs to be considered in advance. Robotics and general automated technologies have been linked over the years with job loss. Therefore introducing this concept in a highly unionised manufacturing organisation can potentially create friction. On the other hand, there are indications to suggest that if properly managed union influence can turn in favour of the organisation.

3.4 Human-automation/robot interaction

Human interaction with automated systems occurs in our everyday routines. An example is when a person stops at an automatic teller machine (ATM) to withdraw cash. The ATM is an automated system and the human in required to interact with it accordingly in order to achieve their goal. Other everyday examples are when humans press the control buttons of a washing machine to start, pause or stop a washing cycle or when pushing the button of a lift. Similarly humans interact with more complex automated systems as part of their work such as, controls of a nuclear power plant, aircraft automation, and automated manufacturing process. Overall, human interaction with automated systems refers to those occasions where humans interact with some sort of automated system to (i) specify to the automation the tasks, goals and constrains (e.g. specify to the ATM that you want to withdraw 10 pound notes); (ii) control the automation and adjust (e.g. start, pause or stop) the task execution accordingly and (iii) receive information or other physical objects from the automation (e.g. receive the money off the ATM) (Sheridan and Parasuraman 2005). At this point it must be noted, the generic term "automated system" is used for both static automated machines/systems (e.g. ATM, computer numerically controlled (CNC) machines) and robotic systems. The reason is because, although static automated machines differ in form from a robotic system, both are used by humans to accomplish a specific task. In chapter 5, where more specific effects on humans are investigated, a distinction will be made between human-automation and human-robot teaming.

Based on the definition given above of human interaction with automated systems, it becomes apparent that humans have a key role to play in order for the interaction to succeed. Humans must not only be in a position to specify to the automation what is required, but also supervise the automated system to ensure it does not deviate from what was specified. If for instance, while on a lift the human pushes the button for the 5th floor but the lift stops at the 10th floor, then the interaction is not considered successful leading to disappointment and frustration from the side of the human. Therefore, the person will need to monitor the actions taken by the automation and intervene accordingly. This represents a new form of interaction which diverts from the traditional interaction where the human was in absolute control of task completion. This new kind of interaction was first identified and described as human meta-control by Sheridan (1960) while later researchers described it as human supervisory control (Sheridan and Verplank, 1978; Moray, 1986; Sheridan, 1992a). Previously the human could use their senses to adjust to any deviations and execute the task. With the supervisory type of control the human is essentially removed from the task execution and is required to monitor the automation. This new type of relationship has been suggested in the literature to introduce a number of human factors issues. These are identified and discussed in the following sections.

3.4.1 **Trust in automation/robots**

Trust is an essential feature of our interactions with other people that require cooperation and interdependence (Corritore, Kracher and Wiedenbeck, 2001). In human interpersonal relationships, Rotter (1967, 1971) described trust in terms of relying on behaviour, verbal or written statements or promises from others. Mayer, Davis and Schoorman (1995) defined trust as the willingness of "*a party to be vulnerable to the outcomes of another party based on the* *expectation that the other will perform a particular action important to the trustor, irrespective of the ability to monitor or control that other party*" (p.712). Therefore, if trust exists, then individuals must be willing to put themselves in a vulnerable position by giving the responsibility for actions to another individual (Lee and See, 2004). For example, people can trust others if they are reliable, but lose trust when they are let down and redevelopment of trust will take time.

Since trust can have a significant impact on performance outcomes, the development of trust between humans and machines could not be neglected. Muir (1988) suggested that human-machine trust could be affected by similar factors as human-human trust. .Extensive research over the years has focussed on the development of trust in automated systems (Sheridan, 1975; Lee and See, 2004; Madhavan and Wiegmann, 2007). With robotic systems becoming highly utilised for a variety of tasks (Barnes and Evans, 2010; Jones and Schmidlin, 2011; Murphy and Burker, 2010), trust has been highlighted to be a key human factor that can determine the success of the interaction (Parasuraman and Riley, 1997; Freedy, Freedy and Weltman, 2006).

The development of trust is essential for the successful operation of any team (Groom and Nass, 2007). In the context of human-automation teaming, trust can influence the willingness of humans to follow suggestions and rely on the information obtained by an automated system, particularly in risky and uncertain environments (Freedy, de Visser, Weltman and Coeyman, 2007; Park, Jenkins and Jiang, 2008). Lack of trust in the automated partner will eventually lead the operator to intervene and take over the task (de Visser, Parasuraman, Freedy, Freedy and Weltman, 2006; Steinfeld, Fong, Kaber, Lewis, Scholtz, Schultz and Goodrich,2006). Trust has been defined extensively in many domains, such as human interpersonal trust (Mayer, Davis and Schoorman, 1995; Rotter, 1971) and human-automation trust (Lee and See, 2004; Madhavan and Wiegmann, 2007). In the field of human-automation interaction, Lee and See's definition of trust is the most widely cited one (Chen and Barnes, 2014). According to Lee and See (2004) trust is defined as "*the attitude that an agent will help achieve an individual's goals in a situation characterised by uncertainty and* *vulnerability*" (Lee and See, 2004, p54). Based on this definition, trust becomes a vital part of any relationship because the individuals involved in the relationship must be willing to depend on the actions of another party (Lee and See, 2004). Also, the authors identified trust antecedents based on three factors, namely purpose, process and performance. The purpose factor is related to the level of automation used, the process factor relates to whether the automated system employed is suitable for the specific task while the performance factor relates to the system's reliability, predictability, and capability. In addition, the degree of the system's transparency and observability available to the human partner has been found important for the development of trust in human-automation interaction (Verberne, Ham, and Midden, 2012). Furthermore, task complexity has been suggested to have an impact on the level to which the human operator relies on the automated system (Parasuraman, Molloy and Singh, 1993; Mazney, Reichenbach, and Onnasch, 2012). Research has also been directed to investigate people's perceived reliability of automated assistance versus human assistance (Dzindolet, Pierce, Beck, Dawe, and Anderson, 2001b) and and machine-like agents versus human-like agents (de Visser, Krueger, McKnight, Scheid, Smith, Chalk and Parasuraman, 2012). Dzindolet and colleagues (2001b) found that humans tend to see the automation as being more reliable compared to a human aid, although the same information were provided both by the automation and the human aid. With increasing risk levels, human reliance on automation support increased when compared to human support. Potentially this can lead to automation misuse or overtrust, which can be detrimental (Parasuraman and Riley, 1997; Chen, and Barnes, 2012). Therefore, calibrating appropriate levels of trust is vital for the success of the interaction.

Effort has also been directed to understand trust development when humans interact with robotic entities rather than general automated systems. Although robots encompass a degree of automation, they also possess different attributes not possessed by general automated systems. For instance, robots can be mobile, have different degrees of anthropomorphism and tend to be purpose-built. These attributes introduce a degree of uncertainty not found in general automated systems and for this reason robots need to be studied independently (Desai, Stubbs, Steinfeld and Yanco, 2009). Subsequently, trust development in human-robot teams may be different to when humans interact with automated systems. Previous literature has suggested that little research was directed in addressing trust in human-robot interactions (Park, Jenkins, and Jiang, 2008) while other researchers supported that trust has been assessed in terms of automation and then applied in the domain of human-robot teaming without considering the different attributes related to robots (Yagoda and Gillan, 2012). Various factors have been suggested to influence trust development in human-robot interactions. Hancock, Billings, Oleson, Chen, De Visser and Parasuraman (2011) carried out a meta-analytic review of 29 empirical studies aiming to quantify the effects of various factors influencing human-robot trust. Their findings highlighted the significance of robot-related factors. Robot related performance-based factors (e.g. reliability, predictability, behaviour) and attribute-based factors (e.g. size, appearance, and movement) were found to be of primary importance for the development of trust. Environmental factors (e.g. performance factor, task complexity), were identified to have a moderate influence on trust, while little effect was found from human-related factors. Thus, different robots attributes should be considered when assessing trust. However, industrial robots can be different than social, healthcare and military robots and very little research has been directed towards understanding the development of trust in industrial HRC.

Summary

Although the aforementioned studies enhance our understanding of trust development when humans interact with robots, the context is different. In a military human-robot teaming, the functions of both agents are very different from an industrial scenario. Also, industrial robots come in various shapes, sizes, end-effectors and degrees of anthropomorphism according to the operation being utilised for. Trust development in an industrial robot can potentially be influenced by other context-related factors.

3.4.2 Mental workload

In everyday life humans perform tasks either concurrently or in isolation. Tasks have been theorised to demand mental resources from humans for their completion, while these resource are limited in their availability (Wickens, 1981; Knowles, 1963). Therefore, when the mental resources demanded by a task (or tasks) exceed the available supply then performance will deteriorate. For instance, assuming a car driver is on a busy city road during peak time while trying to take the right road turn. This task imposes certain mental demands on the driver and the driver supplies mental resources to meet the demands and execute the task. If for instance, while this task scenario is taking place, the mobile phone rings and the driver attempt to answer it and have a conversation, then the task mental demands have increased and the driver must supply additional resources. If the driver cannot cope with the additional task demands, then the driver is likely to experience increased mental workload. Therefore, mental workload, in general, can be defined as the relationship between the demand for mental resources imposed by a task (or tasks) and the ability of the human to supply those resources (Wickens, 2002; Parasuraman, Sheridan and Wickens, 2008).

The interaction with automated systems, as well as robots, requires human operators to monitor the system, exchange information through an interface and take action according to the system's state (Yagoda, 2010). At the same time, human operators can be working on a different task. Therefore, the perceived operator mental workload becomes an important aspect for effective interaction between the human operator and the automation. Therefore, careful consideration must be given when designing an automated system. Automation is introduced, usually, with the aim of reducing workload and ensuring effective operation of the system. However, a poorly implemented automated system can either increase or decrease mental workload which, in turn, has the potential to cause for human error (Miller and Parasuraman, 2007). The aviation industry is an excellent example of this. For instance, the first series of Boeing's 747 aircraft included two pilots and a flight engineer. As automation systems became more sophisticated it was considered to downsize the flight deck by eliminating the position of the flight engineer. Therefore the instruments monitored by the flight engineer were considered to be automated thus reducing the flight crew from three to two members. To support this initiation, it was vital to ensure the mental demands would not exceed the capacities of the two-person crew. This led to an extensive exercise by Sheridan and Simpson (1979) which generated a workload rating scale. The generated scale was utilised for supporting the cockpit downsizing initiation. However, the constant development and introduction of automated systems on board modern airliners has significantly reduced pilot input. This has generated an underlining contributor to human performance problems when interacting with complex automated control systems, the human out-of-the-loop (OOTL) performance (Kessel and Wickens, 1982). OOTL performance problems suggest a reduced ability of the human operator's ability to intervene and assume manual control of the system when needed (Kaber and Endsley, 2004). In a highly automated aircraft where pilot's manual input is reduced, it is possible for the pilot to be left significantly under loaded leading to boredom. The prolonged period of under load experienced by the pilot may not allow them to respond effectively to an unexpected event.

Similar to aviation, an operator's mental workload assigned to collaborate and supervise a robotic entity can impact their performance. For instance, during a human-robot collaborative task the operator will need to make sure the robot is executing the task correctly. If the robotic entity is perceived by the operator as being unpredictable - that is the operator is unable to know what the robot will do next – their mental workload will tend to increase (Miller and Parasuraman, 2007). Therefore, if an automated system is to be used to relieve the operator, the interface must be properly designed to provide useful feedback to the user regarding the task (Nikolic and Sarter, 2000; Parasuraman, 2000). However, if the user does not feel confident regarding the information received from the automation or if the user perceives the automation as being unreliable, then mental workload of the user can increase. For example, Ruff Narayanan and Draper (2002) investigated perceived workload under different types of automation. The authors found that when the users were subjected to an automation that was not 100% accurate, they had to cross-check automation's decisions thus increasing their workload. Therefore, an unreliable automated system is affecting trust which in turn affects operator's workload. This is exacerbated when multiple tasks are being carried out.

Summary

In summary, it is possible in the near future to have one operator supervising multiple robots, each performing a different task, while the operator is working on separate piece of work. In a multitasking scenario, it is necessary for the operator to maintain an optimal workload level to ensure effective cooperation and avoid automation misuse or disuse.

3.4.3 Situation awareness

The automation era has seen the introduction of very complex systems which require a substantial perceptual and cognitive effort from human operators. The new challenges posed by the introduction of new technologies led to the increasing interest of the research community in the construct of situation awareness (SA). Enhancing SA has become a key design goal in a variety of domains such as aircraft design, air traffic control, power plants and AMTs (Endsley, English and Sundararajan, 1997). Although the term was initially derived from operational pilots, various definitions have been given to SA since it heavily depends on the goals and decisions that need to be made to complete a particular job (Endsley, 2000). SA will have a different definition for a high precision surgeon from an airline pilot. However, a generally accepted term embraced in a variety of domains describes SA as "*the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future*" (Endsley, 2006, p.529).

Based on the above definition, there are three important stages (or levels) involved in SA (Endsley, 2000). Stage 1 SA is about perception. If the operator does not perceive the information displayed, then it can be expected from the operator to form an inaccurate picture regarding the state of the system they are operating. Jones and Endsley (1996) investigated the roots of SA errors in aviation. Their findings indicate that 76% of SA errors in pilots come from perception problems. Stage 2 SA involves comprehension. When an operator perceives the data displayed, the next step is to comprehend and interpret them correctly. This stage also involves the combination of other information in order to accurately interpret the information presented. Flach (1995) suggested that it is vital to tackle the problem of interpreting critical information in SA. Stage 3 SA deals with projection. An operator needs to be in a position to predict the future state of the system and anticipate any implications. Accurate projection and anticipation of events gives time to the operator to make decisions. Therefore, SA can be represented as a linkage between the various stages. If a pilot perceives a warning signal, but fails to comprehend its meaning he or she will not be in a position to make accurate projection of the future state of the aircraft; thus leading to a loss of SA. At the same time, it is important to understand the role of time in SA development. Situations are dynamic and so is SA. SA is a dynamic and time dependent construct which can be applied to developing situations (Parasuraman, Sheridan and Wickens, 2008). As shown in the definition, SA can change "*within a volume of time and space*". Therefore, operators need to have a degree of SA for a given time frame, but also assess how soon their SA regarding the state of the system will need to be updated based on the new situation. Failure to update SA according to the situation will result in using an outdated and inaccurate SA model regarding the system being operated.

According to Chen and Barnes (2014), operator's SA of the robot and tasking context is one of the key critical factors to achieve successful cooperation between human and robot teams. If the robotic system is not carefully designed it can have negative performance concequences (Bainbridge, 1983; Sheridan, 2002). One of these challenges is to ensure operators maintain adequate SA of the robot's actions as well as the tasking environment. In an industrial context, robots will replace some parts of the manual tasks. For instance, a welding robot will perform the welding task while the operator will be responsible for loading the part and ensuring the output meets the required standards. However, in this scenario the operator has been removed from the loop

(OOTL). As shown in section 3.4.2, taking the human OOTL can introduce human performance issues (Kessel and Wickens, 1982; Kaber and Endsley, 2004). Marquez and Cummings (2008) investigated human planetary exploration with the aid of robotic assistants. Findings pointed that operators' SA of the tasking environement reduced when the robot's paths were automatically generated. Chen and Barner (2012) studied the impact of automated robot route planning on operators' targetting performance. Their findings indicated that when the automation allowed the operator to focus on their primary task (i.e. target recognition), SA improved. Similar results were highlighted in a meta-analysis of 18 experiments by Onnasch, Wickens, Li and Manzey (2013). Authors investigated how automation-induced human performance consequences depended on the degree of automation. Results supported previous findings that when the decision making is taken by the automation SA significantly reduced. On the contrary, some researchers have found automation to improve SA. Galster and Parasuraman (2003) examined the effects of information automation and decision-support automation in a target detection and processing task. Findings suggested that information automation improved SA. Furthermore, Lorenz, Di Nocera, Rottger and Parasuraman (2002) examined, among other, the impact of a highly computerised flight management computer on human operator SA. Results highlighted that a highly automated computer system does not necessarily have a negative impact on operators' SA as long as the automation is designed to support efficinet information gathering. The contradicting results have been suggested to be routed in the different means of measuring SA (Chen and Barnes, 2014). Overall, the literature appears to suggest that caution must be taken when deciding which tasks to automate as that can have a significant impact on operators' SA.

Furthermore, it has been suggested that in the near future human operators will be required not only to operate a robot, or multiple robots, but also to concurrently perform other tasks (Chen and Barnes, 2012). In this type of environment, where operators will have a primary and secondary task, it is vital to understand how operators' SA can be influenced. This is of particular interest for the industrial environment where it is desired to reach a state where a single operator can supervise and control multiple robots while at the same time they are concurrently working on a separate task. Studies have investigated the cost on SA due to interrupting the primary task (e.g. robot supervision) with an intermittent task (e.g. respond to a message) (Cummings, 2004; Dorneich, Ververs, Mathan, Whitlow and Hayes, 2012). Results indicated that in these occasions there is a significant negative impact on SA. Further on this, Rubinstein, Meyer and Evans (2001) found that after task-switching operators are more susceptible to errors and slower response to events. In the conext of industrial HRC, this can be problematic since different robots can be working on a different piece of work therefore requiring the operator to switch between different task requirements

Summary

SA has been identified as a key element for effective cooperation between humans and automation over the years. Therefore, it can be expected that in an industrial setting where humans and industrial robots will be integrated in close proximity, SA can have a key role for the success of the collaboration.

3.4.4 Operator perceived attentional control

There is an increasing demand for multiple robot operations for industrial processes such as assembling, transporting, painting and welding (Nijmeijer and Rodriquez-Angeles, 2003, Gueaieb, Al-Sharhan and Miodrag, 2007; Akella and Hutchinson, 2002; Gueaieb and Karray, 2007). As discussed above, the greater demand for multiple robot operations indicates that in the near future when industrial HRC will become more embraced, human operators will be required to supervise and monitor multiple robots while performing a concurrent task. Earlier research has shown that individual differences can impact the ability of an operator to control and allocate attention (Rubinstein, Meyer and Evans, 2001; Feldman Barrett, Tugade and Engle, 2004; Schumacher, Seymour, Glass, Fencsik, Lauber, Kieras and Meyer, 2001).

Attentional control has been defined as the ability of an individual to focus and shift attention in a flexible manner (Derryberry and Reed, 2002). Previous work suggested that an individual's flexibility of allocating their attention can be a performance predictor for a variety of tasks such as flight training and bus driving (Kahneman, Ben-Ishai and Lotan, 1973). Furthermore, a study by Bleckley, Durso, Crutchfield, Engle and Khanna (2003) indicated that individuals with better attentional control can more effectively and flexibly allocate their attention.

Attentional control in human-robot teaming has received attention by the U.S military. Currently, there is an increasing trend to utilise robots in military operations while the types of tasks are evolving in complexity (Chen, Barnes and Harper-Sciarini, 2011; Cummings, Bruni and Mitchell, 2010). Attention has also been placed in remote operation of unmanned military vehicles (UVs) which can be remotely operated (Snyder, Qu, Chen and Barnes, 2010; Chen and Barnes, 2012). The task of controlling UVs requires operators to divide their attetnion between various tasks, such as controlling the vehicles, communicate with other member individuals and respond to any changes in the state of the vehicle (Crandall and Cummings, 2005). A survey carried out among US Air Force subject matter experts on unmanned air vehicle operator performance (Chappelle, McMillan, Novy and McDonald, 2010) highlighted operator attentional control as a key determinant of performance. Also, Goodrich, Quigley and Cosenzo (2005) examined operator's attentional control ability during the control of a ground robot in a simulation environment while having to perform a secondary task (identifying and reporting any change in the background). Findings suggested that task switching can have a negative impact on the operator's robot control performance (primary task). Furthermore, findings pointed that the nature of the secondary task, to some extent, can determine the cost of the primary task. Similar findings have been suggested by Crandall and Cummings (2007). In a user study where a single participant controlled multiple simulated UVs, the user's attention allocation was evaluated. Findings indicated that the ability of the operators to switch effectively between different tasks influenced their performance. Individuals with poor attention allocation exhibited degraded performance when controlling multiple robots. In an industrial environment where operators will be required to control multiple robots, each performing a separate task, the issue of operator attentional control is important to address. Individuals with poor attentional control might not be in a position to flexibly and effectively allocate their attention to the different tasks being completed.

Also, operator attentional control appears to influence the type of interaction between the operator and the automation, particularly when the automation is imperfect. It has been suggested in the literature that operators with different attention allocation capabilities may exhibit different compliance and reliance behaviour (Thropp, 2006; Chen and Terrence, 2009; Chen, 2011; Chen and Barnes, 2012). For instance, an individual with poor attentional control may exhibit more severe complacency effects when interacting with automation when compared to individuals with better ability to allocate their attention. Chen and Terrence (2009) studied the impact of imperfect automation (false-alarm-prone automation and miss-prone automation) during a human-military robot multitasking scenario (control of the robot and perform target recognition). Part of the investigation was to examine whether attentional control had an impact on operators' reaction to imperfect automation. Authors identified that individuals with higher attentional control did not comply with automation alerts in the false-alarm-prone condition due to disuse of the automation. For low attentional control participants, on the other hand, miss-prone automation was found to be more harmful due to over-reliance on automation (misuse). A similar study was carried by Chen (2011). The author simulated a military vehicle crew station environment. It was attempted to investigate whether automation-aided target recognition capabilities are affected during a multitasking environment under imperfect automation (false alarm prone or miss prone). Similar to the study by Chen and Terrence (2009), higher attentional control participants were affected more during a false-alarm-prone system while lower attentional control participants exhibited lower performance during miss-prone automation. It appears that lower attentional control participants tended to have higher trust in the automation, thus misusing the automation (over-reliance) when required to perform multiple tasks concurrently. Higher attentional control participants tended to rely on their own abilities regardless of the task load. Feldman Barrett, Tugade and Engle (2004) described this as the “cognitive miser” phenomenon. Due to their low attentional resources, low attentional control individuals strive to reduce the information-processing demands by simplifying tasks which leads to over-reliance on automation. However, during imperfect automation or in conditions where automation provides questionable information this phenomenon can have serious concequences. At the same time, it has been suggested that training interventions, such as attention management, can assist effective attentional switch during multi-tasking environment (Chen, Quinn, Wright and Barnes, 2013). According to behavioural studies, multitask training can improve the performance of each task and reduce the interference of the tasks on each other (Ruthruff, Johnston and Van Selst, 2001; Ruthruff, Johnston, Van Selst, Whitsell and Remington, 2003). Also, a recent study by Dux, Tombu, Harrison, Rogers, Tong and Marois (2009) indicated that extensive training can be used as means to make multitasking more efficient. According to the authors, extensive training speeds up information processing at the central stage of decision-making.

Summary

Overall, operator attentional control is an important factor during a multitasking HRC environment. Although literature comes from the military domain, industrial HRC will require operators to multitask during HRC. It is unlikely for automation to be 100% reliable all the time, therefore, it is important to understand the inter-relations between attentional control and the impact on operator interaction with automation during multitasking scenarios.

3.4.5 **Effects of automation reliability**

The introduction of modern automated systems has changed the way humans interact with machines. These technologies have been designed to assist human operators with tasks such as quick and accurate retrieval and processing of information, decision-making and execution (Parasuraman, Sheridan, and Wickens, 2000). Since their introduction, automated systems have been seen as a means for reducing workload and enhancing performance (Dixon, Wickens and McCarley, 2007). However, many automated systems are not perfectly reliable either due to technological limitations, software and hardware failures or because they must identify events based on imperfect probabilistic information in a changing world (Wickens, Huiyang, Santamaria, Sebok and Sarter, 2010; Wickens and Dixon, 2006). For example, an automated system that involves a range of sensors picking up the states of the system in the environment may produce erroneous information because its sensors have limited detection capabilities (McBride, Rogers and Fisk, 2013). At the same time, studies from the field of human-robot interaction suggested that given very little information or experience about an automated decision aid, people appear to be ready to trust it leading to positive bias (Desai, Medvedev, Vázquez, McSheehy, Gadea-Omelchenko, Bruggeman, Steinfeld and Yanco, 2012; Dzindolet, Peterson, Pomranky, Pierce and Beck, 2003). However, when automated systems do fail concequences can be catastrophic.

The effects of imperfect automation need to be examined in the context of industrial HRC. As this concept will require operators to collaborate with industrial robots in real time and under minimised safeguarding, it is important to understand the impact of automation failures on operators working directly with the robot. For instance, when a robot is in the collaborative mode, it is likely to have an automated aid (e.g. audiovisual aid) indicating this to the operator(s) as well as individuals working within the immediate vicinity. Therefore, when the automated aid departures from perfect reliability, it is vital to understand the impact on operators.

Previous literature has highlighted that when automated system fail, they produce one of types of errors: a false alarm (FA) or a miss (Dixon, Wickens and McCarley, 2006; Levinthal and Wickens, 2006; Dixon, Wickens and McCarley, 2007). A FA is an incorrect indication of an event while a miss indicates a failure of the automation to notice an event (Dixon, Wickens and McCarley, 2006). FAs tend to lead operators to delayed responses towards an alarm since the operators know from experience that many of the alarms do not actually correspond to a system malfunction (Getty, Swets, Pickett and Gonthier, 1995). Misses on the other hand, tend to influence operators' supervisory strategies during non-eventful periods.

These two types of automation errors have been investigated in terms of their impact on human operators. Meyer (2001, 2004) suggested that operators' behaviour will depend upon the type of automation errors. In other words, operator behaviour will differ when the automation exhibits FAs and when it exhibits misses. Meyer described that the two possible cognitive states due to automaton errors are compliance and reliance. Compliance characterises the tendency of the operator to respond when the automation aid provides an alarm. A highly compliant operator will tend to immediately stop any other concurrent task and place attention to the alarm (Wickens, Dixon, Goh and Hammer, 2005b). Compliance reduces when the automation commits a higher frequency of FAs leading to the so called ‘cry wolf’ effect (Bliss and Acton, 2003). When the frequency of FAs becomes so high, operators can even choose not to completely disregard the alerts (Breznitz, 1984). Reliance on the other hand, describes the state of the operator when the automation does not provide any alarm. A highly reliant operator will assume that the automation will indicate when something is out of tolerance. Therefore, the operator can place full attention for the completion of concurrent tasks. In this occasion, imperfect automation that exhibits a high level of misses will tend to reduce reliance (Levinthal and Wickens, 2006). Because the operators no longer trusts the system, he or she will spend more time scanning data to ensure the automation has not missed an event at the expense of attentional resources for concurrent tasks, thus performance can deteriorate (Onnasch, Ruff and Mazney, 2014).

An excessive degree of compliance or reliance can have catastrophic concequences. An overly compliant or reliant operator will have reduced monitoring abilities at the time of failure because they are placing too much trust in it (Parasuraman and Riley, 1997) which in turn causes loss of situation awareness (Endsley and Kiris, 1995). Parasuraman Molloy and Singh (1993) describe this as complacency. A highly reliable (but not perfect) automated system functioning correctly for a prolonged period of time prior to its first failure has the potential to increase operator complacency (Bainbridge, 1983; Yeh, Merlo, Wickens and Brandenburg, 2003). Earlier studies have also pointed that a contributing factor to improper reliance on automation is trust (Muir, 1983; Lee and Moray, 1994). Also, over-reliance and under-reliance on aircraft automated systems due to trust miscalibration have been cited as contributing factors for aircraft accidents (Desai, Kaniarasu, Medvedev, Steinfeld and Yanco, 2013). Desai, *et al.,* (2012) examined the effects of changing reliability on a person's use of autonomy and trust in a robot system. Findings indicated that drops in reliability after a period of continually good performance are more harmful than early failures. Furthermore, results highlighted that after a drop in reliability users switched away from the autonomy mode much faster compared to returning to autonomous mode after an increase in reliability. Therefore the degree to which an automated system is reliable has an important impact on operators' reliance and compliance. Studies have even demonstrated that when reliability level is below 70% operators ignore the automation (Wickens and Dixon, 2005). Wickens and Dixon (2005) in their meta-analytic analysis of 20 different studies found that a reliability of 0.7 is the cut-off point, below which "*unreliable automation is worse than no automation at all*" (p.201).

Summary

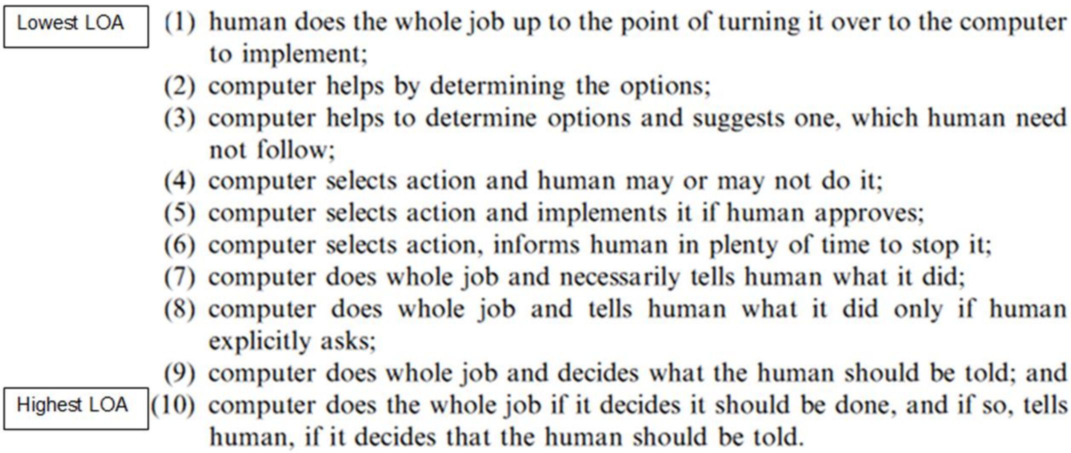
Overall, automation reliability is a key topic in the collaboration between humans and automated systems. To this end, it is important to investigate how and to what extend an imperfect industrial HRC system will impact human operators working directly with it but also in the immediate working area.

3.4.6 Effects of varying levels of automation

Industrial collaborative robots are being designed to operate autonomously within the human environment (Papadopoulos, Bascetta and Ferretti, 2013; Unhelkar, *et. al.,* 2014; Tang, Charalambous, Webb and Fletcher, 2014; Baxter of Rethink Robotics©). The long-term aim is to have intelligent robotic systems on the shop floor able to work alongside human operators as teammates.

Earlier studies have suggested that automated systems must be human-centred to be used effectively and safely by human operators (Billings, 1997; Parasuraman, 2000). As part of a broad set of requirements for human-centred automated systems, Billings (1997) highlighted that it is crucial for operators to remain in command of the system and be actively involved and informed about the status of the automation. Traditionally, automation allocation has been viewed as a static binary relationship. That is either the human or the machine is assigned to a given task (Endsley and Kaber, 1999). However, inherent to the use of static automation are issues of reduced situation awareness, complacency and lack of trust all of which are concequences of the OOTL effect (Parasuraman, Molloy and Singh, 1993; Endsley, 1995a; Endsley and Kiris, 1995; Parasuraman and Riley, 1997). A growing body of literature suggests that automation should not be approached as an all-or-nothing phenomenon, but the degree to which a function in performed by the human or the automation can vary along different levels (Parasuraman, Sheridan and Wickens, 2000; Cosenzo, Parasuraman, Novak and Barnes, 2006). In other words, the level of automation (LOA) can vary from the lowest level (i.e. fully manual) to the highest (i.e. fully autonomous) (Sheridan, 1992). The application of different LOA can potentially mitigate the human performance issues associated with static automation (Kidwell, Calhoun, Ruff and Parasuraman, 2012).

Over the years, several taxonomies have been proposed between the two extremes. Sheridan and Verplanck (1978) developed an early taxonomy for LOA which includes ten levels as shown in Figure 3-20:



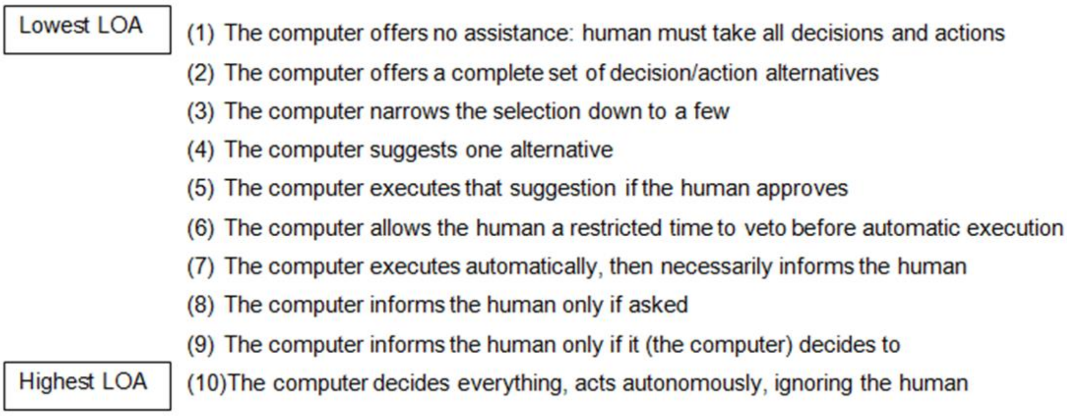
Lowest LOA

(1) human does the whole job up to the point of turning it over to the computer to implement;
(2) computer helps by determining the options;
(3) computer helps to determine options and suggests one, which human need not follow;
(4) computer selects action and human may or may not do it;
(5) computer selects action and implements it if human approves;
(6) computer selects action, informs human in plenty of time to stop it;
(7) computer does whole job and necessarily tells human what it did;
(8) computer does whole job and tells human what it did only if human explicitly asks;
(9) computer does whole job and decides what the human should be told; and
(10) computer does the whole job if it decides it should be done, and if so, tells human, if it decides that the human should be told.

Highest LOA

Figure 3-20 LOA taxonomy from Sheridan and Verplanck (1978) (Retrieved and adapted from Endlsey and Kaber, 1999)

Level 1 represents the lowest LOA (e.g. fully manually) while level 10 represents the highest LOA (e.g. fully automated). Also, this taxonomy includes a feedback loop between the system and the human. For instance, intermediate LOA (e.g. level 2 to level 9) include what the human needs to be told by the system, functions allocation, option selection and implementation. Therefore, as discussed previously by incorporating varying LOA the human operator can stay in the loop and actively involved with the system (Billings, 1997). Wickens, Mavor, Parasuraman and McGee (1998) developed a 10-point automation scale based on Sheridan and Verplanck's (1978) taxonomy (Figure 3-21):



Lowest LOA

(1) The computer offers no assistance: human must take all decisions and actions
(2) The computer offers a complete set of decision/action alternatives
(3) The computer narrows the selection down to a few
(4) The computer suggests one alternative
(5) The computer executes that suggestion if the human approves
(6) The computer allows the human a restricted time to veto before automatic execution
(7) The computer executes automatically, then necessarily informs the human
(8) The computer informs the human only if asked
(9) The computer informs the human only if it (the computer) decides to
(10)The computer decides everything, acts autonomously, ignoring the human

Highest LOA

Figure 3-21 LOA taxonomy by Wickens, Mavor, Parasuraman and McGee (1998)

For instance, using the above taxonomy, at level 2 the system provides the operator with a complete set of possible decisions and actions for the operator to choose. The system has no further authority though. As the level of automation is increased the system's level of authority increases dramatically. For instance, at level 6 the system allows only a specific amount of time for the human operator to intervene and override the proposed action otherwise the system will implement the action.

Also based on the 10-point LOA taxonomy by Wickens *et. al*., (1998), research has also been directed to extent the concept of varying LOA in order to accommodate for the different types of functions in a human-automation system interaction (Kaber and Endsley, 2004). Parasuraman, Sheridan and Wickens (2000) developed a taxonomy which considers the stages of human information processing to which the automation is applied. Authors identified four stages, namely:

- ***Stage 1 – information acquisition***: The first stage involves the acquisition and registration of information where the raw data are pre-processed prior to filtering and allocating selective attention.
- ***Stage 2 – information integration and analysis***: The second stage refers to the conscious selection and integration of processed information to aid the operator with diagnosis and situation awareness.
- ***Stage 3 – action selection***: The third stage involves the decision-making and selecting an action.
- ***Stage 4 – action implementation***: The final stage refers to the implementation of the action chosen in the previous stage.

Although the above breakdown has been acknowledged by authors to be only a "*gross simplification*" (p.287) of the human information processing system, it provides an initial starting point for automation design. Each of these stages could be automated to a different level using the ten-point LOA taxonomy or even a simpler taxonomy (e.g. 5-point LOA) as shown in Figure 3-22:

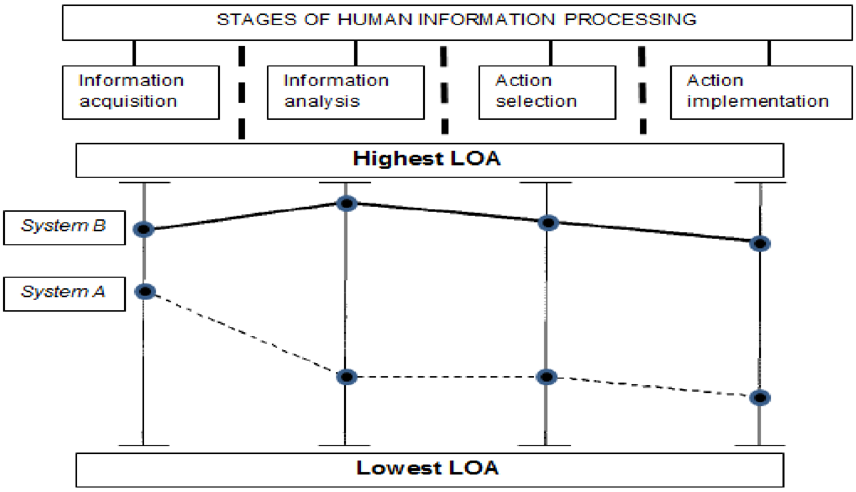


Figure 3-22 Varying LOA based on the stages of human information processing (Retrieved and adapted from Parasuraman, Sheridan and Wickens, 2000)

For instance, for system A, information acquisition could be designed at a high LOA (e.g. 6 on a 10-point LOA scale), while information analysis, action selection and action implementation could be designed at lower LOAs, implying higher level of human discretion. At the same time, another system B could be designed with higher LOA for all stages suggesting lower human involvement.

The difficult question is to decide what LOA on the continuum needs to be applied for each stage. Definitely there are no easy answers on this one as there will always be a trade-off. Onnasch, Wickens, Li and Mazney (2013) suggested that higher LOA can enhance routine performance but they also increase lack of fault management performance, particularly when the automation fails. A possible solution would be to evaluate a particular level of automation against the associated human performance concequences for a given task (Parasuraman, Sheridan and Wickens, 2000).

Empirical research has suggested the use of intermediate LOA in complex tasks in order to avoid the OOTL effect (Endsley and Kaber, 1999). For instance, Endsley and Kiris (1995) investigated the ability to recover from automation failures when individuals performed an automobile navigation task with the assistance of an expert system following Endsley's (1987) taxonomy.

Their findings suggested that with the use of intermediate LOA increased SA and their ability to recover from a system failure when compared to full automation. Similar findings were observed by Sarter and Schroeder (2001) examining the performance of pilots interacting with an automated decision aid that supported decision making in case of in-flight icing events. Higher LOA resulted in greater performance benefits when the system was fully reliable. In case of inaccurate information, however, higher performance decrements were observed when higher LOA was in use. Similar findings have been suggested by more recent empirical studies (Kaber and Endsley, 2004; Li, Wickens, Sarter and Sebok, 2013) supporting that intermediate LOA can reduce OOTL performance decrements particularly when automation fails.

However, in a dynamic environment it is likely to desire various LOA on the continuum according to the changes in the environment. Thus far, the discussion on allocating a LOA involves static function assignments indicating the level to which a particular task is automated (Kaber, 1997). In other words, the choice of assigning a LOA does not change according to the situational demands (e.g. task complexity). It has been suggested that automation allocation can pass and back forth between the human and the automated system over time depending on the demands on the situation (Kaber and Endsley, 2004). This has been described as adaptive automation (Rouse, 1988; Scerbo, 1996, 2006). In adaptive automated systems, the LOA of the system can be modified in real time. Adaptive automation has been suggested to counter balance some of the deficiencies attributable to static automation, such as, “automation surprise” and enhance situational awareness, as well as to contribute overall improved task performance (Cosenzo, Parasuraman, Novak and Barnes, 2006; Kaber and Endsley, 2004).

A key theme here is that in an adaptive automated system, the decision to change LOA (higher or lower) is made by the system itself. The question, however, is what happens if the system decides to change the LOA without the operator being aware or the operator not wishing to do so. This is raising the issue of system unpredictability which in turn can influence system acceptance as well as trust in the system (Billings and Woods, 1994; Dzindolet *et., al.,* 2001). A separate point of view suggests that the user can have the authority for changing the LOA according to the situation and this is described as adaptable automation (Scerbo, 2001). Although an adaptable automated system can be less unpredictable and gives back some control to the operator, it also implies an increase in workload since the human needs to make a decision about when to automate and to what level. Therefore, there is a trade-off (as with choosing an appropriate LOA) between adaptive and adaptable automation. Adaptive automation will result in decreased workload while at the same time reducing user involvement in the control of the system thus raising system unpredictability. Adaptable automation on the other hand, increases user involvement thus reducing unpredictability while increasing user's cognitive demands (Miller and Parasuraman, 2007). Empirical research has supported the benefits of both types of automation (Kaber and Endsley, 2004; Cosenzo *et. al.,* 2006; Parasuraman, Galster, Squire, Furukawa and Miller, 2005; Squire and Parasuraman, 2010). Also, more recently Kidwell *et. al.,* (2012) conducted one of the first studies comparing the effects of adaptive and adaptable automation on human performance. Their findings highlighted that although adaptable automation increased operator workload; it also enhanced change detection and increased operator confidence in task-related decision-making.

Summary

In relation to industrial HRC, there is a growing desire for multiple robot operations while at the same time operating autonomously in the human environment (Papadopoulos, Bascetta and Ferretti, 2013; Unhelkar, et. al., 2014; Gueaieb, Al-Sharhan and Miodrag, 2007). In this kind of collaboration it is possible for different robots to be performing different tasks while being monitored by a human operator. Therefore, varying LOA could be applied according to the task. For instance, a higher LOA could be applied when the robots are performing an autonomous task while a lower LOA could be applied when the robots switch mode (e.g. collaborative mode) to interact with the human operator to complete the task. Also, LOA changes can be initiated according to situational demands. However, the effects of adaptive and adaptable automation within a HRC system will need to be investigated further regarding their impact on human performance.

3.4.7 Attitudes towards robots/automation

Robots are becoming increasingly popular in our daily lives, from offices, houses and schools to industrial and military fields (Nomura, Kanda, Suzuki and Kato, 2006; Tsui, Desai, Yanco, Cramer and Kemper, 2011b; Tung and Chang, 2013). In order to robots to be integrated and accepted in human societies, it is crucial to understand how people feel about them and how they are affected by their presence (Nomura, Kanda and Suzuki, 2006). A key element is to understand the attitudes people might have for robots and how these are affecting or biasing subsequent interactions with them (Nomura, Kanda, Suzuki and Kato, 2005; Nomura, Kanda and Suzuki, 2006; Tsui, Desai, Yanco, Cramer and Kemper, 2011b). This has been a particularly important topic for the HRI research community because it is likely for various users to have different perceptions of the same automated or robotic system (Merritt and Ilgen, 2008). Similarly, attitudes toward industrial robots can vary significantly. As the concept of industrial HRC is becoming more accepted it is vital to understand how people's attitudes of industrial robots will influence adoption.

Peoples' attitudes specifically towards industrial robots have not been thoroughly investigated, mainly due to the preventive health and safety regulation. Much of the research has investigated people's attitudes toward domestic and social robots. According to Nomura, Kanda and Suzuki (2006) negative attitudes toward a robot is a key psychological factor preventing effective interaction. Khan (1998) and Scopelliti, Giuliani, D'Amico and Fornara (2004) explored adults' attitudes towards the design of a domestic-purpose robot. For instance, Scopelliti and colleagues (2004) examined the attitudes in domestic robots held by different generations. Findings suggested that younger individuals achieved a more positive score compared to adults and older adults. Younger people found the robots to be amusing, dynamic and pleasant. One possible explanation is that these individuals were raised during the development of the digital era, therefore they are far more familiar with the potential of interacting with a domestic robot. Furthermore, work has also been directed to understand what status people give to a domestic robot. Do they treat a domestic robot as a friend or as a servant?. Dautenhahn, Woods, Kaouri, Walters, Koay and Werry (2005) examined people's views toward robots in households. Their findings suggested that people were in favour of the view that robots can be companions; however they also tended to see it as having the role of an assistant or servant.

Also, numerous studies have investigated users' needs of domestic robots, personalisation of home technologies and long-term adoption of social robots (Sung, Christensen and Grinter 2009; Sung, Grinter and Christensen, 2010) using commercially available domestic robots, such as 'Roomba'[10] . Within this vein, people's expectations of domestic robots were suggested to be crucial for the acceptance of such robots (Sung, Grinter, Christenses and Guo, 2008). It has been suggested that people tend to have high expectations from domestic robots such as be intelligent and able to learn (Forlizzi and DiSalvo, 2006). This is particularly important, because if the robot cannot meet the owner's expectations then this will result in disappointment from the side of the human partner (Bartneck, Kulic and Croft, 2009). This in turn can negatively influence adoption of such a robot. Furthermore, other studies have shown that the functionality and the context influence what attitude people will hold towards a robot. Goetz and Kiesler (2002) and Goetz, Kiesler and Powers (2003) identified that a social robot is expected to perform in a playful and carefree manner, while a more serious robot is expected to perform in a health related context. Also, Fink, Bauwens, Kaplan and Dillenbourg (2013) in their study using a domestic robot, revealed that a major impediment for robot integration into daily routines is the compatibility with the user's attitudes.

Work has also been directed towards understanding implicit attitudes towards automated systems. Implicit processes affect behaviour automatically and tend

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[10] 'Roomba' is a commercially available vacuum cleaning robot (Fink, Bauwens, Kaplan and Dillenbourg, 2013)

to be triggered unconsciously (Gawronski, Hofmann and Wilbur, 2006). According to Bargh and Chartrand (1999), although most of the time we are unaware of implicit attitudes, they have a large influence on our daily activities, from attitudes toward product brands to alcohol consumption (Maison, Greenwald and Bruin, 2004; Payne, Govorun and Arbuckle, 2008). Potentially, there can be similar implicit attitudes when humans have to collaborate with automate systems. The associated implicit attitudes toward an automated system can range from negative to positive. The triggering of this reaction can sometimes be immediate and what has been described as “gut reaction” (Ranganath, Smith and Nosek, 2008). Furthermore, the implicit attitude reaction (e.g. positive or negative) is thought to be developed through continuous evaluation from stimuli of the outside world (Olson and Fazio, 2001). For instance, if an individual is constantly receiving stimuli that portray automation in a negative way (e.g. leading to job loss, unreliable automated systems leading to accidents, main stream movies), it is likely to generate more negative implicit attitudes toward automation in general. This negative implicit attitude is likely to affect the individual’s behaviour toward the automated system irrespective of whether the individual believes the attitude to be correct or not.

Summary

Having outlined the importance of attitudes toward social robots and automated systems, it is important to understand the impact of attitudes toward industrial collaborative robots. To our knowledge, very little work has been carried out in this domain. Industrial robots are traditionally seen as tools aiding humans to complete a task. However, their role is enhanced to a team member in the concept of industrial HRC. Therefore, a key question is how human attitudes will influence adoption of industrial collaborative robots. As discussed above, it is possible for humans to already have formed certain implicit attitudes regarding industrial robots from external stimuli. Could these attitudes impede acceptance? And if they do, is it possible to alter them through matching user expectations? Therefore, it is crucial to explore and understand the impact of human attitudes toward industrial collaborative robots.

3.5 Theoretical human factors framework

The literature presented has shown that the implementation of a technological change should not be seen simply as a technical challenge. Empirical literature from the domain of advanced manufacturing technologies has stressed that inattention to the human element can be detrimental for the successful introduction of automated technologies. In light of this, the aim of this research is to identify the key human factors that will enable successful implementation of industrial HRC. Therefore, human factors for this framework were identified by reviewing those that have been found relevant in other comparable domains to industrial HRC.

This approach led to the identification of a number of key human factors. The human factors identified appeared to be relevant across two levels:

- Human factors at the organisational level, influencing the organisation (e.g. communication to the workforce, employee participation)
- Human factors at the individual level, influencing the human operator (e.g. mental workload, trust, situation awareness)

To this end, the identified human factors were segregated at two levels, namely the organisational level and the individual level (Figure 3-23). This represents the theoretical human factors framework.

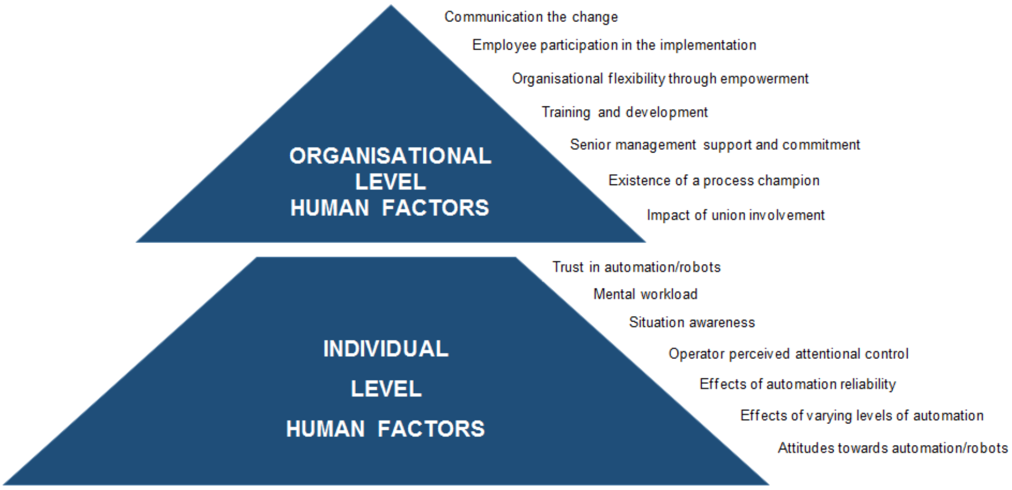

Figure 3-23 The theoretical human factors framework

The human factors at each level represent two areas which, for the needs of this research, have been investigated separately. However, this does not imply these two levels are mutually exclusive. As it will be discussed in chapter 5 the factors across these levels are inter-related.

The human factors across these two levels were investigated in a different approach. Section 3.5.1 presents how the organisational level human factors have been investigated while section 3.5.2 discusses how individual level human factors were approached.

3.5.1 Organisational level human factors

The successful implementation of industrial HRC on a manufacturing shop floor will depend upon a variety of organisational factors and the following have been identified to be of most relevance: (i) communication of the change to employees, (ii) operator participation in implementation, (iii) training and development of workforce, (iv) existence of a process champion, (v) organisational flexibility through employee empowerment, (vi) senior management commitment and support, (vii) impact of union involvement. Having identified these as the most important key organisational human factors we then proceeded to explore further within a real industrial exploratory case study of new robot technology implementation whether they were enablers or barriers. This is described in chapter 4.

3.5.2 Individual level human factors

The literature review of human-automation and human-robot interaction provided a list of the key individual level factors which appear to be of most importance for the successful implementation of industrial HRC: (i) trust in automation/robots, (ii) mental workload, (iii) loss of situation awareness, (iv) operator perceived attentional control, (v) effects of automation reliability, (vi) effects of varying levels of automation and (vii) attitudes toward robots/automation. Each of these individual level human factors is important to investigate separately. However, it appears that trust in automation/robots is the foundation construct influencing all the other identified factors. For instance, previous research has shown that if a robotic agent is perceived by the operator to be unreliable or unpredictable it will increase operator's mental workload (Miller and Parasuraman, 2007). The predictability and reliability of a robotic entity have been identified as key elements for fostering trust in human-robot interactions (Hancock *et. al.,* 2011). In other words, if the operator, for whatever reason, does not have adequate trust in the robotic teammate he or she will place more mental resources on raw data to ensure the robot is taking the correct actions thus increasing mental workload. Therefore appropriate calibration of trust between the operator and the robotic entity will have a direct impact on mental workload.

The same applies for situation awareness. In a human-robot collaboration scenario the robotic agent will be responsible for a particular part of the task. Therefore, the human operator will have to rely that the robot is performing adequately. If for instance the operator does not trust the robot, he or she will, like before, have to allocate additional attentional resources to ensure the robot is performing appropriately thus potentially leading to performance degradation. At the same time, if the operator is at the other end of the trust spectrum (over trust) then he or she is likely to exhibit complacency thus leading to the OOTL performance issues (Kessel and Wickens, 1982; Kaber and Endsley, 2004).

Also, operator trust appears to be related to operator perceived attentional control. PAC was described as the ability of the operator to flexibly and effectively shift attention between different tasks. This has been identified as a key factor for multiple robot operations. Literature has suggested that individuals with poor attention allocation tend to overly rely on the automated system during multitasking. If the system is not 100% reliable then this can have serious consequences. Therefore, as before, it is vital to appropriately calibrate trust levels between the operator and the automated system to ensure effective attention allocation.

According to Hancock and colleagues (2011) the reliability of an automated system is a key trust antecedent. A key discussion point in the literature has been what the consequences are when a system thought to be perfectly reliable eventually fails. A highly reliable (but not perfect) automated system functioning correctly for a prolonged period of time prior to its first failure has the potential to increase operator complacency (Bainbridge, 1983; Yeh, Merlo, Wickens and Brandenburg, 2003). However, if the operator does not trust the system, even when it is 100% reliable, the he or she will be spending monitoring the system at the expense of their task.

An additional factor identified in the literature was the potential for varying levels of automation. Varying LOA imply that at different stages the human operator will have different levels of authority (higher or lower). Once again, appropriate trust is vital to ensure the success of this approach. Lack of operator trust or over trust using such an approach will only create additional human performance issues. Furthermore, if LOA are to be utilised within an adaptive or adaptable automated system, then operator trust in the system becomes even more critical. In an adaptive automation, the system has the authority to change LOA accordingly. Adaptable automation on the other hand, provides the operator with the authority to change the LOA. Therefore, appropriate levels of trust are vital for either approach.

Finally, acceptance of robots within the human environments depends on human attitudes. As shown by literature from the domain of social robotics, human attitudes have the ability to shape the type of interaction not only at a conscious level but also at a sub-conscious level. The construct of trust, however, has been defined as an “attitude that an agent will help achieve an individual’s goals in a situation characterized by uncertainty and vulnerability” (Lee and See, 2004). Therefore, although individuals’ propensity to trust can vary, there is a certain attitude toward certain implicit attitudes toward an object or system influenced by other stimuli. Therefore, understanding how trust develops when individuals interact with industrial robots can be vital for the success of the collaboration.

In summary, it appears that trust is central among all of the identified factors. This does not imply that the other factors are not equally important. However, based on the review it appears that trust is the underlying factor and for this reason, the focus of this research at the individual level was concentrated on understanding trust development in industrial HRC. The work undertaken is described in chapter 5.

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4 ORGANISATIONAL LEVEL FACTORS

4.1 Introduction to the chapter

Literature review from comparable contexts to industrial HRC revealed seven organisational human factors as the most important for the successful implementation of industrial HRC. These are shown in Figure 4-24:

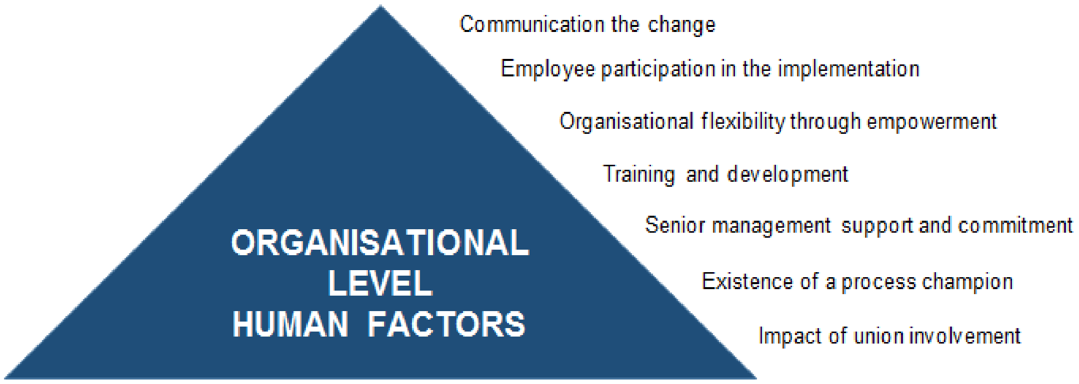


Figure 4-24 The organisational level humans factors

This chapter presents the work carried out, to explore further within a real industrial exploratory case study of new robot technology implementation whether they were enablers or barriers. This is described in section 4.2. The findings of the case study, aided the development of a survey to obtain generalisable results. The survey is presented in section 4.3.

4.2 Exploratory case study

To identify whether the organisational human factors outlined above were enablers or barriers an industrial exploratory case study was conducted where traditional manual work was being automated.

4.2.1 Exploratory case study description

The exploratory case study example that was selected for this work was an in-progress implementation of automated welding in a UK high value aerospace component manufacturing company. Currently, the component is being manually welded on a welding fixture. The component has a varying geometric profile and thickness. Once the component is welded, it is then subjected to a leak inspection process to ensure it has been adequately welded. If a leak is detected, the component will need to be reworked or scrapped accordingly. Due to the challenging geometry of the component, an increasing number of reworks have been noted. Therefore, to enhance product quality and reduce costs a welding robot was being introduced to complete the welding process, to standardise the process and reduce the amount of reworks.

4.2.2 Aim and objectives

The aim was to identify the key organisational level factors that are either enablers or barriers in relation to implementation of HRC work. Principal objectives were: (i) collect qualitative data from personnel involved in the implementation of the automated system and (ii) identify key enablers and barriers.

4.2.3 Method

4.2.3.1 Design

The lack of previous industrial HRC research or existing guiding framework meant that for this study an exploratory qualitative approach was appropriate. Qualitative research has been suggested to be an appropriate approach for understanding phenomena within their context and revealing the links among concepts and behaviors (Glaser and Strauss, 1967; Miles and Huberman, 1994; Crabtree and Miller, 1999). To this end, the list of organisational human factors themes identified in the literature was used as an *a priori* guiding framework within a semi-structured one-on-one interview approach to gather individual experiences and accounts of the transition from a manual to an automated process. Open-ended questions were used to aid eliciting in-depth information from the participants, such as: "*Can you tell me how the new automated system was communicated to the workforce?*" Furthermore, probe words / phrases were used to elicit further information from the participants, such as: "*How did it affect you?*" The interview was designed to last between 30 and 40 minutes. The interview schedule is available in Appendix A.

4.2.3.2 Participants

Interview participants were personnel who were involved in the implementation of automated welding such as: shop floor operators, engineers, system designers, management and union personnel. Initially, 13 participants were recruited but one withdrew, leaving twelve interviewees: 11 males and one female (M=41, SD=9).

4.2.3.3 Ethical considerations

Participants were informed that in order to analyse data, the interview would be tape recorded. Participants were made fully aware that they could stop the interview at any moment without having to give a reason. A separate reference number was given to each participant to ensure anonymity. Following this, a consent form was provided for the participants to sign. Collected data were stored and maintained by Cranfield in accordance with the University’s Ethical Code and the Data Protection Act (1998).

4.2.3.4 Procedure

4.2.3.4.1 Pilot study

Prior to the main study, a pilot study was conducted to ensure the interview schedule was appropriate for the target audience. Two subject matter experts (SMEs) from Cranfield University’s machine shop were voluntarily recruited. These participants were selected as an appropriate match of the audience recruited in the main study. Both participants were experienced operators with extensive knowledge in the use of computer-numerical controlled (CNC) machines.

Participants were interviewed individually. Interviews were carried out and tape recorded with the participants’ consent. The average interview time was 39 minutes. A problem identified in the pilot study was that both participants did not understand what a process champion is. Upon explaining them, both participants suggested that often the process champion is the project manager responsible for introducing the automated system on the shop floor. Both participants suggested providing a brief explanation of this term.

4.2.3.4.2 Main study

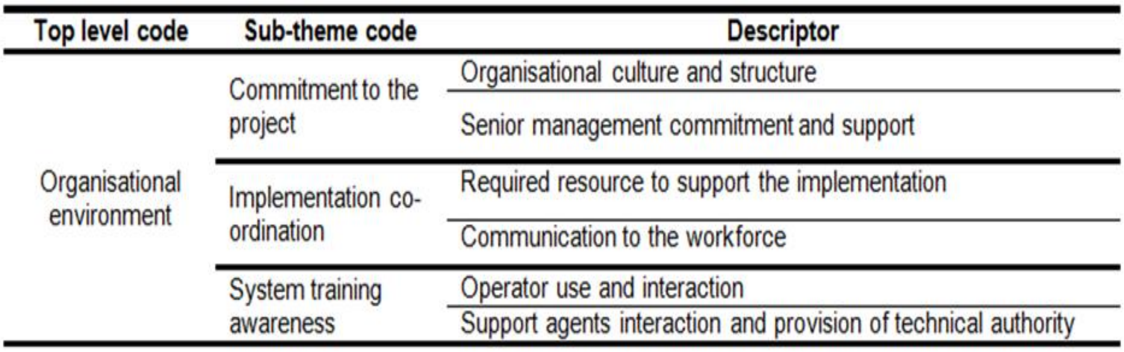
Participants were approached in advance and were aware of their interview schedule. The location of the interview was at the organisation’s facilities. During the interview, no other individual was present.

Participants were initially briefed regarding the aim and objectives of the study, as well as the need to capture data via an interview (Appendix B). Following this, a consent form was provided for the participants to read and sign (Appendix C). Then participant were provided a demographic form to complete (Appendix D). Due to the sensitivity of this study, all participants were reminded of key ethical details from the information sheet such as, withdraw without giving a reason and confidentiality. Finally, for anonymity purposes participants will be given a unique reference number. They were informed that by quoting the number they can have their data removed from the data pool up to seven days after the interview.

4.2.3.5 Data analysis

To analyse the qualitative data, template analysis was used to establish key themes, emergent themes and the relationship between them. This data collection and analysis strategy will not only establish the validity of the factors that have been identified in current literature as most likely to influence the implementation of industrial HRC but will also reveal any factors that have not yet been acknowledged.

Interviews were fully transcribed verbatim and analysed using the Template Analysis’ in accordance with guidelines provided by King (1998). ’Template Analysis’ involves the development of a coding template in which the major themes within written text are identified in a hierarchical form so that top level codes represent broad themes while lower level codes represent sub-themes and descriptive codes. Care was given to code themes identified in a small minority of transcripts. The template structure was revised iteratively to ensure it reflected the data in the most suitable manner. Figure 4-25 shows an extract from the coding template.



Top level code	Sub-theme code	Descriptor
Organisational environment	Commitment to the project	Organisational culture and structure
		Senior management commitment and support
	Implementation co-ordination	Required resource to support the implementation
		Communication to the workforce
	System training awareness	Operator use and interaction
		Support agents interaction and provision of technical authority

Figure 4-25 Extract of the coding template

The template developed by the researcher was subjected to an inter-rater reliability process with an independent researcher to ensure reliable reflection of the data. Because this was a single exploratory case study, the inter-rater reliability process was based on percentage agreement. Two transcribed interviews were randomly selected for the inter-rater reliability process, accounting for 16% of the population. Miles and Huberman (1994) indicate an initial inter-rater reliability rate in the range of 70%. The first interview transcript achieved an agreement rate of 88% while the second transcript achieved an agreement rate of 85%, leading to an average agreement of 86.5% suggesting an acceptable agreement level for this early stage.

4.2.4 Results of the exploratory case study

Through the data analysis, several enablers and barriers have emerged.

4.2.4.1 Enablers

Employee participation in implementation. Operator participation was found to be a catalyst and a major link for the successful implementation and development of the automation. Nearly all of the interviewees indicated that operator involvement aided the transition from the manual to the automated state. Furthermore, it was suggested that the implementation could run even smoother had they been involved since the conceptual stage:

> “*A lot of the modifications we had to do since the cell has been built, we wouldn’t have to do that .So we would have a smoother transition*” (**Participant 15**)

In addition, operator involvement revealed another dimension, important for the success of the implementation process. It was highlighted that worker involvement helped operators gain ownership of the new system which subsequently led to less negativity and higher acceptance during onsite development:

> “*The guys have taken ownership, they show that they want the project to work, they come up with ideas and they have been proactive and they help with the project*” (**Participant 14**)

Communication to the workforce. For most participants, the need to communicate the change to the workforce was a critical factor. Participants stressed that communication to the operators regarding the introduction of the automation was a major enabler. Through open communication, operators received quality information as to the reasons for the organisation choosing an automated system and what the wider benefits of the system were:

> “*They have been fully aware of what the benefits are and what are we trying to achieve […] that’s where this particular project has been good…it’s the fact that they have actually communicated to the shop floor*” (**Participant 14**)

Furthermore, although communication had been an enabler for this project, participants argued that communication to the operators could have been improved by providing further information as to the impact of the automation on their daily routines:

> “*[…] to me I’ve not been convinced that they all know the impact of that’s going to have on the area, and how that group is going to be shaped*” (**Participant 10**)

Senior management support and commitment*.* An additional enabler has been indicated to be senior management support and commitment to the project. Interviewed personnel highlighted that senior management were visibly committed to the project throughout its development which enhanced its credibility. At the same time, findings suggested that senior management support acted as an indirect acknowledgement of the personnel's efforts for producing a process capable system.

> "*Because this pressure is there from them I think it spares everyone on a little bit almost, that they are behind us and they are supporting us*" (**Participant 8**)

Training of the workforce*.* During the early implementation stages, provision of offsite training to a number of end-users (identified as main users) was found to be an important enabler. It allowed end-users to gain confidence and ownership of the new system.

> "*We've been down there (system integrator's facilities) a few times, running the cell in the early stages before it came back up here. It gives you a lot better insights about the system and how it works*" (**Participant 12**)

An additional dimension emerging from this theme was the translation of knowledge from the main users to the rest of manual welders. The training received by the main users was used as a vehicle for informally cascading the knowledge and experiences gained to the rest of their colleagues on the manual cell. This reduced negativity regarding the system and enhanced its acceptance among the rest of the operators.

> "*To [have] them lads coming back and telling stories of what it will do and photos and videos, I think if we hadn't done that it would have been met with a lot more cynicism and scepticism when it hit the shop floor. Because two of the lads have actually seen it and have worked with it, the scepticism wasn't there*" **(Participant 11)**

Organisational flexibility through worker empowerment*.* Although at the time of data collection the automated welding robot was not fully operational, participants' accounts suggested that operators were expected to assume additional control over the system and ensure smooth operation:

> "*Manufacturing Engineers' function is to support the robot and make sure it functions, but if it is on a nightshift or at a time when the MEs are not here then they (operators) will have to do something to keep it going*" **(Participant 15)**

In addition, it has been underlined that it is vital to empower operators with additional control in order to foster acceptance of the system:

> "*Give the lads an interest because if you just tell them that 'you put the parts in, you shut the door, press the button' … if it doesn't work they are going to stand there with the arms crossing… (saying) not my job*" **(Participant 11)**

At the same time, it has been pointed that operator empowerment will be provided through a reaction control plan. Although operators will be empowered to deal with daily issues to ensure the system is running, any problems of technical nature where operators do not feel comfortable enough to rectify will be passed to the manufacturing engineers for further support:

> "*It really depends on what the actual problem is. What we tend to do is release a control plan onto the shop floor which basically says if there's a failure what the next steps are, like contact an ME or contact a supervisor*" (**Participant 14**)

Furthermore, it was pointed that by enhancing operator control the caveat is to turn into blame allocation when the system malfunctions:

> "*But then if it goes wrong there should be no blame. You haven't done that to break it on purpose. If you implement blame culture and then it goes wrong, the next thing is going to be 'I ain't touching that, get your people who are qualified to do it'*" (**Participant 11**)

***Existence of a process champion*.** Three participants found the existence of a process champion to be beneficial to the project. In this instance, the process champion had a project managing role. It was pointed that the champion was knowledgeable regarding the manual process and the previous work carried out to optimise the process. This was seen as important:

> “*[He] has been on the welding, he has been with the project all the time. He was on the project for quite a long time, when it was the bag-less welding*” **(Participant 10)**

Furthermore, the process champion was identified as an important point of contact for co-ordinating the work regarding the implementation as well as disseminating important information to all parties involved. Also, the champion was seen as the liaison between the management and the implementation stakeholders.

> “*Because we kind of go to him and get the information we want you know. And it kind of takes a bit of pressure off us really*” **(Participant 20)**

4.2.4.2 Barriers

Lack of union involvement. The automated welding project initiated some negativity between the union and management. This appeared to have acted as a barrier for the smooth introduction of the system, particularly as the implementation progressed. Findings suggested that the source of the negativity was the lack of communication to the union regarding two aspects of the project. The first one involved provision of sufficient justification to the union regarding the introduction of the system through a business case:

> “*We’ve spend the 650k, but I have failed to see how we are going to meet the business case. … to be perfectly honest, I haven’t seen how the business case will stack up*” **(Participant 21)**

The second point involved provision of information regarding the change of the working environment by the implementation of the auto-welder. Lack of providing information appeared to have hindered the progress of the project:

> “*I’ve asked, for them to set up meetings to have conversations around this. They haven’t been forthcoming, so then I sent out an email on Tuesday, saying ‘this is it, you have to consult or we are not going on’*” **(Participant 21)**

The communication with industrial unions regarding the impact of the initiation to employees has also been highlighted as an important learning curve by participant 19:

> "*It is a sensitivity of [freeing up some individuals] and you always get the question from an industrial relations point of view […]. Right or wrong, I don't know whether the way we've done it is the wrong but, maybe there's an opportunity to look at that and say "how early should [the unions] be engaged?*" **(Participant 19)**

Awareness of manual process complexity by system integrator. For several participants, the need for the system integrator to have a comprehensive understanding of the variability of the manual process to be automated was an important theme. Insufficient understanding can cause delays to the development of a robust and process capable system. This appeared to be particular important in this occasion where the manual process to be automated involved a high level of complexity. According to participants' because of this lack of understanding the development of the system was delayed while additional costs incurred:

> "*So, we then had to knock out another 40k [to add] a vision system … because the [system integrator] didn't understand, I don't think, the key process variables*" **(Participant 19)**

In this instance, the system integrator's lack of understanding of the complexity of the manual process created a barrier for the implementation automated system.

Capturing the manual process variability*.* Many of the participants placed attention to the lack of capturing the manual process prior to making the step change:

> "*[if you] have a data rich environment that's great, [but] we haven't got that … [if you] are data rich [you] you understand what your key process variables are already giving you. Then you make a step change. In this case we didn't*" **(Participant 19)**

Some participants indicated that the new automated process was a radical change and because the initial concept was not process capable it was necessary, retrospectively, to understand how operators completed understand how operators completed the task:

> "*Because we were making such a radical change to the process, we then started looking at exactly what the operators do*" **(Participant 10)**

The lack of understanding of the manual process variability appeared to have led to difficulties later on in the implementation. This theme is closely linked with the theme identified above regarding system integrator's understanding of the manual process. This will be further expanded in the discussion section.

Resources required for the development of the automation*.* Some participants frequently reported that resource required supporting the implementation of the system on the shop floor have been a barrier. Through the analysis, the impact of this was twofold. First of all, the team assigned to develop and roll the system on the shop floor required resources in terms of manpower to assist in the development. Subsequently, this had an immediate impact on the production rates. This was found to create confusion between the production team, responsible for maintaining production rates, and the development team:

> "*It is a production process; we do reflect in capacity models. [..] then you are [taking] two or three of those individuals out and they are not really going to contribute to production figures*" **(Participant 19)**

> "*Production leader has to get his part out. If he doesn't get his part out then at the end of the week his boss wants to know why. And then you've got your development people who are tied to targets, and if they don't get it, he gets kicked*" **(Participant 17)**

The second impact due to this conflict of interests between the two teams appeared to have a negative impact on the employees assigned to assist the development of the system. Analysis revealed that due to the confusion between production and development teams, operators initially assigned to support the development project were then requested to go back to production thus slowing down the development progress. This was found to create more confusion and frustration among operators:

> "*They've got to make their mind up. They want that robot finally running or do they want us welding?. It's frustrating … we are trying to support it and then they tell 'no'... We are messed up about it*" **(Participant 12)**

4.2.4.3 Summary of results

Data analysis from the exploratory case study revealed a number of enablers and barriers relevant to the implementation of industrial HRC.

Major enablers were: operator participation in the implementation, communication of the change to the workforce, visible senior management commitment and support to the project, provision of training to the workforce, empowerment of the workforce and existence of a process champion during the implementation.

Major barriers were: lack of union involvement, lack of awareness of the manual process complexity by the system integrator, capturing the variability of the manual process prior to introducing the automated system and allocation of resources for the development of the automated system.

The next section discusses the results and their implications.

4.2.5 Discussion

The literature review carried out, produced an initial list of seven organisational human factors. To identify whether these were barriers or enablers, an exploratory case study was chosen from one of the project's industrial partners where a manual process was being automated. Qualitative data from 12 individuals involved in the implementation were collected and by using template analysis a number of key enablers and barriers emerged.

First of all, the key role of considering shop floor individuals during a technological implementation is added to the existing body of literature. It was revealed that operator participation in the implementation process was a major enabler. Almost all participants discussed that by allowing operators to participate in the implementation reduces negativity and scepticism among shop floor employees. This is in line with previous research suggesting that employee participation in implementation (Boyer, 1996; Koufteros, Vonderembse and Doll, 1998; Jimmieson and White, 2011) enhance acceptance and leverage employee change supportive behaviour. At the same time, operator involvement as early as the concept phase was pointed as an important learning curve for the individuals involved in the implementation as it could have prevented problems from emerging at a later stage.

At this point, it becomes important to note certain links between operator participation in the implementation and other identified factors. First of all, operator participation was found to be linked to the capturing of the manual process variability. Capturing the manual process variability has not been identified in the literature. In this case study, it was identified that there was a lack of understanding of the manual skills in detail and what were the key process variables. As discussed earlier, the manual welding process under investigation is a complex process because of component's tolerance and varying geometry and thickness. Welders developed skills to accommodate for these variables. Understanding how the operators perform the manual process thus identifying the key process variables in advance was seen as a vital step in order to successfully introduce a process capable automated system. This has been highlighted in the literature of implementation of AMTs. It has been suggested that involving the individuals who have daily interaction with the work environment and processes can provide unique insights when taking a step change to optimise the process (Koufteros, Vonderembse and Doll, 1998; Wemmerlov and Johnson, 2000; Bidanda, Ariyawongrat, Needy, Norman and Tharmmaphornphilas, 2005). In this occasion, understanding the operator's manual skills was vital because of the complexity of the process.

Furthermore, capturing operators' knowledge regarding process variability can then be transferred to the system integrator supplying the automated solution. This inter-relation between the themes does not appear in the literature. This point suggests that closer collaboration between the system integrator and the organisation is required. Close collaboration will assist to obtain a better understanding of the process being automated thus supplying a process capable system. As highlighted, in this occasion, the system integrator was not fully aware of the complexity and variability of the manual process which led to certain delays impeding implementation.

The second discussion point is the emergence of communication as a major enabler and its inter-relations. Similar to employee participation discussed above, participants highlighted that the upcoming change was communicated to the workforce before introducing the system on the shop floor. Participants felt this approach prepared the workforce for its arrival, aided them to accept it as well as understand better the reasons for introducing this system. This finding is adding to the existing body literature highlighting that communication is a key success factor for an organisation undergoing a change period (Bordia, Hobman, Jones, Gallois and Callan, 2004a; Jimmieson, Peach and White, 2008). At the same time, although communication avenues were fairly well established, some participants suggested that more specific provision of information regarding the change in the work environment was seen as a mean for avoiding misunderstandings at a later stage. Provision of quality information regarding an upcoming change has been suggested in the literature as a means for reducing uncertainty (Wanberg and Banas, 2000).

The importance of adequate communication has been found to be important in a unionised environment. As shown, the lack of appropriate union involvement and communication regarding the upcoming change was a barrier. This finding appears to suggest a different approach regarding the impact of unions for the implementation of technological changes. Literature evidence on the impact of unions provide a contradicting picture regarding their influence on the adoption of new manufacturing techniques and technologies (Shah and Ward, 2003; Jayaram, Ahire and Dreyfus, 2010; Pagell and Handfield, 2000). Findings from the exploratory case study tend to suggest that the impact of unions, whether negative or positive, is depending upon establishing adequate communication channels. Unions are representing employees and need to be involved if any change in the nature of work is taking place. In this instance, union involvement came at a later stage and the delay created negativity in the union. The rationale behind the initiation, through the business case, was not adequately communicated thus cause the union to see with scepticism the project. As shown, early communication to the employees reduced uncertainty and aided them to understand the rationale behind the implementation of the automation. Similar outcomes can be expected by communicating the upcoming change to the unions. Avoiding the communication is likely to raise suspicions and scepticism regarding the motives behind the introduction of the new technology thus causing the union to impede the implementation.

Third discussion point is the impact of senior management commitment and support to the project. Previous literature highlighted that senior management commitment and support to the change is used as a gauge by employees to understand the gravity of the project for the organisation (Klein, Conn and Sorra, 2001; Neubert, Kacmar, Carlson, Chonko and Roberts, 2008; Boyer and Sovilla, 2003). Similarly, findings from the case study pointed that visible senior management support enhanced project's credibility and significance to employees. Participants discussed that, even when there were obstacles, the project never reached a dead end because of the constant support at a senior level. Furthermore, the support from the senior management was seen by employees involved in the implementation as an acknowledgement to their efforts thus increasing their morale, particularly when the project faced difficulties.

At the same time, senior management support was seen to be linked with the requirement for allocating the necessary resources for developing automated system once introduced on the shop floor. This theme and its inter-relation with senior management did not appear in the literature. Findings from this case study indicated that resource allocation for developing the automation was a major barrier. The development team needed operator assistance to progress system development, while production team would have to compromise production rates by releasing operators. This is a challenging issue and hard decisions will need to be made. As discussed, senior management with their behaviour and actions will indicate the gravity of the project for the organisation. Allocating the necessary resources for the development of the project will, inevitably, impact production rates. This is a potential trade-off that must be accepted. The benefits of that, however, is that the system will reach a process capable level earlier. Therefore, senior management will need to commit to the project and lead the way in terms of finding the common ground between the two. Furthermore, results from the case study pointed that the confusion created due to resource allocation was negatively impacting operators. Thus key decisions at a senior level need to be taken and communicated clearly to ensure all stakeholders will embrace the initiation.

The next discussion point revolves around the impact on the organisation itself. The semi-automation of a previously manual process and the upgrade of the operator to a supervisory role will require the organisation change the way it functions. Evidence suggested that acceptance of the initiation can be enhanced by adopting a more flexible approach through worker empowerment. It has been pointed by most participants that operators will not passively monitor the automation and turn into ‘button-pushers’. Overall it was seen important to provide additional control to operators rather than concentrating the control to specialised individuals. At the same time, it has been suggested that employee empowerment is desired, but not as an ‘all or nothing’. There will be some control over this through a reaction control plan. The aim of this plan is to identify the steps taken when a deviation occurs that operators do not feel comfortable rectifying. Therefore, technical authority is still required to provide further support. This finding appears to support a, somewhat, limited literature suggesting that a balanced strategy orientation between control and flexibility can be more effective during organisational changes rather than a heavily flexible or controlling strategy (Brown and Eisenhardt, 1995; McDermott and Stock, 1999; Lewis and Boyer, 2002). Findings point that adopting a flexible strategy through worker empowerment over the automation, while complemented with a control strategy by developing a reaction control plan will be a key enabler.

Furthermore, findings also suggested that with enhanced operator control it is easy to turn into blame culture when the system malfunctions. Although not discussed by many participants, this is a vital point and it must be considered. Employee empowerment is a key enabler, however, if blame allocation starts taking place it can backfire and create even more barriers.

Training was seen as an important enabler. Taking a selected number of operators on an initial training was found to have increased users' confidence and ownership of the system. This finding is in line with earlier literature suggesting that training is key enabler for successful implementation of AMTs (Fraser and Harris and Lee Luong, 2007; Singh, Garg, Deshmukh and Kumar, 2007). Also, it has been suggested that taking a selected number of individuals on training can have an additional benefit. These individuals can cascade the knowledge gathered and experience regarding the new system to the rest of the operators. This was suggested to have an important impact in terms of reducing negativity towards the automation by the operators, thus enhancing acceptance of the system when it would be introduced on the shop floor.

Finally, there is some evidence suggesting that process champion is an enabler. Findings tend to point that the champion is seen as an important point for co-ordination and for disseminating important information regarding the project to all key stakeholders. This can be particularly important during the early stages when, understandably, there is a high uncertainty level regarding the new initiation. This role of the project leader was highlighted as important in the literature to support and encourage employees during the implementation of an organisational change (Chen and Small, 1996; van den Bos, Wilke and Lind, 1998; Vanyperen, Van den Berg and Willering, 1999; Dombrowski, Mielke and Engel, 2012). Therefore, the champion can be an important aspect of the implementation. Their role is not limited to managing the project, but also to act a liaison for communicating information to the interested parties and ensuring all key stakeholders are kept committed to the project.

4.2.6 Summary of the case study

The literature review from comparable contexts to industrial HRC revealed that seven organisational human factors were identified as the most important for the successful implementation of industrial HRC. To investigate whether the organisational human factors identified were enablers or barriers an industrial exploratory case study was conducted where traditional manual work was being automated. The list of organisational human factors themes identified in the literature was used as a guiding framework within a semi-structured individual interview approach to gather individual experiences and accounts of the transition from a manual to an automated process.

Findings from the exploratory case study indicated that the organisational human factors captured in the literature review were identified as important factors (e.g. communication of the change, employee participation in implementation, senior management involvement). At the same time, the exploratory case study revealed additional organisational human factors not captured through the literature (e.g. capturing the manual process variability, awareness of manual process complexity by system integrator). Furthermore, findings pointed that the organisational human factors should not be seen as a selective ‘tick in the box’ activity, but rather as a framework of inter-relations. The inter-relations between the factors are shown in Figure 4-26:

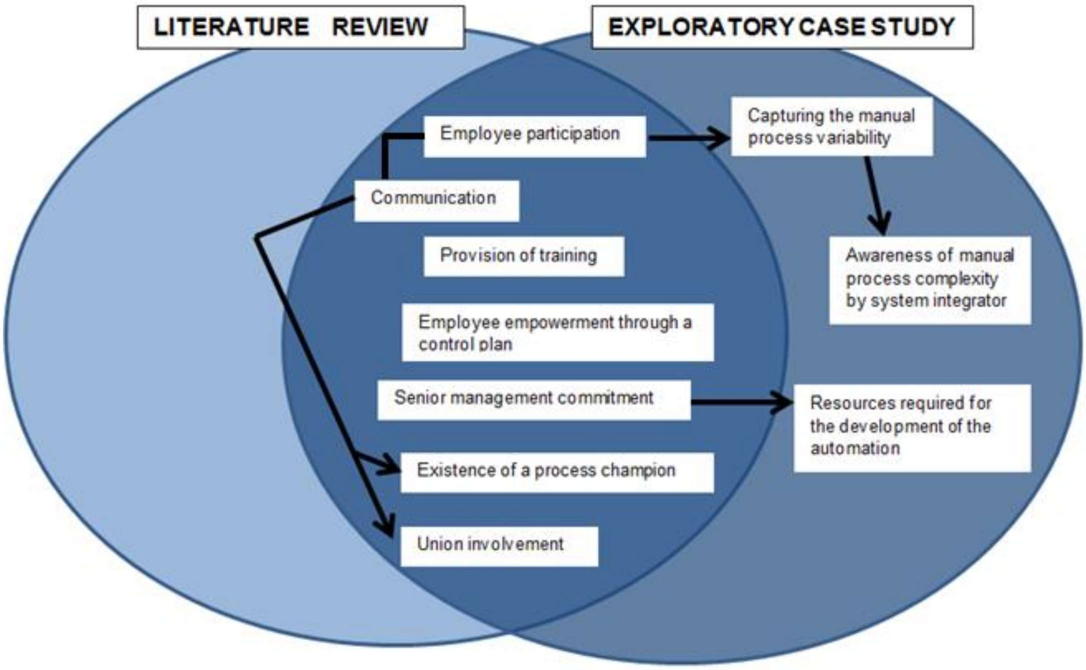


Figure 4-26 The inter-relations between the organisational level human factors

For instance, capturing the variability of the manual process in advance will serve as a vehicle to provide sufficient information to the system integrator to understand the complexity of the process and provide a process capable automated system. At the same time, in order to capture the knowledge of the manual process, shop floor operators need to be consulted and offered to participate at an early stage to provide their insight. To enable that proper communication to the workforce will be required to win their commitment. Also, this is where the process champion acquires the role of providing support and encouragement to low-level employees to embrace the new technology.

Furthermore, adequate communication to the union should not be underestimated, particularly in highly unionised work environments. For example, in a highly unionised environment, simply communicating and allowing operators to participate can be useless if the union is not sufficiently informed regarding the change initiative.

4.2.7 Progression to the next section

Although the findings from this exploratory case study provide an indication as to the key organisational human factors that need to be considered for the successful implementation of industrial HRC, it is acknowledged that a single case study cannot provide robust and generalisable findings. This research initially attempted to collect data from other case studies across different manufacturing settings and organisations for two reasons: (i) validate the identified human factors and (ii) identify any factor variability between large organisations and small and medium enterprises. Various organisations were approached from the UK's manufacturing industry. However, additional data collection was not possible for two reasons. First of all, as discussed earlier the concept of industrial HRC is not a mature concept yet, and not many real industrial applications exist. Secondly, where industrial robots have been implemented, obtaining access to collect data is difficult and time-consuming due to confidentiality and company sensitivity issues. To this end, this research adopted a different approach. This is described in section 4.3.

4.3 Development of a quantitative questionnaire

4.3.1 Introduction

The lack of additional case studies led to the adoption of a different approach. The findings from the exploratory case study were placed in a survey which was then sent to subject matter experts from one of the project's industrial partners for validation. This process is described in section 4.3.2. The result of this survey aided the researcher to develop a quantitative questionnaire described in section 4.3.3. The questionnaire was distributed via electronic mail (email) to numerous manufacturing organisations to allow for quantitative analysis to take place and evaluate the impact of the identified organisational human factors.

4.3.2 Development of a survey

4.3.2.1 Aim and objectives

The aim was to ensure the identified organisational human factors from the exploratory case study could be generalised. Principal objectives were: (i) design a survey based on the exploratory case study findings, (ii) identify suitable subject matter experts and (iii) collect data.

4.3.2.2 Method

4.3.2.2.1 Design of the survey

The findings from the exploratory case study were placed into survey questions. In total, ten questions were developed. Each question referred to a particular theme identified in the exploratory case study:

- Question 1 requested participants to write how the introduction of an automated system is communicated to operators.
- Question 2 requested participants to select who receives training in using the automation.
- Question 3 requested participants to identify whether a manual skill capture takes place prior to the automation of a manual process.
- Question 4 requested participants to identify whether shop floor operators are allowed to participate in the implementation of an automated system.
- Question 5 participants were requested to identify the involvement of the system supplier in the implementation.
- Question 6 requested participants, based on their experience, to identify whether a process champion is involved when an automated system is implemented
- Question 7 requested participants to identify whether operators are empowered to rectify a deviation of the automation from standard operating conditions.
- Question 8 requested participants to select the significance of senior management involvement in the implementation of an automated system.
- Question 9 requested participants to write how the unions receive the implementation of an automated system.

- Question 10 required participants to list, based on their previous experience, three major enablers and barriers in relation to automation implementation.

The survey was designed to include both open and closed ended questions. This is to ensure that participants can answer the survey in a short amount of time while allowing them to add further comments. Closed-ended questions were questions 2 to 7. Closed-ended questions, it was decided to have an additional box named "*Other*" and a line next to it. This is to allow participants to express their opinion if none of the other statements covered them, or if they wished to expand further. Open-ended questions were number 1, 8 and 9.

Also, the survey included a short cover letter at the front. This was used to: (i) provide information to participants as to the reasons they were chosen to participate in this survey and (ii) explain how to answer and submit the survey.

To ensure anonymity a unique reference number was randomly given to each survey. Upon receiving the responses, the surveys would be mixed so that it would not be possible to identify each respondent.

In addition, the survey requested participants to indicate whether they wished, after having submitted their survey, to be approached by the researcher for a short telephone discussion. This was used to: (i) allow for clarification if some answers were not clear, particularly for closed-ended questions and (ii) understand if the felt the survey captured the key human factors based on their experience. During telephone discussion, the researcher took notes. The survey can be found in Appendix E.

4.3.2.2.2 **Participants**

The survey was targeting subject matter experts (SMEs). These should be individuals who were involved in the implementation or where leading the implementation of automated solutions. For this purpose, ten SMEs within one of the project's industrial sponsors were identified and approached. These individuals were indicated by a liaison in the organisation.

4.3.2.2.3 Procedure

4.3.2.2.3.1 Pilot study

Prior to the main study, a pilot study was conducted to indicate any possible shortcomings and ensure the survey questions were appropriate for the target audience. Two individuals from the department of Integrated Systems at Cranfield University volunteered to take part.

Participants completed the surveys independently. The average time taken to read the cover letter and complete the survey was 6 minutes. Both participants commented that for the questions where a tick-in-a-box was required, it was not clear whether multiple boxes could be ticked (if applied) or whether just one. Based on this, an additional phrase was added to some questions, such as "*Tick all that apply*" or "*Tick one*".

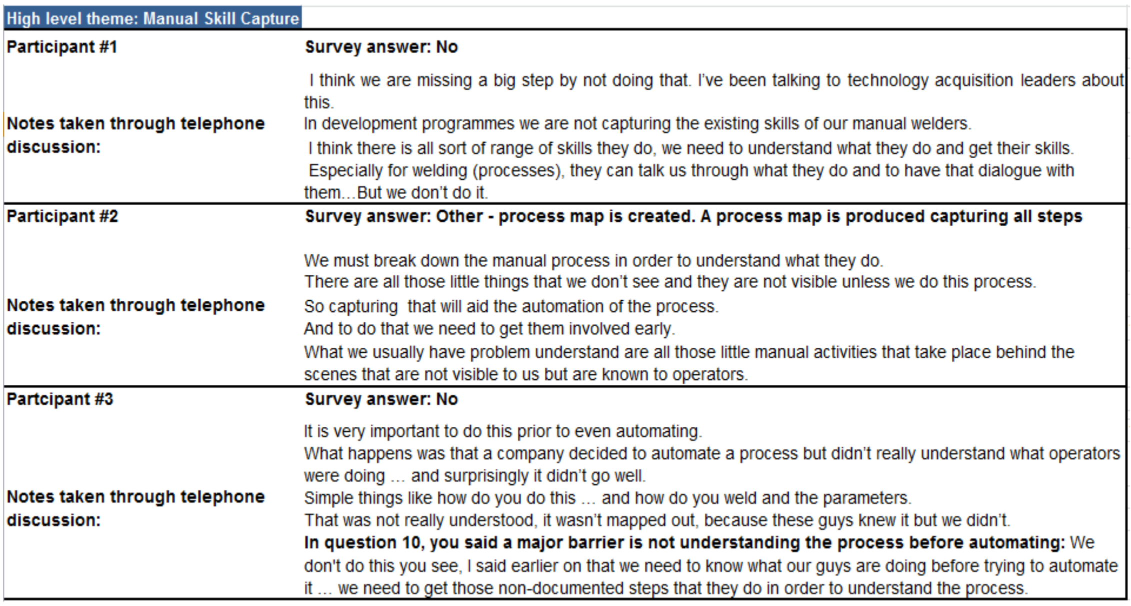
4.3.2.2.3.2 Main study

A liaison from the organisation sent an encouraging email explaining the purpose of the research. Following this, the researcher approached each individual independently by sending an email. The email can be found in Appendix F. The survey was attached in the email. Each completed survey was placed in an archive. If participants wished to have a short telephone discussion, then this was arranged independently at a mutually agreed time.

4.3.2.3 Data analysis

Of the ten surveys distributed, eight were completed and returned. Of the eight individuals who sent a completed survey, seven wished to participate in a follow-up telephone call. One individual did not wish to take part in a telephone call. Also, one individual did not wish to complete the survey, but was willing to take part in a telephone call. Overall, data from nine individuals (survey and telephone calls) were available for analysis.

Data received from the surveys and data collected through telephone discussions were analysed for each participant. Then all data collected (both from the surveys and from telephone discussions) from each participant, were placed on a spreadsheet. Data were segregated according to the high level theme (e.g. communication, manual skill capture, operator participation). This allowed for a collective analysis to identify common themes. An extract of the analysis template is shown in Figure 4-27.



High level theme: Manual Skill Capture	
Participant #1	**Survey answer: No**
Notes taken through telephone discussion:	I think we are missing a big step by not doing that. I've been talking to technology acquisition leaders about this. In development programmes we are not capturing the existing skills of our manual welders. I think there is all sort of range of skills they do, we need to understand what they do and get their skills. Especially for welding (processes), they can talk us through what they do and to have that dialogue with them…But we don't do it.
Participant #2	**Survey answer: Other - process map is created. A process map is produced capturing all steps**
Notes taken through telephone discussion:	We must break down the manual process in order to understand what they do. There are all those little things that we don't see and they are not visible unless we do this process. So capturing that will aid the automation of the process. And to do that we need to get them involved early. What we usually have problem understand are all those little manual activities that take place behind the scenes that are not visible to us but are known to operators.
Partcipant #3	**Survey answer: No**
Notes taken through telephone discussion:	It is very important to do this prior to even automating. What happens was that a company decided to automate a process but didn't really understand what operators were doing … and surprisingly it didn't go well. Simple things like how do you do this … and how do you weld and the parameters. That was not really understood, it wasn't mapped out, because these guys knew it but we didn't. **In question 10, you said a major barrier is not understanding the process before automating:** We don't do this you see, I said earlier on that we need to know what our guys are doing before trying to automate it … we need to get those non-documented steps that they do in order to understand the process.

Figure 4-27 Extract of the organisational survey analysis

4.3.2.4 Results and discussion

Survey participants identified communication to the workforce as a major enabler for the successful implementation of automation. Specifically, participants 3 and 4 highlighted in question 10 of the survey, that communication is one of the major enablers when it comes to the introduction of an automated system. Furthermore, participants 5, 7 and 9 found that communication is a vital element of the integration process. In their experience, shop floor operators need to be kept adequately informed regarding the change in order to embrace the new system. Also, according to participant 7, sending contradicting messages to shop floor employees can be equally harmful as no communication at all. In addition to that, participants 3 and 7 suggested that communication information must provide an explanation as to the rationale for introducing the automation. Interestingly, participants 5 and 9 indicated that communication to shop floor employees is vital because then, they can be more open about discussing how they get the process done. This will assist to understand the non-documented steps taken in the manual process and then understand how these can be accommodated with the automated solution. Therefore, adequate communication will engage shop floor employees and will also provide crucial information about the manual process. Similar findings emerged from the exploratory case study. Participants identified communication to the workforce as one of the major enablers of the implementation of the automated welding robot.

Also, survey responds indicated the link between communication and unions. Although only one participant identified union as a major enabler in question 10, (participant 7) the responses obtained in question 9 suggested that employee communication and union communication is vital. Participants 2, 4 and 9 highlighted that union leaders need to be involved early into the implementation process and be informed as to the rationale behind the change. According to their experiences, it is important to ensure an open communication avenue exists between the organisation and the union leaders regarding the change. Also, participant 4 suggested that communication avenue to unions depends on how strong is the union presence. Furthermore, participants 3 and 5 pointed the significant impact of adequate employee communication to union acceptance. In their opinion, employees can influence union acceptance and vice versa. Therefore, communicating and engaging operators while ensuring an open communication bridge with the union is likely to enhance acceptance by all parties. This was also identified in the exploratory case study, where it was suggested that union communication is important to ensure shop floor employees are committed to the new system.

Also, as highlighted by the case study, some participants pointed that the process champion is an important factor. Participant 7 identified that the presence of "*in-house subject matter experts*" is a major enabler for the change to successful. These are individuals who understand the process and how the automated process will be and can bring everyone on board. Survey results regarding the presence of a champion (question 6) were somewhat mixed. Two participants (participant 5 and 7) indicated that a process champion is present during the implementation while one participant (participant 1) pointed that no process champions are present. Also, one participant (participant 3) indicated that in process champions tend to be present when the organisation had poor implementation experiences. Two other participants (participant 2 and 8) indicated that the champions will need to be automation leaders who understand the automated solution which is implemented. At the same time, discussion with participant 9 indicated that, to some extent, a process champion can assist with in employee communication. According to participant 9, the champion needs to be a shop floor employee who can communicate the change to the rest of the employees and reduce scepticism.

Survey results highlighted that operator participation in implementation is a key enabler. Four participants (participants 3, 4, 5 and 8) reported this factor to be one of the key enablers in question 10. Also, in regards how early are operators involved in the implementation (question 4), three participants (participant 5, 7 and 8) indicated that operators are involved since the concept phase, while two participants (participant 1 and 2) indicated that operators are partly involved. One other participant (participant 3) pointed that it tends to happen very late in the implementation particularly when the consequences of not involving operators (e.g. project failure) are high. One more participant (participant 4) indicated that operator involvement is depending on the project sensitivity. Through further discussion with the SMEs, it was identified that that operators' knowledge and experience is a valuable asset for the organisation when attempting to automate a manual process. Their input is considered vital in order for them to gain ownership of the process rather than just seeing as another management decision. Participants 2 and 4 indicated that by being involved they see the project as their own and helps to reduce negativity. Also, participants highlighted that they would like to have operators involved as early as possible. At the same time, participant 4 indicated that project sensitivity can be a barrier for earlier operator involvement.

Interestingly, participants linked operator participation in implementation with the capture of the manual skill. According to participant 2, 8 and 9 operators are a vital link of the chain. They have acquired skills over a number of years and engaging with them as early as possible and allowing them to participate can assist the automation development team to understand the complexity of the manual process. At the same time, capturing the manual skills was identified in question 10 as a key enabler by participants 3 and 8. Further on this, in the question relevant to the manual skill capture (question 4), the majority of participants indicated that a manual process mapping tends to take place prior to the introduction of automation. Only two participants (participants 1 and 3) indicated that in their experience, a manual skill capture does not take place. Subsequent discussion with these two participants pointed that they felt by not doing this, a "*big step is missing*" from introducing a process capable system. Therefore, the results stress the importance of understanding the complexity of the manual process prior to attempting to automate the process. Similar opinions were expressed by participants 4, 7 and 8.

Survey results indicated that the system supplier has a key role to play. Participants 1, 2 and 7 identified in question 10 that involvement of the system supplier in the implementation is a key element for success. The question regarding the type of involvement from the system supplier (question 5), three participants indicated that there is a need for closer collaboration with the development teams in order to understand the manual process. Particularly, participants 1 and 2 discussed that they experienced projects where the system supplier did not fully understand the process variability and complexity. In their opinion that was a key drawback because it is critical to develop a process capable system and not a "close enough" automated solution. Furthermore, participants 4 and 8 expanded this and suggested that the system supplier must collaborate with all the relevant key stakeholders, particularly the operators to understand the manual process. Similar inter-relations were revealed through the exploratory case study, where participants linked the significance of involving shop floor operators in the implementation process with obtaining vital information about the manual process and then passing that information to the system supplier. Overall, the message presented is that the system supplier is a key element for the success of the implementation. Working closely with shop floor operators to understand the manual process and provide a process capable system is a key step.

Another important discussion point from the survey results is the involvement of the senior management. Four participants (participant 2, 3, 5 and 7) suggested that senior management commitment and support is a key enabler (question 10). At the same time question requesting the importance of senior management (question 8) was found as very important by all participants. Participants' comments in the space provided indicated that senior management need to be kept regularly informed regarding the project and any difficulties, otherwise, there will not be enough progress. According to participant 7, the seniors need to show their support to the project to engage all the key stakeholders, indicating the gravity of adequate management commitment to the project. Also, participants 1 and 9 highlighted the need for senior management to support projects with necessary resources.

In relation to the necessary training, participant surveys highlighted, as expected, that training is an important element. Six participants (participants 1, 3, 5, 7 and 8) indicated that the operators as well as other support agents (e.g. manufacturing engineers) will need to receive appropriate training regarding the operation of the package. Only one participant (participant 2) pointed that only support agents tend to receive training.

Finally, in terms of the question regarding operator empowerment (question 7), results were mixed. Only one survey participant (participant 8) clearly stated that operators are empowered to rectify an issue within their level of knowledge. Also, through telephone discussion with participant 9, the opinion expressed was to empower operators in order for them to be engaged; otherwise they will feel alienated with the process and not embrace it. One participant (participant 5) pointed that the level of empowerment depends on the level of training received. According to this participant's experience, operators are given some level of empowerment however, if something more technical occurs then an expert is brought in (e.g. robot expert from the supplier or a manufacturing engineer). Similarly, participant 7 indicated that initially it will be the robot expert rectifying any issues and then when the system is operational operators will need to follow a set of standard operating instructions (SOIs). Participant 3 indicated that the level of empowerment depends on the organisation. In their experience, operators are not given the authority to rectify but rather experts are called. Participants 1 and 4 indicated that operators tend to follow formal procedures and call for expert support when the system deviates from normal operating procedures.

At the same time, through discussions, it was revealed that participants put value in operator empowerment. Participant 1 and 3 suggested that it is important to give some level of authority to the individuals who will operate the system daily. In their opinion, these individuals will have developed more experience with the system and can react a lot quicker to any issues rather than calling for an external agent. At the same time, it was highlighted that although providing additional authority to operators can be beneficial, there will have to be formal SOIs for operators to follow.

4.3.2.5 Section summary

The lack of additional case studies, led to the use of the findings from the exploratory case study to develop a survey. The aim of the survey was to ensure the identified organisational human factors from the exploratory case study could be generalised. The developed survey consisted of ten open- and closed-ended questions. Ten subject matter experts from one of the project’s industrial sponsors were approached to complete the survey. In total, eight completed surveys were received and follow-up telephone calls were arranged to clarify some of the responses. One additional individual did not wish to complete the survey but agreed to have a short telephone discussion. Findings from the survey suggested that the identified human factors enablers and barriers are applicable to other automation implementation cases. The next step taken was to use the survey to develop a quantitative tool to allow for a quantitative analysis to take place.

4.3.3 Development of a quantitative questionnaire

4.3.3.1 Aim and objectives

The aim was to quantify the identified organisational human factors emerging from the exploratory case study. Principal objectives were: (i) utilise the findings from the exploratory case study and the survey to design a quantitative questionnaire, (ii) identify suitable organisations to distribute the survey and (iii) perform statistical analysis to quantify the impact.

4.3.3.2 Method

4.3.3.2.1 Design of the quantitative questionnaire

The quantitative questionnaire included 15 statements. These statements covered each of the themes emerged through the exploratory case study and the survey sent to SMEs.

The questionnaire requested participant to read the statements and, based on their experience in implementing automation, indicate on a scale of 1 (very low) to 5 (very high) their significance on the success of the implementation.

- Questions 1 and 2 were relevant to the importance of: (i) advance communication to the workforce regarding the change; (ii) explaining the rationale for automating the process.
- Question 3 was relevant to the significance of provision of training.
- Question 4 was relevant to the capture of the manual skill prior to the implementation of automation.
- Questions 5 and 6 referred to the participation of workforce in the implementation of the automated system at different stages.
- Questions 7 and 8 referred to the importance of: (i) the collaboration of the system supplier with the onsite development team; (ii) providing of the system supplier with a comprehensive understanding of the manual process being automated respectively.
- Question 9 was relevant to the importance of having a process champion during the implementation.

- Questions 10 and 11 were relevant to the importance of: (i) senior management commitment to the project; (ii) senior management providing adequate resources for developing the project respectively.
- Questions 13, 14 and 15 were relevant to the importance of: (i) justifying the implementation of automation to the union; (ii) involving the union representative in the implementation at the concept stage; (iii) keeping the union representative in the loop by being involved throughout the implementation phase.

The survey included a short cover letter at the front. As previously, this was used to (i) inform participants as to the reasons for sending the survey and (ii) explain how to answer and submit the survey.

To ensure anonymity a unique reference number was randomly given to each survey.

Also, a short demographic form was included. This requested participants to provide a brief description of the type of automation they implemented/supervised. Also, participants were requested to indicate the size of their organisation as well as indicate whether the organisation was within the UK or overseas. The reason for these questions was to allow for comparison to be made, if possible, between: (i) the key organisational human factors at a large organisation and small and medium enterprises and (ii) UK and non-UK organisations.

The developed questionnaire can be found in Appendix G.

4.3.3.2.2 **Selection of organisations**

The target for distributing the survey was different sized manufacturing organisations across various disciplines. For this purpose, online websites were utilised to identify potential organisations such as, the Processing and Packaging Machinery Association (PPMA) (http://www.ppma.co.uk) and the 192.com (http://www.192.com). For instance, the PPMA is a UK trade association for suppliers of machinery (including industrial robots) to the UK market and includes more than 400 members. Through the website, suitable organisations were identified along with contact details. Similar process was followed for 192.com. Also, the websites of major robotics suppliers such as, ABB, AA Robotics and FANUC were used. Through their advertised case studies section the researcher was able to identify organisations across different disciplines implementing robots. Also, through contacts from the project's industrial sponsors, the researcher was able to come in touch with large aerospace manufacturing organisations.

For selecting a manufacturing organisation to send the questionnaire, the following criteria were used: (i) supply/manufacture automated systems and/or (ii) have implemented automated systems. This process led to the development of a list of suitable manufacturing organisations on a spreadsheet. The list included: (i) the organisation's name, (ii) sector(s) in which the organisation operates, (iii) geographic location, (iv) type of robotics/automated systems implemented and (v) contact details.

In total, 68 organisations were identified. 55 organisations were from the UK, three from the United States of America, three from Germany, two from The Netherlands, two from Denmark, two from Italy, one from Singapore, one from Sweden, one from Turkey, one from Australia, one from Czech Republic. 44 were robot suppliers, 12 were general manufacturing organisations, six were in the food industry, four were from the automotive industry and two organisations were from the aerospace industry.

4.3.3.2.3 Procedure

4.3.3.2.3.1 Pilot study

Prior to distributing the questionnaire, a short pilot study was carried out to indicate any shortcomings and ensure the questionnaire instructions and questions were appropriate. For this purpose, one individual from one the project's industrial sponsors volunteered to take part. The individual was involved in the implementation of automation. The individual was sent the questionnaire via email and was asked to complete it and send back feedback.

Minor alterations were suggested, such as allowing more space between the questions to enhance the readability of the questionnaire. The questionnaire instructions were found helpful. After completing the changes, the questionnaire was distributed.

4.3.3.2.3.2 Distribution of the quantitative questionnaire

The questionnaire was distributed to the 68 organisations identified previously through an email. The questionnaire was attached to the email. The email can be found in Appendix H.

4.3.3.3 Current progress

To date no responses have been received. Therefore, further progress on this topic was not possible. Despite the lack of response, the work presented in this chapter provides an initial indication of the significance of key organisational human factors for the successful implementation of industrial HRC. Furthermore, the findings provide fertile ground for further research. This is discussed in chapter 8.

4.3.4 Section summary

The developed survey assisted to the development of a questionnaire which would allow quantification of the key organisational human factors. 68 different sized and structured organisations across various disciplines received the questionnaire. This would allow identifying any variability of the key organisational human factors across different organisations. To date, no responses have been received

4.4 Chapter summary

This chapter presented the work carried out to investigate whether the organisational human factors listed in the theoretical framework were enablers or barriers in relation to implementation of HRC systems through a real industrial exploratory case study. Findings from the exploratory case study indicated that the organisational human factors captured in the literature review were identified as key success factors (e.g. communication of the change, employee participation in implementation). At the same time, the exploratory case study revealed additional organisational human factors not captured through the literature (e.g. capturing the manual process variability, awareness of manual process complexity by system integrator). However, the results from a single case cannot provide robust and generalisable findings. Due to lack of additional case studies, a different approach was employed. The findings from the case study aided the development of a survey to obtain generalisable results. An initial survey was developed and data was collected from subject matter experts from one of the project's industrial sponsors. This led to the development of a quantitative questionnaire. 68 different sized and structured manufacturing organisations were identified across a number of disciplines. However, no response have been received thus it was not possible to quantify the key organisational human factors. Further research avenues on this topic are discussed in chapter 8.

As discussed in chapter 3 apart from the organisational human factors, this research addressed the key individual level factors. This is discussed in the next chapter.

5 INDIVIDUAL LEVEL FACTORS

5.1 Introduction

The literature review described in section 3.4 provided a list of the key individual level factors which appear to be of most importance for the successful implementation of industrial HRC: (i) trust in automation/robots, (ii) mental workload, (iii) situation awareness, (iv) operator perceived attentional control, (v) effects of automation reliability, (vi) effects of varying levels of automation and (vii) attitudes toward robots/automation. These are shown in Figure 5-28.

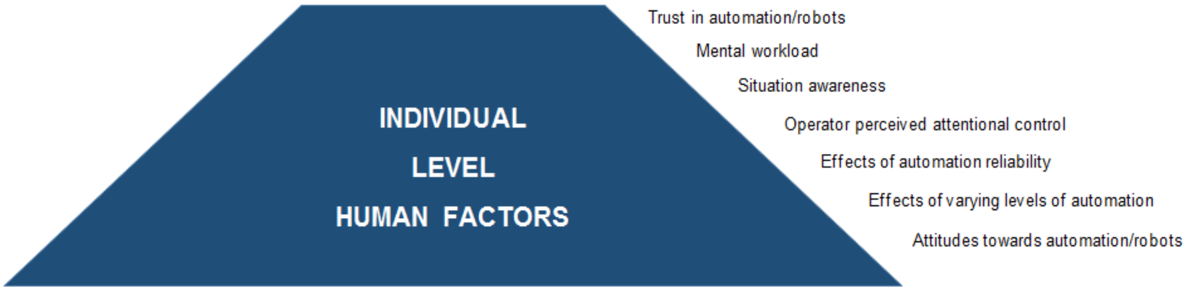


Figure 5-28 The individual level human factors

As discussed in section 3.5.2, although a number of human factors were identified, the construct of trust appears to be central and for this reason the focus of this research at the individual level was concentrated on understanding trust development in industrial HRC. To understand how trust develops in this context, a psychometric scale that measures trust in industrial HRC was developed. This is described in section 5.2.

5.2 Development of a psychometric trust scale for industrial human-robot interaction

Although a trust review was presented in section 3.4.1, it is deemed appropriate to provide the reader with further discussion on trust and differentiate between trust in automation and trust in robots. This is presented in section 5.2.1. Following this, the aim and objectives for the development of the psychometric trust scale are presented in section 5.2.2. Section 5.2.3 presents an exploratory study to collect participants’ opinion when collaborating with industrial robots qualitatively. This led to the development of trust-related themes specifically related to industrial HRC (e.g. robot performance, safety). Based on the trust-related themes a pool of items was developed. Items are short statements describing each of the identified trust-related themes. For example, an item describing safe collaboration can be: "*I felt safe interacting with the robot*". These items were then placed in a rating survey to be used in the next section. Then, section 5.2.4 describes the experimental work undertaken to quantify the key trust-related themes relevant to industrial HRC. The survey developed in the exploratory study was used to collect data. Section 5.2.5 presents the quantitative analysis approach which led to the development of the trust scale. Section 5.2.6 describes a small scale validation study, where the developed scale was utilised to evaluate trust of subject matter experts in a human-robot trial. A short summary is presented in section 5.2.7. Finally, section 5.2.8 discusses the implications of the developed trust scale.

5.2.1 **Trust review**

The following sections provide a review on trust as follows: section 5.2.1.1 describes trust development in automation, while section 5.2.1.2 discusses the differences between automation and robots and presents trust development in robots. Section 5.2.1.3 provides existing measures of trust. Finally, a summary is presented in section 5.2.1.4.

5.2.1.1 **Trust in automation**

The development of trust is essential for the successful operation of any team (Groom and Nass, 2007). Sheridan (1975) and Sheridan and Hennessy (1984) claimed that the same way trust mediates human-human relationships, it can also mediate human-automation interactions. Similarly, Muir (1988) suggested that trust in human-automation interaction is similar to the development of trust between individuals. For example, an individual can trust others if they have shown to be reliable. When they are let down, however, the relationship is broken, trust is lost and the redevelopment of trust takes time. In the context of human-automation teaming, trust can influence the willingness of humans to follow suggestions and rely on the information obtained by an automated system, particularly in risky and uncertain environments (Freedy, de Visser, Weltman and Coeyman, 2007; Park, Jenkins and Jiang, 2008). Lack of trust in the automated partner will eventually lead the operator to intervene and take over the task (de Visser, Parasuraman, Freedy, Freedy and Weltman, 2006; Steinfeld, Fong, Kaber, Lewis, Scholtz, Schultz and Goodrich, 2006).

Trust has been defined extensively in many domains, such as human interpersonal trust (Mayer, Davis and Schoorman 1995; Rotter 1971) and human-automation trust (Lee and See, 2004; Madhavan and Wiegmann, 2007). In the field of human-automation interaction, Lee and See's definition of trust is the most widely cited one (Chen and Barnes 2014). According to Lee and See (2004) trust is defined as "*the attitude that an agent will help achieve an individual's goals in a situation characterised by uncertainty and vulnerability*" (p.54). Therefore, in a human-automation team, the human operator trusts that the automation will take appropriate actions and will not put the human at risk. Trust in automated system is not static, but it evolves according to the experience of the interaction, while the user calibrates their level of trust (Lee and See, 2004; Merritt and Ilgen, 2008; Fallon, Murphy, Zimmerman and Mueller, 2010). Lee and See (2004) have defined trust calibration as "*the correspondence between the person's trust in the automation and the automation's capabilities*" (p.55). Merritt and Ilgen (2008) suggested that trust levels are formed immediately upon encountering another entity (e.g. a machine). They have defined that this reflects dispositional trust. Subsequent interactions with the entity assist to recalibrate trust; this reflects history-based trust. Authors suggested that trust begins as dispositional and eventually evolves to history-based trust. Further, it has been suggested that just as individuals have a general propensity (trait) to trust or distrust others, it is possible to hold a propensity to trust or distrust a machine or an automated system (Atoyan, Duquet and Robert, 2006; Nickerson and Reilly, 2004; Parasuraman, Molloy and Singh, 1993). This reflects a stable, trait-like tendency unique to the individual (Rotter, 1967) and is likely to have some influence in the development from dispositional to history-based trust (Merritt and Ilgen, 2008).

Lee and See (2004) identified trust antecedents based on: purpose, process and performance (“3Ps” framework). The purpose factor deals with the degree to which the automation is being used. The process factor deals with the question of whether the automated system is appropriate for a given tasking situation. The performance factor deals with system’s reliability, predictability, and capability. In addition to the “3Ps” framework, system’s degree of transparency and observability available to the human partner have been found important for the development of trust in human-automation interaction (Lee and See 2004; Verberne Ham and Midden 2012). Also, task complexity and its impact on the degree to which the human operator relies on the automation has also been investigated in the literature (Mazney, Reichenbach and Onnasch 2012; Parasuraman, Molloy and Singh 1993). Mazney and colleagues (2012) investigated the performance outcome of automated aids which can be unreliable during a multitasking supervisory control task. Although the use of automation was found to benefit both primary and secondary tasks, participants exhibited complacency effects. Furthermore, the type of automation unreliability can have an impact on trust development under different levels of task complexity. McBride Rogers and Fisk (2011) found that participants were more likely to exhibit erroneous compliance with a false alarm-prone system under heavy task load.

Research has also been directed to investigate people’s perceived reliability of automated assistance versus human assistance (Madhavan and Wiegmann 2007; Dzindolet, Pierce, Beck, Dawe and Anderson, 2001) and machine-like agents versus human-like agents (de Visser, Krueger, McKnight, Scheid, Smith, Chalk and Parasuraman 2012). Although the same information was provided both by the human and the automated system it was found that people tend to see the automation as being more reliable when compared to the human aid (Dzindolet, *et al*., 2001). Human reliance on decision aids coming from humans and automated systems was also investigated under varying levels of risk (Lyons and Stokes, 2012). It was found that as the level of risk increased, operators relied more on the automation support rather than the human support. Potentially this can lead to the individual operator misusing the automated system (overtrust). However, it appears that people are more sensitive to automation’s errors than to another human’s errors leading to a higher reduction in trust in the automated aid once the errors have been detected. This can lead to the operator disusing the automated system due to lack of trust (mistrust). At both ends of the spectrum, overtrust and mistrust have been suggested to be equally harmful (Parasuraman and Riley 1997). Therefore, calibrating appropriate levels of trust can be vital to ensure effective cooperation.

Summary

Overall, previous research indicates automation’s performance is an important factor for trust development. At the same time, it has been shown that the relationship between the human and the automation can be complex and other factors such as workload and task complexity, risk and perception of automation’s reliability influence operators’ reliance on the system. The focus thus far has been in the development of trust when humans interact with an automated system in general. When humans interact with robotic systems, however, trust development can be different. This is discussed in the following section.

5.2.1.2 Trust in robots

The official robot definition given by the ISO is: “*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*” (ISO10218-1, p2). Based on this definition, robots can be different than a general automated system. Robots can be mobile, can have different physical embodiments, can possess an end-effector and are often designed to fit a purpose. These differences could imply that humans react different when interacting with robots than with any other automated system. According to Desai, Stubbs, Steinfeld and Yanco (2009) robots introduce a degree of uncertainty that automation does not and for this reason robots need to be studied intependetly from automation. Subsequently, trust development in human-robot teams may differ than trust development in automation. Previous literature has suggested that little research was directed in addressing trust in human-robot interactions (Park, Jenkins and Jiang 2008) while other researchers supported that trust has been assessed in terms of automation and then applied in the domain of human-robot teaming without considering the different attributes related to robots (Yagoda and Gillan 2012). The literature indicates that various factors can influence trust development in human-robot interactions. Some factors focus on the robot, while some other focus directly on the human partner. Also, other factors take into consideration environmental aspects of the collaboration (Hancock, Billings, Oleson, Chen, De Visser and Parasuraman 2011).

5.2.1.2.1 **Factors associated with the robot**

5.2.1.2.1.1 Performance

As discussed above, automation performance such as reliability and predictability have been found to be a crucial element for building trust in human-automation teams (Sheridan 1988; Dzindolet , Pierce, Beck, Dawe and Anderson, 2001b). Similarly, robot performance characteristics can have substantial influence trust development. When a human operator can not predict what the robot is about to do, trust decreases (Ogreten, Lackey and Nicholson, 2010). At the same time, reliability has also been one of the major pillars of trust development (Lee and Moray, 1992). When the reliability of the robot decreases (e.g. errors increase during the interaction), human trust subsequently decreases (Dzindolet, Peterson, Pomranky, Pierce and Beck, 2003).

5.2.1.2.1.2 Robot attributes

Apart from the performance factors, robots possess attributes which make them differ from general automation. Robot attributes deal with system design and interface features that are inherent to the robot (e.g. type, appearance, size).

Physical attributes

Research in social human-robot interaction (HRI) has focused on the influence of robots’ physical attributes, such as anthropomorphism, robot types and size. Anthropomorphism refers to the extent the robot’s form or behavior reflects human characteristics (e.g. movement, physical appearance, communication) (Oleson, Billings, Kocsis, Chen and Hancock 2011). A highly anthropomorphic robot can generate high expectations to the human partner that the robot might not be able to accomplish. Failure to meet human expectation will result in dissapointment from the side of the human partner (Bartneck, Kulic and Croft 2009). At the same time, it cannot be neglected that positive or negative impressions about an entity (in this occasion referring to another human) is dependent to a degree on the visual and vocal behaviour of that entity (Clark and Rutter 1985). Robins and Denisi (1994) suggested that when a person makes a positive first impression of another individual often leads to a better evaluation of that individual. Considering that robots and other forms of automated machines (e.g. computers) are being treated as social agents (Nass and Reeves 1996), it becomes apparent that in a human-robot collaborative environment human partners will form an initial impression, positive or negative, upon first encounter. This impression is likely to influence the success of the relationship. Li, Rau and Li (2010) suggested that a more human-like robot (in appearance and demeanor) encourages an emotional connection and trust in the robot. Furthermore, a number of studies have examined human responses to different types of social robots. Some scholars have suggested that robots should not be too human-like (Broadbent, Stafford and Macdonald, 2009), while other studies have found that a social robot with animated behaviour (e.g. animated facial expressions) can engage people a lot longer (Bartneck, Kanda, Mubin and Mahmud, 2009). Also, Bartneck, Kanda, Ishiguro and Hagita (2007) have found that the appearance of a robotic entity can influence its likeability.

Robot size is another type of physical attribute that has received attention in relation to human trust. Tsui Desai and Yanco (2010) found that robot size can influence human level of trust when passing in a narrow corridor scenario and found that and that participants in their study appeared to trust a small mechanoid robot more than a larger one.

Proximity

With more robots integrated in our society, humans will need to work in closer proximity with these robotic agents (Sidner, Lee, Kidd, Lesh and Rich, 2005; Goetz and Kiesler, 2002). Earlier work has shown that embodied robots are found to be more engaging than a video diplayed agent, and sometimes, even as engaging as human (Burgoon, Bonito, Bengtsson, Cederberg, Lundeberg and Allspach, 2000; Jung and Lee, 2004). Other studies have examined the impact of robotic presence on human attitudes and reported trust. Findings indicated that a robot located in the same room generated a more positive attitude among humans when compared to a robot projected on a scree (Powers, Kiesler, Fussell and Torrey, 2007) while participants reported greater trust (Bainbridge, Hart, Kim and Scassellati, 2008).

5.2.1.2.2 Factors associated with the human

In addition to robot attributes, it has also been suggested that when interacting with robots, human-related factors such users' expectations, mental models of robots and safety can be important for fostering trust and acceptance of robots (Broadbent, Stafford and Macdonald, 2009; Ju and Takayama, 2011; Haddadin, Albu-Schaffer and Hirzinger, 2009).

5.2.1.2.2.1 Mental models

Mental models are employed by humans as a mechanism to form a perception and understanding of the people and the world around them (Johnson-Liard, 1983; Rouse and Morris, 1986; Stein, 1992). Humans tend to form mental models or representations of other humans, animals and machines based on their specific interactions and can be used to determine their actions (Phillips, Ososky, Grove and Jentsch 2011). Previous research has shown that humans tend to hold incomplete and primitive mental models of unfamiliar objects, technologies or even ideas with which they have very little experience (Gill, Swann and Silvera 1998). An accurate mental model, however, will serve as a vehicle for the user to correctly assess future system states (Wickens and Hollands 1999). Therefore, inaccurate mental models can pose challenges for effective collaboration between humans and intelligent robots. Although robots are being integrated into human society, the majority of the general population experience robots primarily through media such as science fiction. Science fiction has been suggested to play a strong role in the formative structure of people's expectations about a robot, as well as provide a clear picture of the issues of trust in human-robot interaction (Hancock, Billings and Schaefer 2011). Therefore people's mental models of intelligent robots can be incomplete and inaccurate. An incomplete mental model could potentially lead the human operator to misunderstand a robot's abilities, creating a pitfall for automation underutilisation (e.g. misuse or disuse). Therefore, it is important that a robot user's level of trust is managed through appropriate expectations. Ososky, Schuster, Phillips and Jentsch (2013) proposed that appropriate trust calibration can be achieved when the human holds a sufficiently developed mental model of the robot, whereby robot's capabilities are acknowledged. This implies that the users' trust in the robot is not necessarily driven by the actual capabilities of the robot but rather what the user perceives the robot's capabilities to be. In support of this, Merritt and Ilgen (2008) empirically demonstrated that user's perceptions of automation accounted 52% of trust variance, suggesting that user's perceptions of the automated system mediate trust. At the same time, the authors suggested that trust is dynamic and evolves over time through subsequent interactions.

Earlier research has suggested that human mental models of robots are influenced by physical characteristics, such as robot shape and anthropomorphism (Kiesler and Goetz 2002; Philips *et. al*., 2011; Broadbent, Lee, Stafford, Kuo and MacDonald, 2011; Ososky, Schuster, Phillips and Jentsch, 2013). It was found that humans tend to make assumptions of robot intelligence and aggression based on its physical characteristics. For instance, robotic platforms with arms and spider legs were found to be more aggressive than robotic platforms with human-like legs. (Sims, *et. al.,* 2005). Also, people's mental models about a robot's humanness are an important element for fostering acceptance of social robots (Broadbent, Lee, Stafford, Kuo and MacDonald, 2011). Therefore, in human-robot teaming, appropriate trust can be maintained when human operators develop accurate and appropriate mental model of the robot teammate (Ososky, Schuster, Phillips and Jentsch 2013). This will serve as a guiding framework by the operator to understand robot’s true capabilities thus reducing potential misuse or disuse.

5.2.1.2.2.2 Perceived safety

With robots becoming more mobile and able to perform a number of motions in close proximity to the human, the aspect of safety becomes an important requirement (Albu-Schaffer and Hirzinger, 2009). Numerous safety control mechanisms and safeguarding zones have been developed (Zinn, Khatib, Roth and Salisbury, 2002; Lew, Yung-Tsan and Pasic, 2000, Zurada, Wright and Graham, 2001). However, these mechanisms do not take into consideration human perception of safety during collaboration with a robotic system. Achieving a positive level of perceived safety by the human partner during the interaction with a robot is a key element for successfully implementing robots in human environments (Bartneck, Kulic and Croft, 2009).

It has been suggested that when humans collaborate with robots, it is important to enable the robot to recognise the affective states of the human partner and alter its actions accordingly to enhance human comfort. For example, authors have proposed the use of physiological measures, such as heart rate variability and temperature analysis in an o establish the user’s affective state which in turn will enable the robotic partner to modify its actions (Sarkar, 2002; Rani, Sarkar, Smith and Kirby, 2004). Other scholars proposed the use of a comfort hand-held device to measure human comfort levels when teaming with a robot (Koay, Walters and Dautenhahn, 2005). Furthermore, Kulic and Croft (2005) developed a questionnaire with physiological sensors to estimate users’ levels of anxiety and surprise when an articulated robot performed a number of motions around participants.

5.2.1.2.3 Factors associated with the task

Other potential factors impacting trust in HRI are directly related to the environment in which HRI occurs. For example, the cultural context and norms of the environment where humans interact with robots can affect trust levels (Lee and See, 2004). Empirical research has found that culture accounts for significant differences in trust ratings for robots; some collectivist cultures have higher trust ratings than individualistic cultures (Li *et. al*., 2010). For instance, some literature has suggested that task complexity may moderate trust development (Parasuraman and Riley 1997).

5.2.1.3 **Existing measures of trust**

Existing measures of trust have been heavily focussed on automation, such as automated teller machines (Singh, Molloy and Parasuraman, 1993) and automated process control systems (Muir and Moray, 1996; Jian, Bisantz and Drury, 2000; Master, Gramopadhye, Melloy, Bingham and Jiang, 2000). However, as discussed earlier, the development of trust in human-robot teams can be different from human-automation interactions (Park, Jenkins and Jiang, 2008; Yagoda and Gillan, 2012). A trust measure for human interactions with military robotic systems has been developed by Yagoda and Gillan (2012) while, more recently, Schaefer (2013) developed a trust scale to evaluate changes in trust between an individual and a robot. Although the aforementioned studies enhance our understanding of trust development when in human-robot teams, industrial HRC can pose different challenges. In a military human-robot teaming, the functions of both agents are very different from an industrial scenario. Also, industrial robots come in various shapes, sizes, end-effectors and degrees of anthropomorphism according to the operation being utilised for. Thus a generic trust scale might not be suitable for a purpose-built robot such as the ones used in the industrial environment. Trust development in an industrial robot can potentially be influenced by other context-related factors. To our knowledge, no measure exists which specifically evaluates trust in industrial HRC.

5.2.1.4 **Section summary**

Trust has been the topic of numerous studies over the year and investigated in different contexts. Although earlier work has indicated various possible antecedents of trust in human-robot interaction (Hancock *et. al*., 2011), it has not yet been investigated whether these are relevant to the industrial context and what other context specific factors are crucial to consider.

5.2.2 Aim and objectives for the development of the psychometric trust scale

Although trust has received extensive attention, little research has focused on understanding trust development in industrial HRC. To appropriately understand the development of trust between human workers and industrial robots, it is vital to effectively quantify trust. Such a measurement tool would offer the opportunity to system designers to identify the key system aspects that can be manipulated to optimise trust in industrial HRC.

The aim is to develop an empirically determined psychometric scale to measure trust in industrial HRC. Principal objectives were: (i) exploratory study: Identify the dimensions of trust relevant to industrial HRC and (ii) trust scale development: Develop a reliable psychometric scale to measure trust in industrial HRC.

5.2.3 Exploratory study

Due to the current lack of understanding regarding the influence of trust in an industrial context, as described in previous sections of this chapter and in order to develop an initial basic understanding of the sorts of factors that might be relevant an exploratory study was carried out.

5.2.3.1 Introduction

An exploratory study was designed to collect participants' opinions of industrial robots qualitatively. Qualitative research methodologies have been found to generate rich information that can provide critical insights (Bradley, Curry, and Devers 2007). Furthermore, Cobb and Forbes (2002) highlighted that qualitative research methods can be useful to identify theoretical themes and subsequently develop quantitative tools. Therefore a qualitative approach was adopted in order to identify trust related themes relevant to the industrial context from which a psychometric measurement scale could then be constructed.

5.2.3.2 Method

5.2.3.2.1 Design

The exploratory study was performed in laboratory conditions. Participants interacted with two industrial robots, one at a time, to complete a simple pick and place task. Because this was an exploratory study aiming to identify factors affecting trust in an industrial HRI environment the conditions were not experimental / controlled and the participants were not necessarily experienced in industrial settings; it was therefore chosen to give participants the experience of interacting with a smaller robot before they were asked to interact with the larger one which might have been more imposing.

The task involved the robot picking up and handing two stainless steel industrial pipes, one at a time, to the participants. The participants took hold of the pipes and positioned them on a table. Qualitative data were collected upon completion of each of the interaction task.

5.2.3.2.2 Participants

21 participants took part in this study. Participants were recruited from Cranfield University campus. Seven were females and 14 were males. The mean age of the group was 26.61 years (SD=4), ranging from 18 to 35 years. 20 participants reported having no prior experience interacting with robots or other form of automation, while one participant reported having used a computer numerically controlled machine before.

5.2.3.2.3 Ethical considerations

Participants were informed regarding the aim of the study and told that a short interview would take place and be recorded upon completing each task so that they could provide informed consent. The participant information sheet is available in Appendix I. Participants were made aware that they could stop the interview at any moment without having to give a reason and could withdraw their data at any point up to seven days but that after this time data would be pooled with that of other participants and therefore not retrievable; they were reassured that data would at all times be stored and maintained by Cranfield in accordance with the University's Ethical Code and the Data Protection Act (1998). The study was approved by the Cranfield University's Science and Engineering Ethics Committee.

5.2.3.2.4 Materials

Two types of industrial robots were used as shown in Figure 5-29: a small scale robot (payload of 5kg) and a medium scale robot (payload of 45kg). The small scale robot has built-in safety. In each condition, the robot picked up and handed to participants two flexible stainless steel industrial pipes approximately 60cm long. For the interaction with the medium scale robot a laser scanner was used to ensure safe separation between the robot and the participant (ISO 10218-1:2011).

Figure 5-29 Materials utilised for the exploratory study

5.2.3.2.5 Task

The task was identical for both robots. The robot picked up the two industrial pipes, one at a time and brought them to the participant at their standing location. When the robot stopped, participants took hold of the pipe. Then the robot gripper released the pipe. Participants positioned the pipe on a table next to them. Then the robot picked up the second pipe and executes the same task.

5.2.3.2.6 Data collection

5.2.3.2.6.1 Design of the interview

Interviews are separated into three distinct categories based on their degree of standardisation: structured/standardised, semi-structured and in depth interviews (Britten 1995; McDaniel, Whetzel, Schmidt and Maurer, 1994).

Structured interviews consist of gathering data in a standardised manner allowing to the interviewer very little room to deviate (Britten 1995). Semi-structured interviews utilise a loose structure of topics explored with the use of open-ended questions (Britten, 1995). Semi-structured interviews allow for diversion from the template in an attempt to pursue an idea in more depth.

The aim of this study was to explore participants' opinions about the development of trust when collaborating with an industrial robot. As discussed in the literature review, previous research identified that a non-industrial robot's performance-related and attribute-based factors (e.g. robot reliability, predictability, size, anthropomorphism) had the highest influence on trust, while environmental related factors (e.g. task complexity) had moderate effect (Hancock, *et. al.,* 2011; Hancock, Billings and Schaefer 2011). Therefore, an initial set of interview topics was identified thus unstructured interview would not be suitable. A fully standardised interview could possibly miss areas of interests to the participants and it would be hard to adapt questions to individual respondents. Therefore, a semi-structured interview was chosen. A semi-structure interview has been suggested to be appropriate for collecting an individual's thoughts and opinions about a subject (Honey 1987). A semi-structured interview does not constrain the conversation and allow the interviewer to be more flexible and allow additional topics not covered in the interview guide, but important to the participant, to emerge. However, a disadvantage of a semi-structured interview is the interviewer-researcher bias and possible distortion of respondent's view by unfair probing towards a specific answer. In order to minimise these, an interview schedule was generated and was used to guide participants with the use of indirect probing without unfairly suggesting a specific answer (Thomas, 2004; Rapely, 2007).

The interview schedule was created based on previous research findings and literature regarding trust antecedent factors in HRI. The schedule was used as a guide to ensure participants' opinions were expressed. The interview schedule was divided into the following sections:

- *Introduction* – this was used to break the ice and allow participants to express their thoughts regarding the interaction with the robot without being biased towards a specific path. Also, this question was used to allow topics interesting to the participant to emerge.
- *Robot related themes* – Hancock and colleagues (2011) meta-analytic review provided found robot performance and attribute related factors (e.g. reliability, predictability, appearance) to be the primary drivers of trust in HRI. This led to the inclusion of questions investigating the extent to which participants felt robot related factors influenced their trust. Questions were open in order to allow room for discussion and not direct participants into a certain path.
- *Human related themes* – An important aspect of human-robot interaction raised by previous literature is safety (De Santis, Siciliano, De Luca and Bicchi 2008; Bartneck, Kulic and Croft, 2009). It was also anticipated that safety would be a major discussion point among participants. The question was kept open in an attempt to understand how safety during interaction fosters trust.
- *Other topics* – participants were allowed to contribute their thoughts and suggestions. Therefore, questions were generated to elicit further information from participants.

The interview guide is shown in Appendix J.

5.2.3.2.7 **Procedure**

5.2.3.2.7.1 Pilot study

To develop the procedure a pilot trial was carried out. The pilot trial aimed at identifying potential problems with the procedure and the interview questions. For this purpose, a colleague volunteered to participate.

The participant was briefed regarding the aim of the purpose of the study (Appendix I), signed a consent form (Appendix K) and completed a short demographic form (Appendix L). Then, the participant was instructed regarding the task. To standardise the process a script was generated (Appendix M).

Initially, the participant collaborated with the small scale robot. Upon completing the task, a semi-structured interview was carried out using the pre-developed interview schedule (Appendix J). Then, the participant was taken to the medium scale robot cell to complete an identical task and a short interview took place at the end.

Upon completing the task, the participant was debriefed (Appendix N) and was requested to identify any problems with the procedure. The participant found the instructions clear and no alterations were required. The interview schedule did not receive any changes. The participant found the questions easy to understand.

5.2.3.2.7.2 Main study

Participants were approached and recruited singly around the university campus and were informed regarding the purpose of the study. Participants were fully informed regarding ethics as outlined in section 5.2.3.2.3. Then participants gave written consent and completed the demographic form. Participants were first taken to the small scale robot cell and briefed regarding the task they were requested to complete. The written script generated from the pilot trial was used (Appendix M). Participants were told that the robot would pick up the two industrial pipes, one at a time and would bring them over to them at their standing location. Participants were told that when the robot would stop, they were requested to take hold of the pipe. Then the gripping mechanism would release the pipe and they were requested to position the pipe on a table on their right hand side. Then the robot would pick up the second pipe and execute an identical procedure. Prior to beginning the task participants were given the opportunity to hold the pipes and appreciate their weight. Then participants observed a short robot demonstration to familiarise with the robot and the gripping mechanism. When the demonstration was completed the robot moved to its initial position and participants were asked if they were ready to begin the task. When participants indicated they were comfortable the robot programme was initialised. Upon completion, a short semi-structured interview was carried out to gather information from the participants regarding the interaction.

Then participants were taken to the medium scale robot cell. Participants were given the opportunity to hold the industrial pipes and appreciate their weight. The experimenter instructed participants regarding the task using the script generated from the pilot study. The experimenter pointed to the laser scanner and informed participants that it would stop the robot had they crossed the floor line. Once participants had acknowledged the use of the laser scanner, the experimenter used the written script to brief participants that an identical task as before would be carried out. Then participants observed a short robot demonstration. The demonstration was identical to the previous one. When the demonstration was completed the robot moved to its initial position and participants were asked if they were ready to begin the task. When participants indicated they were comfortable, the robot programme was initialised. Upon completing the task a short semi-structured interview was carried out.

Upon completion participants were debriefed and reminded regarding their right to withdraw and confidentiality. The laboratory technician was monitoring the experiment. To ensure minimal disruption to the participants, no other work was carried out in laboratory. Also, the experimenter and the laboratory technician were standing behind the participant to avoid disrupting the participants.

5.2.3.2.8 Data analysis

Interviews were fully transcribed and analysed using the Template Analysis method in accordance with guidelines provided by King (1998). This process involves the development of a coding template representing the major themes identified in a hierarchical form so that top level codes represent broad themes while lower level codes represent sub-themes. The template structure was revised iteratively to ensure it reflected the data in the most suitable manner. Interviews were read thoroughly and phrases were classified into three elements: (i) robot (ii) human and (iii) external. Each of these elements was assigned a letter to assist with the coding procedure (e.g. ‘R’ for robot element, ‘H’ for human element). Then, emerging trust-related themes were identified and assigned a unique code number. For example, for the robot element two major themes were identified: (i) robot performance (R1) and (ii) robot physical attributes (R2). Following this, each theme was analysed further into lower level themes and a unique letter code was attached. For instance, robot performance included two lower level themes: (i) robot motion (R1m) and (ii) robot and gripper reliability (R1r). The derived coding template is shown in Appendix O.

An inter-rater reliability was carried out to confirm the level of consensus between raters and, therefore, support the accuracy of coding in the developed template. This reliability test involved two independent raters individually coding the interview transcripts using the template to ascertain the degree to which their coding matched that of the other raters. Results were tabulated for calculation of the Cohen's kappa statistic. The Cohen's kappa statistic was chosen because it corrects for the probability of agreement by chance thus giving a more conservative result when compared to simple agreement percentage. The Cohen's kappa statistic among the experimenter and the raters were: researcher- rater 1: 0.73; researcher – rater 2: 0.66; rater 1 – rater 2: 0.68. The average agreement was 0.69. All values indicate 'substantial agreement' among raters according to a recognised source (Landis and Koch, 1977) suggesting the categories developed were sufficiently explaining the collected data.

5.2.3.3 Results and discussion of the exploratory study

Section 5.2.3.3.1 will present the frequency of trust-related themes appearing from the interviews. Section 5.2.3.3.2 describes in more detail participants' accounts for each of the identified trust-related themes. At the end of each trust-related theme a number of items are developed describing the theme. As it was outlined in section 5.2 items are short statements describing each of the identified trust-related themes. These items were then placed in a five-point rating survey. The survey was utilised to collect data in the experimental studies which will be described in section 5.2.4.

5.2.3.3.1 Overview of trust-related themes

Data analysis revealed that lower-level themes could be grouped in three major elements: robot, human and external. Each of these elements consisted of a number of trust-themes which were then decomposed into lower-level themes. Low-level themes were prioritised on the basis of frequency with which they appeared in the data analysis. This is shown in Table 5-1.

Table 5-1 Frequency of trust-related themes

Element	Trust-related themes	Lower level theme	Frequency
Robot	Performance	Motion of the robot	21
		Robot and gripping mechanism reliability	20
	Physical attributes	Robot's size	18
		Robot's appearance	15
Human	Perceived safety	Perceived personal safety and safety features	17
		Safe programming of the robot	6
	Experience	Prior experiences with robots	14
		Mental models of robots	9
External	Task	Task complexity	15

Robot element

All 21 participants discussed that their trust was influenced by the way the robot moved and the speed at which it moved. 20 participants elaborated on how their trust was affected by the robot's reliability in terms of completing the task. Six participants discussed that their trust was influenced by the gripping mechanism.

Robot physical attributes were also frequently discussed. 18 participants mentioned the influence on their trust due to the robot's size while 15 participants discussed the robot appearance.

Human element

17 participants mentioned that trust towards the robots was influenced by their feeling of personal safety during interaction. At the same time, 11 of these 17 individuals discussed that the robot's safety features (e.g. laser scanner) made them feel safe interacting with the robots. Six participants mentioned that they felt safe interacting with the robot because they trusted the robot had been programmed correctly by its operator. Also, participants found that prior robot experiences can be important for the development of trust. Nine participants elaborated on how their robot mental models influenced their initial trust towards the robot. Moreover, 14 participants mentioned that any prior experience interacting with robots or other form of automation would have influenced their trust.

External element

In this element the complexity of the task was the only trust-related theme appearing from the interview. 15 participants discussed that the complexity of the task had an influence on their trust in the robot.

5.2.3.3.2 Participants' accounts for each trust-related theme

This section presents participants' accounts for each of the identified trust-related themes.

5.2.3.3.2.1 Robot element

The robot element included two major trust-related themes, namely robot's performance and the robot's physical attributes.

Robot performance

Robot performance received extensive attention by all participants. Participants' accounts were grouped in two lower level themes: (i) robot motion and (ii) robot and gripping mechanism reliability.

(i) Robot motion

The majority of participants elaborated on the robots' motion. The motion of the robot during the collaboration was found to influence trust. Participants mainly used the phrases *"smooth motion"*, *"fluid motion"* and "*gentle*" to describe the movement of the robots. It was suggested that a fluid robot motion, aids the human partner to predict robot's path and fosters trust in the robot:

> "*It wasn't intimidating in the way it moved. It did have some sort of calmness to it. So, that kind of helped…So that sort of behaviour does elicit some sort of trust*"
>
> (Participant 18, small scale robot)

Furthermore, some comments suggested that although the medium scale robot appeared to be more intimidating on first impression its fluid motion during the execution of the assisted to reduce apprehension and foster trust:

> "*Because it is not so jerky … I would trust it a bit more. Because … although its size it's intimidating the way it moves isn't*"
>
> (Participant 14, medium scale robot)

This is particularly important for industrial human-robot interaction where due to large components introduction of larger, high payload robots is inevitable. Therefore, although on first sight larger robots can be intimidating and provoke fear and distrust on human operator, a non-erratic motion can alleviate these worries and foster trust instead**.** This appears to have been previously supported in the literature. Gielniak, Liu and Thomaz (2013) suggested that action prediction and fluid robot movement are key factors for effective human-robot cooperation. Their work pointed that action prediction and fluidity are key elements for effective human–robot teamwork. To this end, the following items were developed:

"*The way the robot moved made me uncomfortable*"

"*I was not concerned because the robot moved in an expected way*"

Participants discussed that the speed of an industrial robot can assist the human partner to build trust. This was particularly emphasized when participants faced the larger robot. Participants' comments suggested that when interacting with a larger robot, it is important to consider the speed at which it moves.

> "*My first thought was that this one is much bigger compared to the other one…So it might be a little dangerous. But after seeing that it moves slower, I could trust it more*"
>
> (Participant 17, medium scale robot)

The prevailing attitude was that a slow speed between an interactive industrial robot and a human partner can foster trust and make it more comfortable to interact with.

At the same time, some participants suggested that their trust in the robot was influenced by the speed at which the grippers picked up and released the component. Participants' comments indicated that the three-finger gripper used on the medium scale robot gave them more confidence because it picked up and released the pipes in a slow motion:

> "*You know how slowly it lets go so I'd trust this more than the other one … because the other one was slightly sudden*"
>
> (Participant 20, medium scale robot)

Findings appear to be in line with previous literature. Robot speed was found to have a negative impact on operators' mental strain (Kato, Fujita and Arai, 2010). Therefore, based on the above the following items were developed:

"*The speed of the robot made me uncomfortable*"

"*The speed at which the gripper picked up and released the components made me uneasy*"

(i) Robot and gripping mechanism reliability

Robot reliability was another factor that was found to be an important driver of trust. The prevailing attitude among participants was that their trust towards the robot was influenced by its ability to successfully complete the task:

> "*I didn't feel like it was going to drop it before I grabbed it or something*"
> (Participant 7 – small scale robot)

Interestingly, some participants found that the robot's end effector (gripping mechanism) can influence their reliance on the robot. Participants discussed that they could trust the robot because they felt the robot's gripper was reliable when gripping and handing-over the components. This was particularly emphasised in the second study where participants interacted with the medium scale robot:

> "*It had a more secure grip on the pipe, so it wouldn't drop it on the way*"
> (Participant 6 – medium scale robot)

Previous literature suggested that development of trust when interacting with robots and general automation is highly relevant to the performance outcome (Lee and See, 2004). The performance outcome deals with the system's reliability and capability to successfully complete the task. Findings from the study appear to be in line with the literature. Participants developed trust in the robot based on whether it was able to successfully complete its task. Also, findings of this study highlighted the significance of the gripping mechanism emerged. End effectors are a vital part of industrial robots. Interestingly, participants indicated that their trust in the robot was affected based on whether they felt the gripper was reliable to perform the task. Based on the above the following items were developed:

"I felt I could rely on the robot to do what it was supposed to do"
"The gripper seemed like it could be trusted"
"I knew the gripper would not drop the components"
"The robot gripper did not look reliable"

Robot physical attributes

Robot’s physical attributes were also among the most frequently discussed themes. Two lower level themes emerged: (i) robot size and (ii) robot appearance.

(i) Robot size

As it was expected, the medium scale robot was found to be more intimidating by the majority of participants. . The majority of participants found that robot’s size can have an influence on trust upon first encounter. Some participants described it as “*scary*”. The small scale robot, on the other hand, was found to give more confidence due to its small size. The dominant view is that upon encountering the medium scale robot participant felt intimidated by its size and appeared to be worried about interacting with it.

> “*It is a lot bigger. And I don’t know, when something like that is staring at you again you think what’s that thing going to do*”
>
> (Participant 5, medium scale robot)

The following item was developed:

“The size of the robot did not intimidate me”

(ii) Robot appearance

Some participants suggested that robot’s appearance influenced their trust. Participants found that the small scale robot had a simple and clear design making it appear less machine-like when compared to the medium scale robot. Participants found this to make it easier to build trust:

> “*I think I was quite confident, it also looks nice and clean and tidy. It doesn’t have too much going on*”
>
> (Participant 6, small scale robot)

It appears that participants placed emphasis on the general appearance of the robot. The small scale robot seemed easier to interact with due to its simple design whereas the medium scale robot appeared to be more mechanical. In addition, participants found that the general appearance of the robot made them form an impression of its capabilities and whether it could be used for a wider number of tasks:

> "*This one looks it can do a lot more than that the other one. So yes, for me I thought there was more chance of this one doing something wrong because it looks like it can do more*"
>
> (Participant 19, medium scale robot)

Earlier literature suggested that robot appearance can impact the degree of likeability (Bartneck, Kanda, Ishiguro and Hagita, 2007). Although, a recent study reported that a humanoid robot was preferred for an industrial human-robot collaborative task (Stadler, *et. al.,* 2013), it is not yet well understood whether robot appearance can influence trust development. Therefore, based on the above the following items were generated:

"The design of the robot was friendly"

"I believe the robot could do a wider number of tasks than what was demonstrated"

"I felt the robot was working at full capacity"

5.2.3.3.2.2 Human element

In the human element, two trust-related themes were revealed, namely safety and experiences.

Safety

Safety was among the most frequently discussed themes. Two major themes were identified: (i) personal safety and safety features and (ii) safe programming of the robot.

(i) Personal safety and safety features

Personal safety received attention by the participants. The majority of the participants discussed that feeling safe and not threatened is important for effective cooperation with an industrial robot. The prevailing attitude among participants was that they did not feel threatened by the robot during the interaction

> "*I felt very safe and I think this is quite important, to feel safe, when you are interacting with a robot*"
>
> (Participant 1, small scale robot)

At the same time, participants were probed further understand why they felt safe when interacting with the robot. Participants' comments indicated that the robot's safety features made them feel comfortable the robot would not be a threat to them:

> "*It is more intimidating but I trusted it because of the visible mechanism to stop the machine if something would have happen*"
>
> (Participant 18 – medium scale robot)

Based on the above, the following items were developed:

"I felt safe interacting with the robot"

"I was comfortable the robot would not hurt me"

"I trusted that the robot was safe to cooperate with"

(ii) Safe programming of the robot

Some of the participants found that their trust towards the robot was affected by the abilities of the robot programmer. Participants discussed that they trusted the robot was programmed in the correct manner and it would not do something unexpected:

> "*The trust is that someone else does the programme. So, then it's not trusting the robot but trusting the person to set it up*".
>
> (Participant 10, medium scale robot)

The following item was developed:

"I had faith that the robot had been programmed correctly"

Experiences

In this trust-related theme, two major themes were identified: (i) prior experiences with robots and (ii) mental models of robots.

(i) Prior interaction experience

The analysis revealed that trust was also influenced by the participants' prior experiences with robots. The majority of participants reported having no prior experiences in using or interacting with robots or other form of automation. The prevailing attitude among participants was that prior experiences in using similar equipment would have influenced their initial trust towards the robot because they would be aware of their functionality:

> "*I mean I've never really interacted with robots, I mean to this extent anyway. It was more of a trust issue*"
>
> (Participant 18 – small scale robot)

The following items were developed:

"I don't think any prior experiences with robots would affect the way I interacted with the robot"

"If I had more experiences with other robots I would feel less concerned"

(ii) Mental models of robots

Findings from the analysis suggested that trust in the robot was also influenced by the participants' mental models. It appeared that participants had pre-conceived notions of robots mainly through the media. Some participants discussed how surprised they were with the smooth motion of the robot. Some participants held the belief that industrial robots are monstrous, fast and jerky:

> “*I’d say that mainly because of my preconceived ideas…. It’s just I don’t know, because these sort of big industrial robots, I guess I have them associated to big chains of production in which they move fast*”
>
> (Participant 16 – medium scale robot)

Findings appear to be in lined with earlier literature regarding the impact of mental models in the development of trust. The importance of creating appropriate robot mental models for calibrating users’ expectation was identified in the literature (Broadbent, Stafford and Macdonald, 2009). Also the role of mainstream fiction movies in creating robot images has also been suggested to influence trust issues in human-robot teaming (Hancock, Billings and Schaefer, 2011). It appears that participants had preconceived notions of industrial robots and were surprised to find that the robot experience did not match their ideas. Therefore, the following items were developed:

“The way robots are presented in the media had a negative influence on my feelings about interacting with this robot”

“I had no prior expectations of what the robot would look like”

5.2.3.3.2.3 External element

The only theme appearing was related to the task and is described below.

Task

Participants discussed regarding the complexity of the task they were requested to complete while collaborating with the robots.

(i) Complexity of the task

The complexity of the interactive task was identified by participants as a factor for building confidence in the robot. Participants described the task as: “*easy*”, “*straight forward*” and “*simple*”. The majority of participants expressed the opinion that the interactive task was very simple and made it easy for them to rely on the robot, while some mentioned that if a more complicated task was given they would probably be more cautious:

> “*I mean the task was easy itself, because it seems so easy to do it that it makes you trust the robot*”
>
> (Participant 16 – small scale robot)

Based on the above, the following items were developed:

“If the task was more complicated I might have felt more concerned”

“I was uncomfortable working with this robot due to the complexity level of the task”

“I might not have been able to work with the robot had the task been more complex”

“The task made it easy to interact with this robot”

5.2.3.3.3 **Summary**

A number of trust-related themes relevant to trust in industrial HRC were identified. Twenty-four items relevant to each trust-related theme were generated. The items were randomly placed on a rating survey. All items developed and their scoring directions are shown in Appendix P. Reverse-phrased items are shown in grey and were utilised to reduce participant response bias.

5.2.3.4 **Section summary**

Due to little prior knowledge regarding the influence of trust in an industrial context, an exploratory approach was employed. 21 participants collaborated with two industrial robots, one at a time, to complete a pick and place task. The task involved the robot picking up and handing two stainless steel industrial pipes, one at a time, to the participants. Qualitative data were collected upon completion of each of the interaction task. Data were analysed using the Template Analysis method. Using this method, a coding template was developed reflecting the different trust related themes appearing in the data. Then, 24 items were developed relevant to each theme and were placed in a rating survey. The survey was used to collect data in the experimental studies described in the following section.

5.2.4 Experimental studies

This section describes the experimental work undertaken to quantify the key trust-related themes and assist develop the psychometric trust scale for industrial HRC.

5.2.4.1 Introduction

Three experimental studies in laboratory conditions were carried out using three different types of robots. In the first study a medium size single arm industrial robot was used. In the second study a medium size twin arm industrial robot was employed. The tasks in case studies 1 and 2 represented potential industrial scenarios where humans and robots would collaborate. The twin arm robot utilised in case study 2 was more anthropomorphic. Therefore, it could indicate if there is any difference in the survey responses. In the third case study, a single arm large payload industrial robot was used. The robot and the task utilised in case study 3 is aimed to be used in a real industrial environment. Therefore, this collaborative task would be more realistic as it would replicate (as much as possible) the work expected to be carried out by shop floor operators. This could indicate any difference in the survey responses.

Three independent groups of participants were recruited. Upon completing the task, participants completed the survey developed in the exploratory study described in chapter section 5.2.3.

5.2.4.2 Method

5.2.4.2.1 Design

All three studies were an independent design at laboratory conditions. In case study 1, participants collaborated with a single arm industrial robot at Cranfield University to complete an assembly task. In case study 2, participants collaborated with a twin arm industrial robot at Loughborough University to complete an identical task to study 1. In case study 3, participants collaborated with a single arm industrial robot at Cranfield University to complete a pin insertion task.

5.2.4.2.2 Participants

Because this was an initial attempt to develop a trust scale specifically applicable to industrial HRC, university population was recruited. Sample characteristics for the population in each case study are shown in the following sections.

5.2.4.2.2.1 Case study 1

60 participants completed the study. Participants were recruited from staff and students at Cranfield University. Table 5-2 shows the case study's sample characteristics.

Table 5-2 Sex, age and standard deviation of case study 1 population

Sex	Count	Mean age (SD)
Female	15	36.6 (10.9)
Male	45	28.5 (7.48)
Total	60	30.56 (9.02)

19 participants reported having some experience with robots and automation (e.g. CNC machines, industrial robots, social robots used for research projects) while 41 reported having no prior experience with robots and automation. This is shown in Table 5-3.

Table 5-3 Experience with automation/robots of case study 1 population

Sex	Count	
	Some experience	No experience
Female	2	13
Male	17	28
Total	19	41

5.2.4.2.2.2 Case study 2

50 participants completed the study. Participants were recruited from staff and students at Loughborough University. Sample population was matched to the

sample population recruited at Cranfield in terms of male vs female and experience vs non-experienced. Sample characteristics are shown in Table 5-4.

Table 5-4 Sex, age and standard deviation of case study 2 population

Sex	Count	Mean age (SD)
Female	13	31.7 (9.8)
Male	37	31.1 (9.62)
Total	50	30.96 (9.37)

20 participants reported having some experience with robots and automation while 30 reported having no prior experience with robots and automation as shown in Table 5-5.

Table 5-5 Experience with automation/robots of case study 2 population

Sex	Count	
	Some experience	No experience
Female	2	11
Male	18	19
Total	20	30

5.2.4.2.2.3 Case study 3

45 participants completed the study. Participants were recruited from staff and students at Cranfield University. Table 5-6 shows the sample characteristics.

Table 5-6 Sex, age and standard deviation of case study 3 population

Sex	Count	Mean age (SD)
Female	19	36.7 (12.54)
Male	26	29.8 (7.15)
Total	45	32.7 (10.35)

17 participants reported having some experience with robots and automation while 28 reported having no prior experience with robots and automation. This is shown in Table 5-7.

Table 5-7 Experience with automation/robots of case study 3 population

Sex	Count	
	Some experience	No experience
Female	6	13
Male	11	15
Total	17	28

5.2.4.2.3 Ethical considerations

Participants were informed regarding the aim of the study and told that they would collaborate with a robot to complete a short assembly task so that they could provide informed consent. The participant information sheet is available in Appendix Q. Participants were made aware that they could stop the study at any time without having to give a reason and could withdraw their data at any point up to seven days but that after this time data would be pooled with that of other participants and therefore not retrievable. They were reassured that data would at all times be stored and maintained by Cranfield in accordance with the University's Ethical Code and the Data Protection Act (1998). The study was approved by the Cranfield University's Science and Engineering Ethics Committee and the Loughborough Ethical Advisory Committee.

5.2.4.2.4 Materials

5.2.4.2.4.1 Case study 1

A single arm industrial robot with a payload capability of 45kg was used in this study. To adhere to health and safety regulations (ISO 10218-1:2011), a laser scanner was used. The reason for this was to ensure the robot would stop had the participant entered the robot's working zone when the robot was in motion. The laser scanner was positioned at the base of the robot. The robot and the laser scanner are shown in Figure 5-30.

Figure 5-30 Single arm industrial robot (left) and the laser scanner (right)

For the completion of the assembly task three pipes and three sets of fittings were utilised. Each of the pipes had a small and large side as shown in Figure 5-31. Three sets of large fittings and three sets of small fittings were provided.

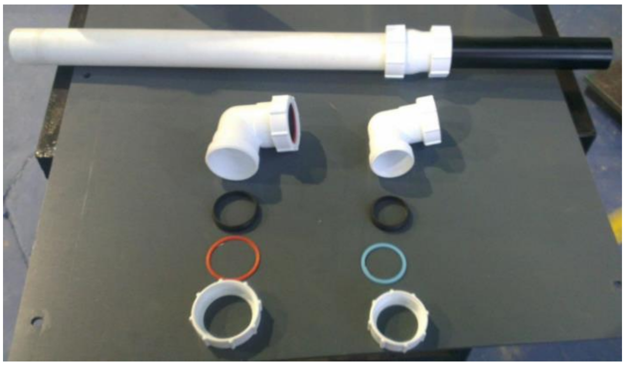


Figure 5-31 Task components for experimental case study 1

5.2.4.2.4.2 Case study 2

A twin arm industrial robot with a total payload capability of 20kg was used (Figure 5-32). Only the left-hand side robot gripper was operational. An identical laser scanner to the previous study was used. For the assembly task, two sets of plastic pipes and plastic fittings were utilised identical to study 1.

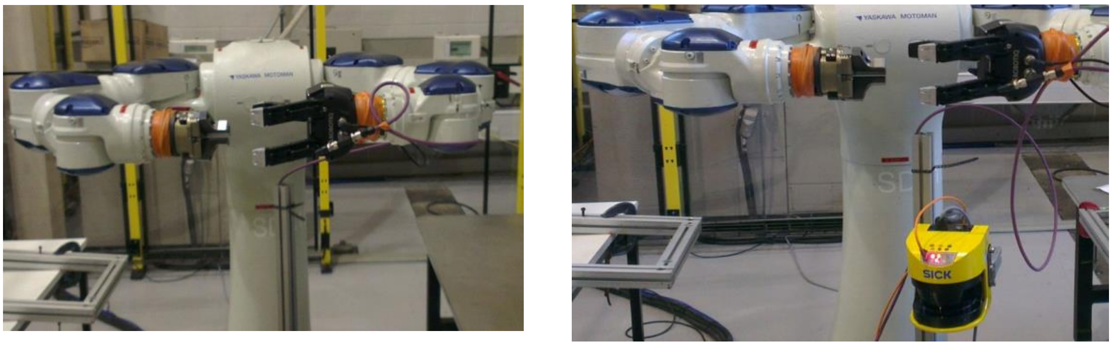


Figure 5-32 Twin arm industrial robot (left) and the laser scanner (right)

5.2.4.2.4.3 Case study 3

A single arm industrial robot with a payload capability of 200kg was used. The component lifted by the robot was a representative aerospace sub-assembly. The sub-assembly comprised of two bearings. For securing the sub-assembly a pair of carriages on a stand was designed. For pinning the bearings onto the carriages two identical bearing pins were used. Figure 5-33 shows the industrial robot, the component, the stand with the carriages and the bearing pins.

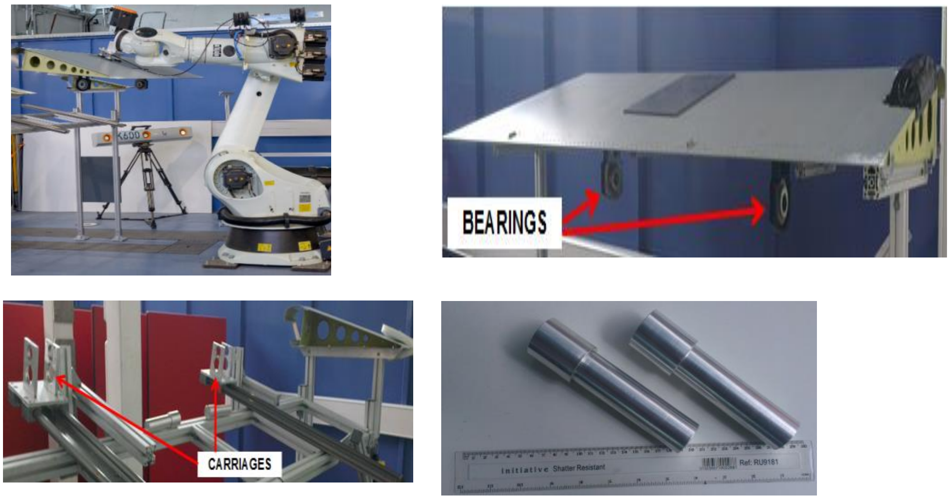


Figure 5-33 The industrial robot (top left), aerospace sub-assembly (top right), carriages (bottom left) and the bearing pins (bottom right)

A laser scanner identical to the previous case studies was used. The laser scanner was positioned at the base of the robot. Because of the size of the robot an overhead safety eye was utilised. This was used to monitor the robot cell from above and ensure the robot would stop if the participant entered the robot's working zone from a point which was not covered by the laser scanner. Also, because participants would be working in an area with protruding edges, a head protection cap and safety glasses were provided to avoid potential injuries. The safety eye and the personal protection equipment are shown in Figure 5-34.

Figure 5-34 The safety eye (left) and the personal protection equipment (right)

5.2.4.2.5 Experimental tasks

Identical tasks were employed in case studies 1 and 2. The aim was to apply the appropriate fitting on the pipe. The pipes were located next to the robot. The robot picked up one pipe at a time and brought them to the participant horizontally at their standing location. While the robot was holding the pipe, participants attached the appropriate fitting. A time allowance was introduced before the robot turned the pipe around for the participant to apply the other fitting. The fittings were disassembled into their components in a sequential order. Once both fittings were attached, the completed component was taken by the robot at a separate location and released.

The aim of the task in case study 3 was to secure the sub-assembly onto a carriage by using two bearing pins. The robot picked up the sub-assembly and positioned it on the stand. When the robot stopped, participants were told to walk towards the stand and align the carriages, one at a time, with the sub-assembly's bearings. Then participants secured the sub-assembly's bearings on the carriages using the bearing pins. Then participants walked back to their standing location. The robot pushed the sub-assembly on the carriages and released it, indicating the end of the task.

5.2.4.2.6 Data collection

Data were collected using the 24 item questionnaire developed in the exploratory study (Appendix P). A five-point Likert scale was used to rate each of the items. The decision to use a five-point Likert was scale was taken because other scales assessing complacency when using automation used a five-point Likert scale (e.g. Singh, Molloy and Parasuraman, 1993). Furthermore, Dawes (2008) investigated in an expertiment whether data are affected by the use of five-point, seven-point and ten-point Likert scales. Findings indicated that five-point and seven-point scales can be rescaled with the resultant data being comparable (Dawes, 2008). Therefore, the decision was taken to use a five-point Likert scale to collect data.

The questionnaire was administered on a computer station. The computer station was located next to the robot cell.

5.2.4.2.7 Procedure

To develop the procedure for each experimental case study, pilot trials were carried out. Because case studies 1 and 2 employed identical tasks, the same procedure was used. This is described first. The procedure for case study 3 is described second.

5.2.4.2.7.1 Pilot trials for case studies 1 and 2

Two pilot trials were conducted in advance. The first pilot trial aimed to: (i) develop a set of instructions for completing the task and (ii) identify the time taken to apply each the fittings on the pipe. The second pilot trial aimed at carrying out the entire process and identifying potential problems.

Pilot trial 1

In the first pilot trial, three pilot participants took part individually. The pilot trial took place in a laboratory. Participants were briefed regarding the aim of study (Appendix Q), signed a consent form (Appendix R) and completed a short demographic form (Appendix L). Then, the participants were instructed how to complete the assembly task. To standardise the process a script was generated (Appendix S). Then participants completed the task. The time taken to apply each fitting was recorded. Participants were not aware they were being timed to avoid bias. The average time taken was 25 seconds (SD= 0.81) for the small side and 23 seconds (SD= 0.47) for the large side. Based on the average times a 30 second time allowance was introduced to apply the fittings on the pipe before the robot would move the pipe.

Upon completing the task, participants were requested to identify any problems in the instructions provided. Participants did not point any changes.

Pilot trial 2

Two participants volunteered to take part individually. The written script generated in the first pilot trial was used to familiarise participants on how to apply the fittings on the pipe (Appendix S). Then, participants completed the familiarisation task. The familiarisation task took place in the room in the laboratory. Following this, they were taken in the robot cell to complete the task while being assisted by the robot. Participants were instructed regarding the task. To standardise the process a written script was generated (Appendix T). A time allowance of 30 seconds was introduced before the robot turned the pipe. Participants were not aware of this so that they remain focussed on the task. Both participants completed the task within the time allowed.

Upon completion, participants were requested to identify any problems in the instructions provided. Participants did not suggest any changes to the written script.

5.2.4.2.7.2 Procedure for case studies 1 and 2

Case studies 1 and 2 employed identical tasks and for this reason the same procedure was followed. Participants were recruited individually from the Universities' campuses. Participants were fully informed regarding ethics as outlined in section 5.2.4.2.3. Then participants gave written consent (Appendix R) and completed the demographic form (Appendix L).

Then, the procedure was segregated in two parts: (i) familiarisation with the assembly task and (ii) collaboration with the robot.

(i) Familiarisation with the assembly task

The room utilised for this purpose was in the same area with the robot cell, however, there was no visual contact between the participants and the robot to be used for the experiment. This was done to avoid biasing the participants. Also, during the familiarisation task, no other work was carried out in the room in order to reduce participant distraction.

First, the experimenter informed participants how to complete the task using the script developed in pilot trial 1 (Appendix S). Participants were shown by the experimenter how to apply the fittings on the pipe. Then participants completed the task once. Upon completion, participants were allowed to ask the experimenter any questions.

The pipe used for the familiarisation task was identical to the pipes used for the collaboration task. The fittings were disassembled into their components and placed in a sequential order to minimise difficulty (Figure 5-35).

Figure 5-35 The plastic fittings disassembled

(i) Collaboration with the robot

Participants completed an identical task while being assisted by the robot. Initially participants were told where to stand. Also, they were made aware of the laser scanner and were informed it would stop the robot if they entered the robot's working zone when in motion.

Then, the experimenter instructed participants regarding the task using the script developed in pilot trial 2 (Appendix T). The robot picked up one pipe at a time and brought them to the participant at their standing location. The pipes were oriented horizontally as shown in the following figure. While the robot was holding the pipe, participants attached the appropriate fitting. This is shown in Figure 5-36.

Figure 5-36 The robot picks-up the pipe (left) and positions it for assembly (right)

Participants were requested to apply the appropriate fitting on the pipe. Throughout the experiment the robot presented the pipe on the same side.

The fittings were located on the left hand side of the participants' standing location as shown in Figure 5-37.

Figure 5-37 Positioning of the fittings

Fittings were disassembled into their components in a sequential order identical to the familiarisation task. Once the first fitting was applied, the robot turned the pipe and participants applied the other fitting. The time allowed for assembling each fitting was 30 seconds (from pilot trial 1). Participants were not aware of this to remain focussed on the task.

Then, the completed component was then released by the robot at a drop-off location shown in Figure 5-38.

Figure 5-38 Drop-off position of the completed item

Participants observed a short robot demonstration to familiarise with the robot and the gripping mechanism. When the demonstration was completed the robot moved to its initial position and participants were asked if they were ready to begin the task. When they indicated they were comfortable, the robot programme was initialised.

Upon completion, the 24 item questionnaire was completed on a computer station. The computer was within the laboratory and participants had a visual contact with the industrial robot. At the end of study participants were debriefed (Appendix N) and reminded regarding their right to withdraw and confidentiality. To ensure minimal disruption to the participants, no other work was carried out in laboratory.

5.2.4.2.7.3 Pilot trial for case study 3

Because the task for case study 3 was different than the other two case studies, a new procedure was needed. Two participants volunteered to take part individually.

The pilot trial took place in the laboratory. As before, participants were briefed regarding the aim of study, signed a consent form and completed a short demographic form. Then, participants completed a short familiarisation task. For this reason a script was developed to instruct participants on how to complete the task (Appendix U). The familiarisation task was similar to the actual task but in a smaller scale. The reason is because it was not possible to have an exact replica of the component used for the actual task. Following this, participants were taken in the robot cell to complete a similar task while being assisted by the robot. Participants were instructed regarding the task with the use of a written script (Appendix V).

Upon completing the task, participants were requested to provide feedback regarding the instructions provided. Both participants suggested making it clearer that the familiarisation task is not identical to the collaboration task. Therefore, the script used for the familiarisation task was amended to reflect participants' feedback.

5.2.4.2.7.4 Procedure for case study 3

Participants were recruited individually from the University campus and were fully briefed regarding ethics as outlined in section 5.2.4.2.3. Then participants gave written consent (Appendix R) and completed the demographic form (Appendix L).

The procedure is segregated in two parts: (i) familiarisation with the task and (ii) collaboration with the robot.

(i) Familiarisation with the pin insertion task

The room utilised for this purpose was in the same area with the robot cell but there was no visual contact to avoid biasing the participants. Also, during the familiarisation task, no other work was carried out in the room in order to reduce distraction.

First, the experimenter informed participants how to complete the familiarisation task (Appendix U). As discussed, it was not possible to have a replica of the component used for the actual task. Therefore, a smaller scale pin insertion task was developed. Initially, participants were told that they were requested to complete a pin insertion task. The aim was to secure two plastic ’shoulders’ on two metal bearings using two identical pins as shown in Figure 5-39.

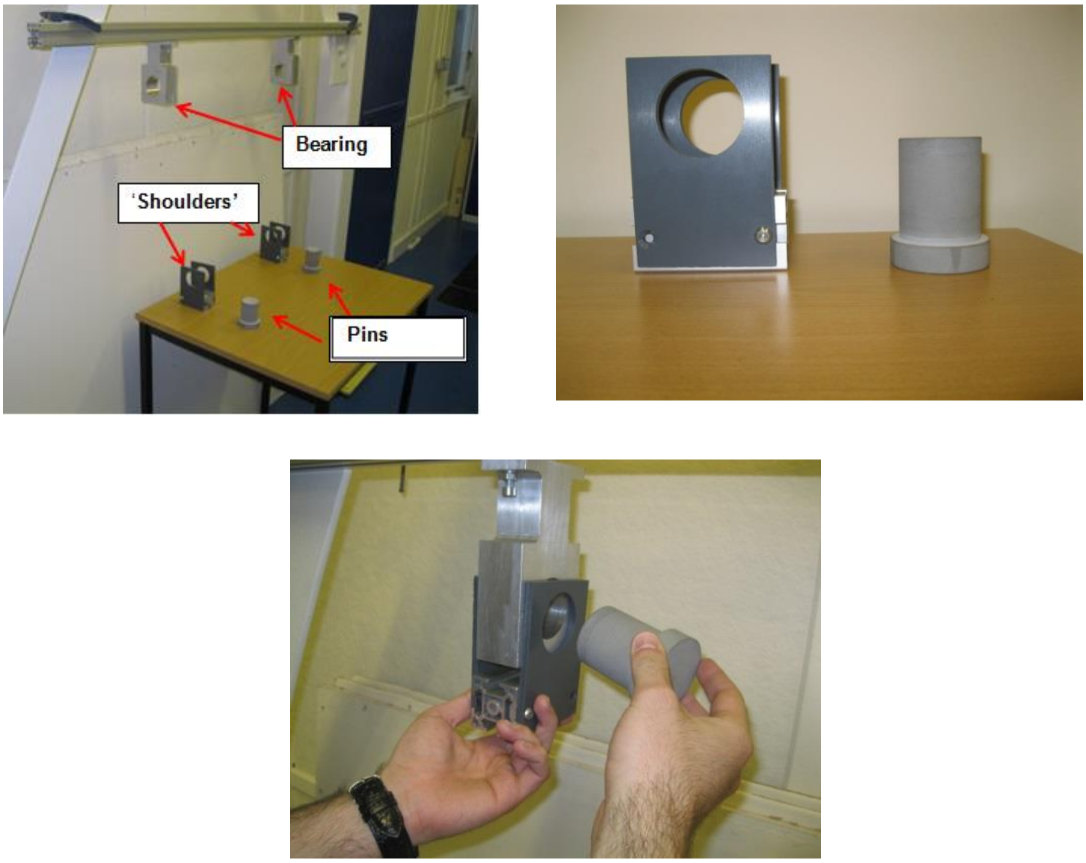


Figure 5-39 Familiarisation task components for case study 3

Participants were told the “shoulders”, the pins and the bearings were identical. Participants were then shown by the experimenter how to complete the task. Then participants completed the task once. Upon completion, participants were allowed to ask the experimenter any questions.

(i) Collaboration with the robot

Participants were then taken to the robot cell to complete an identical task while being assisted by the robot. First, a head protection cap and safety glasses were provided. The experimenter instructed participants where to stand and made them aware of the laser scanner and the overhead safety eye. They were informed that these were used to stop the robot if they entered the robot's working zone when the robot is in motion.

Then, the experimenter gave instructions regarding the collaboration task (Appendix V). The purpose of the task was to secure the sub-assembly's bearings onto the carriages using two bearing pins. First, the initial location of the sub-assembly was shown and the experimenter indicated the two bearings (Figure 5-40).

Figure 5-40 Initial position of the aerospace sub-assembly

Then it was explained that the robot would pick up the sub-assembly, position it on the stand and stop as shown in Figure 5-41.

Figure 5-41 Positioning of the sub-assembly on the stand by the robot

Then participants were instructed to walk towards the sub-assembly to align the carriages with the sub-assembly's bearings by pushing them down. Then using the bearing pins they secured the bearings on the carriages. This is shown in Figure 5-42. It was explained that both pins where identical and could be inserted in any direction.

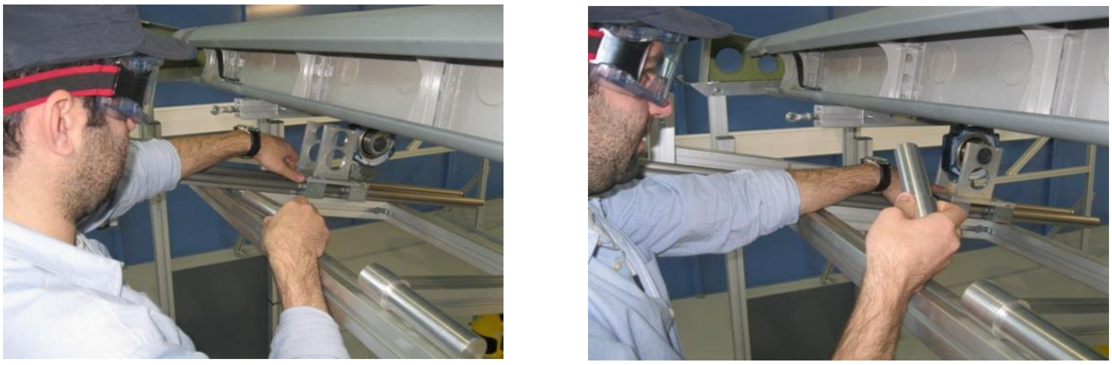


Figure 5-42 Alignment of the carriages to the sub-assembly's bearings (left) and securing them using a bearing pin (right)

Then upon completing the task, participants were instructed to move back to their initial standing position and were told that the robot would drive the flap on the carriages before releasing it indicating the end of the task.

Prior to beginning the task participants were given the opportunity to hold the bearing pins and appreciate their weight. Also, they observed a short robot demonstration to familiarise with the robot and the gripping mechanism. When the demonstration was completed the robot moved to its initial position. When participants indicated they were comfortable, the robot programme was initialised.

Upon completion, the 24 item questionnaire was completed on a computer station. The computer was within the laboratory and participants had a visual contact with the industrial robot. At the end of study participants were debriefed (Appendix N) and reminded regarding their right to withdraw and confidentiality. To ensure minimal disruption to the participants, no other work was carried out in laboratory.

5.2.4.3 Section summary

Three experimental studies in laboratory conditions were carried out using three different types of robots. Tasks represented potential industrial scenarios where humans and robots would collaborate. Three independent groups of participants were recruited. Upon completing the task, participants completed the survey developed in section 5.2.3. The next step taken was to perform a quantitative analysis of the collected data. This is described in the following section.

5.2.5 Quantitative analysis of experimental studies

5.2.5.1 Exploratory data analysis

The analysis of variance (ANOVA) can be used to compare the means of more than two groups. In the context of the study, it was wished to investigate whether there was a statistically significant difference between the mean responses obtained between the three groups.

ANOVA is a parametric test and is based on certain assumptions:

- The sampling distribution is normally distributed
- Data are measured at least at the interval level

Therefore, prior to carrying out an analysis of variance, a test of normality and a test of homogeneity of variance was carried out to ensure the assumptions were not violated.

5.2.5.1.1 Test of normality

The test of normality is performed to investigate whether collected data is approximately normally distributed. Normally distributed data is a fundamental assumption among numerous parametric statistical methods, such as t-test and ANOVAs. Therefore, the test of normality will determine whether a parametric or a nonparametric statistical analysis will be performed at a later stage.

Normality tests can be examined by investigating the: (i) numerical z-values of skewness and kurtosis, (ii) Shapiro-Wilk significance test and (iii) graphically using histograms, normal Q-Q plots and Box plots (Field, 2012). For the data to be normally distributed the following criteria shown in Table 5-8 must be met:

Table 5-8 Criteria for normal distribution

Criterion		Reference
Numerical z-values for skewness and kurtosis	Z-values for all groups to be between +/- 1.96	Kim, 2013
Shapiro-Wilk and/or Kolmogorov-Smirnov significance tests	Greater than 0.05	Field, 2012
Histograms, normal Q-Q plots and Box Plots	Visually inspect that data is approximately normally distributed for each group	Field, 2012

Skewness and kurtosis are values of zero in a normal distribution. In an ideal state where data is following a normal distribution we would expect skew and kurtosis of the bell shape curve to be zero. However, real world data is expected to have a degree of skewness and kurtosis thus a degree of departure from zero can be accepted. Skewness indicates whether there is a heavy pile-up data either on the left or the right of the curve. Positive values of skewness indicate a concentration of values to the left of the distribution, while negative values of skewness indicate a concentration of values to the right of the distribution. Kurtosis on the either hand indicates how “pointy” or “flat” the distribution is. Positive value of kurtosis suggest a pointy and heavy-tailed distribution whereas negative values of kurtosis indicate a more flat and light-tailed distribution. The further the value is from zero, the more likely it is the data is not normally distributed.

The Shapiro-Wilk (S-W) and the Kolmogorov-Smirnov (K-S) tests investigate whether the distribution of collected scores deviates from a normal distribution. The tests compare the scores collected in the sample against a normally distributed set of scores with the same mean and standard deviation. The hypothesis in this occasion would be that the collected set of scores is not significantly different from a normal distribution ($p>0.05$). If data is not normally distributed then there would be a significant statistical difference ($p<0.05$). It is suggested that the S-W test is more powerful at detecting deviations from normality (Field, 2012) and for this reason the S-W will be used. Also graphical representation will be used in order to make an informed decision about normality or non-normality of the observed sample size. Graphical representations (e.g. histograms, Q-Q plots) assist to visually inspect whether data is approximately normally distributed. This can be achieved with the inspection of histograms and normal Q-Q plots. Histograms show whether data set is approximately following a normal curve while normal Q-Q plots the values one would normally expect to obtain if the distribution were normal against the values observed.

Data were entered into SPSS and a normality test was carried out using the S-W test. The following sections describe the output in terms of: (i) skewness and kurtosis; (ii) S-W significance test and (iii) visual inspection of normality.

Skewness and kurtosis

Skewness and kurtosis were investigated for data received in the three case studies. An export table of the skewness and kurtosis for case study 1 is shown in Table 5-9 below:

Table 5-9 Skewness and kurtosis for case study 1 population

Case study 1		**Statistic**	**Standard Error**
Mean		96.7	1.2
95% Confidence Interval for Mean	Lower Bound	94.4	
	Upper Bound	99	
Median		96	
Variance		80.8	
Std. Deviation		8.9	
Skewness		.179	.309
Kurtosis		-.801	.608

Z-values for skewness and kurtosis were calculated by dividing the statistic by the respective standard error and the values are shown in Table 5-10:

Table 5-10 Skewness and kurtosis z-values for case study 1 population

Descriptive	Z-value	Criterion check
Skewness	0.58	Falls between -1.96 and +1.96
Kurtosis	-1.31	Falls between -1.96 and +1.96

Both values are within the suggested limit of +/- 1.96 therefore the first criterion of normality is met. The skewness and kurtosis for the population of case study 2 were investigated. An export of skewness and kurtosis is shown in Table 5-11:

Table 5-11 Skewness and kurtosis for case study 2 population

Case study 2		Statistic	Standard Error
Mean		93.9	1.35
95% Confidence Interval for Mean	Lower Bound	91.1	
	Upper Bound	96.6	
Median		94	
Variance		92.3	
Std. Deviation		9.6	
Skewness		.079	.337
Kurtosis		.031	.662

Z-values for skewness and kurtosis were calculated as above and the respective values are shown below:

Table 5-12 Skewness and kurtosis z-values for case study 2 population

Descriptive	Z-value	Criterion check
Skewness	0.23	Falls between -1.96 and +1.96
Kurtosis	0.04	Falls between -1.96 and +1.96

Both values are within the suggested limit of +/- 1.96 therefore the first criterion of normality is met.

Following this the skewness and kurtosis for the population of case study 3 were investigated. An export of skewness and kurtosis is shown below:

Table 5-13 Skewness and kurtosis for case study 3 population

Case study 3		Statistic	Standard Error
Mean		95.5	1.5
95% Confidence Interval for Mean	Lower Bound	92.4	
	Upper Bound	98.5	
Median		96	
Variance		104.9	
Std. Deviation		10.24	
Skewness		-.333	.354
Kurtosis		-.636	.695

Z-values for skewness and kurtosis were calculated as above and the respective values are shown in Table 5-14:

Table 5-14 Skewness and kurtosis z-values for case study 3 population

Descriptive	Z-value	Criterion check
Skewness	-.9406	Falls between -1.96 and +1.96
Kurtosis	-0.915	Falls between -1.96 and +1.96

Both values are within the suggested limit of +/- 1.96 therefore the first criterion of normality is met.

Results indicate that although data across all three groups appear to have some skewness and kurtosis they do not vary significantly from a normal distribution.

Shapiro-Wilk significance test

The Shapiro-Wilk (S-W) test for the three case studies is shown in Table 5-15:

Table 5-15 Shapiro-Wilk test for all case studies

Case studies	Shapiro-Wilk		
	Statistic	df	Sig.
Case study 1	.979	60	.378
Case study 2	.986	50	.828
Case study 3	.969	45	.277

The significance values are above 0.05 indicating there is no significant difference of the sample sizes from a normally distributed data set.

Visual inspection of normality

The final step is to visually inspect normality across both data sets using histograms and normal Q-Q plots. The histogram and normal Q-Q plot for the Cranfield experimental group is shown in Figure 5-43.

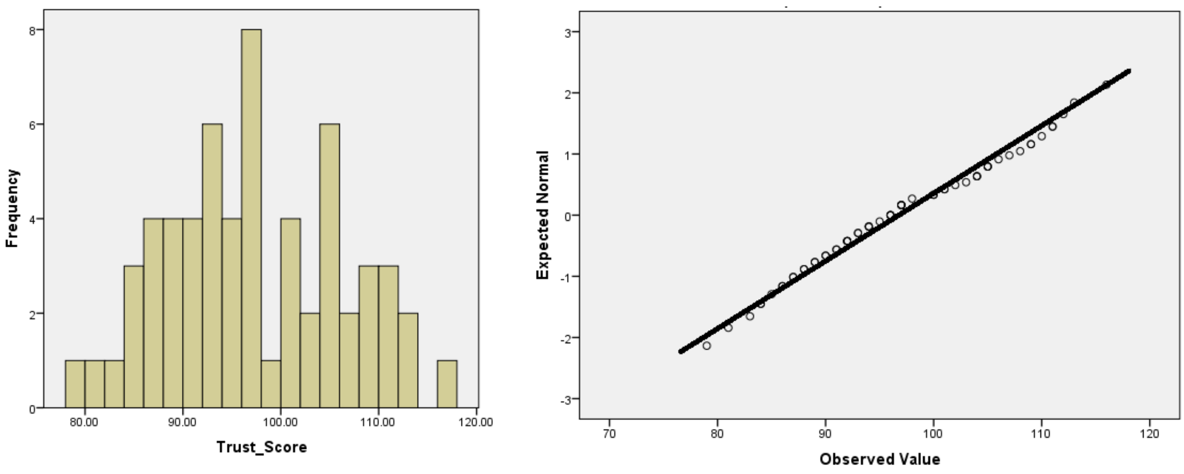


Figure 5-43 Histogram (left) and normal Q-Q plot (right) for case study 1 population

The histogram indicates the sample size approximately follows the shape of a normal curve. The normal Q-Q plot shows the expected normally distributed values with a diagonal line (bold black). The observed values are plotted as individual points. In an ideal state where data is exactly normally distributed we would expect the observed values falling onto the diagonal line. Any deviation from the straight line indicates a deviation from normality. Investigating the normal Q-Q plot it can be seen that there is some deviation above and below the line. However, the corresponding histogram indicates an approximate normal curve. In addition, S-W test suggested non-significant departure from normality (*p*=0.378) which is confirmed with the visual inspection of both the histogram and the normal Q-Q plots.

The histogram and normal Q-Q plot for the Loughborough experimental group is shown in Figure 5-44.

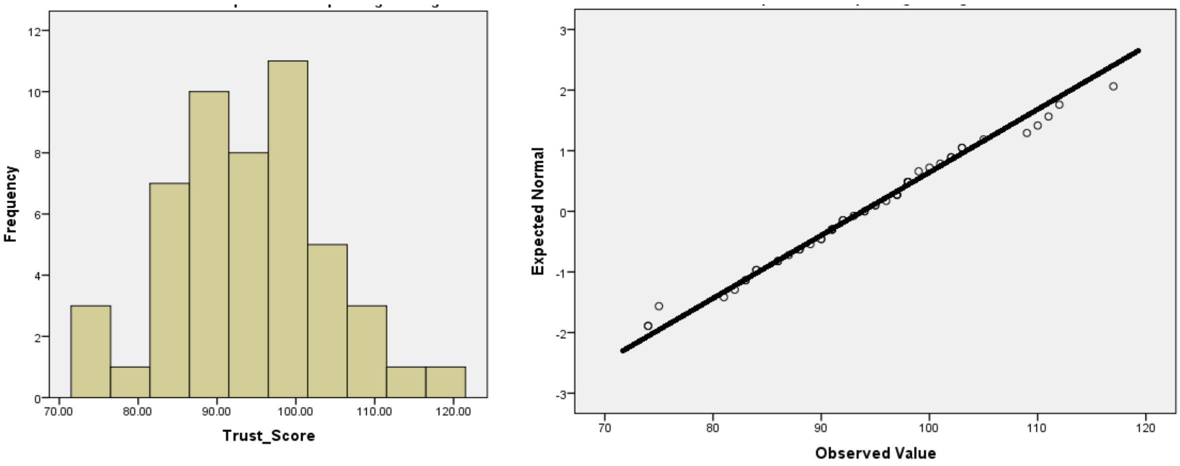


Figure 5-44 Histogram (left) and normal Q-Q plot (right) for case study 2 population

The histogram indicates the sample size approximately follows the shape of a normal curve. From the normal Q-Q plot it can be seen that there is some deviation above and below the line. However, the corresponding histogram indicates an approximate normal curve. Also, S-W test suggested non-significant departure from normality (*p*=0.828) which is confirmed with the visual inspection of both the histogram and the normal Q-Q plots. The histogram and normal Q-Q plot for case study 3 population is shown in Figure 5-45.

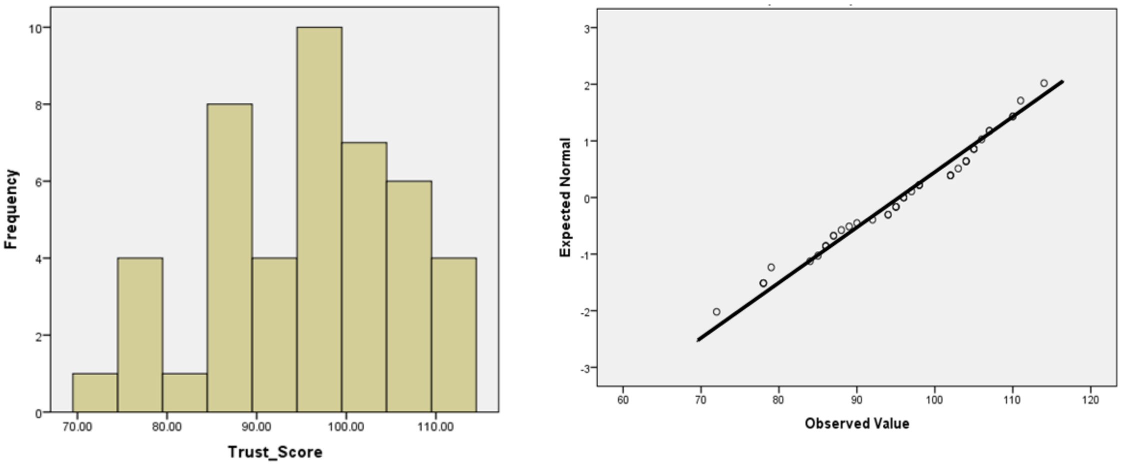


Figure 5-45 Histogram (left) and normal Q-Q plot (right) for case study 3 population

The histogram indicates the sample size approximately follows the shape of a normal curve. The normal Q-Q plot suggests that there is some deviation above and below the line. However, the corresponding histogram indicates an approximate normal curve. S-W test suggested non-significant departure from normality (*p*=0.277) which is confirmed with the visual inspection of both the histogram and the normal Q-Q plots.

Summary from the test of normality

A normality test was carried out to identify whether data across all three experimental groups were normally distributed. The Shapiro-Wilk test for trust scores obtained in case study 1, *D*(60)=0.979, *p*>0.05; case study 2, *D*(50)=0.986, *p*>0.05; and case study 3, *D*(45)=0.969, *p*>0.05, indicated no significant difference from normally distributed data.

5.2.5.1.2 Homogeneity of variance

The Levene’s test (mean) will be used initially to observe whether the assumption of homogeneity of variance is violated. The choice for carrying out a Levene’s mean test was based on the earlier confirmation that data across both groups were normally distributed. The output is shown in Table 5-16:

Table 5-16 Homogeneity of variance test across the three groups

Levene Statistic	df1	df2	Sig.
.400	2	152	.671

For the trust scores obtained between the three case studies, Levene's statistic for equality of variances indicated no significant difference (p>0.05). Hence, there is no significant statistical difference between the trust scores obtained across the three groups.

Summary from the homogeneity of variance test

Collected data across the three case studies have no statistical difference hence the assumption of homogeneity of variance is supported. Therefore, parametric statistical analyses can be used for performing statistical analyses. To this end, a one-way analysis of variance was carried out to explore any difference between the mean scores obtained across the three case studies. This is described in the following section.

5.2.5.1.3 One-way analysis of variance

A one-way analysis of variance was carried out between the three case studies. The group statistics results are shown in Table 5-17.

Table 5-17 Descriptive statistics for the groups across the three case studies

Case study	N	Mean	SD	SE Mean
Case study 1	60	96.7	9	1.16
Case study 2	50	93.9	9.6	1.36
Case study 3	45	95.5	10.2	1.53

Participants in case study 1 on average experienced a higher level of trust (M=96.75, SD=8.989, SE=1.160) when compared to participants in case study 2 (M=93.88, SD=9.608, SE=1.359) and case study 3 (M=95.51, SD=10.244, SE=1.527). At the same time, participants in case study 3 experienced on average higher level of trust when compared to participants in case study 2.

The result of one-way ANOVA is shown in the Table 5-18:

Table 5-18 One way ANOVA output

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	224.8	2	112.9	1.228	.296
Within Groups	13907.7	152	91.5		
Total	14132.5	154			

Although on average there is a difference in the trust score experienced between participants in the three case studies, this was not found to be statistically significant. $F(2)=1.228$, $p>0.05$.

Summary of the one-way ANOVA

The analysis of variance indicated no significant difference between the responses obtained between the three groups. Therefore, the data were merged into a single dataset, providing 155 cases for further analysis. The next step taken was to carry out a preliminary reliability analysis. This is described in the following section.

5.2.5.2 Preliminary reliability analysis

In order to improve the reliability of the questionnaire, a full reliability analysis was carried out. Participant responses were transposed by variable creating twenty-four new variables corresponding to the twenty four questions in the scale. A reliability analysis was then performed using Cronbach's alpha. Before proceeding further with the analysis, it is deemed important to present some background regarding the particular statistics utilised in this section.

5.2.5.2.1 Cronbach's alpha statistic

Cronbach's alpha is a statistic that reflects the internal consistency of a scale (Kline 2005). A generally accepted level is above 0.7 (Nunnally 1978; Kline 1999; Bartneck, Kulic and Croft, 2009). Kline (1999) suggests that although a generally accepted value of 0.8 is appropriate, when measuring psychological constructs values below 0.8 can also be acceptable. Although minimum cut-off levels have been suggested, Cronbach alpha like any other statistical measure needs to be interpreted with care, particularly because Cronbach alpha depends on the number of items used in the questionnaire (Cortina 1993). This can be further investigated by considering the actual equation for calculating Cronbach's alpha (Equation 5-1):

$$Cronbach's\ alpha = \frac{N^2\left(\overline{Cov}\right)}{\sum s^2(item) + \sum Cov(item)}$$

Equation 5-1 The Cronbach alpha formulae

The numerator of the above equation indicates that Cronbach's alpha is proportional to the number of items squared (N^2). As the number of items in the questionnaire increases, alpha will also increase. Potentially, this may lead to a high alpha value because there are a lot of items and not because the questionnaire is reliable. Thus by performing a preliminary reliability analysis, poor items will be removed thus enabling a more careful assessment of Cronbach alpha at a later stage.

5.2.5.2.2 **Results of the preliminary reliability**

Response to items was assessed using a five-point Likert scale from 1 (strongly disagree) to 5 (strongly agree). Scores from questions worded in a negative direction were subtracted from six (maximum scale + 1) and then all scores were summed to give a single number representing subjective trust ranging from 24 to 120. This process is necessary when performing reliability analysis. When negative-worded items are not reversed Cronbach alpha will be negative. This can be explained by looking at the Cronbach alpha equation above. The numerator includes the average covariance between items ($\overline{Cov}$). Negative-worded items will therefore have a negative relationship with other items hence producing a negative value which is not useful.

Data were reversed as indicated above and entered into statistical package for social sciences (SPSS) and a reliability analysis was performed. The reliability and scale statistics are shown in the following Table 5-19:

Table 5-19 Reliability and scale statistics of all scale items

Mean	SD	Cronbach alpha	Number of items	Sample size
95.46	95.80	0.811	24	155

The corresponding item-total statistics is shown in Table 5-20. The item-total statistics is an important output as it will assist to critically evaluate and remove any poor items that do not contribute to the overall reliability. The item-total statistics output produced by SPSS includes another three columns, however, only columns labelled '*Correct item-total correlation*' and '*Cronbach alpha if item deleted*' have been retained from the original one. This is because only these two columns are required for performing additional analysis.

Table 5-20 Item-total statistics

Item No	Correct item-total correlation	Cronbach alpha if item deleted
1	.440	.801
2	.410	.802
3	.368	.804
4	.332	.805
5	.358	.805
6	.533	.794
7	.428	.801
8	.203	.810
9	.528	.797
10	.294	.808
11	.444	.800
12	.245	.813
13	.352	.804
14	.089	.824
15	.081	.815

16	.217	.811
17	-.005	.818
18	.428	.802
19	.445	.800
20	.585	.798
21	.427	.802
22	.594	.796
23	.494	.799
24	.683	.795

5.2.5.2.3 Item elimination process

Preliminary reliability analysis yielded a Cronbach alpha of 0.811. Previous literature suggests a minimum cut-off value between 0.7 and 0.8 (Nunnally 1978; Kline 1999; Bartneck, Kulic, and Croft, 2009). The value of 0.811 is within this recommendation.

The next step taken to improve the scale is to identify the items that do not contribute to the overall reliability. To do this, Table 5-20 will be utilised. Removal of any items begins by investigating the column labelled '*Cronbach alpha if item deleted*'. This column indicates the value of Cronbach alpha upon removal of the corresponding item. If by deleting an item Cronbach alpha changes by a significant amount, this is an indication that the item does not relate to the scale and may have to be removed. The greatest offenders are items 12, 14, 15 and 17 where alpha co-efficients on removal of a single item vary between 0.813 and 0.824. Therefore, removal of any item does not change Cronbach's alpha by a significant margin. The decision to remove items was made on the basis of the '*Corrected item-total correlation*'. This is a correlation between the item score and the overall test score, excluding the item in question from the total score. This correction is performed to avoid inflation of the item-total correlation (Kline, 2005). Field (2005) suggests that item with correlations below 0.3 may have to be dropped. Similarly, Lowenthal (1996) suggests a removal threshold of between 0.15 and 0.30. However, because of the exploratory nature of this questionnaire the mean item-total correlation was taken as an indicator (Nixon 2008). The mean item-total correlation is 0.374 giving a higher cut-off margin than the one suggested in literature (Lowenthal 1996). Applying this rule resulted in the removal of 11 items. Removed items are greyed in Table 5-21.

Table 5-21 Removed items

Item No	Correct item-total correlation	Cronbach alpha if item deleted
1	.440	.801
2	.410	.802
3	.368	.804
4	.332	.805
5	.358	.805
6	.533	.794
7	.428	.801
8	.203	.810
9	.528	.797
10	.294	.808
11	.444	.800
12	.245	.813
13	.352	.804
14	.089	.824
15	.081	.815
16	.217	.811
17	.005	.818
18	.428	.802
19	.445	.800
20	.585	.798
21	.427	.802

22	.594	.796
23	.494	.799
24	.683	.795

Upon removal of the 11 items shown above a new reliability analysis is run on the remaining 13 items. The new scale statistics following removal of items is shown in the following Table 5-22.

Table 5-22 Reliability and scale statistics of remaining 13 items

Mean	SD	Cronbach alpha	Number of items	Sample size
53.03	6.329	0.838	13	155

The new scale consists of 13 items and Cronbach's alpha has increased to 0.838 suggesting increased reliability of the scale.

5.2.5.2.4 Summary of preliminary reliability analysis

The preliminary reliability analysis removed poor items and improved the reliability of the questionnaire. The remaining 13 items were subjected to an exploratory factor analysis (EFA) using principal components analysis (PCA) to clarify the various components measured by the groups of items. This will aid the development of the trust scale. This step is described in the following section.

5.2.5.3 Exploratory factor analysis

Exploratory factor analysis (EFA) represents a descriptive statistical family of techniques aiming to identify a common underlying structure within a dataset (Hair, Anderson, Tatham and Black, 1998). Two highly utilised and very similar methods are principal component analysis (PCA) and Factor Analysis (FA). As before, prior to presenting the statistical analysis carried out, some background information regarding PCA will be presented in the following section.

5.2.5.3.1 Background on PCA and FA

Factor analysis represents a family of multivariate statistical methods whose main aim is to identify the underlying structure of a data set (Hair, *et. al.,* 1998). Principal component analysis (PCA) and factor analysis (FA) are two statistical techniques highly related and tend to be referred to generically as Factor Analysis (Hair *et. al.,* 1998). Factor analysis techniques allow the investigation of correlations between variables (e.g. questionnaire items) by developing a set of common dimensions, described as factors. Factor analysis methods can be utilised to: (i) understand the structure of a set of variables, (ii) construct a questionnaire able to measure a dimension that cannot be directly measured (e.g. trust) and (iii) reduce a given dataset to a manageable size (Field, 2009). Although both PCA and FA are used to generate a set of factors, there are some differences in the way they do it (Hair *et. al.,* 1998). FA utilises a mathematical model from which factors are then established while PCA simplifies the original dataset into a set of linear variables (Dunteman, 1989). Previous literature investigated whether the two techniques can generate a different solution. Guadagnoli and Velicer (1988) suggested that principal component analysis solutions have very little difference from factor analysis solutions. Stevens (2002) on the contrary discussed that under certain circumstances solutions can be different. It is suggested that it is unlikely to obtain different solutions with 30 or more variables and communalities greater than 0.7 for all variables. At the same time, with fewer than 20 variables and some communality scores below 0.4, differences can occur. According to Field (2009), PCA represents a psychometrically robust technique, which is less complex than factor analysis. Principal component analysis (PCA) is a type of factor analysis used to determine the major components measured by the different scale items. PCA has been used in the literature for development of measure scales, such as the Driver Behaviour Inventory (Glendon, *et. al.,* 1993), the Driver Stress Index (Matthews, *et. al.,* 1997), Police Driver Risk Index (Gandolfi 2009), Bus Driver Behaviour Assessment (Dorn, *et. al.,* 2010) and the Integrated Navigation Questionnaire (Nixon, 2008).

5.2.5.3.2 Sample requirements for PCA

PCA results, just like any other statistical procedure, are unavoidably connected to the properties of the data set. The debate mainly focuses on the minimum sample size required to for PCA to be carried out (Dorn *et. al.,* 2010). Traditionally, PCA results were judged based on the absolute sample size and the ratio to the number of components generated (Nixon, 2008). Earlier literature supports a minimum ratio between five and ten participants per variable (Nunnally, 1978; Kass and Tinsley, 1979). Similarly, Ferguson and Cox (1993) indicate that a minimum ratio of participants to variables needs to be in the range of 2:1 to 10:1. More recently, Tabachnick and Fidell (2007) reported that a sample size of 300 is sufficient for carrying out factor analysis. However, development of empirical research using simulated data has shown that the ratio of participants to variables made little difference to the factor structure (Arrindell and Van der Ende, 1985). Further on this, Guadagnoli and Velicer (1988) suggested that the important determinant of a reliable solution is the factor loadings. For a factor with four or more loadings over 0.6 then the solution is reliable regardless of the sample size. Furthermore, they indicated that factors with ten or more loadings greater than 0.4 can be considered reliable if the sample size is above 150. MacCallum, Widaman, Zhang and Hong (1999), on the other hand, have shown that the minimum ratio of sample to variable depends on other aspects. The authors have shown that the communalities of each variable are the important determinant for the appropriateness of the sample size. Communality represents the proportion of common variance present in a variable when compared to the overall model generated by the analysis. If for example all variables had a communality of zero, then each variable would not share its variance with any other variable hence making it unique. In this occasion no further reduction would be necessary. Conversely, if all communalities were one, then each variable would represent the entire variation of the data. MacCallum *et. al*., (1999) suggest that sample sizes, traditionally considered as too low for PCA (less than 100), are appropriate if communalities are consistently greater than 0.6. When communalties are in the 0.5 region a sample size of 100 – 200 is very acceptable.

Another aspect which can be consulted when investigating sample adequacy when running a PCA is the Kaiser-Meyer-Olkin measure of sampling adequacy (KMO) (Kaiser, 1970). The KMO statistic represents the ratio of the squared correlation between variables to the squared partial correlation between variables (Field, 2009). The KMO statistic can take a number between zero and one. The KMO criterion suggested by Kaiser (1974) is as follows:

- 0.5: Barely acceptable
- 0.5-0.7: Mediocre
- 0.7-0.8: Good
- 0.8-0.9: Great
- Above 0.9: Excellent

Therefore, it becomes apparent that there is no one single standard for determining sample adequacy. It appears that, several aspects will have to be taken into consideration in order to decide as to whether PCA results can be relied upon.

5.2.5.3.3 **Initial PCA**

Having provided some of the theoretical background regarding PCA, this section will discuss the initial PCA analysis.

An initial PCA was carried out on the 13 items left from the preliminary reliability analysis. One important aspect when running the analysis is choosing a factor rotation method. Factor rotation is utilised to distinguish between components and assist interpretation of the output (Field, 2009). There are two types of rotation that can be applied: (i) orthogonal (e.g. varimax, quartimax and equamax) and (ii) oblique (direct oblimin and promax). In orthogonal rotation, components are kept unrelated while oblique rotation allows components to correlate between them. Traditionally, orthogonal rotation preferred because it assists interpreting the factor structure output (Harris, Chan-Pensley and McGarry, 2005). In this analysis, a varimax rotation was applied to the component loadings in an attempt to improve the interpretability of the component matrix. This orthogonal rotation also allows for each component to be treated as a separate subscale and the component scores analysed as such. Oblique rotation would confound the scales developed from the components and make separation of the questionnaire into subscales difficult to interpret in a meaningful manner.

5.2.5.3.3.1 Sample characteristics

PCA was carried out on the 13 items retained from the preliminary reliability analysis. The first step taken was to investigate the KMO sampling adequacy Table 5-23.

Table 5-23 Initial KMO sampling adequacy and Bartlett's test of spericity

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.846
Bartlett's Test of Sphericity	Approx. Chi-Square	626.6
	Df	78
	Sig.	.000

A KMO statistic of 0.846 was achieved which is above the 0.5 minimum cut-off level and represents a good sample size (Kaiser, 1974). Also, Bartlett's test of sphericity is statistically significant (χ^2 (91) = 533.022, $p < 0.001$). This result indicates that there is significant correlation within the dataset so components are unlikely to occur by chance.

Following this, the communalities of the 13 items were investigated. Table 5-24 shows the communalities for each variable after extraction:

Table 5-24 Communalities for the 13 items

Item Number	Item	Initial	Extraction
1	The way the robot moved made me uncomfortable	1	.535
2	The speed at which the gripper picked up and released the components made me uneasy	1	.582
3	I knew the gripper would not drop the components	1	.482
4	The robot gripper did not look reliable	1	.674
5	I trusted that the robot was safe to cooperate with	1	.530
6	The gripper seemed like it could be trusted	1	.633
7	I was comfortable the robot would not hurt me	1	.725
8	The size of the robot did not intimidate me	1	.633
9	I felt safe interacting with the robot	1	.722
10	I felt I could rely on the robot to do what it was supposed to do	1	.504
11	I had faith that the robot had been programmed correctly	1	.470
12	If the task was more complicated I might have felt more concerned	1	.403
13	The task made it easy to interact with this robot	1	.359

The average communality is 0.558 which is within the recommended level of 0.5 as suggested by MacCallum *et. al*., (1999). Two items have communalities slightly below 0.5 (items 3 and 11), while only two items have communalities a lot lower than the recommended value (items 12 and 13). Therefore, the sample size of 155 appears to be satisfactory. According to Hair, *et. al.,* (1998) low communalities indicate that the items do not share a great amount of variance with other variables in the analysis and would be beneficial to remove them. The next section deals with item removal and component extraction.

5.2.5.3.3.2 Item elimination

The rotated component matrix was investigated and is shown in Table 5-25 below. The rotated component matrix was selected because it shows the variable loadings after rotation making interpretation much easier.

Table 5-25 Rotated component matrix of the 13 items

		Components		
		1	**2**	**3**
1	The way the robot moved made me uncomfortable			-.690
2	The speed at which the gripper picked up and released the components made me uneasy			-.752
3	I knew the gripper would not drop the components		.634	
4	The robot gripper did not look reliable		-.804	
5	I trusted that the robot was safe to cooperate with	.612		
6	The gripper seemed like it could be trusted		.758	
7	I was comfortable the robot would not hurt me	.779		
8	The size of the robot did not intimidate me	.778		
9	I felt safe interacting with the robot	.754		
10	I felt I could rely on the robot to do what was supposed to do		.473	.509
11	I had faith that the robot had been programmed correctly		.514	.454
12	If the task was more complicated I might have felt more concerned			
13	The task made it easy to interact with this robot			.576

Based on this matrix, three major components were identified. The first thing to notice is that a minimum factor loading of 0.45 was selected initially. Typically factor loadings above 0.3 are being utilised (Field, 2009), however this will depend on the sample size. Hair *et al*., (1998) suggest a minimum factor loading of 0.5 for a sample size 120 and 0.45 for a sample size of 150 while Stevens (2002) recommends a minimum of 0.512 for a sample size of 100. Therefore, a minimum factor loading of 0.45 was selected in this occasion. The blank spaces in the matrix represent loadings below 0.45 thus have been supressed. Another important point to notice is that item 12 does not load onto any component. According to Hair and colleagues (1998) it is beneficial to remove such items from the analysis. Also, the communality of item 13 was much lower (0.359) compared to the rest. Low communalities indicate that the items do not share a great amount of variance with other variables in the analysis and would be beneficial to remove them (Hair *et. al.,* 1998). To this end, items 12 and 13 were removed from the analysis. Also, it is important to notice that items 10 and 11 load almost evenly on components 2 and 3. However, their respective communalities are in the range of 0.5 as suggested by MacCallum *et. al.,* (1999). Therefore, it was decided not to remove them at this stage. To this end, only items 12 and 13 were removed from the analysis and a secondary PCA was run again to observe if there are any differences in the factor structure.

5.2.5.3.4 **Secondary PCA**

5.2.5.3.4.1 Sample characteristics

The secondary PCA yielded the following KMO statistic Table 5-26.

Table 5-26 Secondary KMO sampling adequacy and Bartlett's test of spericity

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0.851
Bartlett's Test of Sphericity	Approx. Chi-Square	511.2
	Df	55
	Sig.	.000

As before, the KMO statistic of 0.851 is well above the minimum cut-off level of 0.5 suggested in the literature (Kaiser, 1974). Also, Bartlett's test of sphericity is statistically significant (Bartlett's test is significant ($\chi 2$ (55) = 511.2, p < 0.001).

This result indicates that there is significant correlation within the dataset so components are unlikely to occur by chance.

The communalities of the 11 items after extraction are presented in the Table 5-27.

Table 5-27 Communalities of the 11 items

Item No.	Item	Initial	Extraction
1	The way the robot moved made me uncomfortable	1	.580
2	The speed at which the gripper picked up and released the components made me uneasy	1	.684
3	I knew the gripper would not drop the components	1	.481
4	The robot gripper did not look reliable	1	.666
5	I trusted that the robot was safe to cooperate with	1	.543
6	The gripper seemed like it could be trusted	1	.652
7	I was comfortable the robot would not hurt me	1	.740
8	The size of the robot did not intimidate me	1	.652
9	I felt safe interacting with the robot	1	.721
10	I felt I could rely on the robot to do what was supposed to do	1	.447
11	I had faith that the robot had been programmed correctly	1	.497

The average communality is 0.606 which is within the limits suggested by MacCallum *et. al.,* (1999). Items 3, 10 and 11 show communalities slightly below the 0.5 limit however, they are still within the 0.5 range. Further item removal will be investigated in the next section.

5.2.5.3.4.2 Item elimination

The new rotated component matrix was exported for investigation and is shown in Table 5-28:

Table 5-28 Rotated component matrix of the 11 items

		Components		
		1	2	3
1	The way the robot moved made me uncomfortable			-.716
2	The speed at which the gripper picked up and released the components made me uneasy			-.817
3	I knew the gripper would not drop the components		.634	
4	The robot gripper did not look reliable		-.803	
5	I trusted that the robot was safe to cooperate with	.623		
6	The gripper seemed like it could be trusted		.758	
7	I was comfortable the robot would not hurt me	.788		
8	The size of the robot did not intimidate me	.788		
9	I felt safe interacting with the robot	.759		
10	I felt I could rely on the robot to do what was supposed to do		.506	
11	I had faith that the robot had been programmed correctly		.540	.453

The component structure was replicated with three major components generated. As noticed before, item 11 still cross loads evenly on components 2 and 3. Therefore the decision was made to remove it from the analysis. The remaining items load clearly on the components. Thus, item 11 was removed and the analysis was re-run to ensure the component structure does not change.

5.2.5.3.5 Third PCA

5.2.5.3.5.1 Sample characteristics

The third PCA yielded the following KMO statistic:

Table 5-29 Third KMO sampling adequacy and Bartlett's test of spericity

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0.847
Bartlett's Test of Sphericity	Approx. Chi-Square	465.6
	Df	45
	Sig.	.000

A KMO statistic achieved of 0.847 is still above the minimum cut-off level of 0.5. Similar as before, Bartlett's test of sphericity is statistically significant (Bartlett's test is significant ($\chi^2(45) = 465.6$, $p < 0.001$) indicating significant correlation within the dataset so components are unlikely to occur by chance.

The communalities of the 10 items after extraction are presented in Table 5-26:

Table 5-30 Communalities of the 10 items

Item Number	Item	Initial	Extraction
1	The way the robot moved made me uncomfortable	1	.628
2	The speed at which the gripper picked up and released the components made me uneasy	1	.734
3	I knew the gripper would not drop the components	1	.503
4	The robot gripper did not look reliable	1	.702
5	I trusted that the robot was safe to cooperate with	1	.569
6	The gripper seemed like it could be trusted	1	.684
7	I was comfortable the robot would not hurt me	1	.734
8	The size of the robot did not intimidate me	1	.606

9	I felt safe interacting with the robot	1	.735
10	I felt I could rely on the robot to do what was supposed to do	1	.455

The average communality is 0.635 which is within the limits suggested by MacCallum *et. al*., (1999). Item 10 has communality slightly below 0.5 however, it is still within the 0.5 range. Further item removal will be investigated in the next section.

5.2.5.3.5.2 Item elimination

The new rotated component matrix was exported for investigation and is shown in Table 5-31:

Table 5-31 Rotated component matrix of the 10 items

		Components		
		1	**2**	**3**
1	The way the robot moved made me uncomfortable			.759
2	The speed at which the gripper picked up and released the components made me uneasy			.848
3	I knew the gripper would not drop the components		.651	
4	The robot gripper did not look reliable		-.828	
5	I trusted that the robot was safe to cooperate with	.688		
6	The gripper seemed like it could be trusted		.793	
7	I was comfortable the robot would not hurt me	.782		
8	The size of the robot did not intimidate me	.754		
9	I felt safe interacting with the robot	.787		
10	I felt I could rely on the robot to do what it was supposed to do		.506	

The component structure was replicated. Three major components were generated and items loaded clearly on each of the components. Therefore, no further item removal was necessary. The next step is to assess whether the correct number of components has been extracted.

5.2.5.3.6 Component extraction investigation

The rotated component matrix has produced four components. It is important to inspect whether the components extracted sufficiently describe the data. To investigate this, there are three criteria to be investigated: (i) latent root criterion (or Kaiser's criterion), (ii) scree plot criterion and (iii) percentage of variance criterion. Before proceeding with the investigation, some background on each of them is provide below:

(i) **Latent root criterion**: According to this criterion, components with an eigenvalue greater than one are extracted. Eigenvalue is the sum of the squared loadings for a factor. The eigenvalue represents the variance in a component. Hair *et al*., (1998) suggest that for a factor to be useful, it should account at least the same amount variance than a single variable. Therefore, a minimum eigenvalue of one has been selected as the cut-off level.

(ii) **Scree plot criterion**: Scree plot is a graphical representation of the eigenvalue on the y-axis against the number of components on the x-axis. As described earlier, when performing a PCA, components carry an amount of unique variance. The scree plot criterion aims to graphically identify the inflexion point at which the unique variance of components dominates the common variance. This is indicated when the graph begins to flatten. The point before the flattening is an indication of the number of factors to be extracted (Hair and colleagues 1998). It becomes apparent that this criterion can be subjective and will be used in conjunction with the other two criteria.

- **(iii)** **Percentage of variance criterion**: The aim of PCA is to produce a component structure that describes sufficiently the data. This is represented with the amount of total variance explained by the components. However, the solution generated by the software produces as many components as variables thus 100 per cent variance is achieved. The key is to identify the number of components that summarise the data sufficiently by explaining an adequate amount of variance without losing important information. Hair, *et. al*., (1998) suggest a minimum variance of 60 per cent.

Therefore, based on the above criteria the first aspect to be investigated was the scree plot. The scree plot is shown in Figure 5-46:

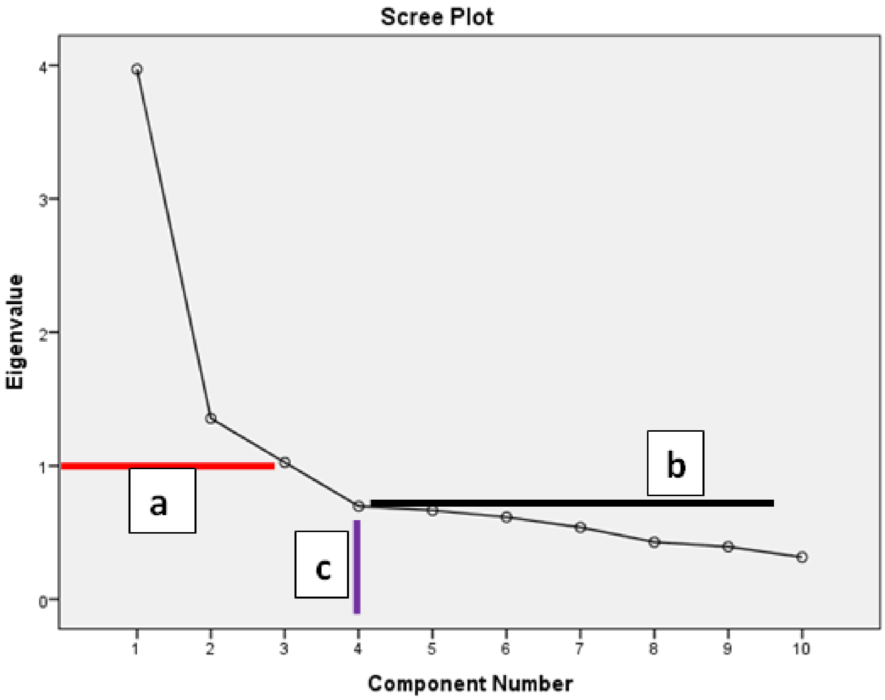
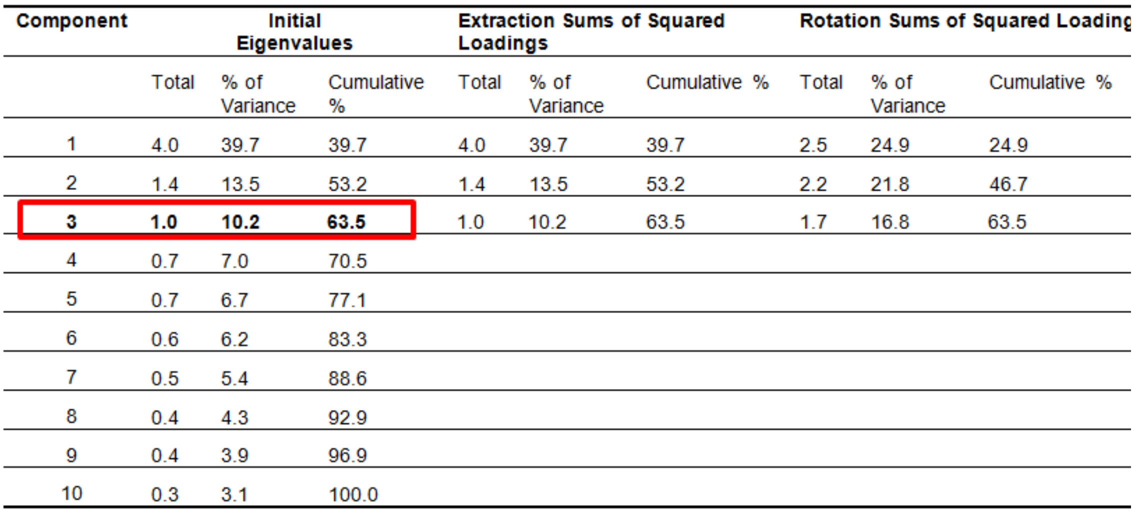


Figure 5-46 The scree plot

For the analysis of the scree plot, three different coloured points have been used. First, a red line (noted “a”) on the graph represents the latent root criterion. As discussed before, a minimum cut-off eigenvalue of one was selected. Therefore, a horizontal line was drawn at an eigenvalue of one (line “a”).

The next step was to identify the inflexion point on the scree plot. As discussed above, the inflexion point is the point after which the graph flattens out. Investigating the scree plot, it appears that the graph flattens out at component number 4. A vertical purple coloured line (noted “c”) has been drawn. Also to show the flattening, a black coloured line (notes “b”) was drawn. According to Hair *et. al*., (1998) the point before the flattening is the number of factors to be extracted. On the Scree plot above, this point is component number 3.

Finally, to ensure the correct component number was selected, the third criterion was used. The total variance explained by the components is shown in Figure 5-47:



Component	**Initial Eigenvalues**			**Extraction Sums of Squared Loadings**			**Rotation Sums of Squared Loading**		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	4.0	39.7	39.7	4.0	39.7	39.7	2.5	24.9	24.9
2	1.4	13.5	53.2	1.4	13.5	53.2	2.2	21.8	46.7
3	**1.0**	**10.2**	**63.5**	1.0	10.2	63.5	1.7	16.8	63.5
4	0.7	7.0	70.5						
5	0.7	6.7	77.1						
6	0.6	6.2	83.3						
7	0.5	5.4	88.6						
8	0.4	4.3	92.9						
9	0.4	3.9	96.9						
10	0.3	3.1	100.0						

Figure 5-47 Export showing the total variance explained by the components

The minimum variance explained by the selected components needs to exceed a minimum of 60 per cent. The figure above indicates that at an eigenvalue of one, the cumulative percentage of variance explained is 63.5 per cent (in the red box). This is suggesting that the number of components extracted (i.e. 3 components) is sufficiently describing the data. The next step is to interpret the components.

5.2.5.4 Component interpretation and reliability analysis

Having identified the three major components, the next step taken was to interpret them and perform a reliability analysis for each component. Each component is analysed separately in the following sections.

5.2.5.4.1 Component 1 interpretation and reliability analysis

Component 1 comprised of four items: 5, 7, 8 and 9 and are shown in Table 5-32:

Table 5-32 Component 1 item loadings

Questionnaire No.	Item	Item loading
5	I trusted that the robot was safe to cooperate with	.688
7	I was comfortable the robot would not hurt me	.782
8	The size of the robot did not intimidate me	.754
9	I felt safe interacting with the robot	.787

In order to interpret the components, keywords were used. Items 5, 7 and 9 relate to safe cooperation with the robot. Regarding item 8, participants did not feel unsafe interacting with the robot due to the size. Therefore, component 1 is labelled “perceived safe cooperation”. Reliability analysis for component 1 yielded an overall alpha of 0.802 and this is shown in Table 5-33. This is above the minimum cut-off limit of 0.7 suggested in the literature (Kline, 1999; Bartneck, Kulic and Croft, 2009) indicating good reliability of the subscale.

Table 5-33 Component 1 interpretation and reliability analysis

Component 1: Perceived safe cooperation	Overall alpha
I trusted that the robot was safe to cooperate with	.802
I was comfortable the robot would not hurt me	
The size of the robot did not intimidate me	
I felt safe interacting with the robot	

5.2.5.4.2 Component 2 interpretation and reliability analysis

Component 2 included the items: 1, and 2 and are show in Table 5-34:

Table 5-34 Component 2 item loadings

Questionnaire No.	Item	Item loading
1	The way the robot moved made me uncomfortable	.759
2	The speed at which the gripper picked up and released the components made me uneasy	.848

The items are relevant to the robot's way of movement and speed. Item 5 is relevant to the speed of the robotic gripper. Therefore, component 1 is labelled "perceived robot's motion". A reliability analysis for component 2 yielded an overall alpha of 0.612 and is shown in Table 5-35.

Table 5-35 Component 2 interpretation and reliability analysis

Component 2: Perceived robot's motion	Overall alpha
The way the robot moved made me uncomfortable	.612
The speed at which the gripper picked up and released the components made me uneasy	

Although this figure is below the generally accepted cut-off level of 0.7, literature suggests that when measuring psychological constructs, lower values can be accepted (Kline 1999). Furthermore, this alpha value is acceptable for newly developed scale (deVellis, 1991, Nixon 2008) particularly given the small number of items in this sub-scale (two).

5.2.5.4.3 Component 3 interpretation and reliability analysis

Component 3 included four items: 3, 4, 6 and 10 and are shown in Table 5-36.

Table 5-36 Component 3 item loadings

Questionnaire No.	Item	Item loading
3	I knew the gripper would not drop the components	.651
4	The robot gripper did not look reliable	-.828
6	The gripper seemed like it could be trusted	.793
10	I felt I could rely on the robot to do what was supposed to do	.506

The items relate to the ability of the robot and the gripping mechanism to perform the task in a reliable manner. Therefore, component 3 is labelled "perceived robot and gripping mechanism reliability". Reliability analysis for component 3 yielded an overall alpha of 0.712 (Table 5-37) which is above the cut-off level of 0.7 indicating good reliability of the subscale.

Table 5-37 Component 3 interpretation and reliability analysis

Component 3: Perceived robot and gripping mechanism reliability	Overall alpha
I knew the gripper would not drop the components	.712
The robot gripper did not look reliable	
The gripper seemed like it could be trusted	
I felt I could rely on the robot to do what it was supposed to do	

5.2.5.5 Summary of the quantitative analysis

Upon completion of the experimental work, a dataset consisting of 155 cases was available for analysis. The development of the trust scale proceeded in four stages.

- An exploratory data analysis was carried out to ensure there was no statistically significant difference between the responses obtained between the three case studies. This was described in section 5.2.5.1.
- A preliminary reliability analysis was performed to remove any poor items and enhance the reliability of the questionnaire. This was described in section 5.2.5.2.
- The output of the preliminary reliability analysis was subjected to a PCA to identify the key factors influencing trust in industrial HRC. This process was described in section 5.2.5.3.
- Finally, the key factors identified in the PCA were extracted, interpreted and checked for internal consistency. This was described in section 5.2.5.4. Overall, the developed scale included 10 items. These items were grouped in three sub-scales.

Because this was an initial attempt to develop a trust scale specifically applicable to industrial HRC, a convenient sampling approach was taken, where university students were recruited. Therefore, most of the individuals recruited did not come from an industrial background. Therefore to enhance confidence that the developed trust scale can be used to evaluate trust among experienced users, the developed scale was used in a small scale exploratory validation study using subject matter experts (SMEs). This is described in the following section.

5.2.6 **Small scale validation study**

5.2.6.1 **Introduction**

The developed trust scale (i.e. 10-item scale) was used in a small scale human-robot trial to collect data from SMEs. The aim was to provide an indication as to whether a difference exists in the trust score between SMEs and the trust score recorded in the three case studies described in section 5.2.4. Although the sample size of this study does not allow for statistical analysis to be carried out, the mean and standard deviation were used to provide evidence for any difference.

5.2.6.2 Study overview

The SMEs participated in a human factors study, in which measuring trust in the robotic assistant was one part of the study. Participants' trust was evaluated by administering the newly developed trust scale (10 items) upon completion of the task. Results were analysed separately and then compared against the data collected in previous trials.

5.2.6.3 Participants

In total, five participants took part in the trial. Two individuals reported having no prior experience with automation and their data were removed. Therefore, data from three participants were available for analysis. Two individuals reported working in academia while the third individual reported working in aerospace research and development. All of the participants were male. The mean age of the group was 34 years (SD=10.6). Two individuals reported having experience using industrial collaborative robots while the third individual has extensive experience of aerospace manufacturing tasks and has used automated manufacturing machines.

5.2.6.4 Analysis

As discussed, the sample size of this study does not allow for statistical analysis to be carried out in order to identify any statistical significant difference between the SMEs and the results obtained in the three previous case studies. To this end, the mean and standard deviation were used.

5.2.6.4.1 SMEs study analysis

Table 5-38 illustrates participants' rating for each of the questionnaire items along with the mean and standard deviation. Also, the table indicates the total trust score for each participant as well as the mean trust score and standard deviation. The total trust score for each participant was obtained by adding the recorded rating for each item.

Table 5-38 Total trust score, mean and standard deviation for each SME

	Questionnaire Items										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Trust score**
SME_1	5	5	5	5	5	5	5	4	2	4	45
SME_2	5	5	4	2	4	4	4	3	4	4	39
SME_3	4	5	4	3	3	4	4	4	3	4	38
Mean (X)	4.7	5.0	4.3	3.3	4.0	4.3	4.3	3.7	3.0	4.0	40.7
SD	0.5	0.0	0.5	1.2	0.8	0.5	0.5	0.5	0.8	0.0	3.1

The mean and standard deviation for each questionnaire item indicate that participants' ratings do not greatly differ. This is also indicated by the total trust score for each participant. Maximum trust rate was 45 while minimum was 38 and the average recorded trust score was 40.7 (SD=3.1).

5.2.6.4.2 Comparison between the SMEs study and the three case studies

The next step taken was to compare the results recorded by the SMEs with the results obtained in the previous three case studies. Table 5-39 illustrates the mean and standard deviation for each of the questionnaire items as well as the mean trust score and standard deviation obtained across all four studies:

Table 5-39 Comparison between the validation study and the previous case studies

		Questionnaire Items										
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Trust score**
SME study	**X**	4.7	5.0	4.3	3.3	4.0	4.3	4.3	3.7	3.0	4.0	40.7
	SD	0.5	0.0	0.5	1.2	0.8	0.5	0.5	0.5	0.8	0.0	3.1
Case study 1	**X**	4.3	4.3	4.2	3.9	4.2	4.3	4.0	4.4	4.0	4.4	42.0
	SD	0.7	0.9	0.7	0.9	0.9	0.6	0.8	0.5	0.9	0.5	4.2
Case study 2	**X**	3.8	3.9	4.2	3.7	4.3	4.3	4.2	4.2	4.4	4.2	41.1
	SD	0.9	1.2	0.9	1.0	0.8	0.6	0.7	0.9	0.6	0.6	5.0
Case study 3	**X**	4.4	4.3	4.1	3.6	3.8	4.3	3.9	4.3	4.0	4.3	41.1
	SD	0.7	0.7	0.9	1.2	0.8	0.6	0.8	0.7	0.9	0.7	5.7

As it can be seen from the table above, the mean and standard deviation recorded for each questionnaire item does not greatly differ between the SMEs' study and the other three case studies. The greatest difference between the means is recorded for item 7 between the SMEs' study and case study 2 (difference between the means of 1.1) and for item 23 between the SME's study and all three case studies (difference between the means of 1.4, 1 and 1 respectively). Furthermore, the average trust scores for each study are clustered between 40 and 42 suggesting no great difference.

5.2.6.4.3 Discussion for the small scale validation study

The developed trust scale was used in a small scale human-robot trial to collect data from SMEs. These were individuals with experience in using industrial collaborative robots, automated manufacturing machines and manufacturing processes. The aim was to obtain evidence for any difference in the trust score between experienced individuals and the trust score recorded in the three previous trials.

Results indicated that the SMEs' average rating for each of the items did not greatly differ with the average response recorded for each of the case studies.

Also, the average trust score recorded in the SMEs' study is clustered in the same region as the average trust score recorded for the three case studies. Thus, the results provide an indication that the developed trust scale can potentially be used to evaluate trust among experienced users. At the same time, It is acknowledged that the small sample size utilised in this study is masking effects and does not allow for investigation of effects at statistical significance levels (e.g. 0.05). This provides avenues for further research which will be discussed in chapter 8.

5.2.7 Summary and progression to the next section

Section 5.2.3 described an exploratory study where qualitative data were collected. The qualitative approach led to the development of trust related themes relevant to the industrial context. Following this a pool of items was developed describing the identified themes. The pool of items was placed in a survey.

To identify the key trust-related themes relevant to industrial HRC, three experimental case studies in laboratory conditions were carried out. Three independent groups of participants were recruited. Upon completing the task, participants completed the survey developed in the exploratory study. A dataset consisting of 155 cases was subjected to a quantitative analysis. The quantitative analysis was described in section 5.2.5. Finally, section 5.2.6 presented the results from a small scale validation study. The aim was to provide evidence for any differences in the recorded trust scores between SMEs and the three case studies. The following section discusses the implications of the developed psychometric scale to measure trust in industrial HRC.

5.2.8 Discussion on the developed trust scale

The statistical analysis suggests that trust in industrial HRC depends on three components: perceived safe cooperation, perceived robot and gripper reliability and perceived robot's motion and pick-up speed. The components exhibited fairly good internal consistency. Components 1 and 2 are within the general acceptable cut-off limit of 0.7 suggested in the literature (Nunnally, 1978) indicating good reliability. Although component 3 exhibited an alpha value (0.612) lower than the minimum acceptable limit, Kline (1999) suggests that for psychological constructs values lower than 0.7 can also be accepted. At the same time, this alpha value is acceptable for newly developed scales (deVellis, 1991), particularly given the small number of items in this component (two).

One of the major components identified through the analysis was safety during the co-operation between the human and the industrial robot. This finding is consistent with earlier work, suggesting that a positive level of perceived safety can be a key element for the successful introduction of robots in human environments (Bartneck, Kulic and Croft, 2009). The items grouped in this component indicate that both mental (impact of the robot size) and physical safety (not being injured by the robot) is important during a HRC task in industry which is in line with previous literature (Inoue, Nonaka, Takubo and Arai, 2005). This is particularly important for the industrial context where human operators will be required to work in close proximity with industrial robots. In some occasions, such as the one used for study 3, these robots can have a very high payload capability and their size can be intimidating. It appears that ensuring operators are exposed to a collaborative scenario where safety is facilitated, can generate a positive feeling of safety. This in turn can assist the human operator to develop trust in the robotic partner.

The performance aspects of the robotic system and specifically, the perceived reliability of the robot and the gripping mechanism was the second trust related component. Robot reliability is in line with previous literature (Lee and See, 2004). In a meta-analysis by Hancock and colleagues (2011) robot performance factors (e.g. reliability) had the highest impact on trust. The findings of this study highlight once again the criticality of a reliable robot system. An unreliable robot will eventually decrease operator’s trust which in turn will be detrimental for accepting and using the robot. Also, considering that humans are far more sensitive to automation errors thus leading to a significant drop in trust (Jian, Bisantz and Drury, 2000), robot reliability becomes a very important aspect.

Interestingly, the reliability of the gripping mechanism appeared to have an impact on trust. To our knowledge, this context specific aspect has not appeared in previous literature. This is of particular relevance to industrial HRC, since the gripper is a vital component of an industrial robot. The gripping mechanism is the mean with which the robot will manipulate components and interact with the human partner during a collaborative task. As industrial robots come in a variety of gripping mechanisms depending on the task being utilised for, findings suggest that the reliability of the gripping mechanism is an important determinant for trust development. When the reliability of the gripping mechanism decreases, human trust in the robotic partner decreases.

The third trust component was relevant to the robot’s motion and the component pick-up speed. It appears that the motion of the robot is an important factor for the development of trust. This is in line with previous research indicating that robot’s movement can assist the human partner to predict and anticipate robot’s intentions (Huber, Rickert, Knoll, Brandt and Glasauer, 2008; Mayer, Kuz and Schlick, 2013). A fluent, non-disruptive robot movement can put the human partner at easy and increase trust. This is particularly important for an industrial environment where the robot will be collaborating in close proximity with a human operator. Furthermore, industrial settings can be cluttered with other operators therefore it is important for other operators to predict the robot’s movement. Also, the final component suggested that the speed at which the gripping mechanism picks-up components has an impact on the development of trust. Similar with the previous component (robot and gripper reliability) the robot’s gripping mechanism appears to have an important role in the development of trust.

In addition, the statistical analysis indicated that that the appearance of the robot did not emerge as a contributing component to trust development. Previous literature in the domain of social robotics provides contradicting results in terms of the effects of robot appearance on user preferences; some suggest robots should not be too human-like in appearance whereas others indicate that more human-like appearance can engage people more (Broadbent, Stafford and MacDonald, 2009; Bartneck, Kanda, Mubin and Mahmud, 2009; Li, Rau and Li, 2010). At the same time, it has been suggested that anthropomorphic appearance should be treated with care in order to match the appearance of the robot with its abilities without generating unrealistic expectations to the human user (Bartneck, Kulic and Croft, 2009). This finding possibly indicates that people perceive industrial robots as tools used to complete a task. Therefore it appears that robot appearance for industrial HRC is not a major contributor to trust development when compared to social robots used as social companions.

This instrument can have significant practical implications. First, the proposed scale provides a means for evaluating trust between humans and industrial robots based on empirical data. From a practical point of view, this measurement tool would be useful not only for quantifying trust in industrial HRC, but to assist system designers and engineers understand how system characteristics can affect operators' perception of trust. For instance, the scale identified three key design aspects fostering trust industrial HRC namely, perceived safe cooperation, perceived robot and gripper reliability and perceived robot's motion and gripper pick-up speed. These three areas appear to be the major determinants for trust development. Furthermore, the instrument can be used to identify the relationship of each individual operator and raise awareness regarding personal tendencies. For example, poor scores on robot and gripper reliability might identify those operators in need for further training regarding the capabilities and technical aspects of the gripping mechanism.

5.3 Summary of the chapter

This chapter presented the work carried out to understand trust development in industrial HRC. For this purpose, a psychometric scale to measure trust in industrial HRC was developed. Section 5.2.3 described an exploratory case study where data were collected qualitatively. This approach led to the development of trust related themes relevant to the industrial context. Based on the trust-related themes, a pool of items was developed. The pool of items was placed in a survey.

Following this, section 5.2.4 described the approach employed to identify the key trust-related themes relevant to industrial HRC. Three experimental case studies in laboratory conditions were carried out using three different types of robots. Tasks represented potential industrial scenarios where humans and robots would collaborate. Three independent groups of participants were recruited. Upon completing the task, participants completed the survey developed in the exploratory study. A total of 155 participants were recruited.

Section 5.2.5 presented the quantitative analysis of the collected data. Statistical analysis proceeded in four steps. Initially, a one way analysis of variance was carried out to identify whether there was a statistical significant difference in the responses obtained between the three studies. Following this, a preliminary reliability analysis was executed to remove any poor items from the analysis. Then a PCA was executed to identify the major components. Finally, components were extracted, interpreted and checked for internal consistency. Three components emerged from the PCA. Component 1, was termed ‘Perceived safe cooperation’, consisted of four items and had a Cronbach’s alpha of 0.802. Component 2 was termed ‘Perceived robot and gripping mechanism reliability’, consisted of four items and had an alpha value of 0.712. Component 3 was termed ‘Perceived robot’s motion’, consisted of two items and resulted in a Cronbach’s alpha of 0.612.

Section 5.2.6 described a small scale validation study, where the developed scale was utilised to evaluate trust of SMEs in a human-robot trial. The aim was to provide evidence for any differences in the recorded trust scores between SMEs and the three case studies. Although the sample size of the validation study did not allow for statistical analysis, early results provide an indication that the developed trust scale can potentially be used to evaluate trust among experienced users.

Finally, section 5.2.8 discussed the output of the statistical analysis and the practical implications of the developed psychometric scale.

6 OVERALL RESULTS

This chapter presents an overall summary of the results of this research. Section 6.1 makes a short review of the work presented up to this point. Section 6.2 provides a summary of the results from the work carried out to identify the key organisational human factors. Section 6.3 presents a summary of the results from the development of the psychometric trust scale for industrial HRC.

6.1 Review of the work presented

Prior to discussion the overall findings of this research and their practical implications for practitioners, it is deemed important to make a brief review of the work presented in this thesis.

Chapter 2 introduced the concept of industrial HRC and its benefits for the manufacturing industry. Furthermore, in this chapter, the importance of considering human factors for the successful introduction and implementation of advanced automated technologies was discussed.

Chapter 3 presented the approach taken to develop a theoretical human factors framework which identified the key theoretical human factors relevant to industrial HRC implementation. The identified key human factors were segregated at two levels as shown Figure 6-48: (i) human factors at the organisational level, influencing the organisation and (ii) human factors at the individual level, influencing the human operator.

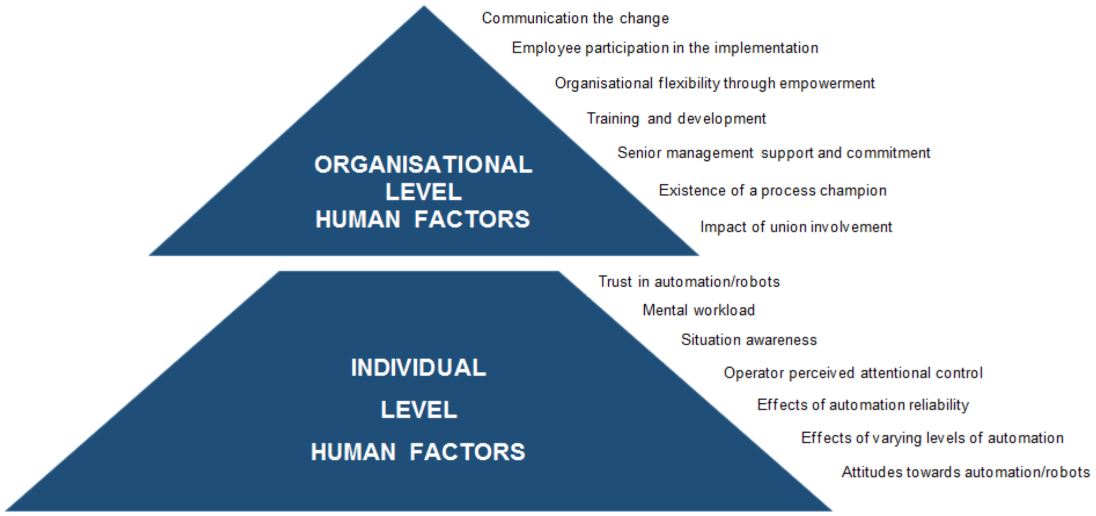


Figure 6-48 The theoretical human factors framework

The human factors at each level represent two areas which were investigated separately. Also, this chapter discussed that although a number of individual level human factors were identified in the theoretical framework, the focus of this research was placed on trust.

Chapter 4 presented the work carried out to investigate whether the organisational human factors outlined in the theoretical framework were enablers or barriers. For this purpose, an industrial exploratory case study was conducted where traditional manual work was being automated. Furthermore, the findings of this study led to the development of a quantitative survey.

Chapter 5 presented the work carried out to investigate the development of trust in industrial HRC. Due to little knowledge of trust development specifically in industrial HRC, a psychometric scale that measures trust in this context was developed.

6.2 Organisational level human factors

The purpose for this part was to identify whether the organisational level human factors identified in the theoretical framework were either enablers or barriers in relation to implementation of HRC work. Furthermore, through the case study it was wished to identify any additional human factors not captured in the theoretical framework. To accomplish this, an industrial exploratory case study was conducted where traditional manual work was being automated at a high value aerospace manufacturing organisation.

The first important finding of the case study is that it adds to the existing body of literature the importance of considering human factors when implementing manufacturing technologies.

Second, the exploratory case study revealed a number of key human factors enablers and barriers. Major enablers identified through the exploratory case study were:

- operator participation in the implementation
- communication of the change to the workforce
- visible senior management commitment and support to the project
- provision of training to the workforce
- empowerment of the workforce
- existence of a process champion during the implementation

Major barriers were:

- lack of union involvement
- lack of awareness of the manual process complexity by the system integrator
- capturing the variability of the manual process prior to introducing the automated system
- allocation of resources for the development of the automated system

In summary, these findings provide a guideline to practitioners implementing industrial HRC of the key organisational human factors.

The third important finding from the exploratory case study is that the identified key organisational human factors need to be viewed as a framework of inter-relations and not a selective “tick-in-the-box” activity. These inter-relations between the organisational human factors need to be taken into consideration. This is shown in Figure 6-49.

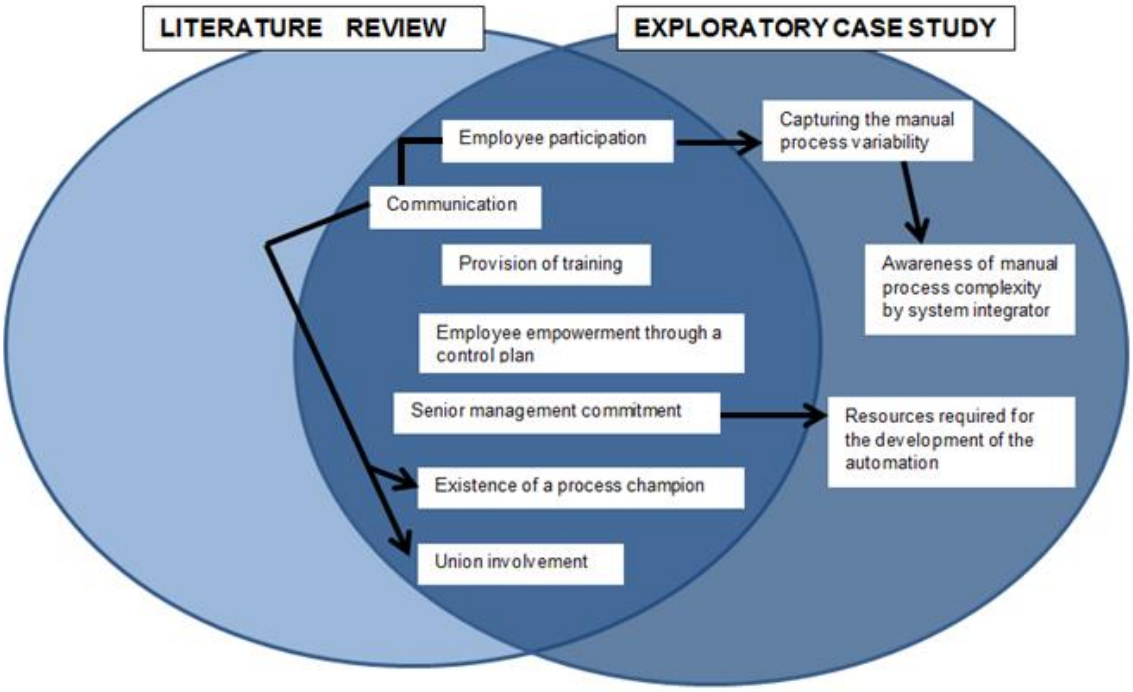


Figure 6-49 The inter-relations between the organisational level human factors

The importance of the inter-relations can be described with an example. For example, capturing the variability of the manual process in advance will enable to provide this knowledge to the system integrator in order to supply a process capable system. However, in order to capture the knowledge of the manual process, shop floor operators need to participate at an early stage. To enable that proper communication to the workforce will be required to win their commitment and reduce resistance.

As it was discussed in chapter 4, findings from a single case study cannot provide concrete and generalisable conclusions. The lack of additional case studies led to the development of a survey (described in section 4.3). The aim of the survey was to ensure the identified organisational human factors from the exploratory case study could be generalised. Ten subject matter experts from one of the project’s industrial sponsors were approached. Findings from the survey suggested that the identified human factors enablers and barriers are applicable to other automation implementation cases. This enabled the development of a quantitative questionnaire which was distributed across different manufacturing organisations to allow statistical quantification of the key organisational human factors. However, due to lack of response this was not further pursued. Despite this, the findings provide additional avenues for further work which will be discussed in chapter 8.

6.3 Trust in industrial HRC

The theoretical framework (Figure 6-48) identified a number of key individual level human factors. However, as it was discussed in section 3.5.2, the focus of this research was placed on trust. Although trust has received extensive attention, little research has focused on understanding trust development in industrial HRC. Therefore, to appropriately understand the development of trust between human workers and industrial robots it is vital to effectively quantify trust. Such a measurement tool would not only allow us to quantify trust in industrial HRC, but it would also offer the opportunity to system designers to identify the key system aspects that can be manipulated to optimise trust in industrial HRC.

The development of the psychometric trust scale was carried out in three phases. Initially, an exploratory study to collect participants' opinions when collaborating with industrial robots was carried out (section 5.2.3). This led to the development of trust-related themes specifically related to industrial HRC. Based on these themes a pool of items was developed which were then placed on a rating survey. Then, a series of experimental case studies took place to quantify the key trust-related themes relevant to industrial HRC (section 5.2.4). The survey developed in the exploratory study was used to collect data. Finally, a quantitative analysis of the collected data was undertaken which led to the development of the trust scale (section 5.2.5)

The developed psychometric scale indicated that trust in industrial HRC depends on three major factors:

- perceived safe cooperation
- perceived robot and gripping mechanism reliability
- perceived robot's motion

The findings of this scale can have important practical implications. First, the tool offers the opportunity to quantify trust specifically in industrial HRC. Second, the three major factors identified in the scale highlight to system designers and engineers understand the key system characteristics that can affect operators' perception of trust in industrial HRC. For instance, the scale identified three key design aspects fostering trust industrial HRC namely, perceived safe cooperation, perceived robot and gripping mechanism reliability and perceived robot's motion. Therefore, particular emphasis needs to be given on these system characteristics. Third, this scale can assist to examine the relationship of each operator and enhance awareness regarding personal tendencies. For example, a poor score on a particular sub-scale (e.g. robot and gripping mechanism reliability) or on the entire scale can identify those operators in need for further training.

6.4 Chapter summary

This chapter presented an overall summary of the results from this research across the two levels (i.e. organisational level human factors and psychometric trust scale development). The next chapter will gather the results to present a human factors guiding tool to enable practitioners successfully implement industrial HRC.

7 HUMAN FACTORS GUIDANCE TOOL

The overall aim of this research was to develop a human factors tool with the key human factors at an organisational and individual level for the successful implementation of industrial HRC. Therefore, this chapter will gather the findings from chapters 4 and 5 to provide practitioners with a human factors guidance tool (HFGT), in the form of propositions, which will enable the effective implementation of industrial HRC.

The developed HFGT includes two parts, part A and part B. Part A of the HFGT is described in section 7.1. Part A discusses how and when the identified organisational human factors need to be considered during the project implementation timeline. Part B of the HFGT is described in section 7.2 and presents the inter-relation between some of the organisational human factors with the developed trust scale. Part B provides practitioners a guide with which operators’ trust levels can be continuously optimised. Section 7.3 provides a summary of the chapter.

7.1 Part A of the HFGT – Consideration of organisational human factors

Upon identifying the key organisational human factors, it is also important to understand when these factors must be considered. For instance, findings have suggested that it is important to communicate the change to the workforce and involve shop floor operators in the implementation process, but the question “*When should we do that?*” is still unanswered. This section will make an attempt to provide an initial guideline. Although this is a subjective attempt, it can still be a useful first step towards obtaining a holistic understanding of the impact of these factors. This is presented in the following sections.

7.1.1 Technology readiness levels

To assist practitioners understand when each of the identified organisational human factors can potentially be considered, the technology readiness levels (TRL) will be used. The reason for selecting TRLs as a timeline is because this is a widely used scale communicating the maturity of a new technology before it can be utilised (Mankins, 2009). TRLs were first used by the National Aerospace and Space Administration (NASA) in the mid-1970s as a means for planning and communicating the maturity of space technology (Mankins, 1995; Mankins, 2009). In 1995, the first definitions of each level were added (Mankins, 1995). Figure 7-50 provides an overview of the TRL scale and the definitions used for NASA's purposes.

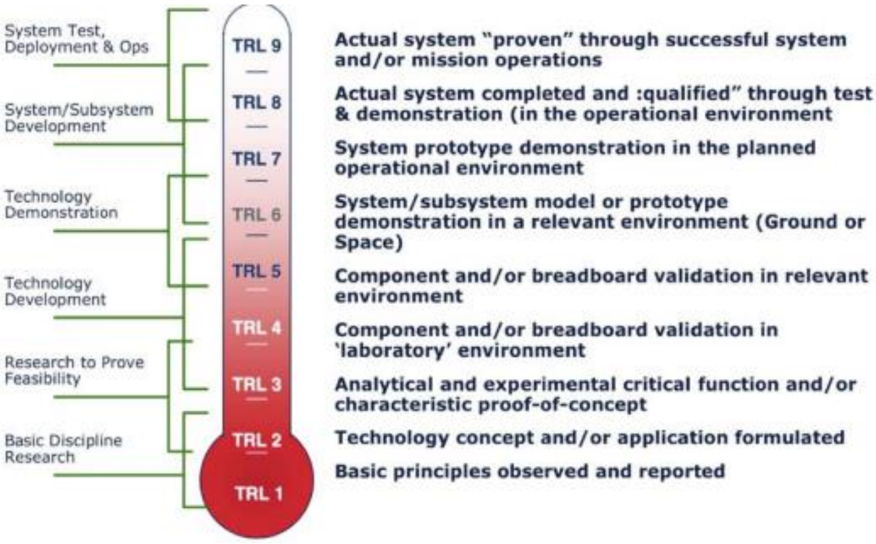


Figure 7-50 NASA's Technology Readiness Levels scale (Retrieved from Mankins, 2009)

As shown, the scale consists of nine levels, each of which represents a different technology maturity level. As the TRL level increases, the technology reaches a higher level of operational readiness. Since their development, TRLs were adopted by the U.S Deprtment of Defence (Mankins, 2009) and other organisations, such as aerospace organisations (Nakamura, Kajikawa and Suzuki, 2013). The scale can easily be adapted according to the needs and functionality of the organisation. This implies the definitions for each TRL will be relevant to the discipline. At the same time, the organisations may choose to use a more suitable name for their scale. For instance, some manufacturing organisations define this scale as "Manufacturing Capability Readiness Levels" (MCRLs). Although a different name is used, the fundamental underpinning is still the same.

From the scale presented above it becomes obvious that as the TRL increases, the criticality of ensuring the technology is accepted and adopted by the workforce becomes a vital element. If for example, the project reaches a TRL 6 or 7, but the ground work to prepare the workforce has not been carried out, then acceptance and adoption are likely to be poor. This could potentially translate to a major financial loss for the company in addition to the negativity and scepticism that is likely to plague any future technological implementation attempts. Therefore, it is important to integrate the key human factors on the TRLs as the project progresses the levels.

An initial attempt to map the key organisational human factors identified by this research on a TRL scale for the successful implementation of industrial HRC is presented in the following section. For the needs of this discussion, the TRL scale shown above will be used, however, the definitions will be adapted to suit the implementation of industrial HRC.

7.1.2 **Human factors mapping on TRLs for the implementation of industrial HRC**

7.1.2.1 **TRLs 1 and 2**

TRLs 1 and 2 are looking at the basic principles of the technology concept and a description/early demonstration of the applicability and validity of the concept. In the context of industrial HRC, it is important to understand the current manual process and how a HRC scenario can be used to optimise the manual process. Therefore, at this stage it is critical to capture the complexity and variability of the manual process. To do this, it implies that shop floor operators will need to participate. It is proposed that at this stage the most experienced operators are invited to participate. This is because the more experienced ones have a greater understanding of the overall process and how is completed. These individuals are defined here as “major users”. The benefits of doing this are twofold:

(i) Experienced operators (i.e. major users) are engaged and feel the organisation values and acknowledge their knowledge. This is likely to make them less reluctant releasing information about how they complete the task.

(ii) A data base is created whereby the manual process variability is recorded. This is a crucial point. It is possible that for some processes no standard operating procedures (SOPs) exist. In some other occasions, SOPs exist; however, operators adapt the procedures to complete the process. Therefore, by doing a human skill capture of the manual process at an early stage will provide vital information regarding the key process variables and the complexity of the process. The outcome of this process will dictate what parts of the process can be automated and what parts of the processes are better retained manual

Figure 7-51 summarises the propositions suggested for TRLs 1 and 2.

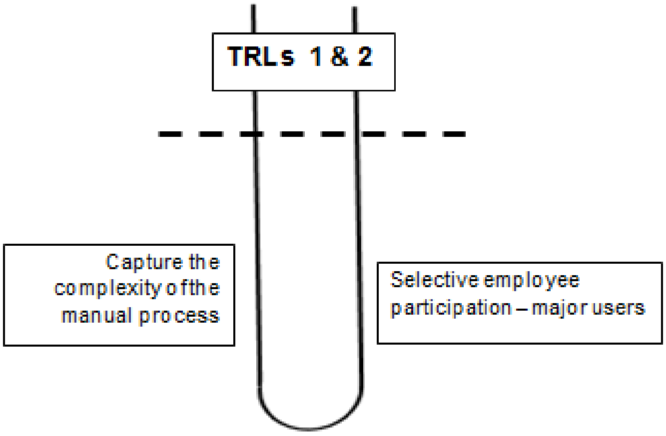


Figure 7-51 Organisational human factors at TRLs 1 and 2

7.1.2.2 TRLs 3 and 4

TRLs 3 and 4 reflect trial tests using representative equipment at laboratory conditions are taking place.

First of all, at this stage the system integrator (SI) will be involved in order to supply the equipment (e.g. industrial robot and any other equipment) and run trials. Therefore, there are two important points to note: (i) SI involvement and (ii) trial execution. To accomplish these, the following suggestions are made:

SI involvement: The SI will need to have a comprehensive understanding of the process to deliver a process capable system. The knowledge gained during the human skill capture (at TRLs 1 and 2) must be passed to the SI. This will enable the SI to understand the complexity of the process. An off-the-shelf industrial robot might not be applicable, particularly if the process to be automated is complicated and requires significant manual input. Therefore, understanding the complexity of the manual process will enable an early discussion between the SI and the development team (company's team assigned to implement the technology) as to how the system can reach a process capable stage.

Trials execution: A selective number of shop floor operators will need to be further engaged at this stage as they will be working closely with the SI to run the trials. First of all since trials will start taking place it is important for operators to participate more rigorously. As before, during these trials it is important to have experienced operators. Therefore, the more experienced individuals (i.e. major users) could be invited to participate and assist the trials which will take place either in-house (i.e. within the company's premises) or externally (e.g. SI's premises). The benefits of this approach are:

- Operators (i.e. "major users") gain ownership of the system and becomes their process rather than thinking of it as "management's pet"
- Their involvement will provide valuable information to the SI and the development team regarding the usability of the system. For example, operators might want a special rack nearby to place tools
- The major users can act as an indirect means of cascading information to the rest of the operators at the working cell. Operators are more likely to be open regarding information coming from "one of their own". Therefore, will reduce scepticism and negativity when the system eventually is brought on the shop floor.

Second, communication avenues with the affected workforce must be initiated. Two major points need to be addressed: (i) who is to do the communication and (ii) what must be communicated.

Who is to do the communication? The communication process can be initiated by the process champion. The process champion is likely to have some knowledge regarding the manual process as well as what is expected in the future process (i.e. in a HRC scenario). This will appear more credible to the employees.

What must be communicated? As discussed in the literature in section 3.2.3, effective communication can be used to provide employees with degree of information as to why, how and when these changes will take place (Wanberg and Banas, 2000). Therefore, it is important to communicate the rationale for the change. According to Jimmieson, Peach and White (2008), communicating the reasons for the change reduces uncertainty while increasing employee personal control over the upcoming change which in turn can generate change-supportive intentions. Shop floor employees need to be aware of why the changes are taking place, when the change is likely to occur and the impact of the change on their work routines. It is understood that in some cases the development team might not have all the answers, however, it is still important to provide as clear information as possible to avoid rumour spreading which can doom the project before it even starts (Smelzer and Zener, 1992; DiFonzo and Bordia, 1998).

Third, at this stage it is also beneficial to begin communicating the need for the change to the union. This is particularly important for unionised environments. In a unionised environment, employees are likely to belong to a union body. In the example of HRC implementation scenario, if, as suggested above, shop floor operators are being communicated information regarding a new technology and are supporting trials, the union representatives will need to know. Lack of communicating to the union will create friction and possible impediment, because the union can potentially influence its members not to support the project. Furthermore, the union, just like the employees, need to be provided with a clear rationale. It is suggested to be provided with the business case indicating the reasons for the change. Also, it is important to communicate to the union an overall plan highlighting what is the likely impact of this change to the workforce. If for instance, shop floor employees are to be deployed to other work areas, then this need to be presented and discussed with the union. Finally, a key aspect is to ensure that the same message is communicated to the shop floor employees and to the union. If contradicting messages are being communicated then this is likely to have an adverse effect.

The propositions for TRLs 3 and 4 are summarised shown in Figure 7-52.

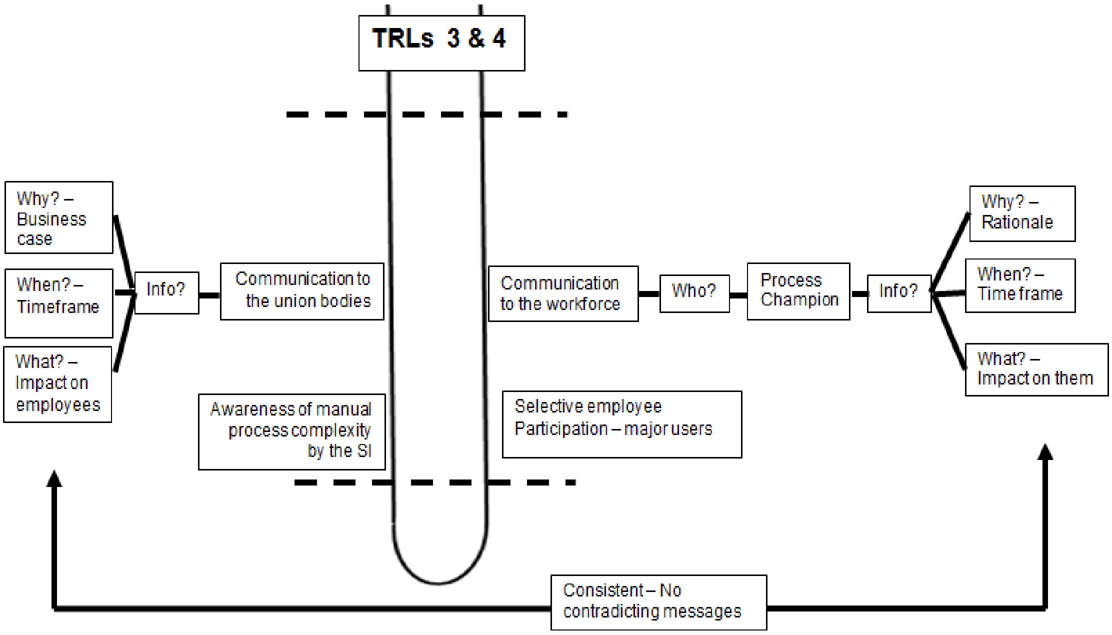


Figure 7-52 Organisational human factors at TRLs 3 and 4

7.1.2.3 TRLs 5 and 6

TRLs 5 and 6 reflect, in a HRC scenario, the capability of the system to achieve satisfactory production rates using actual components. Also, at this stage, the system is likely to be brought to the production facility (i.e. shop floor) and allow a selective number of production personnel (e.g. major users and manufacturing engineers) to operate it. Therefore, at this level we must note the following: (i) significant input from production personnel and (ii) increasing use of the system on the shop floor for trials. The following suggestions are made:

Significant input from production personnel: First of all, at this level, the operational personnel will need to operate the system using actual components to ensure they are satisfied with the system. It is expected that the major users will be involved in this process as before. As the project is essentially at a pre-production phase, a higher commitment and input from these individuals will be needed. Normally, these individuals would be contributing to the production of their work cell. Therefore, as these individuals are spending more time in developing the system rather on the production, it is possible for the production rates to experience a decline. This could potentially lead to frictions between the production leaders and the project's development team (i.e. the team assigned to implement the new technology). As shown by the exploratory case study, this could have a negative impact on the operators involved. To reduce negative concequences, it is suggested for the senior management to have a more visible input. Their input can be shown particularly by allocating the necessary resources (i.e. support from major users and other agents) for the development of the new technology. As discussed in chapter section 3.3.1, senior management can be role models for the rest of the employees and their behaviour and statements can strongly shape employees' beliefs about what is important for the organisation (Neubert, Kacmar, Carlson, Chonko and Roberts, 2008; Kark and Van Dijk, 2007). Therefore, ensuring the necessary resources are provided for the development of the technology will indicate the importance of the project for the entire organisation. If the allocation of these resources will cause an impact of production rates, these need to be identified and discussed. It is crucial for the senior management to have active role at this stage as the project is entering a critical phase. As literature has highlighted, lack of senior management involvement and support will have adverse effects on the successful implementation of the project (Vollman, 1996; Somers and Nelson, 2001; Boyer and Sovilla, 2003).

Second, at this stage it is suggested to initiate an operator empowerment plan. This will indicate the level of operator control over the system during failures, errors and/or deviations. Literature presented in section 3.3.3, indicated that when complex automated systems are introduced a flexible-oriented strategy, whereby operators are empowered to make decisions, is more appropriate (Zammuto and O’Connor, 1992; Wall, Cordery and Clegg, 2002). Operator empowerment will aid operators to gain ownership of the system and understand its operation, rather than passively monitor and call for expert during events. It is acknowledged that some organisations can be strictly hierarchical where decision-making is given to higher levels, such as manufacturing engineers or production managers. However, for the implementation of industrial HRC it is vital to dissipate control in the decision-making to the individuals who will be working with the system daily. This will enable greater acceptance. At the same time, it is understood that empowerment will take place in a controlled manner through an official plan where a list of steps are outlined during abnormalities. As suggested in the literature, flexible-oriented and control-oriented strategies can be used to complement each other (Quinn, 1988; McDermott and Stock, 1999). Therefore, a reaction plan can provide a structured approach to abnormal events and can be complemented with enhanced operator control. In addition, the level of control could be discussed with the major users. Their input could be helpful to develop the reaction plan.

Increasing use of the system on the shop floor for trials: The increasing trial use of the system will inevitably attract attention from the rest of the shop floor employees, particularly if the factory does not have any previous history with automated systems. At this point it is vital to continue the communication to employees. As suggested at TRLs 3 and 4, employees need to be communicated why this change is taking place, when will it happen and what is the impact on their daily jobs. It is vital to continue communicating these messages to ensure employees are aware and prepared, as much as possible, for the upcoming change.

Second, at this stage it is suggested to develop a training programme for the rest of the workforce operating the system. This will allow them to engage with the system at an early stage and gain confidence. In addition, the training can be also be used as a means of gaining further participation. This will make the new technology more accessible rather than feeling it is being hidden in fear of resistance. It is proposed that the major users are used to deliver part of the training. This has two benefits: (i) major users are feeling valued for their input which has a positive impact on their morale and (ii) as discussed before, operators are more likely to accept the system this, if "one of their own" is giving them the knowledge.

Finally, it is suggested that the union bodies are involved more significantly. This can be through walk-through whereby they observe the activities taking place for the development of the system. Also, it is suggested that the senior management are engaged in the communication process with the union. This can assist to show the significance of the project for the organisation while at the same time keeps the union in the loop which in turn enables acceptance of the system.

The propositions suggested for TRLs 5 and 6 are summarised in Figure 7-53.

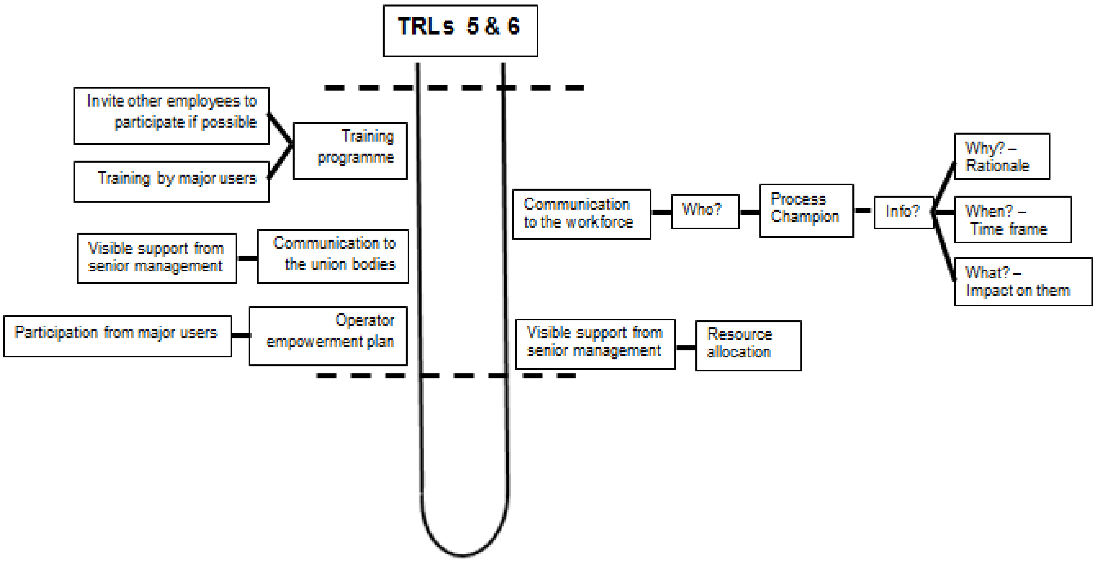


Figure 7-53 Organisational human factors at TRLs 5 and 6

7.1.2.4 TRLs 7, 8 and 9

The latter three stages of the TRLs reflect the state where the system has proven its capability and the process is qualified for production use. At this final phase, there will be significant more involvement from the majority of the production personnel. First of all, the operator empowerment plan needs to be established. This approach will assist operators to understand what is expected from them in this new role. Also, as the system is new it is possible to experience abnormal events. Therefore, through the experience gained during these events, the operator empowerment plan can be updated accordingly making it a live document.

Second, because a new manufacturing method is being used, it is expected that uncertainty will be high. It is important for the senior management to show their support in their employees. This can be done with open communication and regular updates from management individuals in an attempt to understand any production issues. At the same time, in a unionised environment, the communication between senior management and union needs to continue. The union can communicate to the senior management employees' concerns regarding the new manufacturing method.

Figure 7-54 summarises the mapping of the organisational human factors at TRLs 7, 8 and 9.

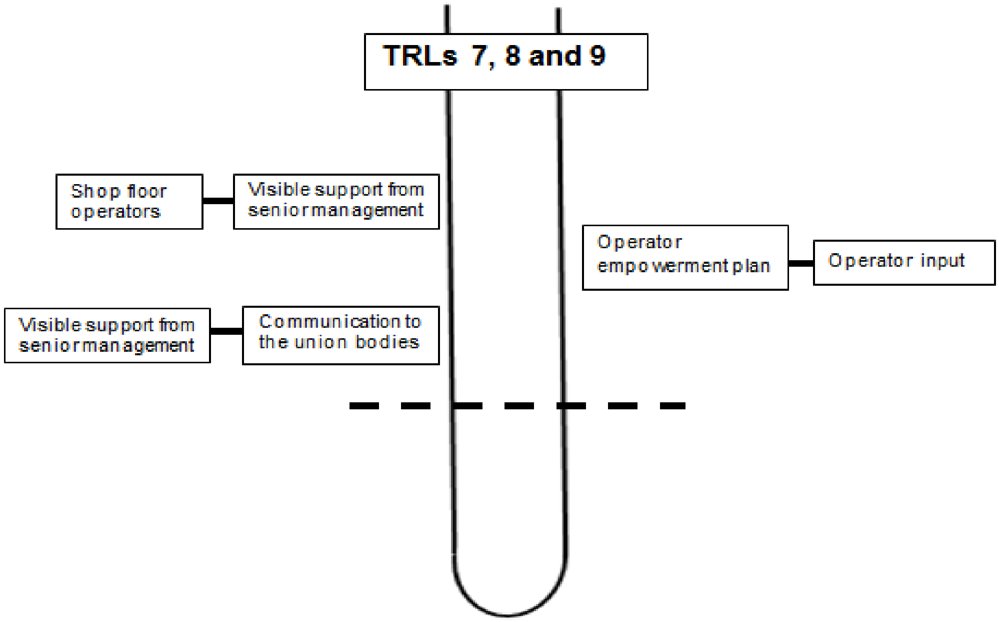


Figure 7-54 Organisational human factors at TRLs 7, 8 and 9

7.1.2.5 Summary for Part A of the HFGT

This section presented the key organisational factors identified by this research on a TRL scale for the successful implementation of industrial HRC. The aim is to provide practitioners with a concise tool that will not only indicate the key organisational human factors that need to be considered for the implementation of industrial HRC, but also highlight when and what kind of action is needed at different TRLs. An overall schematic for part A of the HFGT showing the key organisational factors across all TRLs is provided in Appendix W.

This tool can be utilised according to the organisations' needs. For instance, while in a large manufacturing organisation union influence can be an important factor to consider; in a smaller sized organisation union might not exist. Therefore, the tool can be adapted accordingly making it attractive not only to large manufacturing firms but to small and medium enterprises.

7.2 Part B of the HFGT – Inter-relations between organisational level human factors and the trust scale

The second part of the tool is presented in this section. Taking the evidence as a whole it appears that there is an inter-relation between some of the factors at the organisational level and the developed trust scale.

At the organisational level, two of the key human factors that emerged were: (i) provision of training of to the workforce and (ii) operator empowerment. These two factors can be utilised along with the developed trust scale to provide a tool with which operators' trust levels in the robotic teammate can be continuously calibrated. This part of the tool consists of two sub-parts which are inter-linked:

- sub-part 1 discusses how the trust scale can be utilised in an initial training programme to assist operators' initial trust calibration. The benefits of this proposition are presented section 7.2.1.
- sub-part 2 discusses how operator empowerment is vital for continuous trust calibration which in turn will dynamically optimise operators' trust in the robotic teammate. The benefits of this proposition are presented in section 7.2.2.

Finally, the propositions discussed in sections 7.2.1 and 7.2.2 are summarised into a guiding framework for practitioners in section 7.2.3.

7.2.1 Sub-part 1 – Operator training programme to assist initial trust calibration

To describe how training can be used to influence operator trust calibration in the robotic teammate, the literature from mental models will be used Section 5.2.1.2.2 (“Factors associated with the human”), discussed, among other, that mental models are frameworks used by humans to help understand and interpret the world (Johnson-Liard, 1983). When humans interact with an entity (e.g. robot), mental models are used to assist the user perceive and interpret the entity’s intentions and actions (Phillips, Ososky, Grove and Jentsch, 2011). At the same time, it was discussed that humans tend to have incomplete or even inaccurate mental models (Ososky, Sanders, Jentsch, Hancock and Chen, 2014). In an industrial HRC scenario humans will be requested to share the same workspace and collaborate with an industrial robot to complete a task. An inaccurate or incomplete mental model can potentially lead the human operator to either overestimate or underestimate the abilities of the robotic teammate. This has been described in the literature as misuse (i.e. overestimation) and disuse (i.e. underestimation) (Parasuraman and Riley, 1997). Both can be equally detrimental. The key is to achieve appropriate trust calibration. To calibrate appropriate trust in the robotic partner, it is vital for the human to hold a sufficiently developed mental model of the robot, whereby robot’s capabilities are acknowledged (Ososky, Schuster, Phillips and Jentsch, 2013). Therefore, to assist future human operators develop a sufficient mental model of their robotic teammate; it is proposed to incorporate the trust scale findings in an operator training programme.

The aim of this training programme would be to provide operators with an understanding of the robot’s abilities and limitations, rather than simply understanding how to use the robot to complete the process. This approach can help operators develop an appropriate mental model of the robot they will be requested to collaborate with. For instance, a key trust factor identified in the trust scale is the “perceived robot and gripping mechanism reliability”. Does it mean that if the robot or the gripping mechanism is not 100% reliable all the time they are useless? Section 3.4.5 (“Effects of automation reliability”) discussed that automated systems are not perfectly reliable due to technological limitation and/or due to software and hardware failures (Wickens, Huiyang, Santamaria, Sebok and Sarter 2010). Therefore, in a HRC scenario it is expected that at some point, the robotic teammate’s performance (i.e. the robot itself and/or the gripping mechanism) will be less than perfect. As Ososky and colleagues (2013) have proposed, appropriate trust calibration is primarily influenced by the “*human’s mental model of the robot’s ability and limitations, than the ground-truth reliability of the robot itself*” (p.63). In other words, perception and reality are not necessarily the same and, as suggested by Merritt and Ilgen (2008), trust can be heavily driven by user’s perception of the robot irrespective of whether this perception is correct, partially correct or completely incorrect. Therefore, an initial training programme, before the implementation of the robotic system, could be used as a strategy to raise operators’ awareness regarding the ability and limitations of the robot and assist matching operators’ perceptions with the system’s actual capabilities. Madhavan and Wiegmann (2007) indicated that optimal trust levels can be achieved when the users’ perceptions of machine characteristics reflect the actual machine characteristics. Lack of this knowledge will leave the operator with an incomplete mental model which in turn will make the robot’s actions (or inactions) unpredictable thus significantly reducing trust in the robotic partner.

An additional key point in this discussion is how the training programme can accommodate for individual differences. Each individual will have different propensity to trust others (Rotter, 1967). Therefore, not all operators will start from the same point. This is a promising area for future work and will be further discussed in chapter 8.

Summary

In summary, an initial training programme incorporating the key system characteristics as identified by the trust scale will assist operators make an initial trust calibration. However, when the robot is in production, the subsequent collaboration will require operators to update their mental model of the robot and recalibrate their trust based on the collaboration exposure. This can be achieved through operator empowerement. The following section describes how operator empowerement can be used to continuously recalibrate operator trust in the robotic teammate after implementation and use.

7.2.2 Sub-part 2 – Operator empowerement is key to enable continious trust calibration

To describe this, the mental model theory will be used again. Section 5.2.1.2.2 ("Factors associated with the human"), discussed that the development of mental models is a dynamic process and these models are refined through continuous interaction (Ososky, Schuster, Phillips and Jentsch, 2013). Similarly, section 5.2.1 ("Trust review") indicated that trust development is not static. As Merritt and Ilgen (2008) highlighted, trust evolves over time from dispositional (i.e. upon first encounter) to history-based trust (i.e. cumulative collaboration). As this transition occurs, users retrieve history-based mental models to interprete the actions of the system they are working with. Therefore, if the mental models created during the subsequent exposure (i.e. history-based) are not sufficiently developed, this is likely to lead to trust miscalibration. In an industrial HRC scenario, the more operators are collaborating with a robot, the more likely it is to experience a variety of real failure, errors or system deviation scenarios (particularly during the early stages of implementation). While these events occur, it is vital for operators to understand the sources of these events and the possible outcome of these events (whether a failure, error, or deviation). Also, through exposure they will be in a position to identify factors that deminish or enhance the robot's ability to perform as well as detect cues that suggest a potential malfunction. According to Ososky, Sanders, Jentsch, Hancock and Chen (2014) trust can be calibrated by providing an accurate understanding of the factors that may lead the robot to fail and the outcomes of those failures. To leverage this potential and enable effective HRC, it is proposed that operator empowerement can be a key strategy.

Operator empowerement was found to be one of the key enabling organisational humans factors in the exploratory case study in chapter 4. Literature has suggested that, in a highly complex system, higher operator control and empowerement once the system is implemented will lead to operators understanding the new system and task requirement much better (Wall, Cordery and Clegg 2002). Through operator empowerment, operators' already established mental model of the robot (from the initial training programme) will be updated based on their history of collaboration. If on the other hand, operators are not empowered but an expert is called (e.g. manufacturing engineer) without the operators being involved, then operators are likely to be alienated from the system. This will not only turn operators into "button-pushers" which as shown in section 4.2.4 ("Results of the exploratory case study") will reduce system acceptance, but will also reduce their ability to develop an in-depth understanding of the system's source of events (i.e. failures, errors, deviations). Subsequently, their ability to recalibrate their trust is reduced leaving them with an incomplete mental model.

This is not to say that experts (e.g. manufacturing engineers and/or robot experts) should not be involved. As described in the exploratory case study in chapter 4 operator control over the system will not be "all or nothing". A reaction plan will be issued which will highlight the necessary steps according to the events. However, it is crucial, at all stages for the operators to be involved rather than simply turn into passive monitors of the system. This will enable them to obtain a greater understanding and awareness of the source of the event, thus making the system more transparent and understandable.

Finally, the knowledge gained by the operators, can then be passed into the training programme. Then, the training programme of future novice operators will be updated with real event scenarios. Subsequently this will accelerate appropriate trust calibration of novice operators during the initial training programme by enabling greater match between their perceptions of the system and the actual system's capabilities.

7.2.3 Schematic representation for practitioners

The propositions suggested in sections 7.2.1 and 7.2.2 can be merged in a schematic (Figure 7-55) which can be used as a guiding framework by practitioners. For clarity purposes, the remaining organisational human factors have not been included in this schematic.

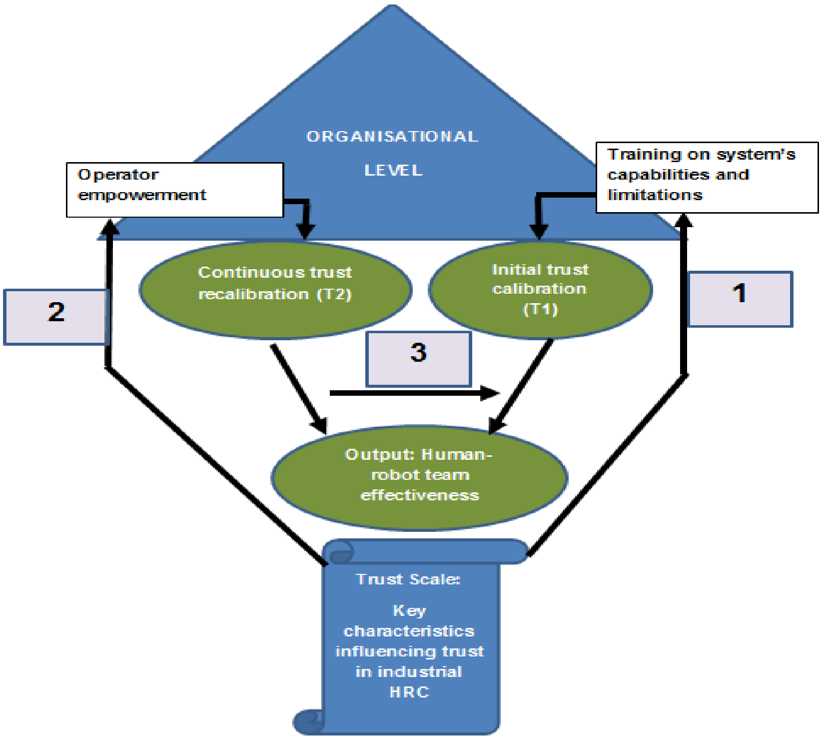


Figure 7-55 A guide for calibrating appropriate levels of operators' trust

The schematic has three key phases, each of which is described below:

Phase 1

Phase 1 takes place when the system is still at a pre-production stage (e.g. TRLs 5 and 6). Phase 1 suggests that the operators selected to use the robot (e.g. major users) receive training not only on how to use the robot to complete the task, but also to understand the system's capabilities and limitations as highlighted by the trust scale (i.e. perceived robot's motion; perceived robot and gripping mechanism reliability; perceived safe cooperation). This in-depth training can be provided by the system integrator (i.e. robot supplier). The training will assist operators to shape their expectations and make an initial calibration of their trust in the system (e.g. T1 on the schematic). As operators spend more time collaborating with the robot, the experience gained during this time will start shifting their trust to history-based. Any experienced robot failures, errors or deviations will influence their mental model formation. The more they collaborate with the robot the more they will retrieve these history-based events to make sense of the robotic teammate. If their dynamic mental model formation is incomplete or innacurate, then this will result in trust miscalibration which will eventually be reflected in the effectiveness of the team. For this reason, the second phase of the schematic suggests that operator empowerement is crucial.

Phase 2

Empowerement will allow operators to understand the reasons behind the events, helping them to form an accurate mental model of the robot. Table 7-40 shows how empowerement can serve as a vehicle for operators to achieve an accurate mental model of the robot based on historic events.

Table 7-40 Dynamic trust calibration through operator empowerment

Event	Existing operator mental model is challenged by the event	Action	Why did it happen?	Operator new mental model of the robot	Operator trust in the robot
Robot produces an error – it stops operating	"*I thought it was reliable … It never did this before – I wonder why…is something wrong with it?*"	Operator becomes involved in the rectification	E.g. Component mispositioned on the fixture – Understand how the robot "reads" the position of the component	"*This robot is very sensitive to material positioning - I must inspect more carefully the positioning of the component on the fixture*"	Trust is recalibrated based on this event.

Assume the robot produces an error and stops operating (first column of the table). This anomaly, challenges operator's existing mental model of the robot operating reliably (second column of the table). Operator is empowered to take rectification action and/or be part of the recovery process (third column of the table). This assists the operator to understand the source of the error as well as understand how the robot’s system operates (fourth column of the table – how it “reads” the position of the component). This new knowledge assists the operator to mould a new mental model based on this event (fifth column of the table). Subsequently, his or her trust in the robotic teammate is recalibrated. If for example, the “Action” (third column) did not take place, then the operator would not be in a position to understand the reason for the error, hence leaving them with an outdated mental model. Subsequently, the operator will attempt to update their outdated mental model based on their perception, potentially leading to trust miscalibration.

Phase 3

Finally, in phase 3, the knowledge gained by the exposure is fed into the training programme which will then be used to accelate appropriate trust calibration for future novice operators.

7.3 Chapter summary

To meet the overall aim of this research, this chapter gathered the findings from chapters 4 and 5 to provide the human factors guiding tool to leverage the successful implementation of industrial HRC. Section 7.1 presented a set of propositions for implementing the key organisational human factors using the TRLs. These propositions provide guidelines as to how and when the identified organisational human factors must be considered in the implementation timeline.

Section 7.2 presented the inter-relations between some of the factors at the organisational level and the developed trust scales. This led to the development of a proposed framework for practitioners to consider. This guiding framework aims to assist operators to continuously calibrate appropriate levels of trust in the robotic teammate through training and empowerment.

8 FUTURE WORK AND LIMITATIONS

As with any research, some limitations were identified. However, these limitations provide fertile ground for future work to enhance understanding for the influence of human factors in industrial HRC. Future research avenues and limitations for each level (i.e. organisational level human factors and trust scale) are discussed in sections 8.1 and 8.2 respectively. Also, section 8.3 presents future work for further development of the HFGT.

8.1 Organisational human factors

The work carried out for identifying the key organisational human factors was based on a single exploratory case study. Although the findings of this case study provided an indication, a single case study cannot provide robust and generalisable results. This is a limitation of this research and the reasons were outlined in section 4.2.7. At the same time, this limitation opens an avenue for future work.

Future work needs to be geared towards collecting data through additional case studies. It would be particularly beneficial to collect data from a variety of manufacturing organisations across various disciplines. The benefits of this would be twofold:

(i) Further development of the organisational survey

The developed organisational survey for quantifying the key organisational human factors (described in section 4.3) was based on the key findings of the exploratory case study. Therefore, expanding the data pool would allow researchers to modify/enhance the organisational survey hence enabling to quantify the key organisational human factors.

(ii) Identify any factor variability between large organisations and small and medium enterprises or between organisations across different manufacturing disciplines

The data collection for the exploratory case study took place in a high value aerospace manufacturing organisation. However, some of the key organisational human factors identified by the case study may not be applicable to a smaller size organisation or in an organisation from a different manufacturing discipline. For instance, capturing the complexity of the manual process prior to automating can be a key factor for a high value manufacturing organisation which produces complex components requiring heavy manual input for high risk industries (e.g. aerospace components). However, this factor could possibly not be relevant for a smaller manufacturing organisation which produces much simpler and standardised components (e.g. food industry). If the human factors tool developed by this research is to be attractive and useable to a variety of manufacturing organisations, it needs to accommodate for these differences. Therefore, collecting data from a variety of organisations (i.e. size and discipline), would complement the existing work by making the tool more adaptable according to the organisation's needs.

Finally, through this research it became obvious that obtaining access to collect data is a time consuming process. Although this is a limitation we have to accept, future work could be geared towards informing manufacturing organisations, not only about the benefits of industrial HRC, but also about the significance of considering human factors to successfully implement the concept. Simply rolling industrial robots on the shop floor does not guarantee workforce acceptance and effective collaboration. The HFGT presented in chapter 7, can be utilised by human factors practitioners as a springboard to highlight how such a human factors tool would enable successfully implementation of industrial HRC. This could potentially gain greater buy-in from manufacturing organisations thus allowing additional case studies.

8.2 Trust in industrial HRC

To understand how trust develops between human workers and industrial robots, a psychometric scale to measure trust in industrial HRC was developed in chapter 5. Some limitations have been acknowledged which at the same time can be used as topics that future work can expand upon.

First of all, to the researcher's knowledge, no scale exists which measures trust specifically in industrial HRC (as described in section 5.2.1.3, other trust measures exist but are not relevant to the industrial domain). Due to the exploratory nature of this attempt, it was deemed appropriate to employ a convenient sampling approach. Hence, the sample population used came from a student population. The majority of the recruited individuals did not have extensive experience working with industrial robots or automated systems. Therefore, it could be argued that the developed trust scale is not suitable for individuals with extensive experience working with industrial robots or automated systems. This limitation was acknowledged, and in response, a small scale validation study was carried out (section 5.2.6) where trust scores of SMEs were collected after taking part in a human-robot trial. Results indicated that the SMEs' average rating for each of the items and the average trust score did not greatly differ with the average response recorded for each of the case studies. However, as the small sample size of this study does not allow for any statistical analysis to be performed, future work could be directed towards a larger sample size validation study using SMEs. This will then allow for statistical analysis to be carried out quantifying effects at a statistical significance level, thus producing more concrete conclusions.

Second, future work can investigate each of the trust subscales (i.e. perceived safe cooperation, perceived robot and gripping mechanism reliability and perceived robot's motion) separately. For instance, the reliability of the robot and the gripping mechanism is a key trust element. It would be beneficial to understand how trust is affected at different reliability levels (e.g. 100%, 70% 50%). This could potentially indicate a trust threshold below which trust drops significantly. Similarly, it would be advantageous to understand further how an industrial robot's motion profiles influence trust. This would provide valuable information to system designers and automation specialists.

Third, future work could utilise the propositions made in section 7.2 to enhance their usability. It was suggested that the developed trust scale could be incorporated in an operator training programme to assist operators' initial trust calibration. For instance, research could investigate the impact on trust scores between participants who are given some initial training regarding the capabilities and limitations of the robot (i.e. calibrate their trust before collaborating) and participants who have not been given the same information. Research in this avenue could indicate whether making humans aware of the robot’s abilities and limitations, can mitigate severe trust drops due to robot’s poor performance.

Fourth, in this work individual differences, and specifically propensity to trust, were not accounted for. Propensity to trust, which is a stable trait-like tendency, can have some degree of influence to the overall trust score. Future work can complement the developed trust scale by incorporating Rotter’s (1967) interpersonal trust scale. This would provide a holistic trust package which would allow for comparison between individuals with different levels of initial trust.

Fifth, drawing from the fourth point above, the training programme proposed in section 7.2 can be adapted to accommodate for individual differences. For example, each operator will have a different propensity to trust. Therefore, not all operators taking part in the training programme will have the same initial trust. This implies that the required time for each operator to appropriately calibrate their trust in the robot will vary. Therefore, by capturing individuals’ propensity to trust can assist the customisation of the training programme according to the individuals’ needs. This would allow for all operators to calibrate their trust in the robotic teammate in a timely manner.

Finally, for the development of the trust only one robot had higher degree of anthropomorphism (section 5.2.4.2.4.2 “Case study 2”). Future work could be directed to utilise the scale on robots with higher level of anthropomorphic features such as, head and facial characteristics. This could potentially enhance our understanding on the relationship between human workers and anthropomorphic industrial robots.

8.3 Further development of the HFGT

Future work could be directed towards further development of the HFGT. For instance, the developed HFGT could be used by system designers and automation specialists. The benefits of practitioners utilising the HFGT on real case studies would be twofold:

(i) A database will be created with which the usability and applicability of the tool can be assessed. The output of this would enable to understand whether the tool can be adapted or modified thus optimising its usability. Furthermore, by utilising the HFGT across different manufacturing disciplines would allow the tool to be customised according to the organisations' needs.

(ii) Further use of the HFGT would enhance our understanding as to how human factors can be integrated on the TRL scale. To data, human factors are not incorporated on the scale and the developed tool made a subjective attempt to answer this question. Therefore, further use of this tool would provide more a more concrete picture as to when the key human factors need to be considered on the TRL scale.

Such as attempt would have profound implications, as it would provide a holistic understanding of the human factors for the successful implementation of industrial HRC.

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APPENDICES

Appendix A Interview schedule

Themes

Worker involvement / Union involvement / Process champion present

Can you describe what steps were taken to introduce the automation on the production line?

- Probe: People from different departments involved? (HR, Quality,Eng, Operators)
- Probe: Who was co-ordinating the people involved? – at which stage?
- Probe: What were his/her responsibilities?
- Probe: To what extent were the operators involved? – at which stage?
- Probe: Were any 3rd parties involved during the introduction, such as the unions?

Senior management involvement

To what extent was the top management personnel involved (senior)?

- Probe: How were they involved?
- Probe: Which stage?
- Probe: How did you feel about this?

Employee training

What type of training, if any, did you receive regarding the use of the automation?

- Probe: Who provided the training?
- Probe: Duration?
- Probe: Was the HR department involved?

Organisational structure and culture (flexibility versus control)

If there is a break-down of the automation, what steps do you take to rectify?

- Probe: Is this the usual practice?
- Probe: Are you constrained by company rules and regulations?

Communication to the workforce

Can you tell me how the new automation system was communicated to the workforce?

- Probe: Aware about the new system?

Probe: How did it affect you?

Appendix B Participant information sheet

My name is George Charalambous and I am a doctoral researcher at Cranfield School of Integrated Systems.

The aim of my project is to explore the human factors for the implementation of automated systems.

You have been selected for this study because you have been involved in the implementation of an automated system.

I am interested to collect data regarding the experience you have had during the implementation. To do this I need to collect data through an interview.

The interview generally takes place in approximately 30-40 minutes. (***Personal note***: clarify if the interviewee is comfortable with the duration of the interview in terms of her/his schedule).

To assist data analysis, I would like to record this interview. I would like to stress that the information from this interview will be kept confidential and will not be used for another purpose. Your name (or your organisation's name) will not be mentioned without your consent in any of the analysis or resultant publications. Data collected will be stored and maintained by Cranfield in accordance with the University's Ethical Code and the Data Protection Act (1998).

Also, you can stop the interview at any moment without having to give a reason.

Are you comfortable with us recording the interview? (*if* **YES** proceed to the interview, *if* **NO** thank the participant and stop the process).

Appendix C Participant consent form

RESEARCH PROJECT INTO HUMAN-AUTOMATION COLLABORATION

PARTICIPANT CONSENT FORM

I fully understand the purpose of this research and I agree to participate in an interview.

I understand that the data generated will be used for research purposes only.

I agree to the interview being tape recorded for transcription later.

I agree to possible direct quotes from my responses given during the interview being used in a written report, although they will not be traced back to an individual.

I understand that I may stop the interview at any time, without having to give a reason.

I understand that I may withdraw my data from the study up to seven days after this interview. After seven days, all data will be pooled and it will not be possible to withdraw my data.

PRINT NAME: ________________________________

SIGNED: ____________________________________

DATE: ______________________________________

Appendix D Participant demographic form

Participant Reference Number: ______________ **Date:** ______________

1. **Sex:**

   Male________ Female________

2. **Please state your nationality?** ________________________

3. **Please state your highest educational level:** ________________________

4. **Please state your age:** ________________________

5. **Please state how many years you have been at your current role:** ________

6. **Are you considered:**
   experienced / under development / novice operator? ____________________

Appendix E The developed survey

Cover letter

My name is George Charalambous and I am a doctoral researcher at Cranfield University working on the development of a design framework for the implementation of human-robot collaborative systems. I am sending you this survey as I am trying to collect information that will give me an understanding of factors that are important for successful implementation of automation, as I understand you have been / are currently involved in such development projects.

The survey requires you to tick the boxes and in some occasions write responses in the spaces provided – this is because this is an exploratory stage of my research so I need to ask open questions. I realise this will require some of your time but I would be very grateful if you would write as much as you can to describe things to me.

For anonymity purposes a participant number has been provided at the top of the next page. This is to stress that your individual responses will be anonymised and personal details will not be shared. All data will be stored and maintained by Cranfield in accordance with the University's Ethical Code and the Data Protection Act (1998).

Finally, I would be very grateful if you would agree for me to contact you after the survey if necessary for purposes of clarification or elaboration, for a short telephone discussion at a mutually convenient time. If so, please tick the box below.

Thank you for your participation.

Contact Details:

Name: George Charalambous Email: g.charalambous@cranfield.ac.uk.

I agree that the researcher may approach me after submitting this survey for a short telephone discussion at a mutually agreed time **(**please tick the box**)**	

Participant Number: ______

Based on your experience in the implementation of automation in general, please answer the following questions:

1. How is the automation of a manual process communicated to the operators?

2. Who in the workforce receives training in using the automation? (*Tick all that apply*)

☐ Shop floor operators

☐ Support agents (e.g. Manufacturing engineers, maintenance etc.)

☐ No training provided

☐ Other: ____

3. In your experience, when a manual process is being automated does a manual skill capture process take place? (*Tick one*)

☐ Yes

☐ No

☐ I don't know

☐ Other: ____

4. When a manual process is being automated, are operators asked to participate (*input their knowledge and ideas*) in the implementation of automation? (*Tick one*)

☐ Yes, they participate since the concept phase

☐ Partly participate (state at which project phase:______________________)

☐ Do not participate

☐ Other:____

5. Based on your experience, is there a project champion involved during implementation of automation (*an individual who is an automation expert and can co-ordinate and supervise the implementation process*)? (*Tick one*)

☐ Yes

☐ No

☐ Other: ____________________________________

6. If there is a problem/malfunction with the automation, how is the problem rectified by operators? (*Tick one*)

☐ Operators must follow formal procedures and call for expert support (e.g. Manufacturing engineers)

☐ Operators are empowered to rectify within their level of knowledge

☐ Other: ____

7. In your experience, please indicate the importance of senior management support for the implementation of a new automated process.

☐ Very important because: ____
____

☐ Less important because: ____
____

8. How is the introduction of automation received by the local union?

9. In your experience, please state the three major enablers and the three major problems when implementing a new automated process.

The three major enablers are:	*The three major problems are*:
1.____________________________	1. ____________________________
2.____________________________	2. ____________________________
3.____________________________	3. ____________________________

Appendix F Electronic mail sent to SMEs

Dear (*name of the participant*)

My name is George Charalambous and I am undertaking my PhD at Cranfield University investigating the human factors in the implementation of human-robot collaborative systems.

Following (*name of the liaison at industrial sponsor*) email I would like to thank you for taking part in this survey. The survey attached is attempting to collect information regarding factors that are important for successful implementation of automation, and your experience will be valuable.

I would like to highlight that data will be anonymised and for this purpose a unique reference has already been provided in the document attached.

I would be grateful if you could complete and send back the survey in order to analyse data. Your support will be appreciated.

If further information is required, please feel free to contact me.

Kind regards

George Charalambous

Appendix G The quantitative questionnaire

Introduction

My name is George Charalambous and I am a doctoral researcher at Cranfield University working on the development of a human factors framework for the implementation of human-robot collaborative systems. I am sending you this survey as I am trying to quantify the factors that are important for successful implementation of automation, as I understand you have been involved in such development projects.

The survey requires you to simply rate the significance of fifteen (15) statements for the successful implementation of automation based on your experience using a five-point scale ranging from: 1 (very low) to 5 (very high). To complete the survey, please read each statement and the check (X) the preferred box on the scale underneath the number. Once you have completed the survey, save it and send it back to the email given below.

For anonymity purposes a participant number has already been provided at the top of the next page. This is to stress that your individual responses will be anonymised and personal details will not be shared. All data will be stored and maintained by Cranfield in accordance with the University's Ethical Code and the Data Protection Act (1998).

I realise this will require some of your time but I would be very grateful if you could complete the survey and return it.

Thank you.

Contact Details:

Name: George Charalambous *Email*: g.charalambous@cranfield.ac.uk

Participant Number: _____

Demographic information

Sex: ______________

Age**:** ______________

Brief description of the type of automation implementation(s) you have experienced? ______________________________________

Type / size of organisation in which the automation was implemented? ____

Position held during automation implementation: ______________

Geographical location

- If UK (Please specify location)**:** ______________

If overseas (Please specify country): ______________

Based on your experience of implementing automation, please indicate whether the following have had a significant impact on the success of the implementation (1-very low to 5-very high). To complete the survey, please read each statement and then check (X) the preferred box on the scale underneath the number.

1. Advance communication of the new automation to the workforce

1	2	3	4	5
Very low	Quite low	Neutral / NA	Quite high	Very high

2. Explaining to the workforce the rationale for automating the process

1	2	3	4	5
Very low	Quite low	Neutral / NA	Quite high	Very high

3. Providing training to the workforce on the automation prior to installation/ implementation

1	2	3	4	5
Very low	Quite low	Neutral / NA	Quite high	Very high

4. Skill mapping (capturing operators' skills developed through experience) of the original manual process at an early stage

1	2	3	4	5
Very low	Quite low	Neutral / NA	Quite high	Very high

5. Operator participation at concept/design phase

1	2	3	4	5
Very low	Quite low	Neutral / NA	Quite high	Very high

6. Operator involvement during installation/implementation of the system

1	2	3	4	5
Very low	Quite low	Neutral / NA	Quite high	Very high

7. Close collaboration between system integrator/supplier (external) with the onsite development team (internal)

1	2	3	4	5
Very low	Quite low	Neutral / NA	Quite high	Very high

8. Providing system integrator with a comprehensive understanding of the manual process

1	2	3	4	5
Very low	Quite low	Neutral / NA	Quite high	Very high

9. Having a process champion (an individual who understands the technology to be implemented and can motivate people to accept it) assigned within the company during implementation

1	2	3	4	5
Very low	Quite low	Neutral / NA	Quite high	Very high

10. Senior management commitment to the project in evidence

1	2	3	4	5
Very low	Quite low	Neutral / NA	Quite high	Very high

11. Senior management allocating appropriate human/operator resources for the development of the new automated system

1	2	3	4	5
Very low	Quite low	Neutral / NA	Quite high	Very high

12. Giving operators some control over system monitoring and decision making when the new automated system deviates from normal operating conditions

1	2	3	4	5
Very low	Quite low	Neutral / NA	Quite high	Very high

13. Justification of the new automation to the union

1	2	3	4	5
Very low	Quite low	Neutral / NA	Quite high	Very high

14. Involving union representative(s) at concept/design phase

1	2	3	4	5
Very low	Quite low	Neutral / NA	Quite high	Very high

15. Involving union representative(s) during system installation/implementation

1	2	3	4	5
Very low	Quite low	Neutral / NA	Quite high	Very high

Thank you for your participation in the survey

Appendix H Electronic mail sent for distributing the questionnaire

Dear (*name*),

My name is George Charalambous and I am a doctoral student at Cranfield University. I am working on the development of a human factors framework to assist the implementation of human-automation collaborative systems in manufacturing. The reason for emailing you is because of your company's expertise in the implementation of automation.

To accomplish the aim of the research, I have developed a short questionnaire (please see attached) as I am trying to quantify the factors that are important for the implementation of automation. I believe your company's experience in the field will be of great help. I am interested to collect data from automation project managers who have been involved in such development projects.

The questionnaire requires the participant to rate the significance of fifteen (15) statements for the successful implementation of automation. All data is anonymous and will be stored and maintained by Cranfield in accordance with the University’s Ethical Code and the Data Protection Act (1998).

I am aware of your busy schedule; however, I would appreciate it if you could complete the survey and return it back. If you have any further queries, please feel free to contact me.

Yours sincerely

George Charalambous

Appendix I Participant information sheet for the exploratory human-robot collaboration study

My name is George Charalambous and I am a doctoral researcher at Cranfield University studying on human factors in industrial human-robot collaboration. As part of my study, I am currently conducting an exploratory human-robot collaboration study. The study will take place at aero structures group robotics laboratory and will take approximately 25-30 minutes.

Would you be interested to take part?

If No: Thank you very much for your time

If Yes: Thank you for your participation. Before I take you to the laboratory and to comply with Cranfield University's ethics policy, I would like to take a few moments to inform you about the experiment and your rights:

- You will collaborate with two robots, one at a time, to complete a simple pick and drop task. You will observe a short demonstration in a few moments.
- At the end of each task there will be a short interview to collect your thoughts regarding the interaction with each of the robots.
- Full risk assessments have been carried out and approved by the head of the department of Integrated Systems
- The experiment will be supervised by the laboratory technician and myself.
- To ensure confidentiality during the interview process, an ID number will be used.
- The interviews will be audio recorded for subsequent analysis (*Personal Note: Ensure the participant is comfortable to have the interview audio recorded*)

- Any data collected will be anonymous and will be stored in accordance with the University’s Ethical Code and the Data Protection Act (1998)
- You have the right to stop the process at any time without having to give a reason
- You have the right to withdraw your data up to seven days after today. After seven days, the data will be pooled and will not be able to withdraw
- The researcher’s details will be provided at the end of the experiment

Are you comfortable to proceed?

If No: Thank you very much for your time

If Yes: Provide the participant with the consent form, the ID number and demographics form. Proceed to the laboratory.

Appendix J Interview schedule for the exploratory human-robot collaboration study

Section	Main Question	Probe
Introduction	Can you talk to me about your first thoughts regarding the interaction with this robot?	Why did you feel this way?
Robot related	Did you feel you could rely on the robot to hand you over the components safely?	Why?
	Can you talk to me about the robot's ability to hand you the components?	Why? Can you tell me more?
	How did the appearance of the robot influence your trust?	Why?
Safety	Did you have any concerns when you interacted with the robot?	What? Why?
Other topics	Considering the task you have just completed, what has encouraged you to trust the robot?	Can you talk to me more about this?
	Is there anything else about the robot that encouraged you to trust this robot?	Why? Can you tell me more?

Appendix K Participant consent form for the exploratory human-robot collaboration study

PARTICIPANT CONSENT FORM

I fully understand the purpose of this research and I agree to participate in a task using two robots.

I agree to participate in a short interview following the completion of the two tasks.

I understand that the study will be supervised by the researcher and the laboratory technician.

I understand that the data generated will be used for research purposes only.

I agree to the interview being recorded for transcription later. Any collected data (recordings and transcripts) will only be available to the research team and will be stored in accordance to the University's Ethical Code and the Data Protection Act (1998)

I agree to possible direct quotes from my responses given during the interview being used in a written report, although they will not be traced back to an individual.

I understand that I may stop the interview at any time, without having to give a reason.

I understand that I may withdraw my data from the study up to seven days after this interview. After seven days, all data will be pooled and it will not be possible to withdraw my data.

PRINT NAME: ________________________________

SIGNED: ____________________________________

DATE: ______________________________________

Appendix L Participant demographic form for the exploratory human-robot collaboration study

Participant Reference Number: ________________ Date: ________________

1. Sex (*Please tick*):

   Male ______ Female______

2. Please state your nationality? ________________________________

3. Please state your highest educational level: _____________________

4. Have you ever had any experience with robotics/automated machines?

☐ No

☐ Yes: ____

5. Please state your age: ____________________________________

Appendix M Task description sheet for the exploratory human-robot collaboration study

Small scale robot

Task briefing

- Enter to the robot area
- These are the components that will be handed over by the robot
- Please take them to appreciate their weight. Are you ok with their weight?
- The robot has a built-in safety function. It stops in case of collision
- The robot's gripping mechanism will pick up the components and hand them over in this area (**Show**)
- When the robot stops, take hold of the pipe
- The robot's gripping mechanism will release it
- Place it on the table next to you.
- Do you have any questions? (**Yes/No**)

Demonstration run

- You will observe a short robot demonstration
- This is the speed that the robot will be moving at
- When the robot stops, take hold of the component
- The robot's gripping mechanism will release it
- Remove it from the grippers and place it on the table
- Any questions? (**Yes/No**)
- Are you ready to begin? (**Yes/No**)

Interview

- We will now carry out the interview
- Are you comfortable to tape record the interview? (**Yes/No**)

Medium scale robot

Task briefing

- Enter to the robot area
- The same components will be handed over by the robot
- Please take them to appreciate their weight. Are you ok with their weight? (**Yes/No**)

Demonstration run

- You will observe a short demonstration of the robot
- This is the speed that the robot will be moving at.
- The robot's gripping mechanism will pick up the components and hand them over in this area (**Show**)
- When the robot stops, take hold of the component
- The robot's gripping mechanism will release it
- Place it on the table next to you
- Also, please note of the laser scanner (**Show**) – it creates a human-robot safety zone
- If you attempt to enter robot's working zone it will stop the robot
- Any questions? (**Yes/No**)
- Are you ready to begin? (**Yes/No**)

Interview

- We will now carry out the interview
- Are you comfortable to tape record the interview? (**Yes/No**)

Appendix N Participant debriefing sheet for the human-robot collaboration studies

Dear Participant,

First of all, I would like to thank you for your participation to the study.

The aim of the study as stated previously is to study human factors for industrial human-robot collaboration, with particular interest placed on trust development during a human-robot interaction task.

I would like to remind you, that you can withdraw your data within seven days from today by contacting the researcher. After this, the data will be pooled and it will not be possible to do so.

I would like to stress that your data will remain anonymous throughout the study. Your data will not be passed to any third parties.

Thank you for your time once again.

Appendix O The coding template developed for the exploratory human-robot collaboration study

Element	Trust-related theme (code sign)	Lower level theme (code sign)
Robot (R)	Robot’s performance (R1)	Robot motion (R1m)
		Robot and gripper reliability (R1r)
	Robot’s physical attributes (R2)	Robot size (R2s)
		Robot appearance (R2a)
Human (H)	Safety (H1)	Personal safety (H1p)
		Safe programming of the robot (H1prog)
	Experience (H2)	Prior interaction experiences (H2int)
		Robot mental models (H2mm)
External (E)	Task (E1)	Complexity of the task (E1comp)

Appendix P The developed items of the trust scale

Items	Direction
The way the robot moved made me uncomfortable	-
I was not concerned because the robot moved in an expected way	+
The speed of the robot made me uncomfortable	-
The speed at which the gripper picked up and released the components made me uneasy	-
I felt I could rely on the robot to do what it was supposed to do	+
I knew the gripper would not drop the components	+
The design of the robot was friendly	+
I believe the robot could do a wider number of tasks than what was demonstrated	+
I felt the robot was working at full capacity	-
The robot gripper did not look reliable	-
The gripper seemed like it could be trusted	+
The size of the robot did not intimidate me	+
I felt safe interacting with the robot	+
I was comfortable the robot would not hurt me	+
I trusted that the robot was safe to cooperate with	+
I had faith that the robot had been programmed correctly	+
The way robots are presented in the media had a negative influence on my feelings about interacting with this robot	-
I had no prior expectations of what the robot would look like	+
I don’t think any prior experiences with robots would affect the way I interacted with the robot	+
If I had more experiences with other robots I would feel less concerned	-
I was uncomfortable working with the robot due to the complexity level of the task	-
If the task was more complicated I might have felt more concerned	-
I might not have been able to work with the robot had the task been more complex	-
The task made it easy to interact with this robot	+

Appendix Q Participant introduction sheet for the experimental human-robot collaboration case studies

My name is George Charalambous and I am a doctoral researcher at Cranfield University studying on human factors in industrial human-robot collaboration. As part of my study, I am currently conducting experiments and I would like you to participate. The study will take place at aero structures group robotics laboratory and will take approximately 25 minutes.

Would you be interested to take part?

If No: Thank you very much for your time

If Yes: Thank you for your participation. Before I take you to the laboratory and to comply with the University's ethics policy, I would like to take a few moments to inform you about the experiment and your rights:

- You will interact with a robot to complete a short assembly task.
- At the end you will be provided with a survey to complete
- Full risk assessments have been carried out and approved by the health and safety officer
- The experiment will be supervised by the laboratory technician and myself
- To ensure confidentiality an ID number will be used
- Any data collected will be anonymous and will be stored in accordance with the University's Ethical Code and the Data Protection Act (1998)
- You have the right to stop the experiment at any time without having to give a reason
- You have the right to withdraw your data up to seven days after today. After seven days, the data will be pooled and will not be able to withdraw
- The researcher's details will be provided at the end of the experiment
- Also the contact details of a local counsel will be provided should you feel the experiment has affected you in any way

Are you comfortable to proceed with the experiment?

If No: Thank you very much for your time

If Yes: Provide the participant with the consent form, the ID number and demographics form. Proceed to the laboratory

Appendix R Participant consent form for the experimental human-robot collaboration case studies

I fully understand the purpose of this research and I agree to participate in an experimental task using a robot.

I understand that the experimental study will be supervised by the researcher conducting the experiment and the laboratory technician.

I understand that the data generated will be used for research purposes only.

Any collected data will only be available to the research team and will be stored in accordance to the University's Ethical Code and the Data Protection Act (1998).

I understand that I may withdraw my data from the study up to seven days after this interview. After seven days, all data will be pooled and it will not be possible to withdraw my data.

PRINT NAME: ________________________________

SIGNED: ___________________________________

DATE: _____________________________________

Appendix S Instructions for completing the familiarisation task for experimental human-robot collaboration case studies 1 and 2

1. The task requires you to apply these plastic fittings onto the drain pipe.

2. The drain pipe has two ends: the large end and a smaller end. For the large end you must fit the large fitting and for the smaller end you must fit the small fitting

3. I will now show you how to complete the task:
    3.1. First take the roller and insert it into the pipe
    3.2. Then take the washer and insert it into the pipe
    3.3. Then take the rubber band and position it here
    3.4. Then take the fitting and fit it into the pipe
    3.5. Thread the components together
    3.6. Thread it until you feel some resistance
    3.7. You are not being assessed as to how tight you do it
    3.8. I would like you to complete the task at a pace you feel comfortable

4. I will now disassemble the components and I would like you to complete the task using both fittings. If you have any questions please feel free to ask me

5. (*Participant completes the task*) Do you have any questions regarding the task?
    5.1. If **YES**: Answer the questions

    5.2. If **NO**: Please come with me to the robot cell.

Appendix T Human-robot collaboration script for experimental case studies 1 and 2

You will complete an identical task as before, while being assisted by this robot

Please stand behind the white floor line at all times.

A laser scanner is being used for health and safety reasons. If you move beyond the line and into the robot's working zone, the scanner will automatically stop the robot.

The robot will pick-up one of the drain pipes and will present it at your standing location. The drain pipe will be presented horizontally.

When the robot stops, and according to which side is given, you must apply the appropriate plastic fitting. **<u>The robot will be holding the pipe and you have to apply the appropriate fitting.</u>**

You will complete the task twice. For this purpose two sets of large fittings and two sets of small fittings have been provided.

Upon completing the task, the robot will position the completed item in the drop-off area.

Do you have any questions?

- If **YES**: Answer the question
- If **NO**: Proceed .

You will now observe a short robot demonstration

(*<u>Robot demo is initialised</u>*): This is the maximum speed the robot will be moving at during the collaboration task. This is the maximum gripper speed. Now the robot will move back to its initial position. The demonstration is now over.

Are you ready to start the task?

- If **YES**: Start the process
- If **NO**: Answer any question the participant may have

Appendix U Task description sheet for the experimental human-robot collaboration case study 3

1. The task requires you to secure two metal pieces together by inserting two bearing pins at two locations.

2. These are the bearing pins you must use to complete the task (**Show participant**)
   2.1. The bearing pins are identical
   2.2. Please take hold of them to appreciate their weight (**Hand them to participant)**

3. These are the two metal pieces you need to secure together using the bearing pins (**Show participant**)

4. I will now show you how to complete the task:
   4.1. The bearing pins are positioned on this table
   4.2. Take the bearing pin
   4.3. Insert the bearing pin to secure the two pieces together.
      4.3.1. The long side of the pin (**Show participant**) goes in first
   4.4. To ensure the pin has been fully inserted, the bearing pin ‘shoulder’ (**Show participant**) must touch on the metal.
   4.5. Then take hold of the second bearing pin and repeat.
   4.6. Please do not place your fingers anywhere between the bearing and the driving guide
   4.7. Then step back. The task ends.
   4.8. You are not being assessed as to how fast you complete the task.
   4.9. Pins can be inserted in any direction, so please do not worry about the orientation of the pins between them.
   4.10. Both pins are identical. You can choose to attach them in any order your like.

5. I will now place the bearing pins on this table and I would like you to complete the task. If you have any questions please feel free to ask me.

6. (*Participant completes the task*) Do you have any questions regarding the task?
   6.1. If **YES**: Answer the questions
   6.2. If **NO**: Please come with me to the robot cell.

Appendix V Human-robot collaboration script for experimental case study 3

The flap has two bearings (**Show participant**). The aim of the task is to secure the flap bearings on these two carriages **(Show participant**) using two pins. I will now explain the procedure to do this.

1. Please stand at this position during the interaction (**Show participant**)
2. The robot will pick-up the flap, bring it on this stand and will stop (**Show picture**).
3. When it stops, walk towards the flap and align the carriage to the bearing by pushing it down.
4. Pick-up a bearing pin and insert to secure the flap on the carriage (**Show participant**).
5. The long side of the pin (**Show participant**) goes in first.
6. To ensure the pin has been fully inserted, the bearing pin ‘shoulder’ (**Show participant**) must touch on the carriage.
7. Then align the second carriage to the bearing by pushing it down.
8. Then pick up the second bearing pin and insert the bearing pin to secure the flap bearing on the carriage (**Show participant**).
9. The long side of the pin (**Show participant**) goes in first.
10. To ensure the pin has been fully inserted, the bearing pin ‘shoulder’ (**Show participant**) must touch on the carriage.

11. Upon completing the task, walk back to your initial position. The robot will drive the flap on the carriage and will then release it. Then the task will end.
    - Please do not place your fingers anywhere between the flap bearing and the carriage.
    - You are not being assessed as to how fast you complete the task.
    - Both carriages are identical; you can start with either one of them.
    - Pins can be inserted in any direction, so please do not worry about the orientation of the pins between them.
    - Both flap bearings and pins are identical in diameter. You can choose to attach them in any order your like.
    - Please take hold of the bearing pins to appreciate their weight (**Hand them to participant**)

A laser scanner (**Show participant**) is being used for health and safety reasons. If you walk into the robot’s working zone while the robot is moving, the scanner will automatically stop the robot. Also, an overhead safety eye (**Show participant**) is used to constantly monitor the cell.

- Do you have any questions?

Because I must not interfere with the trial, I will be standing at the back.

- You will now observe a short robot demonstration

(*Robot demo is initialised*): This is the maximum speed the robot will be moving at during the interaction task. This is how the end-effector picks up the component. Now the robot will move back to its initial position. The demonstration is now over.

Are you ready to start the task?

Appendix W Schematic for practitioners indicating the organisational human factors at different TRLs