A Framework to Support Automation in Manufacturing through the Study of Process Variability

by

Angel Sanchez-Salas

A Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of

Doctor of Philosophy of Loughborough University

April 2016

ABSTRACT

In manufacturing, automation has replaced many dangerous, mundane, arduous and routine manual operations, for example, transportation of heavy parts, stamping of large parts, repetitive welding and bolt fastening. However, skilled operators still carry out critical manual processes in various industries such as aerospace, automotive and heavy-machinery. As automation technology progresses through more flexible and intelligent systems, the potential for these processes to be automated increases. However, the decision to undertake automation is a complex one, involving consideration of many factors such as return of investment, health and safety, life cycle impact, competitive advantage, and resources and technology availability.

A key challenge to manufacturing automation is the ability to adapt to process variability. In manufacturing processes, human operators apply their skills to adapt to variability, in order to meet the product and process specifications or requirements. This thesis is focussed on understanding the variability involved in these manual processes, and how it may influence the automation solution.

Two manual industrial processes in polishing and de-burring of high-value components were observed to evaluate the extent of the variability and how the operators applied their skills to overcome it. Based on the findings from the literature and process studies, a framework was developed to categorise variability in manual manufacturing processes and to suggest a level of automation for the tasks in the processes, based on scores and weights given to the parameters by the user.

The novelty of this research lies in the creation of a framework to categorise and evaluate process variability, suggesting an appropriate level of automation. The framework uses five attributes of processes; inputs, outputs, strategy, time and requirements and twelve parameters (quantity, range or interval of variability, interdependency, diversification, number of alternatives, number of actions, patterned actions, concurrency, time restriction, sensorial domain, cognitive requisite and physical requisites) to evaluate variability inherent in the process. The level of automation suggested is obtained through a system of scores and weights for each parameter. The weights were calculated using Analytical Hierarchical Process (AHP) with the help of three experts in manufacturing processes.

Finally, this framework was validated through its application to two processes consisting of a lab-based peg-in-a-hole manual process and an industrial process on welding. In addition, the framework was further applied to three processes (two industrial processes and one process simulated in the laboratory) by two subjects for each process to verify the consistency of the results obtained. The results suggest that the framework is robust when applied by different subjects, presenting high similarity in outputs. Moreover, the framework was found to be effective when characterising variability present in the processes where it was applied.

The framework was developed and tested in manufacturing of high value components, with high potential to be applied to processes in other industries, for instance, automotive, heavy machinery, pharmaceutical or electronic components, although this would need further investigation. Thus, future work would include the application of the framework in processes in other industries, hence enhancing its robustness and widening its scope of applicability. Additionally, a database would be created to assess the correlation between process variability and the level of automation.

ACKNOWLEDGEMENTS

Producing a PhD thesis is not an individual accomplishment; it involves a social environment including people whom I would like to thank sincerely.

Therefore, I would like to thank all the people who contributed in some way to the work described in this thesis. First and foremost, I thank my supervisors, Dr Yee Mey Goh and Professor Keith Case. During these three years and a half, they contributed to an enjoyable experience by giving me freedom, good advice and making me think out of my comfort zone.

Every result achieved in this thesis was accomplished with the help and support of my research centre colleagues.

I am grateful to the EPSRC Centre for Innovative Manufacturing in Intelligent Automation and its industrial partners for the funding sources and support that allowed me to pursue my PhD study.

Finally, I would like to acknowledge to my family and friends. First and foremost I would like to thank to my love Sandra, who supported me through this journey and always had nice words in the most difficult moments. To my daughter Julia who was born during my studies and makes me fight for a better world every day. I would like to thank Mom, Dad and my sister for their constant love and support.

LIST OF FIGURES

LIST OF TABLES

TABLE OF CONTENTS

GLOSSARY OF TERMS

The definitions of some key terminology used in this thesis are described below.

Actions. An *action* is defined as every indivisible activity that can be described by a single verb and which is absolutely necessary to successfully finish the task. For example, drill, pick, insert and fasten are actions which executed in sequence would finish a given task. It is the lowest level of division in a process and actions cannot be further dissected.

Controls. Controls are utilised to address the work in the task. Plans, standards and checklists are all forms of control. Consequently, controls regulate the accomplishment of the task and influence or determine the outputs (Feldmann 2013).

Established Process. A process is established when both the outputs and the process constantly achieve the required quality and safety standards for the volume of production demanded.

Inputs. Inputs apply to *parts*, *tools*, *data*, *stimuli*, *information cues* or *instructions* needed to perform a *task*. Therefore, they are also introduced to achieve the desired outputs in tasks (Feldmann 2013).

- *Part* defines any of physical components constituting the expected output.
- *Tools* are instruments utilised to perform a specific task.
- *Data* refers to quantitative information presented to the operators and it is required to complete a task satisfactorily. For this reason, the operator, according to previous experience or training received, would need to interpret data in order to complete the task.
- *Stimulus* is a sensorial perception which helps to evaluate an action within a task, supporting the manner in which the task is performed (Wood 1986; O'Hare et al. 1998; Wiker et al. 2009).
- *Information cue* is a piece of information used by the subject to make decisions during the completion of a task (Wood 1986). To differentiate *information cues* from *data*, the former should be considered as "supporting information" used to conceive a decision. Moreover, *information cues* could be presented as

qualitative information. For example, welding experts rely on the noise made by the weld to check if the welding is being done properly.

Manufacturing process. A manufacturing process is a designed course of actions that physically and/or chemically transform inputs to outputs, adding value through the transformation. It refers to industrial process. It is the highest level in the hierarchy. In manufacturing, a process is a set of steps through which inputs are transformed into outputs. These outputs can be inputs for other process or final products. This definition is similar to the definition given in ISO 9000 where a process is "a set of interrelated or interacting activities that transforms inputs into outputs. Inputs to a process are generally outputs of other processes. Processes in an organisation are generally planned and carried out under controlled conditions to add value".

Mechanisms. Mechanisms can be systems, staff or equipment employed to carry out a task. Therefore, mechanisms are the means by which the task is executed (Feldmann 2013).

Output. Output refers to those goods that underwent a transformation during a task (Feldmann 2013). This refers to those goods coming out of the task whether or not they comply with the requirements. For example, those sent to rework or scrap are outputs although they are not final outputs.

Production line. The definition of process imply that in a manufacturing facility, there will be more than one process and thus, the set of processes designed in sequence to manufacture a product from raw materials or semi-finished products will be named as a *production line* in this thesis.

Standard Operating Procedure (SOP). It refers to the set of instructions and rules that shall be followed to successfully complete the process.

Strategies. The procedure applied during the execution of tasks which leads to the completion of the process. In the case of processes where humans are involved, this *"procedure"* will or will not coincide with the SOP of the process, due to inherent variability in humans.

Tasks. A task is a well-defined set of actions that should be performed to complete a process. This set of actions performed in sequence or parallel conducts to the completion of the task. Tasks are grouped to designate a process and they are executed in sequence or parallel in order to obtain a specific output from the process. The way tasks have to be executed is defined in the SOP. A task will usually have inputs, outputs, controls and mechanisms.

Variability. It is any inherent deviation from the nominal occurring in a manufacturing process. Variability may come from many different sources such as unplanned and undesired disparity, anomaly, inconsistency or irregularity and is not contemplated in the specifications previously defined for the inputs, outputs or processes. There are different types of variability. The National Institute of standards and technology classifies the types of variability in two: *controlled variability* and *uncontrolled variability*. Controlled variability is defined by a stable and consistent pattern of variation over time. Uncontrolled variability is distinguished by a pattern of variation that changes over time, therefore unpredictable (National Institute of Standards and Technology 2016).

1. INTRODUCTION

The UK manufacturing industry is the fifth largest in the world (United Nations Statistics Division 2013), accounting for 10% of national economic output (Rhodes 2014) . For example, the UK has the second largest aerospace and defence industry in the world, with a revenue of £27,8bn (Rhodes et al. 2015) and the fourth largest automotive industry in Europe, with total sales of around £34bn (11% of the UK's total exports) (SMMT 2014).

In manufacturing, automation has replaced many dangerous, mundane, arduous and routine manual operations, for example, transportation of heavy parts, stamping of large parts, repetitive welding and bolt fastening. However, skilled operators still carry out critical manual processes in various industries such as aerospace, automotive and heavy-machinery. The majority of these processes might be difficult to automate because of variability present in the process (Thornton et al. 2000). This variability typically require operators to adapt continuously to achieve the desired outcomes (Sandom & Harvey 2004).

1.1 Problem definition

Manufacturing variability can be defined in many ways. In this research, variability is defined as any inherent deviation from the nominal occurring in a manufacturing process and can be found in inputs, outputs or processes. This variability inherent to manufacturing processes (Mantripragada & Whitney 1999; Apley & Shi 2001; Zheng et al. 2008) is expected, and it has been suggested as the principal cause of lack of robustness in production processes (Glodek et al. 2006). Manufacturing process variability could arise from many sources due to limitations such as technical (positioning and dimensional accuracy, forces, temperatures, etc.), material (elasticity, resilience, hardness) or processes (design, space, techniques, etc.).

Variability has to be taken into account during manufacturing to produce acceptable outcomes (MacDonald 2003). For example, a number of manufactured parts may have uncontrolled geometric variations from the nominal values. However, it is not only parts assembled in processes which can introduce variability in a process. Variability can also be introduced by other inputs actively used in the process, including tools which might behave differently under working condition due to different causes such as wear/conditions/states, inadequate maintenance or misuse. These factors could introduce variability into the processes.

Currently, this variability is eliminated or reduced to acceptable levels by experienced operators who have been working on these processes for several years. In these processes operators are the ones dealing with variability. The training of new operators is difficult and time consuming because these processes require tacit knowledge which is difficult to transfer (Ferdows 2006). In addition the specialisation of these operators make them hard to replace and less flexible to work in other processes. In manufacturing environments, humans can accommodate variability and carry out tasks that otherwise would be impossible to be finished within time and quality requirements (Sandom & Harvey 2004).

Intelligent automation aims to fully understand human skill in advanced manufacturing and use this information to provide human-automation and intelligent automation solutions (EPSRC Centre for Innovative Manufacturing in Intelligent Automation 2014). This is achieved through observing people at work in a manufacturing environment to understand whether their tasks can be enhanced by automation solutions to improve both operator well-being as well as production performance.

The motivation of this research is to provide industry with a framework to support the decision for automation based on the understanding of variability that need to be controlled during the execution of manual manufacturing processes.

The hypothesis for this thesis is stated as follows:

The variability embedded in manufacturing processes can be characterised, providing useful information to support the decision of automating. This characterisation can be used to suggest a level of automation to be implemented.

1.2 The decision for automation

In order to automate a process, the team in charge of the decision will determine the suitability of the process taking into consideration many factors. These factors are enumerated and explained in this section.

Figure 1-1 shows various factors that affect a decision of automating a process. The broken line represents the imaginary border of the framework applicability, focusing mainly on the influences of variability on the decision.

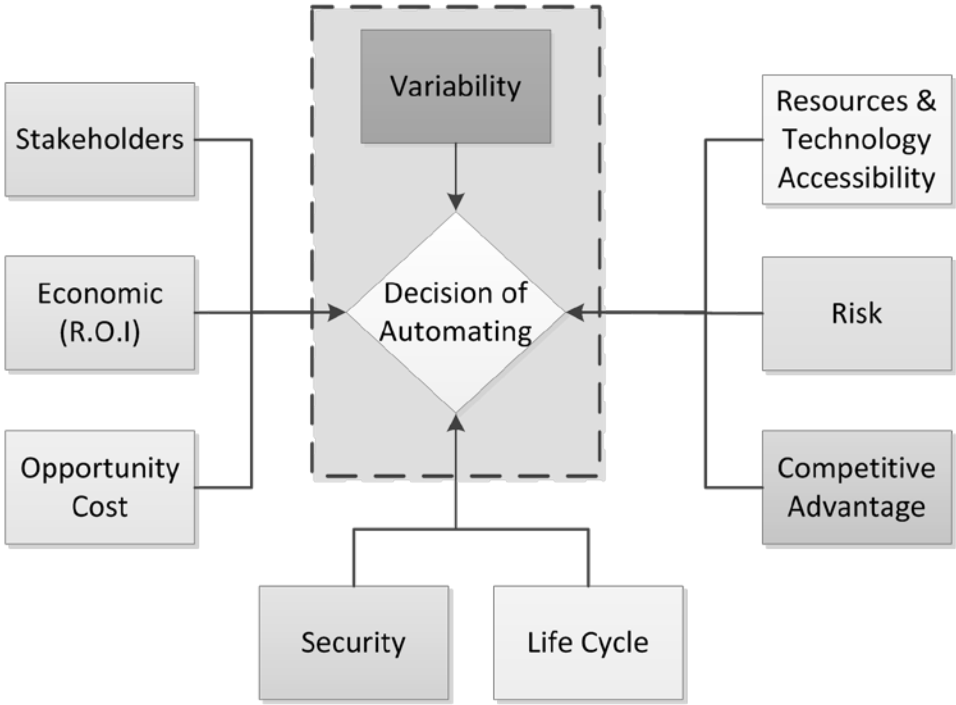


Figure 1-1. Factors affecting the decision of automating a process

The other factors affecting the automation decision are explained in the following sub-sections.

Stakeholders

A *stakeholder* is understood here as a person or group of people who can influence the automation decision, either negatively or positively. The following bullet points briefly describe these stakeholders:

- ***Society:*** the decision may impact socially, i.e. job creation/destruction, job quality, community empowerment or impoverishment, and company's social image.

- ***Company*****:** the company needs to align any decision with the company's mission, vision and culture, as well as maintaining effectiveness within company's processes.
- ***Managers*****:** in reference to the managers' support, if the decision is to automate, managers will have the authority to make decisions in relation to *budget*, *resources* and *project strategy*. This may require the collaboration of other managers in the company. Both the size and the scope of the project will determine the level or degree of such involvement.
- ***Workers***: the success of any solution implemented will be subject to acceptance by the workers and their implication on the project itself, which will require both inputs and feedback, of those currently working in the process.
- ***Trade unions***: trade unions may have an influential role in the company's affairs and have to be consulted before making decisions. Trade unions can stop a project if they consider it could affect worker's rights or their interests.
- ***Policy makers***: the company must comply with the applicable law and regulations. In addition, the legal department should consider present and future law and regulations affecting the project, including environmental regulations.
- ***Customers***: The opinions of customers may be affected by the automation process. The manner in which the novel solution may alter the customer's perception of the products, or the impact it might have on the customer's experience, should be contemplated.

Return on Investment (ROI) and other metrics

Return-On-Investment (ROI) is a formula that is frequently used to evaluate the viability of a project. The return on investment, relates the benefits and costs of the project as follows:

ROI = ((total benefit - total costs)/total cost) * 100, represented in a percentage.

1. Total benefit = the payback to a business unit for a given period (also including savings in materials).
2. Total cost = cost to implement and maintain the project for the same given period.

ROI evaluates an investment only from an economic perspective, making the method incomplete. Companies have started to apply other metrics to assist in evaluating a project beyond ROI and including the following;

- *Adaptability levels* with the existing processes in the company.
- *Efficiency* in the usage of energy, water, raw materials and other natural resources.
- *Job productivity*: the novel solution will or will not improve overall productivity?
- *Workforce Skills*: the implementation of a novel solution will increase the value of the workforce if they have to be trained or get further education, which will potentially increase the company's competitiveness. This is directly linked with other metrics to be considered such as training costs per employee, employee motivation and team harmony, attendance rates, employee retention rates and enrolment rates.

Opportunity cost

Opportunity cost represents the "economic losses" of choosing one option over another. For example, if it is decided to invest in automating X, this could be to the detriment of investing in Y. Thus, any potential benefit to be obtained from Y would be the opportunity cost of automating X. Assessing the opportunity cost of future projects helps to prioritise some projects over others but only from an economic point of view.

Cycle Time

Cycle time is important in manufacturing to meet demand rate, therefore consideration of how automation might affect the cycle time is important. Cycle time is a characteristic of a task which might have direct impact on the decision for automation. Automation might be better justified for those tasks where the automated solution will reduce the operator cycle time or when that automation releases the operator to perform other tasks, resulting in a reduction of the cycle time of the process.

Volume of production

Volume of production is a characteristic of a manufacturing process which has an effect on the decision for automation. Automation of a process will have an initial investment due to space, infrastructure and equipment requirements but it could be justified as the investment spreads across the production volume. However, this investment might not make sense if the automation does not reduce production costs enough to recover the investment over the period required, unless the automation is justified by other factors such reduced risk of accident, improved competitive advantage or fulfills the stakeholders' needs

Security considerations

Security should be evaluated prior to the decision to automate a process. Both data and its level of confidentiality should be properly evaluated, including a study of the type of data being processed by both providers and the system. If data are highly confidential, additional security measures should be implemented along with the project's execution to avoid theft of data by third parties.

Life cycle

Life cycle refers to the length of time the solution is expected to last: a key component to estimating solution life cycle is a comparison of the flexibility of the solution. If the solution has to be redesigned over time to adapt changes in demand, or product requirements, then the solution will need higher flexibility to sustain a long life cycle. Increasing this flexibility will increase cost, time of implementation and resources needed.

Competitive advantage

Competitive advantage is a set of attributes that allows companies to outstrip its competitors. These attributes include, in the case of automation, the adoption of innovative technologies and the implementation of new processes. Anticipating how the novel solution will bring competitive advantage to the company will reinforce the automation decision.

Risk

Risks are always present when implementing a new process or technology therefore identifying and predicting the potential damage, could mitigate its negative effects. The following are the main areas of risk associated with automation:

- ***Economic Risk***: the cost estimation of the automated solution will require assessing unpredictable contingencies.

- ***Social and Cultural Risk***: the automation decision must consider whether or not the company's objectives will be achieved by identifying potential negative impact in both social and cultural sectors.
- ***Political Risk***: political risks should include both internal and external perceptions of the automated solution therefore, solving legal and compliance issues, the commitment of stakeholders to the adoption of the automated solution, the execution within the time allocated and the abilities and capabilities of the responsible team.
- ***Technical Risk***: Technical risk judges the feasibility of the automated solution from a technical point of view; it should include a state-of-the-art review of current technologies available to perform tasks within the process, including compliance with the product's requirements and demands.
- ***Accident reduction***: it should also be considered whether the automated solution would or would not reduce accidents.

Resources and technology time availability

Time availability of resources considers resources that will be needed and available during the implementation of the automated solution. On the other hand, *technology time availability* refers to state-of-the-art of technology that is available, and the suitability and compatibility with the current existing equipment and devices, required for implementation, including all of the following:

- ***Equipment and devices***: time availability, accuracy, repeatability, durability, working conditions, energy consumption.
- ***Integration***: integration of the equipment and devices, that is, programming, data recognition or space available.
- ***Level of flexibility***: the solution can be used in other processes; it can be valid for other products, the solution's life cycle, and in the reuse of components.
- ***Level of autonomy***: the adopted solution may work with minimal or no supervision.
- ***Level of "intelligence"****:* the solution can be "trained" or self-learn to accomplish the required tasks, given that the process will have a level of variability embedded.

Technology time availability is closely related to variability because the solution to be adopted must be technologically feasible. For example, to overcome variability, the solution might need flexibility, autonomy, a certain level of intelligence and the equipment and devices to be used should, at a minimum, equalise human performance in accuracy and repeatability and should be compatible (integratable).

All of these factors will influence the automation decision to some extent. However, to prioritise which of them will have the biggest impact will depend on the people making the decision. For example, if the person making the decision is highly influenced by economic reasons, return of investment, opportunity cost and life cycle will predominate. On the other hand, if the person or group is driven by technological reasons, probably competitive advantage and technology time availability will inspire the decision.

The scope of this research establishes variability as the factor to be taken into consideration, ignoring the others, not because they are not important but because the objective is to understand the influence of process variability when automating.

1.3 Scope and domain of study

The domain of study is focused on established, manual and low volume manufacturing processes of high value components; taking into consideration only variability in the processes. Variability is defined as inherent deviation from the nominal. The extrapolation of the results to processes in other manufacturing activities should be made with prudence. It is intended to extend the scope of this research to other industries and this is discussed in chapter 8.

It is not within the scope of this research to study the variability introduced by operators. Operators introduce variability in manufacturing process by the mere fact of being humans (Sandom & Harvey 2004). This variability is found between different individuals with a range of internal and external factors. Internal factors are (among others): age, gender, race, culture, education, physical condition, tiredness, motivation, social factors and human relationships inside and outside the workplace. External factors are, for instance, environmental conditions (light, cold, noise) or constraints (time, space). In addition, other factors affecting human variability include social and organisational factors (Digiesi et al. 2009).

The results provided by the framework will help to decide a suitable level of automation, depending on the variability found in the process. This would allow a higher flexibility among operators as they will work in different processes and it would also increase operators' control, supervisory and management duties, rising operators' satisfaction and performance (Kahya 2007).

Information regarding variability should be considered in conjunction with other external factors affecting the decision of automating such as stakeholders, return of investment, opportunity cost, cycle time, security considerations, life cycle, competitive advantage, risk and resources and technology time availability which are not covered in this thesis.

1.4 Aim and objectives

The aim of this research is to establish a framework to categorise variability in manufacturing processes to support the decision for automation.

In order to accomplish this aim, three research objectives were established:

1. To identify the extent of the variability, and how, it is being managed by the operators.
2. To propose a framework to study manual manufacturing processes in order to characterise variability affecting the process.
3. To validate the framework to determine its effectiveness and robustness.

1.5 Research Methodology

Two industrial processes were analysed, information regarding the processes was collected and operators working in the processes were observed and interviewed. This analysis together with the literature review, helped to define the attributes and parameters included in the framework. Finally, this framework was validated through an experiment and an industrial process study and its usability and robustness was tested through the application of the framework by different users, comparing the outcomes. The detailed research methodology is described in Chapter 3.

1.6 Thesis outline

The thesis is structured as follows:

Chapter 1: Introduction

The introduction gives a preliminary presentation of variability in manufacturing, followed by a justification for this research, the aim and objectives of the research and the scope and domain of the study.

Chapter 2: Literature review

This chapter reviews the literature found in topics related to this research. Variability in manufacturing environments, task complexity, human, ergonomics, human-machine interaction, level of automation and design of automated solutions are all connected topics affecting this research.

Chapter 3: Research methodology

This chapter describes the methods used to conduct this research. This includes identification of variability in processes through interviews, observations and process analysis, in conjunction with experiment methods.

Chapter 4: Process study. Grinding and polishing of high end components.

This chapter refers to information collected, interviews and observation conducted and analysis made of an industrial process consisting of grinding of high value components. The results are presented and the convenience of conducting further process studies is discussed.

Chapter 5: Process study. De-burring of high end components

This chapter complements the former chapter by studying a different industrial process. The methods used are the same which helps to build a methodology for identifying variability in manufacturing process and to design a framework which is able to categorise the variability found, going a step further in the knowledge of the process variability.

Chapter 6: Decision for automation Framework

This chapter describes the framework designed to categorise variability in manual manufacturing processes. This framework will support the decision of automating a process and it will suggest a level of automation depending on the extent of the variability embedded within the process.

Chapter 7: Application and robustness

This chapter validates the framework through its application to one experiment and one industrial process. In addition, the usability of the framework is tested by different users and the outcomes compare to probe its robustness. Finally, the framework is applied to the two process studies described in chapter 4 and 5, to reinforce the applicability by exposing the framework to more industrial case studies.

Chapter 8: Conclusions and future work

This chapter summarises the findings from the thesis, the limitations of this research and proposes future work.

2. LITERATURE REVIEW

This chapter is intended to review the research which has taken place in manufacturing processes regarding: variability, methods to control variability, challenges in automation and task complexity. All these areas affect manufacturing processes and their relationships will be exposed in this chapter. The aim is to find areas in this knowledge which can be further investigated.

A manufacturing environment is an environment where inputs such as raw materials are transformed into outputs such as engineering components through manufacturing processes. A manufacturing process is a systematic succession of activities executed by a set of technologies and methods transforming inputs into outputs (Qiao et al. 2011), is one of the most important stages of the life cycle of a product and is composed of a group of tasks which must be executed in a specific order and manner. Likewise, these tasks are composed of actions that are performed in sequence or parallel, conducting to the completion of the task. The way tasks need to be executed is defined in the Standard Operating Procedure (SOP).

In this context, variability can be defined differently. For example, some authors define variability as the "variety" of outputs in two ways; the range of different components manufactured and the variation of those outputs in volume (Corrêa 1996; Griffiths et al. 2000). Other authors describe variability in a sense of resources change, in reference to variations in workforce (human factors) and machine resources (equipment capacity and limits) as a consequence of absenteeism and machine malfunction, accelerated orders, supplier irregularities (e.g. variability between lots and vendors), transport interruptions and other operational issues within the plant facility (Kara & Kayis 2004; Glodek et al. 2006).

Variability is defined in this research as any inherent deviation from the nominal. Inherent deviation refers to unplanned and undesired disparity, anomaly, inconsistency or irregularity that is not contemplated in the specifications previously defined for the inputs, outputs or processes. There are methods proposed to control this variability in manufacturing processes which are described in next subsection.

2.1 Methods to control variability

Sources of variability affecting manufacturing, such as the thickness of a given component (input), shape of a certain cutting tool (process), gap between door and frame in a car model (output), are considered for the purpose of this research. On the other hand, changes in temperature or substituting a provider of a component will not be considered as variability if it is not affecting the inputs, outputs or process in any way. There are some studies to determine sources of variability affecting a manufacturing process.

Statistical Process Control (Loose et al. 2008; Apley & Shi 2001), Total Quality Management (Montgomery 2008) or Six-Sigma (Dai & Yang 2011) are methodologies to control manufacturing variability. They typically rely on conditions monitoring or redesigning the processes.

Some authors have created methods to detect variability. For example, Antony et al. (Antony et al. 1999) identified a critical quality characteristic of an industrial process and seven factors which have some impact on the critical characteristic, analysed through statistical analysis to find which factors have the highest impact in order to reduce variability in this critical characteristic. They were able to calculate the optimal setting of factors to reduce variability in the process and to improve the process capability (C_p), which measures the capability of the process to produce outputs within specifications.

Thornton (Thornton 1999a; Thornton 1999b; Thornton 2004; Thornton, Donnelly, and Ertan 2000; Thornton 2000) uses a Key Characteristic (KCs) method to identify where product quality will be most significantly affected by variation. A feature in the product is transformed into a Key Characteristic if the variation from the specification has considerable impact on fit, performance, or service life of the product. A Key Characteristic is any attribute of an output, input or process that is quantifiable and whose variations from the expected have an inadmissible impact on the cost, performance, or safety of the output. This means that this attribute varies in one or a few of its properties from one element to another and this is causing a non-desirable output. Different KCs can be found in a process, for example in inputs (e.g. dimensions, features' positions, surface's roughness, elasticity), in the machines (e.g. configuration, characteristics, data input, energy input, condition), tools (e.g. condition, use, shape) and environment (e.g. light, temperature, noise, vibration). Therefore, these KCs should be identified as they might affect outputs. The interaction of operators with these KCs will also determine whether workers are successfully eliminating or reducing this variability to acceptable levels.

These studies have successfully identified variability in the processes studied but, in order to reduce variability to acceptable levels, the previous processes have to be redesigned. However, there are processes which cannot be redesigned for diverse reasons, for example due to the high cost of the redesign or lengthy certification process.

The methods applied to reduce variability are mainly applied to the design stage. They are catalogued as concurrent design concepts (Maskell 1991). For example, Design for X (DFX) tools are ideal techniques for improving the inputs and processes from design. DFX include numerous tools such as Design for Manufacture and Assembly (DFMA) and Design for Reliability (DFR). Design for Manufacture and Assembly (DFMA) tries to reduce the number of assembled parts through design, resulting in fewer assembly tasks and reduction of manufactured parts. Design for Reliability (DFR) allows the design team to detect likely design failures in the initial design stage, enabling it to identify design aspects that should be improved. When the reliability issues are detected and corrected at early stages, project cycle time will be shortened.

Methods such as Poka-yoke can also be included in design techniques for dealing with variability. Poke-yoke means "mistake-proofing" in Japanese. It was invented by Shigeo Shingo, a Japanese industrial engineer. A poka-yoke is a mechanism in a manufacturing process that prevents operators from committing mistakes. Its goal is to eliminate product faults by impeding or correcting human mistakes at the same instant they occur (Shingo 1986). Shingo differentiated between defects in the products and unavoidable human mistakes. Defects arise when mistakes are permitted to be transmitted to products. Shingo presents three types of poka-yoke:

- Contact method. The defect is detected by testing the product’s physical attributes.
- Fixed-value method. The operator is warned if certain movements have been missed.

- The motion-step method defines if the operator has followed the assigned steps of the task (Shingo 1989).

According to Shingo's studies, in manufacturing processes human mistakes are inevitable, although poka-yoke systems can prevent these mistakes, decreasing defects in products. The poka-yoke method has proven effective in manual processes to prevent human mistakes. These human mistakes are often associated to the level of complexity of the task being performed (Park et al. 2004; Ogle et al. 2008; Gregoriades & Sutcliffe 2008). There are different models trying to explain what makes a task complex (Liu & Li 2012).

Critically, variability in the task will add complexity to the task. This complexity can be determined from operator's point of view or from the own variability embedded in the task being performed and how this variability has to be solved. These implications are further discussed in the next section.

2.2 Methods for process modelling

Models of processes are constructed to study and understand the process by showing important information visually. The modelling of processes and information flows in engineering has been applied widely through various process modelling approaches (Pavkovic et al. 2001). The objective is to identify a method that allows modelling all the important information about variability in a process, including the human systems. With this goal, the model should be able to define variability in the process, to build a hierarchical functional diagram and to model the dependencies of activities within a system.

The following methods are available to designers for modelling design processes. These methods are briefly reviewed in this section. They are grouped by different views of a system: the functional, dynamic, object and task-based views (Goh et al. 2003). For this research, only functional and task-based models are considered suitable for defining variability and process in building blocks. These two characteristics are used to describe the process and its tasks considering variability.

Functional models

Functional models describe data flow and transformation in a system. They use nodes and arcs to graphically represent processes and data flows respectively. Three types fall into this category: data flow diagram, the structured systems analysis and design method (SSADM) and the Integrated Definition (IDEF0) method.

a) **Data Flow Diagram (DFD).** Each node in DFD symbolises a process or activity in which data is processed. It represents the process, external agent, data store and data flow through different graphical notations. DFD identifies transformation (or activities) in a system but it only indicates the direction of information flow in the process.

b) **Structured Systems Analysis and Design Method (SSADM)**. SSADM is based on DFD but adding additional views for Logical Data Structures (LDS) and Entity Life Histories (ELH), improving the modelling capabilities (Middleton & McCollum 2001). SSADM is used to model transformation processes together with data flows in a system (like DFD) plus structural view of system data (LSD) incorporating the effect of time on the system data (ELH).

c) **Integrated Definition (IDEF0)**. The IDEF family models different views of a system. In the case of IDEF0 (U.S. Department of Commerce 1993) produces a structured function model to gain understanding, support analysis, provide logic for potential changes, specify requirements, or support systems level design and integration activities. An IDEF0 diagram describes what a system does, what controls it, what things it works on, what means it utilises to execute its functions, and what it delivers. The components in the IDEF0 are: inputs (I), controls (C), outputs (O) and mechanisms (M). Input data or objects are transformed by the function to produce the output. A control is utilised to address the work in the process. Plans, standards and checklists are all forms of control. Mechanisms can be systems, staff or equipment employed to carry out a task.

Task-based modelling

Task-based models are focused on sequence of tasks and the design process' optimisation. Two of these techniques are discussed below: design structure matrix (DSM) and signposting.

A DSM (Eppinger & Browning 2012) is a reduced representation of a system in the form of a matrix which focuses on information needs and requirements, task sequencing and iterations. The matrix is restructured in an iterative process, resulting in a triangular matrix, representing the optimal process execution.

The Signposting tool (Clarkson & Hamilton 2000) is based on a knowledge model which identifies the key parameters in a task which prioritise or "signpost" the next appropriate task supported by the confidence in these parameters. The information related to the relative importance of tasks is stored by Signposting which generates a confidence mapping, determining new parameters produced and confidence changes in existing parameters. A confidence matrix is built to relate the "minimum confidence" of the inputs required to deliver a determined level of confidence in the outputs depending on the information available.

Table 2-1 shows a comparison of these models against the requirements for this research.

Table 2-1. Process modelling methods and requirements

Modelling Approaches	DFD	SSADM	IDEF0	DSM	Signposting
Definition of variability	☒	☒	☑	☑	☑
Building Blocks	☑	☑	☑	☒	☒

From comparing different methods of process modelling, it is concluded that IDEF0 is appropriate for this research.

2.3 Task Complexity

In processes executed by humans, most of the time they deal with complex tasks (Greitzer 2005; Boot et al. 2010) which need cognitive and physical skills as well as dexterity in order to be performed. Some of this complexity has been identified as coming from variability (Wood 1986; Campbell 1988; Xiao et al. 1996; Carey and Kacmar 1997; Williams 1999; Bell and Ruthven 2004; Liu and Li 2012). In addition, complexity has also been identified as one of the main challenges for automation (Bailey & Scerbo 2007; Wang et al. 2013).

Therefore, it is interesting to understand complexity and its implications for manufacturing processes. Although there is no universally accepted definition of task complexity (Liu & Li 2012), some authors have tried to define complexity, separating subjective complexity (complexity seen from the executer of the task perspective) from objective complexity and complexity from difficulty.

Consequently, objective task complexity has been defined as the perspective which takes into account only task characteristics, independently from the performers as opposed to a subjective task complexity perspective which considers task complexity as a combination of qualities of the task and task performer characteristics (Wood et al. 1987). In addition, task complexity has been defined as objective characteristics of a task, whereas task difficulty involves the interaction among task, task performer, and the context. Task difficulty applies to what task performers “feel” regarding how laborious it is to execute a task.

However, there is no agreement among researchers whether complexity and difficulty are the same or should be differentiated when applied to tasks. On one hand, there are authors claiming that task complexity and difficulty are synonymous (Vakkari 1999; Lamberts & Shanks 2013; Campbell 1988). To the contrary, other authors believe that task complexity and difficulty allude to two different concepts (Backs and Boucsein 2000; Braarud 2011; Ham, Park, and Jung 2012; Liu and Li 2012).

For example, in Bonner's work (1994), task complexity has two dimensions: task difficulty (i.e.: the amount of information) and task structure (i.e.: the clarity of information) whereas Robinson (2001) stated that task complexity is the cognitive demands in a task and task difficulty is connected to the grade of knowledge an executer brings to the task.

For some authors, task complexity is the aggregation of any intrinsic task characteristic that influences the performance of the task. Thus, if a task characteristic imposes specific resource requirements (e.g., cognitive and physical demands, required knowledge and skills) on task performers, it is considered to influence the performance of the task (Liu & Li 2012).

Other authors claim that task complexity is highly related with previous knowledge and how it can be applied when performing the task. When learning relative to distinct actions, people behave as if these new actions will be compatible with previous knowledge (Vakkari 1999). According to Heit (1997), learning of fresh actions is influenced by our former knowledge in at least three aspects: integration, selective weighting and facilitation effects. The more previous knowledge a person has, the easier it is for him to successfully finish a complex task.

It is not the scope of this research to find a definition of task complexity or task difficulty, but to discover which task characteristics play a key role in human performance when developing a task. This review of the literature tried to explain the subjectivity and ambiguity of the definition of task complexity and how vague the boundary is between complexity and difficulty.

As a consequence of this lack of clarity in task complexity factors and characteristics, several authors have created different models of task complexity, describing the factors affecting task complexity and dimensions of the complexity. The most relevant are (by date published):

Wood (1986) argued that all tasks contain three essential components; required acts, information cues and products. Acts and information cues (inputs) and products (outputs) can be used to describe any task and, therefore, represent the basis for developing a general theory of tasks. Three types of task complexity are defined: component, coordinative and dynamic.

Campbell's (1988) complexity model states that complex tasks have a number of the following characteristics: multiple paths, multiple outcomes, opposed correlation among paths, and uncertain or probabilistic associations. Campbell defines a complex task as one where the task performer is requested to utilise high cognitive skills. Task complexity increases as goal discrepancy increases, i.e.: if achieving one requested output differs with achieving another desired output. On the contrary, if all paths (i.e. alternatives) are likely to reach the same desirable outcome, this redundancy may reduce task complexity. The more highly structured the problem of a task (the more defined are its information requirements, process, and outcomes), the clearer the performer knows the basic elements of a task, consequently, more accurately s/he is able to determine what kind of information s/he needs and what processes are required for its completion. Simple tasks are typically tasks with structured problems (Nembhard & Osothsilp 2002). Campbell's work mentions the factors of task complexity, however does not indicate how these factors add complexity to the task. It is also missing whether these factors are related somehow or they are independent.

Bonner (1994) classified elements of task complexity into three types: input, processing, and output. Each of them have two dimensions: the amount of information and clarity of information. Each dimension has different factors affecting complexity of the elements (input, process and output). Bonner's model is simple and easy to understand. On the other hand it does not explain what the relationships are among factors is or how these factors affect overall task complexity.

Braarud and Kirwan (2011). Their work is based on experiments developed with operators from a boiling water reactor and a commercial nuclear plant. They identify four complexity factors from a literature review: process complexity, task complexity, interface complexity and subjective complexity. They propose eight dimensions of complexity: ambiguity, spread/propagation, coordination requirements, information intensity, familiarity, knowledge, severity and time pressure/stressors. It is essential to mention that Braarud and Kirwan's study shows a high correlation among dimensions. A significant finding of their work for this research is that for complex scenarios, high variability was found among operators.

Ham, Park and Jung (2012). In their task model, they differentiate three task aspects: functional aspect (i.e. goals of a task), behavioural aspect (information collection, information analysis, decision and action collection, action implementation and action feedback), and structural aspect (i.e. task expression, structural forms, lexical aspects, etc.). Task complexity has three dimensions: size, variety, and order/organisation. Complexity factors are identified and organised by the combination of the three aspects of tasks and the three complexity dimensions.

Liu & Li (2012). They present six task components: goal, input, process, output, presentation and time. These components have different "complexity contributory factors" which are indicators of the complexity of each task. Therefore, they also included ten complexity dimensions: size, variety, ambiguity, relationship, variability, unreliability, novelty, incongruity, action complexity, and temporal demand which facilitates the estimation of the level of complexity of the task. In this model, variability (as inherent deviation) is identified as one of the factors adding complexity to a task.

Table 2-2 shows parameters found in these models and other literature which can be potentially used to describe variability. These parameters provide a basis for understanding variability. However, they do not include quantification of variability.

Table 2-2. Task Complexity Models

Parameters	Found in
Number of elements	(Baccarini 1996; Rouse & Rouse 1979; Williams & Li 1999)
Number of information cues, information load	(Steinmann 1976; Simnett 1996; Hartley & Anderson 1983; Wood 1986; Bonner 1994; Asare & McDaniel 1996; Carey & Kacmar 1997; Zhang et al. 2009)
Number of products/outcomes	(Wood 1986; Campbell 1988; Ho & Weigelt 1996; Harvey & Koubek 2000)
Variety/diversity of elements	(Gardner 1990; Ham et al. 2011)
Presentation heterogeneity	(Bonner 1994; Marshall & Byrd 1998)
Uncertainty	(Campbell 1988; Wood 1986; Carey & Kacmar 1997; Xiao et al. 1996; Williams 1999; Bell & Ruthven 2004)
Connectivity/relationship	(Rouse & Rouse 1979; Wood 1986; Campbell 1988; Bonner 1994; Baccarini 1996; Williams 1999; Boag et al. 2006)
Number of paths/solutions	(Campbell 1988; Bonner 1994; Harvey & Koubek 2000)
Number of alternatives	(Payne 1976; Kim & Khoury 1987; Payne et al. 1992)
Number of operations/sub-tasks/acts	(Wood 1986; Speier 2006; Xu et al. 2009; Zhang et al. 2009)
Structure/specification/clarity	(Bonner 1994; Byström & Järvelin 1995; Harvey & Koubek 2000; Nadkarni & Gupta 2007; Mascha & Miller 2010; Skjerve & Bye 2011; Liu & Li 2012)
Repetitiveness/non-routinely	(Harvey & Koubek 2000; Schwarzwald et al. 2003)
Concurrency	(Xiao et al. 1996; Molloy & Parasuraman 1996; K. C. Hendy et al. 1997; Skjerve & Bye 2011; Liu & Li 2012)
Time pressure	(Payne et al. 1992; Skjerve & Bye 2011; Liu & Li 2012; Greitzer 2005; Svenson & Edland 1987; Klein 1993; K. C. Hendy et al. 1997)
Format/mismatch/inconsistency/compatibility	(Steinmann 1976; O'Donnell & Johnson 2001; Greitzer 2005; Liu & Li 2012)
Difficulty	(K. C. Hendy et al. 1997; Greitzer 2005; Liu & Li 2012)
Cognitive demand	(Campbell & Gingrich 1986; Campbell 1988; Sintchenko & Coiera 2003; Bailey & Scerbo 2007; Liu & Li 2012)
Physical demand	(Campbell & Gingrich 1986; Campbell 1988; Sintchenko & Coiera 2003; Bailey & Scerbo 2007; Liu & Li 2012)

In manufacturing, how task complexity affects operators and disparity of outputs has gained importance in recent years. Task complexity influences performance, motivation, learning, productivity and human variability and it is affected by internal human factors such as experience. As a result of this connection, it is pointed out that, for jobs of greater complexity, an increase in job experience results in higher job knowledge and task performance (Kahya 2007).

Studies have shown a correlation between task complexity and productivity. These findings suggest that differences in individuals' abilities seem to be a major cause of variations in productivity for complex tasks. The more complex a task is, the more likely dissimilar results will be obtained among individuals, considering it demands extra attention and effort (Backs and Boucsein 2000). However, Wood (1986) claims that the relation between task complexity and productivity is curvilinear, where higher complexity leads to higher challenge and motivation. Therefore, results in higher productivity, to a certain point whereas as complexity increases, task demand surpasses individual capacities to respond, and consequently productivity decreases.

There are other studies that suggest that external factors such as time pressure or environmental conditions may reduce the number of cues analysed, thereby reducing the quality of the decision (Klein 1993). Svenson and Edland (1987) demonstrate that decisions and choices can be affected by time pressure. Time pressure influence affected the majority of the subjects hence an alternative was chosen under time pressure and another alternative was chosen when decision time was unlimited. Under extreme environmental conditions or when the subject is fatigued, an extra effort is required, producing different outputs among individuals (Backs and Boucsein 2000). These external factors might also cause variations in human task execution even with the limitations and control imposed by job simplification and automation in modern manufacturing systems (Osman 2010).

In manufacturing environments, ergonomics is the science which studies human behaviour when dealing with internal and external factors, which is described in the next section.

2.4 **Ergonomics**

Although it has been shown that humans might introduce variability in a manufacturing process, it is also well documented that humans are capable of interacting with different sources of variability due to the human capability of adapting to external conditions, making decisions accordingly and consequently, accomplishing tasks that otherwise would be impossible to be finished within the established time and quality standards (Sandom & Harvey 2004). This unique attribute cannot be found in machines at reasonable cost and cause humans to be qualified to assimilate sources of variability in manufacturing, reducing or mitigating their damaging effects. This adaptability is an essential asset when talking in relation to manufacturing environments although can be affected by several factors.

Humans are able to perform tasks in multiple ways, depending on factors surrounding them although they are also supported by intrinsic characteristics inherent to each human being. For example, in a specific aeronautical process, it has been found that a few operators execute the process in a way that final output dimensions are inside the acceptable range of tolerances, whereas others attempt to obtain zero deviation in their outcomes (Thornton 2004). This behaviour is produced by internal human attributes making people, working in the same environment, perform the task in different ways due to personal motivations. The same can be stated in other manufacturing processes; people are diverse when performing tasks and, this is what makes humans to be just so complex and adaptable.

The definition given by the International Ergonomic Association (IEA 2016), “ergonomics is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimise human well-being and overall system performance”. According to this Association, the origin of the word ergonomics comes from the Greek “ergon” meaning work and “nomos” meaning laws. As a science, ergonomics is classified into three different disciplines: physical ergonomics, cognitive ergonomics and organisational ergonomics. Table 2-3 shows ergonomics disciplines, their field of study and principal topics studied (International Ergonomics Association 2000).

Table 2-3. Classification of ergonomics studies(International Ergonomics Association 2000).

Classification	Field of study	Topics
Physical	Human anatomical Anthropometric Physical activity	Working postures Materials handling Repetitive movements Work-related musculoskeletal disorders Workplace layout Safety and health
Cognitive	Mental processes (perception, memory, reasoning, and motor response). Interactions among humans and other elements of a system	Mental workload Decision-making Skilled performance Human-computer interaction Human reliability Work stress and training.
Organisational	Optimisation of organisational structures Optimisation of policies Optimisation of processes	Communication Crew resource management Work design and Design of working times Teamwork Participatory design Community ergonomics Cooperative work New work paradigms Organisational culture Virtual organisations and Telework Quality management

Physical ergonomics studies physical postures, movement, work injuries, optimal working lay-outs and safety and health hazards. This field of ergonomics is extensively studied in relation to humans in working environments but no research has been carried out in physical human dynamic and movements to overcome variability which could potentially be applied to automation problems.

Cognitive ergonomics is fundamental in order to understand human behaviour in working environments. The nature of complex manual processes implies that cognitive processes play a fundamental role in dealing with variability. The analysis of cognitive aspects of human performance is carried out by process analysis. Process analysis is a extension of traditional process analysis techniques which allows the generation of information with reference to the knowledge, thinking processes and goal structures that lie beneath observable task performance (Schraagen, Chipman, and Shalin 2000). These techniques could be extended to link human cognitive processes with artificial intelligence in order to solve variability in manufacturing processes.

There are a few studies aiming to model these cognitive processes. For example Rasmussen's (Rasmussen 1983) model of cognitive control, distinguished skill-based, rule-based, and knowledge-based behaviour operating within the context of a decision ladder that permitted heuristic cut-off paths, where skill-based behaviour is performed during familiar acts or activities and it takes place unconsciously, in smooth, automated, and highly integrated patterns of behaviour. Secondly, at the level of rule-based behaviour, a chain of subtasks in a common work situation is commanded by a stored rule or procedure which may have been acquired from previous events, revealed for others' know-how or it may be elaborated by intentional problem solving and planning. Finally, during unfamiliar situations, where know-how or rules are not available from previous experience, the performance is knowledge-based. In this situation, the goal is explicitly formulated, based on an analysis of the environment and the overall aims of the person. At this point, among a bunch of plans considered and tested against the goals, one is selected, considering its suitability with the expected outcomes. Rasmussen's model explains satisfactorily the majority of the situations that people face on a daily basis. For example, driving a car may be skill-based for experienced drivers or rule-based for new drivers however, it can switch to rule-based and knowledge-based respectively with extreme weather conditions.

Although this model helps to understand human behaviour when facing different problems, depending on the level of knowledge and experience, it does not explain why the performance of people with the same level of knowledge can be substantially different when they deal with identical situations. This would be useful when a task is to be automated as more than one solution will overcome the variability but one of them would be easier for replication by an automated solution.

Fundamentally, when a task is to be automated, the implications of introducing those devices into the process have to be investigated, in terms of health and safety in workplace but also the interactions which will occur between operator and machine.

2.5 Human-machine interaction

Human-machine interaction plays a key role in manufacturing environments. Machines have become a major support for humans when developing certain tasks, given that those are dangerous, tedious, repetitive, physically demanding (for example: heavy weights or restricted access), etc. Nowadays, humans perform tasks that cannot be performed by machines and vice versa, machines execute tasks not suitable for humans due to a variety of reasons (for example, dangerousness and physically demanding).

This collaborative environment is being researched under “human-machine interaction” label.

Fitts was the first who took into consideration of the incorporation of machines in manufacturing and how human-machine interaction occurred in manufacturing environments (Fitts 1951). He stated ten basic differences between humans and machines and this is known as The Fitts’ list and continues to be cited today (De Winter & Dodou 2011) and it is summarised in Table 2-4.

Table 2-4. Fitts’ List (Fitts 1951)

HUMAN IS SUPERIOR	**MACHINE IS MORE SUITABLE FOR**
Detecting a minuscule amount of visual or acoustic energy	Responding quickly to control signals and Applying great force smoothly and precisely
Perceiving patterns of light or sound	Performing repetitive, routine tasks
Improvising and using flexible procedures	Storing information briefly and erasing it completely
Storing large amounts of information for long periods and recalling relevant facts at the appropriate time	Reasoning deductively, including computational ability
Reasoning inductively	Handling highly complex operations, i.e.: doing multiple different actions at once
Exercising judgment	

In a human-machine system, one of the significant differences is that machines work with digital data whereas human skills and capabilities vary in a much extended context. A Fitts’ list separates those tasks which are better performed by humans and those where machines are more suitable. The list recommends that those functions that are better performed by machines should be automated while the other functions should be assigned to the human operator (De Winter & Dodou 2011). However, there are new approaches looking for adaptive function allocation between humans and machines rather than separation (Feigh et al. 2012).

In human-machine interaction, the safety of the worker is an essential precondition. Researchers will need to improve the cooperation of humans and machines not only for one human but also for groups working in complex tasks aided by more than one machine at the same time (Krüger et al. 2009). Accordingly, a detailed literature review of human-machine cooperation can be found in (Agah 2000), including machines, smart appliances, computers, new technologies and robots.

In relation to variability, it is interesting to look at studies measuring human performance in tasks when assisted by some form of automation, due to the fact that in some manufacturing processes, it might be a plausible solution (human-machine system). Table 2-5 presents by date of publication different studies in task performance with automated aid and their findings. There are a high variety of automation aided solutions ranging from a robotic arm interface (Park & Woldstad 2000), a flying simulator (Mosier et al. 2007), search and rescue tasks (H. Wang, Lewis, et al. 2009) and victims location and team collaboration (H. Wang, Chien, et al. 2009). These studies show that highly demanding tasks, requiring additional subject responses, had a negative impact on performance. Some studies also indicated the relationships between performance and workload. For example, less time to perform a task increased performance, but it also augmented workload and error rate (Mosier et al. 2007).

Table 2-5.Summary of studies in task performance

Author	Parameter	Criteria	Findings
(Park & Woldstad 2000)	Size of location for placing	Efficiency and workload when transferring an object with robotic arm	Higher workload and less efficiency with smaller targets
(Mosier et al. 2007)	Low/high time pressure	Errors and efficiency in assessing system problem in flight simulator	Adding time pressure increased pilot efficiency, but also increased assessment mistakes.
(H. Wang, Lewis, et al. 2009)	# Of tasks assigned	Search and rescue task: people saved, area examined, efficiency, and workload	Subjects examined greater area, switched between robots more often, and reported less workload with simple exploration task. Subjects with search and locate tasks had worst productivity.
(H. Wang, Chien, et al. 2009)	Individual vs. shared robot control	Victims located, area examined, and team collaboration	Individual control of a robot conducted to slightly more people found and significantly more surface area explored. Sharing control of a various robots brought loss of team communication and coordination

In addition, if a human-machine system is to be implemented, it would be worthy to investigate the reliability of the automation aid as well as the performance of subjects with different levels of reliability of the automated aid. Table 2-6 presents by year of publication some studies investigating human performance in relation to automation reliability. Reliability and accuracy of automated support has a significant effect on performance. False alarms decrease performance more than true misses (Levinthal &

Wickens 2006) and subjects do not rely on the recommendation made by the automated solution, ignoring raw data more frequently (Dixon & Wickens 2006). Unreliable automation solutions reduced performance (Rovira et al. 2007). The findings suggest giving operators access to data and informing operators on the reliability of the system may improve the outcome (L. Wang et al. 2009).

Table 2-6. Summary of studies investigating automated aid reliability

Study	Parameter	Criteria	Findings
(Muthard & Wickens 2003)	For route selection, flight aid: reliable vs. unreliable	Errors, efficiency, and confidence in route selection and implementation	When route was automated, subjects ignored environmental changes more often. Automation was best in selecting the route but not implementing it
(Dixon & Wickens 2006)	3 different automated alerts reliability: 100% reliable, 67% with false alarms, and 67% with misses	Errors, reaction time (RT), and situational awareness	False-alarm decreased the use of aids leading operators to ignore raw data Imperfect automation lead to better detection of a target miss
(Levinthal & Wickens 2006)	Different levels: No automation, 60% reliable with true misses, 60% reliable with false alarms and 90% reliable	Efficiency in controlling unmanned aerial vehicle (UAV), RT to alarms	False alarms reduced performance more than 90% reliable or 60% reliable with true misses
(Goodrich et al. 2007)	Remote robot operation vs. semi- autonomous navigation with failure warning on/off	RT	Semi-autonomous results in faster recognition of problems, but with failure warning “off”, it turned into a disadvantage. Semi-autonomous drove to dependence when secondary tasks were engaged
(Rovira et al. 2007)	60% vs. 80% decision reliability in automated aid	Errors, RT, workload, and trust on automated decision	Non-reliable automation decision was prejudicial to performance.
(Chen 2009)	Focus on aids with irregular reliability (false-alarm or miss-prone): spatial ability and attentional control	Mistakes and workload for communication and gunnery tasks	Higher automation drove to better performance and lower workload High attentional control conducted to false alerts being more detrimental
(L. Wang et al. 2009)	Target identification task with: no aid, 67% reliable aid, or 80% reliable (disclosed to participants or not)	Trust on automation	80% reliable aid improved performance compared to 67% reliable and no aid Reliability information disclosed resulted in more trust on aids

Hence, when the complexity of tasks increase it is necessary to dynamically manage the workload of operators to maintain an optimum performance. Therefore it is critical to choose the appropriate level of automation, depending on the nature of the tasks and the reliability of the automated solution.

2.6 Levels of Automation

Throughout the last century, manufacturing companies have put a lot of effort in developing automated processes in order to increase productivity while maintaining a high quality of products. Automation has been applied not only to manufacturing processes, but also to subsidiary tasks such as handling, transport and storage (Reveliotis 1999). However, a considerable amount of manufacturing processes are either manual or semi-automatic, combining automated and manual tasks. Moreover, the intricacy of manufacturing systems is increasing due to customised products and the increment of product complexity (Satchell 1998). Therefore, the human factor is an important asset in the manufacturing process, and as such, skilled operators and automated systems are essential to achieve flexible and productive manufacturing environments. Hence, automation decisions are extremely important as disproportionate level of automation may be detrimental to the operator performance (Parasuraman et al. 2000; Chmiel 2008). Consequently; finding the right Level of automation to apply has become critical.

Many authors have proposed the concept of levels of automation from many different areas. Table 2-7 shows a selection of definitions of levels of automation.

Table 2-7. Different level of automation definitions

Author	Levels of Automation definition
(Billings 1997)	The level of automation ranges from direct manual control to autonomous operation where the human intervention is minimal.
(Satchell 1998)	The level of automation is defined as the division between the human and machines with different grades of human implication.
(Parasuraman et al. 2000)	Level of automation is a progression from manual to fully automatic operations.
(Groover 2007)	The level of automation is an amount of the human level of implication around the machines, which can be either manually operated, semi-automated, or fully automated.
(Frohm et al. 2008)	The distribution of physical and cognitive tasks between humans and technology, varying from totally manual to totally automatic

According to Williams and Li (1999) automation can be divided into mechanisation and computerisation. Mechanisation refers to the substitution of human physical force.

Computerisation refers to the substitution of cognitive tasks, such as human sensorial activities and mental tasks including acquisition, memorisation, analysis and use of information, to be able to perform the manufacturing process.

Most tasks within manufacturing processes present a mix of both, mechanisation and computerisation. Taking into consideration these two aspects, automation in manufacturing should be considered as an interaction between physical tasks and cognitive tasks. The physical tasks are basic manufacturing tasks, for example; welding, drilling, polishing, and the cognitive tasks are controlling and supporting those physical tasks.

Frohm et al. (2008) propose a classification composed of seven different levels, considering two separate scales associated to the two types of level of automation, physical and cognitive as seen in Table 2-8.

Table 2-8. Classification of level of automation according to Frohm et al (Frohm et al. 2008)

LoA	Mechanisation	Information and control
1.	**Totally manual**. No tools are used, only the users own muscle power. e.g. The users own muscle power	**Totally manual**. The user creates his/her own understanding for the situation, and develops his/her course of action based on his/her earlier experience and knowledge. e.g. The users earlier experience and knowledge
2	**Static hand tool**. Manual work with support of static tool. e.g. Screwdriver	**Decision giving**. The user gets information on what to do, or proposal on how the task can be achieved. e.g. Work order
3	**Flexible hand tool**. Manual work with support of flexible tool. e.g. Adjustable spanner	**Teaching**. The user gets instruction on how the task can be achieved. e.g. Checklists, manuals
4	**Automated hand tool**. Manual work with support of automated tool. e.g. Hydraulic bolt driver	**Questioning**. The technology question the execution, if the execution deviate from what the technology consider being suitable. e.g. Verification before action
5	**Static machine/workstation**. Automatic work by machine that is designed for a specific task. e.g. Lathe	**Supervision**. The technology calls for the users' attention, and direct it to the present task. e.g. Alarms
6	**Flexible machine/workstation**. Automatic work by machine that can be reconfigured for different tasks. e.g. CNC-machine	**Intervene**. The technology takes over and corrects the action, if the executions deviate from what the technology consider being suitable. e.g. Thermostat
7	**Totally automatic**. Totally automatic work, the machine solves all deviations or problems by itself. e.g. Autonomous systems	**Totally automatic**. All information and control is handled by the technology. The user is never involved. e.g. Autonomous systems

This classification takes into consideration both physical and cognitive actions separately. In contrast to other models, it classifies actions into two types: mechanisation (physical) and information and control (cognitive) which allow the assessment of independent levels of automation for both types of actions. This scale will be used later in the thesis (Chapter 6) to suggest levels of automation for tasks. However, because the level of automation will be applied to a task level, the distinction between physical and cognitive actions cannot be made. This is a similar approach to that found in the literature, where most authors apply levels of automation to tasks (Kotha & Orne 1989; Billings 1997; Endsley & Kaber 1999; Parasuraman et al. 2000; Lorenz et al. 2002; Sauer et al. 2013) without any distinction between physical and cognitive tasks.

If the lowest level of automation is completely manual and the highest level of automation is fully automated, studies have demonstrated that intermediate levels of automation entail superior performance (Manzey et al. 2008; Lorenz et al. 2002) and decreases labourers' workload (Röttger et al. 2009). Being dependent on automation makes operators highly vulnerable to situations when a system crashes, and the degree of their reliance will increase the magnitude of the impact proportionally (Reichenbach et al. 2011).

2.7 Intelligent Automation

Classical automation is a method of standardisation of processes. Full automation of a process will eliminate variability introduced by humans in the process. However, the high value manufacturing industries have applied limited automation because of the highly skilled nature of the finishing, inspection and assembly work inherent in the manufacturing processes. These processes are difficult to automate because of minor variation in components that influence interaction between processing equipment and component being processed. In addition, parts are often made from expensive materials, with many parts requiring careful handling in a high added value state (e.g. gas turbine fan blades). Whilst humans can accommodate variation at certain levels, they often introduce variations or errors by virtue of being human (e.g. through lack of concentration).

Variability is a critical issue when automating a manufacturing process. Metrology systems can be included in the processes, to measure the range of variability but, in order to design an automated solution which is capable of overcoming this variability, these measurements need to be collected before the automated solution is implemented which makes them less appealing. Complementarily, the robustness of the automated solution can be increased by corrective actions and error compensation algorithms (Jamshidi et al. 2010), but it is effective only if the source of variability is known.

In addition, different solutions are available and broadly used in the manufacturing industry such as industrial robots and other automatic systems; however, their poor positioning accuracy is a main issue when it comes to overcoming variability (Jamshidi et al. 2010). Furthermore, specified requirements for a process might not be within the capabilities of the existing technologies, for example in terms of tolerances, accuracy, physical requirements (high loads and forces involved) and complexity of products and processes (Kihlman 2005). In order to cope with variability, and therefore to reach the demanded level of adaptability, these systems need to "learn" from previous experiences, make a decision accordingly and implement it.

Soft computing is a branch of computer science which tries to "imitate" the outstanding ability of humans for learning from experience and analysing new situations. Soft computing techniques have potential to deal with complex engineering problems including variability in manufacturing processes (Dixit & Dixit 2008; Deb & Dixit 2008). Soft computing techniques include neural networks, fuzzy logic, particle swarm optimization, genetic algorithms and ant colony optimization.

A neural network is a system able to store and apply "knowledge" gained from experience. Artificial neural networks (ANN) can successfully learn from a set of experimental data designed to describe nonlinear and interaction effects in a system (Dixit & Dixit 2008). Fuzzy logic is a tool for "computing with language" which has proven effective when transforming subjective knowledge of the skilled operators into a mathematical model (Chandrasekaran et al. 2009). Particle swarm optimisation is a technique inspired by bird flocking/fish schooling where each solution is called a "particle" and the optimisation runs consecutive interactions; assessing the results against the objective function (Kennedy 2010). Genetic algorithms imitate natural evolution by introducing the "survival of the most adapted" theory. In Genetic algorithms, a point is represented by binary or decimal numbers, known as string or chromosome. Each chromosome is assigned a fitness value that indicates how closely it satisfies the desired objective (Goldberg 1989). The Ant colony optimisation algorithm is inspired by behaviour of ants' colonies which establish the optimum routes from their nest to the food by deposing pheromones which can be tracked by other ants. Basically, the algorithm works by building "solutions" representing artificial ants which can lead to other solutions closer to the optimum (Dorigo et al. 1996).

These techniques can be implemented in automated solutions which need to deal with variability. However, they would take advantage of a comprehensive knowledge of the variability involved in the process before the solution might incorporate any of them. This is why, those parameters which affect variability need to be further investigated.

Adaptive Automation was born to describe the changes in automation trends. Adaptive Automation refers to the allocation of tasks between the operators and automation which is dynamically adjusted based on task demand, user capabilities, total system requirements and optimal system performance and can help to provide intelligent human-automation solutions. Conceptually, the principal advantage of adaptive automation is that operator workload and fatigue can be regulated as a function of the shifting level of automation (Byrne & Parasuraman 1996). Operators manifest a clear preference for less automation, despite its benefits, by the reason of the retention of manual control and this can be attributed to operators' aspiration for decision-making authority (Chmiel 2008). Contrarily, Sauer et al. pointed out in their study that there are not strong unbiased benefits from adaptive automation although it reconfirmed the subjective operators' preference for higher levels of control (Sauer et al. 2013).

Nevertheless, other authors believe that next step in automation should focus on "symbiotic technologies" that can increase human physical and cognitive capabilities (Boff 2006). The proposed design requirements should balance the strengths and weakness of humans and machines in a distributed system of information processing communication, decision and control, instead of automating all that can be automated and leaving the rest to workers or automating all that is found difficult by operators. Therefore, the next level will be to ameliorate operators' physical and cognitive capabilities with machine assisted aid. It seems to be clear that in modern manufacturing process, a more effective configuration balance between human capabilities and machines is required (Boff 2006).

Variability in operator's technique may contribute to process variability. It may be necessary to evaluate variability among operators as much as variability of the same operators on different days (when performing the same task) in order to assess the robustness (or weakness) of a manufacturing process. This variability could be reduced with training and clearer instructions (Glodek et al. 2006). To the contrary, operators have the capacity to reduce or eliminate this process variability by skills and experience, becoming an essential part of process robustness. However, when operators perform tasks in manufacturing environments they might achieve the required goals by executing those tasks in different ways (Patrick & James 2004). This fact could lead to a customised manufacturing process where operators would play a key role and the process will be designed for their capabilities, attitudes and experience. This trend and the classical approach are graphically explained in Figure 2-1.

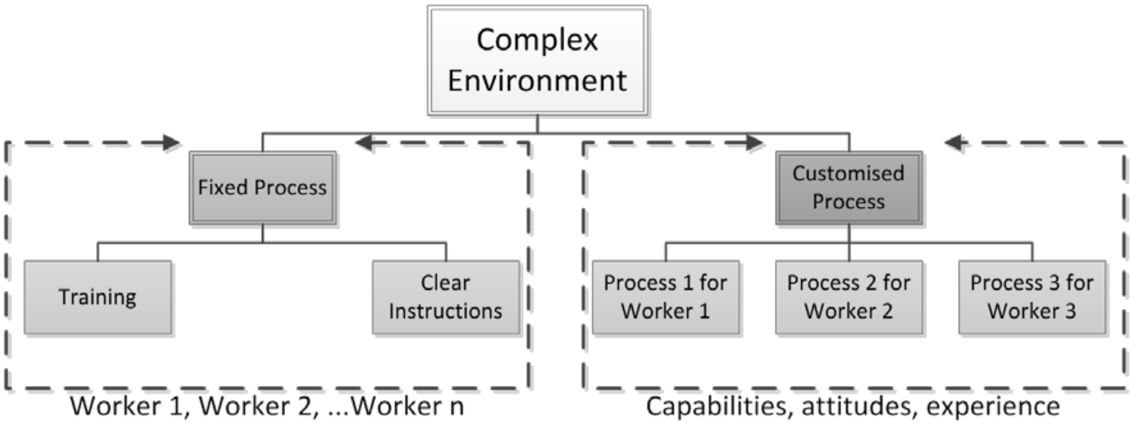


Figure 2-1. Process Design trends

Historically, individual attributes have been ignored in management. Attempts to combine individual behaviour and job design into models of production have been imprecise. The heterogeneity and variability of individual employee should be taken into consideration when designing production lines (Doerr and Mitchell 2002). The workers, as a basic source of variability (Doerr and Arreola-Risa 2000), should be appraised and managed with careful attention.

2.8 Summary

After the review of several aspects involved in manufacturing, variability, automation, task complexity, human factors and human-machine interaction it has been observed that there is a lack of connection between research in variability, task complexity and human factors with research conducted in automation. In addition, research in automation has not fully identified variability as one of the challenges to be addressed for processes that are currently difficult to automate in industry.

Therefore, there is an opportunity to link these fields by bringing the study of variability into automation of processes as an additional variable to be taken into consideration when a process is being considered for automation. Diagram in Figure 2-2 shows variability and its connections to other disciplines reviewed in literature.

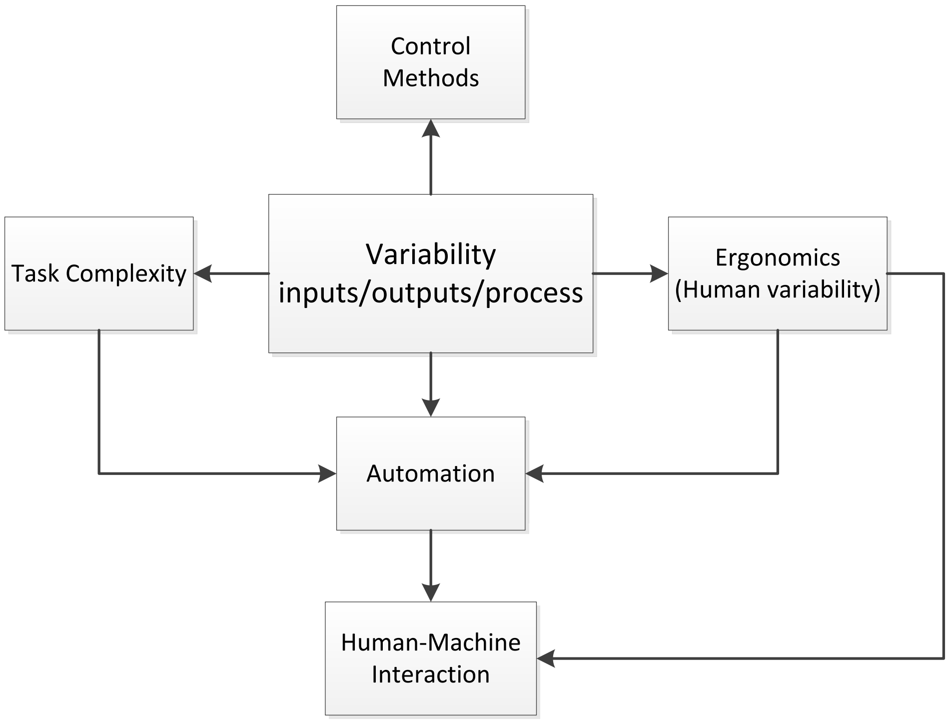


Figure 2-2. Variability and links to other disciplines

In order to do that, task complexity models can be used as a starting point to look into the parameters to characterise variability in processes as variability has been identified as one of the parameters contributing to tasks complexity: uncertainty (Campbell 1988; Wood 1986; Carey & Kacmar 1997; Xiao et al. 1996; Williams 1999; Bell & Ruthven 2004) or variability (Steinmann 1976; O’Donnell & Johnson 2001; Greitzer 2005; Liu & Li 2012).

3. RESEARCH METHODOLOGY

In this chapter, the research methodology to achieve the research aim and objectives is explained, i.e. how different studies and methods are used to answer the questions posed in this research. The research methodology is divided into three phases.

The first phase comprises the study of actual manufacturing processes previously identified by our industrial collaborators as processes where variability is present. The aim of this phase is to establish a procedure to identify the sources of variability embedded in the processes studied along with how operators are coping with this variability. This will lay the foundations to build the framework, setting the context of some of the parameters which will be used to categorise the variability in the framework to be proposed afterwards.

The second phase involves building the framework considering findings from process studies and the literature review. In this phase, those parameters that were found to be suitable to describe variability within the studied processes are compared with parameters in the literature describing task complexity to define the parameters to include in the framework.

The third phase validates the framework built from the study of the industrial processes and literature review by studying an experiment and an industrial case study through the application of the framework. In the experiment, the sources of variability are known and controlled; therefore, the human behaviour coping with this variability can be measured. In the industrial process, manual and automated solutions coexist and they can be compared to present the challenges and limitations of the automated solution adopted when dealing with variability. Finally, the framework will be tested by different users to probe its usability and the robustness of the outcomes. The phases are summarised in Table 3-1.

Table 3-1. Research Methodology phases and objectives

Stage		Objectives	Outcomes
Process Studies	**Process Study 1.** Grinding and Polishing **Process Study 2.** De-burring	Identification of variability in the process. How operators are coping with this variability. To determine parameters to be used in the framework to categorise variability	- Identification of the sources of variability in the process - Description of Key Characteristics for variability - Establishment of some parameters to be included in the framework.
Framework building	**Findings** from processes studied and **literature**	To select the parameters to be used in the framework	- Twelve parameters within five attributes to categorise variability in manufacturing processes
Validation	**Experiment.** Peg in a hole **Case study.** MIG Welding **Three processes.** Usability	Framework application and robustness	- Categorisation of the variability present in the processes where the framework was applied. - Comparative of the outcomes obtained by different users when applying the framework to the same process.

Following, the methods used in this research are described and justified.

3.1 Gathering information

The identification process starts by searching for the sources of variability in the information available about products, equipment, process, suppliers, quality and maintenance reports and customers.

Product

Product Requirement Documents: this defines the requirements of the product, e.g. materials, shape, dimensions and CAD models.

Functional structure of the product: this describes what the product is designed for and what its working conditions are. This gives an idea of what the critical features are when the product is being used.

Equipment

Equipment Requirement Documents: it determines the requirements of the equipment used in the process (for example: inputs, interface requirements, energy consumption and signals requirements).

Process

It delimits how the product is made. It is essential to understand how different components are manufactured and assembled. Tracking the product through the process from inputs to outputs is a good way to find sources of variability.

Suppliers

It identifies the suppliers (internal or external) of every input of the process. These inputs can be raw material, semi-finished inputs or finished inputs (tools, machinery and equipment). The composition of raw material might vary from one batch to another, affecting the physical and chemical characteristics of the material. Similarly, for semi-finished inputs variations could be found among the same types of input which may be transferred through the process, producing unacceptable outputs at the end of the process. Finally, tools, machinery or equipment from different suppliers might differ, which could potentially affect outcomes. Traceability is essential to identify the origin of the variability for inputs.

Quality and maintenance reports

Quality: rework or scrap rate and Statistical Process Control (SPC) data are ways to show discrepancies during processes. This data are usually displayed in quality reports. Maintenance: these reports present any process incidents. The maintenance department records any non-programmed break down occurrences in the process.

Customers

Customer complaints and warranty data: this gives information of what are the most common failures and defects of the outputs. This kind of information should be filed and consulted and gives the company great feedback relative to how the product is behaving in working conditions. A trusty relation with customers and a trustworthy post-sales service provides valuable information on a product’s performance.

3.2 Observations

Observation has been revealed as a powerful tool for studying manufacturing environments and its variations, related to processes or workers: workers performance's variations (Fletcher et al. 2006), selection of variability for quality purposes (Thornton 2000) and identification of sources of variability (Loose et al. 2008).

There are different ways of using observation as a research method: participant vs non-participant (direct and indirect), overt vs covert and structured vs unstructured (Slack et al. 2001).

In this research, a non-participant, direct, overt and structured observation has been conducted as it is the most suitable for the environment and the nature of the tasks observed. Non-participant observation is when the observer stands apart from the process being observed versus participant observation where the observer engages in the action. Direct observation is carried out when the researcher observes and takes notes in the facilities. Overt observation means that the observed knows that the observer is watching. Structured observation requires previous research from the observer in order to delimit what it is necessary to observe.

This type of observation has been selected by virtue of the special characteristics of the industrial environment. Participant observation would not be an option as the processes are carried out by experienced workers; indirect observation would miss details although video camera recording is used to re-watch the process therefore, acquiring deeper understanding of operators' skills and senses utilised when performing the processes. The use of covert observation is not suitable for the characteristics of the processes where the subject being observed is working in a small volume and small tools are handled in a highly precise location. Finally structured observation was necessary although no previously tried and tested framework was used due to the special environment of the process which was extremely restrictive and strongly dominated by confidentiality.

The observation is targeted to:

- Create a process analysis. This will break the process down, making it easier to identify in which exact step of the process the operator is facing the variability.
- To identify what skills and senses operators use to perform the process and overcome this variability.

The maximum number of expert operators was observed. The observation was supported by video recording and the camera was placed in order to capture ordinary movements of the operators and so as not to block the operations being recorded.

Photographs of the work cell were taken as the operators use a significant number of different tools and equipment and photographs facilitated the description of the cells. Notes were also written when observing. These notes completed the video recorded and brought back a few events and details that were forgotten.

Written consent was granted by the operators recorded and a brief explanation of the aims of the study was verbally provided. Contact details were also given to the operators who were observed, in case the persons required access to the material collected or published.

3.3 Interviews

The interviewing process was carried out after the observation process. To perform the interview after the observation makes easier to come up with other questions from the observation and notes that have not been considered in the original set of questions (questionnaire). The questionnaire was used to conduct the interviews, after the operators finalised an entire process (either a batch or a component). There are three types of qualitative interviews: structured, semi-structured, and in-depth interviews (Britten 1995). Structured interviews present an organised questionnaire where the questions are prepared prior the interview. Semi-structured interviews are developed in a way where the questions are open and the interviewer or interviewee might deviate in order to clarify something in more detail. Finally, in-depth interviews are not structured and basically are based on an open concept or general idea, for example “what do you think of process variability?” and subsequent questions from the interviewer would be constructed on previous answers and are often used to clarify the initial ideas.

In this research, the interviews were semi-structured, with a mix between closed and open questions (see Appendices). Closed questions had different answers to choose from whilst open questions allowed the researcher to find out more through a specific answer (Clark et al. 2008; Militello & Hutton 2000; Mulhall 2003).

Questions were subdivided into groups: work experience, procedure and tools. The aim was to capture quantifiable data. The questions were addressed to obtain:

The course of actions needed to finish the task. This helps to compare with the SOP and define an accurate representation of the process through the IDEF0 framework.

The group of decisions made to finish the tasks. The concepts, principles and procedure used to perform the process. This gave a complete framework of the procedure including basic parameters controlled, notions behind actions, rules and general philosophy of the process.

The parameters considered before proceeding. This presents those parameters analysed before executing the next step in the procedure.

The senses involved. The senses involved in the process are a great source of information for automation purposes. Understanding what senses humans rely on when performing a task may be used to assist the design and refinement of an automated solution considering that, the sense used are strongly related to the feature or characteristic being checked. For example, vision is used for dimensions, positioning or shape, tactile is used for minute surface defects or roughness and hearing is mainly used to find functioning anomalies.

The equipment and materials required. The equipment and materials also serve to assess the skills and physical conditions required to evaluate the tasks with the process.

After the interviews were completed, all the answers were reviewed with the interviewee for verification, refinement and revision to ensure that the responses are complete and accurate. The interview process confirmed quantifiable data from the collected data (years of experience, tools used, number of pieces per batch, etc.), investigated a number of unexpected findings from the observation process and finally, corroborated how operators dealt with the process' variability.

Collected data and observations showed the sources of variability and how operators coped with it and the interviewing process completed the findings with evidence.

The interview process was critical in order to better understand operators' skills, procedures and the key features to be controlled. A consciously prepared interview extracts the maximum from operators, solving enigmas, linking ideas and giving answers to hypotheses contemplated.

3.4 Process analysis

There are a great number of task analysis tools to choose from, depending on experience and the desired outcomes. The challenge then becomes to decide which method to use. IDEF0 has been chosen for the purpose of this research. IDEF0 is a functional model which breaks-down a process displaying a hierarchy structure. Based on information from documents, observations and interviews, the researcher must identify top-level operations (and its goals) and then break them down into sub-operations (and its goals) until the last indivisible sub-operation.

The selection of IDEF0 for this research was highly influenced by the fact that IDEF0 is intended to break down the process, from the observer's perspective. Understanding the influence of variability in the process was the major concern, and IDEF0 is the most suitable method to provide this outcome. In addition, IDEF0 has proved to be successful in manufacturing processes. This is due to the fact that IDEF0 allows the analyst to decide the viewpoint to be used to control different aspects of the process (Feldmann 2013). The objective is to determine the key steps in the process, to identify where in the process variability is present, what senses operators are using and finally, to present conclusions.

The process is represented graphically, using a cascade chart. This gives a simplified version of the process plus a simple way of presenting the process to others. The analysis decomposes the process from level A0 which is the highest level in the hierarchy and denotes the whole process. From level A0, the method breaks down into the next level A1, composed of those tasks needed to be performed sequentially to finish the process. Usually, the decision on which tasks are included in this level is supported by the SOP and the answers of experienced operators during the interview by inducing the expert to walk through the process in his/her mind, verbalising major tasks.

This, together with SOP helped to build the IDEF0 diagram. The subsequent levels can be decided by the observer, as IDEF0 implies certain subjectivity depending on the observer and the perspective.

Summarising, the IDEF0 diagram consists of breaking down the process in levels such that each of them is simpler that its "*parent*" (upper level in the analysis). The different levels show the hierarchy of the process. In this thesis, the processes have been broken down into a first sub-level; this first sub-level contemplates tasks and is at this level where the framework will be applied (Chapter 6).

3.5 Key Characteristic for Variability

The method used was based on the identification procedure for Key Characteristics in Variation Risk Management (Thornton 2004). This method has been proved efficient through several manufacturing processes and basically finds the sources of variability through the scrutiny of relevant documentation of the process.

A Key Characteristic (KC) is any attribute of an output, input or process that is quantifiable and whose variations from the expected has an inadmissible impact on the cost, performance, or safety of the output (Thornton 1999b). This means that this attribute varies in one or a few of its properties from one element to another and this is causing a non-desirable output. Different KCs can be found in a process, for example in inputs (e.g. dimensions, feature positions, surface roughness, elasticity), in the machines (e.g. configuration, characteristics, data input, energy input, condition), tools (e.g. condition, use, shape) and environmental (e.g. light, temperature, noise, vibration). The interaction of operators with these KCs will determine whether workers are successfully eliminating or reducing this variability to acceptable levels. It is helpful to create a flowchart diagram to finer classify the KCs into the basic categories: Product KCs, process KCs, system KCs and part KCs.

The Key Characteristics identification method was used in this research to identify and classify features being affected by variability within the processes. A proper KC identification and classification will allow visually arrangement of the sources of variability hence facilitating the planning and prioritisation of what KCs to study. Figure 3-1 represents Key Characteristics for variability for a MIG welding process (the process is explained in detail in Subchapter 7.2) used in this research to validate the framework.

Here, the process is broken down; first it shows the expected outcomes (outcome KCs). After that, it can be seen those features of the product being affected by variability (subsystem KCs). In the next level, it is found where these features are (parts, tools, fixture or machines). Finally, the diagram presents the tasks within the process where variability is presented. Consequently, it is at this level where variability can be eliminate or reduced but also augmented.

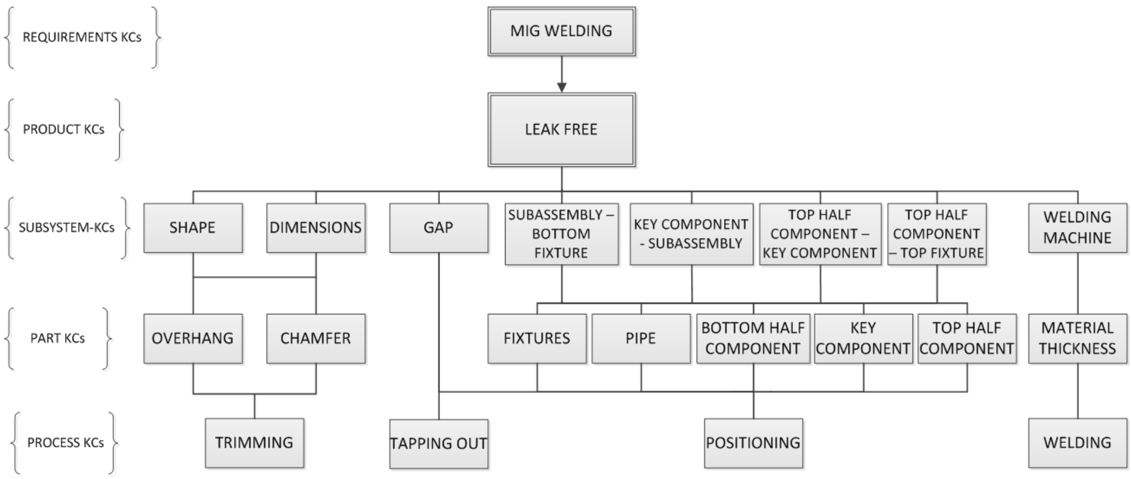


Figure 3-1: KCs Flowchart for a welding process

Humans can also introduce variability into the process affecting the outputs. Therefore, “human variability” should be identified and it has to be determined if it is affecting the outputs. In the two cases studied variability introduced by operators existed, although the final outputs delivered by different operators consistently comply with the requirements. Besides, it was not the aim of this research to study variability introduced in the process by humans.

4. PROCESS STUDY: GRINDING AND POLISHING OF HIGH END COMPONENTS

The first objective in this research is to understand the variability involved in a manual manufacturing process, and how the operators applied their skills to overcome it. In order to do that, two manufacturing processes were selected by virtue of their characteristics. These two processes are selected on the basis of the potential complexity for automation due to the inherent reliability on manual operators. The two processes selected were: grinding/polishing and de-burring of high-end components.

This chapter details the first process study, focussing on grinding and polishing tasks for high-end components by skilled workers. Research data were collected primarily through observations and interviews with the grinding and inspection workers. Documentation regarding the process such as Standard Operating Procedure (S.O.P), quality reports and measurement data of random samples of components were also collected and studied.

The main objectives for carrying out this study are:

- To detect and recognise variability in the process. It was expected that this study would provide useful data which, later on, would serve to define a framework to categorise variability present in manufacturing processes.
- To determine how this variability was affecting the Key Characteristics in the process. The study would supply a key characteristic map, highlighting those key characteristics affected by variability.
- To investigate the operators' approach in dealing with variability. The study will provide an understanding of the strategies and skills the operators were using in the process to overcome variability, which can be linked to each of the key characteristics, giving an insight of what should be prioritised when automating the process.

4.1 Process and product description

The purpose of the finishing processes is to achieve a smooth transition or flow among the surfaces on each component. The material removed in finishing processes has to be kept to a minimum and the components' form should not be modified significantly from its original geometry. The flow among surfaces is critical to the functionality of the components. According to the operators in the company where process was studied, the goal is to ensure that “surfaces flow smoothly”.

Two types of finishing processes are carried out by the company: grinding and polishing. The process of grinding consists on removing a minimal amount of material from the surface of the component using a rotational tool spinning at high speed (2800 rpm and above). The grinding processes are used to improve the dimensional precision with respect to that obtained from machining processes, for example turning or milling.

The polishing process consists of removing tiny particles from a surface to achieve a smooth surface profile. This smoothness is obtained by rubbing the surface against the polishing wheel using a rotational tool spinning at high speed (2800 rpm and above). Polishing is used to generate surfaces with high tolerances in geometry, surface texture, and roughness.

Company Background

The company where this process study was conducted provides finishing services for components to different industries. The facility is situated in a converted factory from the 1960s. Their specialist finishing capabilities and production processes are accredited for these industries and to international quality standards. They are able to perform process inspection both manually and using Coordinate Measuring Machines (CMM). They pride themselves for complying and exceeding the EU and international directives relating to health and safety of the workforce.

The company provides their services to a few customers. However, their work comes largely from one major client. In addition, they work mainly on demand with this customer, meaning that this customer increases or decreases orders as needed, leading to minimal control of the workload and hence, to a short-term production plan. The demand variation is dealt with by having qualified operators working on different components and various extra work stations. However, due to the lack of control of the production flow, on occasions the company has been unable to accept orders from other customers.

The company workforce is paid for components successfully processed, but they cannot complete more than a certain number of components which are assigned by the company and determined by the type of component. This number varies widely depending on the complexity of the component being processed from two dozen to three hundred.

The system offers the operators flexibility in managing their own time. They complete their working day once they have finished with the batches they have been assigned for the day. Working hours are from 6 am to 2 pm. They are able to have a break when they need it, in addition to the allocated lunch break. Some operators find this particular way of working convenient as it rewards productive workers with spare time.

The shop floor is divided into eight different sections. The different sections are: inspection, CMM (Coordinate Measuring Machine) for thin shell parts, sand blasting, plate form, large plate and variable vanes de-burring area, de-burring of narrow vanes, root rad area and barrelling. The shop floor is well maintained and sufficiently illuminated, although there is a lack of natural light. It is quite noisy (earplugs are provided) which makes communication difficult. The working cells for manual grinding and polishing processes are relatively clean considering the processes carried out mainly due to the fact that the working stations are equipped with an extractor to remove particles generated. Furthermore, operators clean up the stations every day before leaving. In addition to ear protection, the operators are provided with other personal protective equipment (PPE) such as safety glasses, safety gloves, safety shoes and aprons.

The company works on a wide range of components for their customers. The components are semi-finished components coming from a casting process and hence, requiring surface finishing. When the finishing processes are completed, the components are shipped back to the customers to be assembled into the final assembly.

The components received to be processed vary in size and geometry, going from 100 mm to 500 mm and from single curvature to double curvature and other features. There are features which are common to all components.

The turning machines used from grinding and polishing processes vary in specifications, ranging from 2800 r.p.m (revolutions per minute) for double-ended polishers to 75000 r.p.m for high speed grinder pencils. However, the same model of machines are used to process the same component. The grinding tools used vary in the composition of the abrasive material and adhesive. Different abrasive wheels can be used on the same component. The process studied requires reconditioning of certain wheel tools which is carried out by the operator himself.

Operators are trained to process a specific component and some experienced operators are qualified to process different components which allow them to cover occasional peak workloads.

Component object of study

In the study concerned, the grinding and polishing process for a specific component was investigated. Although, the processes of different components are different, all of them keep similarities in the actions executed.

The component studied is the most complex component currently processed in the company. The process cycle time for this component is approximately 10 min/ component. Only three workers were qualified to work on this component at the time the study was conducted. The number of components being processed currently is 48 per day. Two operators are fully dedicated to finishing these components, meaning each operator produces 24 per day. The other operator capable to work on this process also carries out the duties of workshop manager but he is able to work in the process if needed.

The components received from their customers for this specific process are in their final geometrical dimensions. A maximum deviation of ±100 microns from nominal is allowed in certain points, keeping a maximum deviation of ±50 microns or smaller for most of them.

The main features to be processed in the component are named below:

- Double curvature
- Two fins, Leading Edge, Trailing Edge and Main surface.
- A Platform including
    - A slope
    - A joint
    - Radii between surfaces
    - Radius between platform and main surface

Seven features of the component have to be controlled: platform slope, main surface roughness, fin surface roughness, platform radii, main surface-platform radii, main surface-fin radii, main surface-fin flow. During the process, the operators modify the transitions between features and the geometry and dimensions of the features.

A component with some similar features to the one studied is shown in Figure 4-1 in an attempt to illustrate the component's complexity, as the actual component studied cannot be illustrated due to confidentiality.

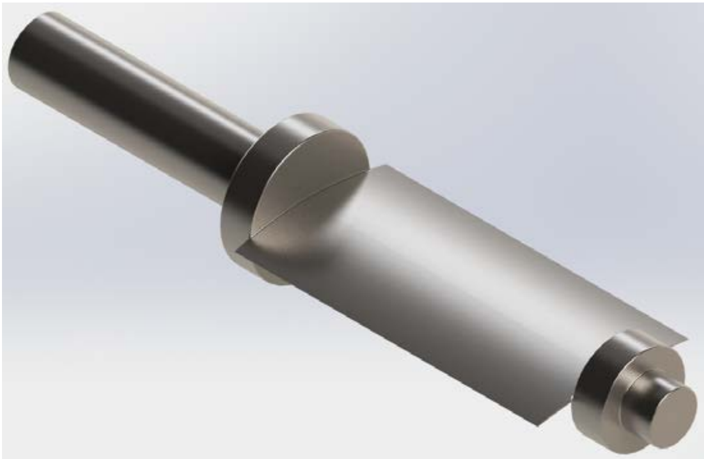


Figure 4-1. Representation of a complex component with similar features to the one studied

It was observed that between sixteen and nineteen changes of wheel tools were made (depending on operator observed) during observation period. Wheel tools need to be changed in order to grind and polish different features along the component. They differ in composition and grain size, giving them different degrees of abrasion.

Tools are sharpened during processing at the discretion of the operator. This sharpening is to restore the shape of the tool's edge. In addition, they re-condition some of the tools, including grinding and polishing tools, according to operators but no episode of reconditioning was witnessed during the observation period.

Each work-cell is provided with an extractor, a lamp and a table where tools (wheel tools, sharpening tools and other tools) are placed. The configuration of the twin work-cell is shown in Figure 4-2.

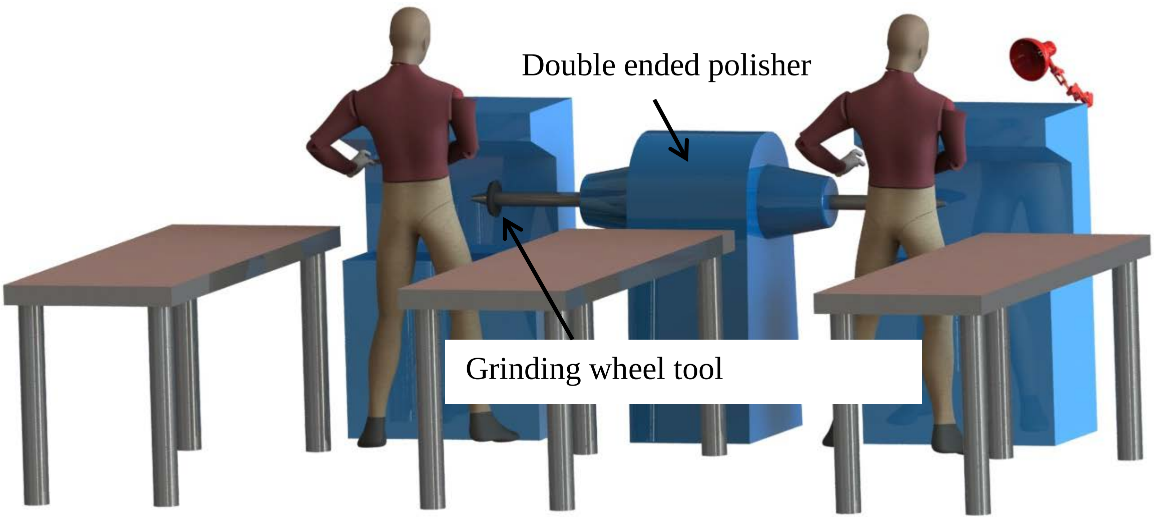


Figure 4-2. Working-cell set up

The equipment and tools used during the process are:

- Double Ended Polisher.
- Spindle 2800 RPM Grinding wheels
- Rubber stone
- Polishing Mop: 120 Grit silicon carbide
- Polishing Mop: 120 grade 120279.

Justification of the process selection

The company was selected since they showed interest in improving health and safety by considering automation. In addition, the company identified its processes as “difficult to automate” requiring a workforce that is experienced and skilled. Due to the nature of the components processed and the complexity of the processes, the training of inexperienced workers is challenging as well as being expensive in resources and time consuming.

The managers also recognised some range of variation in the batches received from their main customer. This variability makes their processes highly manual. The processes are described as “profoundly dependable on hands”. Furthermore, vibration from the machine makes the job physically demanding. This vibration cannot be eliminated and therefore adds health and safety issues.

Among all the processes performed within the company, the specific process studied was selected owing to the complexity of the geometry of the component, where a considerable number of surfaces are ground and polished with concave and convex surfaces, holes, planes and their intersections. It also has a low “right first time” rate (lower that 20%) hence a significant proportion of the components have to be reworked. Moreover, a large number of tools are used during the process where the operators need to select, change and recondition the tools as appropriate. Although this particular component is low volume, the study is useful to understand the variability present into the process and the human skills and strategies used to deal with it.

For these reasons, automation or semi-automation is an attractive alternative solution which would allow the company to speed up the processes and to stop the vibration being transmitted to the operators’ hands, eliminating the risk of injuries and illness related to vibrations and therefore improving the quality of the job. Automation solutions would be considered for overall processes as different processes on other components share some tasks.

The company has already invested in automated solutions such as barrelling, which automatically polishes the components by placing them in a barrel with small ceramic blocks and rotating the barrel for a few hours. During barrelling the ceramic blocks abrade the components, polishing them. The drawback is that this process cannot be used for all types of components processed in the company. They still need to manually finish some types.

4.2 Data Collection

Documentation

Prior to observation and interviews, preliminary understanding of the process requirements is gathered from the following documentation:

- Product Requirements.
- Equipment Documents.
- Functional structure of the product.
- Manufacturing process.
- Supplier. The supplier (in this case it is also the customer) delivers a semi-finished product which is processed to its final state for assembly.
- Quality plans and reports.
- Customer non-conformity reports.

The principal sources and evidence of variation in machines, materials, procedures and measurements were noted and verified later. The customer delivers three measurement reports with each batch (composed of twenty four pieces). The customer randomly measures three pieces in every batch (sample size). This report measures one hundred and seventeen different points of interest on the component before they are processed. Table 4-1 shows only those points whose values are out of the limits permitted (Non-Conformity) from one random batch. The full report comprises points numbered from 1 to 117. The table “UTL” and “LTL” stand for “Upper Tolerance Limit” and “Low Tolerance Limit” respectively. “Actual” refers to the measurement obtained at the point. All the dimensions are presented in millimetres.

Table 4-1. Random components’ simplified dimensional report

	Point	UTL	LTL	Actual
Component #1	83	38.26	37.86	**38.34** (OUT 0.08 mm)
Component #2	83	38.26	37.86	**38.31** (OUT 0.05 mm)
Component #3	77	104.09	103.89	**103.87** (OUT -0.02 mm)

It can be seen that the components are competently manufactured and only one out of one hundred and seventeen dimensions are out of range in each component (three measures in total out of three hundred and fifty one). These dimensions are out of range by 0.08mm, 0.05mm and 0.01mm. Components are ground and polished using the normal procedure and the operators are not made aware of these reports nor asked to treat those areas differently. It is unknown by the company whether these points are within range after the components are processed. However, it is known by the managers that the rejection rate is four times lower than the minimum rejection rate allowed by their customer. Although the company has no measurement data of the finished components, the customer has not communicated to them any quality report for the past two years before the visit. The last recorded customer non-conformity was dated 23/11/2011.

These reports demonstrate there are variability in the dimensions of the components. However, it was undisclosed whether after the grinding and polishing process, these three points were re-instated to the acceptable range.

Observations

In this process study, a non-participant, direct, overt and structured observation was conducted. This type of observation was described and justified in 3.2. The observation was supported by video recording the process. Photographs of the work cell were taken to capture the different tools and equipment used. Notes were also written when observing.

Written consent was granted from the operators recorded in order to comply with regulations for research involving human participants of the Ethics Committee at Loughborough University.

The process performed by two operators was observed during two different days. Operator 1 was observed once, during the completion of six pieces (working batch). Operator 2 was observed twice, on two different days working to complete a batch (six pieces) in each observation. Operator 3 was not observed when processing the component object of the study, only interviewed.

Both operators 1 and 2 were video recorded; Operator 1 processed only one piece during the whole procedure (approximately ten minutes) and Operator 2 was recorded processing one whole batch (approximately sixty minutes) twice (a complete batch in each observation).

The main aim of observation was to recognise the main parameters to characterise variability previously identified in the literature. The parameters identified during the observation are shown in Table 4-2.

Table 4-2. Parameters from literature found in the process of grinding

Parameters	Found in	Variability to describe
Number of elements	Documentation, observations	Number of inputs/outputs affected by variability
Number of information cues, information load	Observations	Number of inputs affected by variability
Number of products/outcomes	Documentation, observations	Number of outputs affected by variability
Variety/diversity of elements	Documentation, observations, interviews	Number of sources of variability in inputs/outputs
Presentation heterogeneity	Not observed	-
Uncertainty	Documentation, observations, interviews	Interval of variability in inputs/outputs
Connectivity/relationship	Observations	Interdependency
Number of paths/solutions	Observations	Number of alternatives
Number of alternatives	Observations	Number of alternatives
Number of operations/sub-tasks/acts	Observations	Number of actions to solve variability
Structure/specification/clarity	Not observed	-
Repetitiveness/non-routinely	Observations	Pattern
Concurrency	Observations	If sources of variability are managed at the same time
Time pressure	Observations	If time available is enough to solve variability
Format/mismatch/inconsistency/compatibility	Not observed	-
Difficulty	Documentation, observations, interviews	Physical/cognitive requisites
Cognitive demand	Observations, interviews	Cognitive requisites
Physical demand	Observations, interviews	Physical requisites

Secondary aims were to corroborate whether operators were following the Standard Operating Procedure and to clarify some instructions which were not clear in it. From the observations, it can be said that operators followed the Standard Operating Procedure, but did not necessarily copy the sequence of tasks as described.

Moreover, observations served to modify some of the questions in the questionnaire in order to make them easier to understand as some of the words were originally general and the observations allowed these to be made more precise.

Finally, the observations revealed that a number of actions were performed quick enough to consider that these actions are executed by obeying a “stored rule”. This means that operators follow unconsciously a mental sequence (stored rule) when they face a familiar work situation. This “rule” may have been gained from experience, taught by others or have been developed by a problem solving process (Rasmussen 1983).

Interviews

The interviewing process was carried out after the observation process. In this research, the interviews were semi-structured, with a mix between closed and open questions. A full description of this type of interviews can be found in Section 3.3. Questions were divided into groups: work experience, procedure and tools (see Appendix 1 for the proforma). The questions aimed to find and understand:

- The course of actions needed to finish the task.
- The decisions made during the process.
- The concepts, principles and procedure used through the process.
- The parameters considered before proceeding.
- The senses involved.
- The equipment and materials required.

Collected data, observations and interviews served to identify the sources of variability and how the operators were coping with it. Three operators were interviewed in total. Operators 1 and 2 worked daily in this component. Operator 3 worked only when needed and carried out other duties in the company. Operators 2 and 3 were interviewed after they had completed a batch. Operator 1 was interviewed when he was performing other tasks.

The proforma used and a list of questions are included in Appendix 1 to follow up on operators responses to a number of questions in the proforma. Table 4-3 presents a summary of the questions and their answers.

Table 4-3. Operators' answers

Question	***Operator 1***	***Operator 2***	***Operator 3***
Years working in the company?	22	19	13
Years working with this type of component?	More than 20	9	8
Do you notice differences between components? What is the most common?	Yes. Surface Finish	No	No
Do you notice differences between batches?	No	Surface Finish	No
How do you cope with these differences?	I spend time eliminating the mark and I report to quality	I spend time eliminating the mark	I always proceed in the same way, with all the parts
What do you control when you are performing the task?	Flow between surfaces and radii	Flow between surfaces, radii and dimensions	N/A
How often do you check the component?	All the time	All the time	All the time
Do you notice when wheel tool is degraded (wear in tool)?	Yes	Yes	Yes
How often?	Depending on tool	Depending on tool	Depending on tool
Do you work differently when you feel degradation in the tool? What do you change?	Yes, I apply more pressure and I keep processing for longer time	Yes, I keep processing for longer time and I change the tool	Yes, I apply more pressure, I keep processing for longer time and I change the tool
Who prepare and recondition the tools?	I do	I do	I do
Do you customize your tools?	Yes	Yes	Yes
What do you focus on when customizing?	Sharpness and Edge's Shape	Edge's Shape	Edge's Shape
What do you think are the main sources of variation?	Parts	Parts	Don't Know
What do you think is the most critical in order to comply with customer's standards?	Parts	Parts	Don't Know
How do you think this variation could be reduced / eliminated?	Improving prior processes	Don't Know	Don't Know
How do you think your job could be improved?	Reducing Vibrations	Don't Know	Don't Know

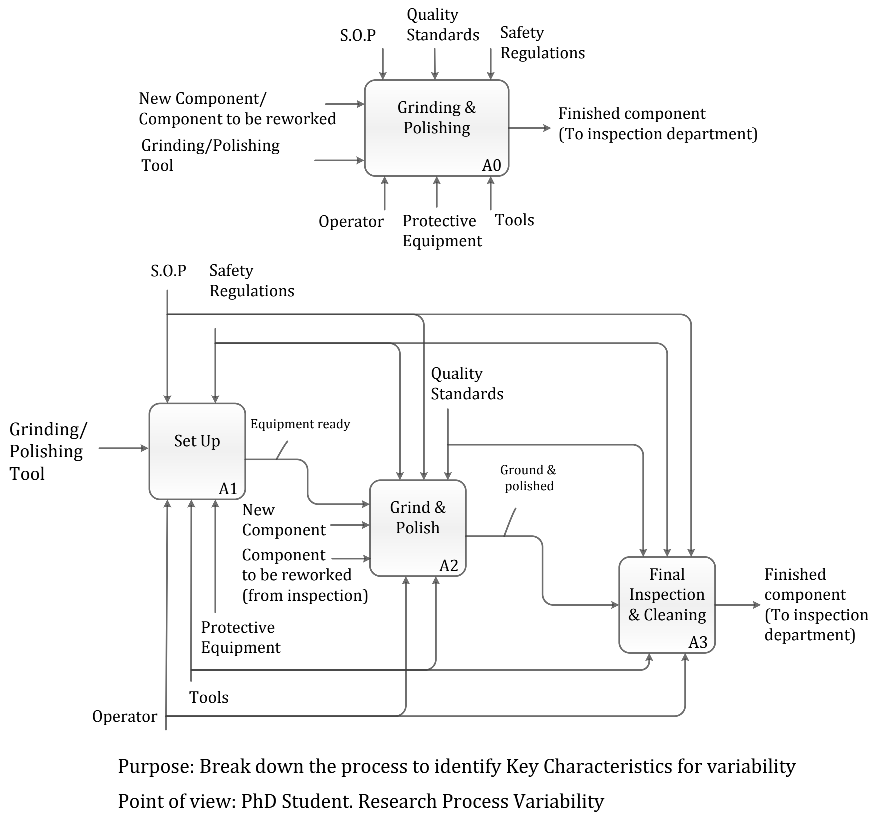
4.3 Analysis

The purpose of analysis is to interpret the results and according to the research objectives, to define the next steps of the research.

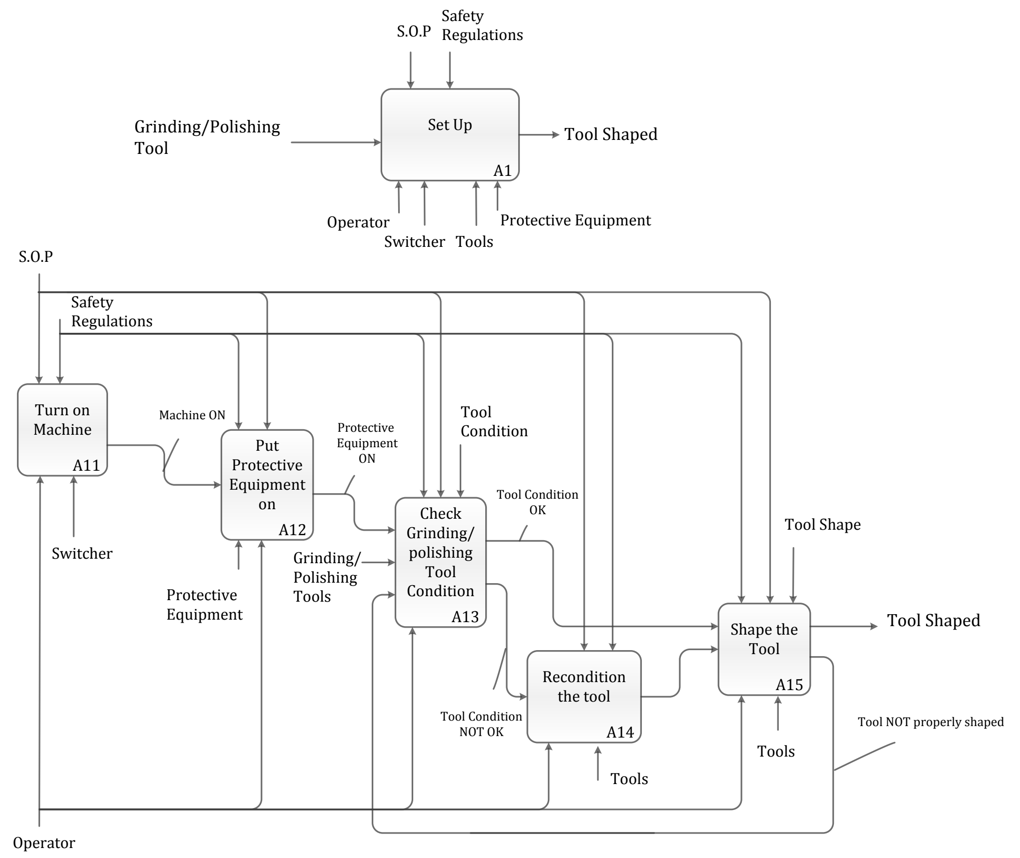
Process decomposition (IDEF0 Diagram).

An IDEF0 analysis was carried out for this process study. A description of IDEF0 can be found in Section 3.4. The IDEF0 analysis was carried out from the researcher's perspective and its objective was to decompose the process of grinding and polishing of a component to identify variability contained in the process and to establish where this variability is introduced.

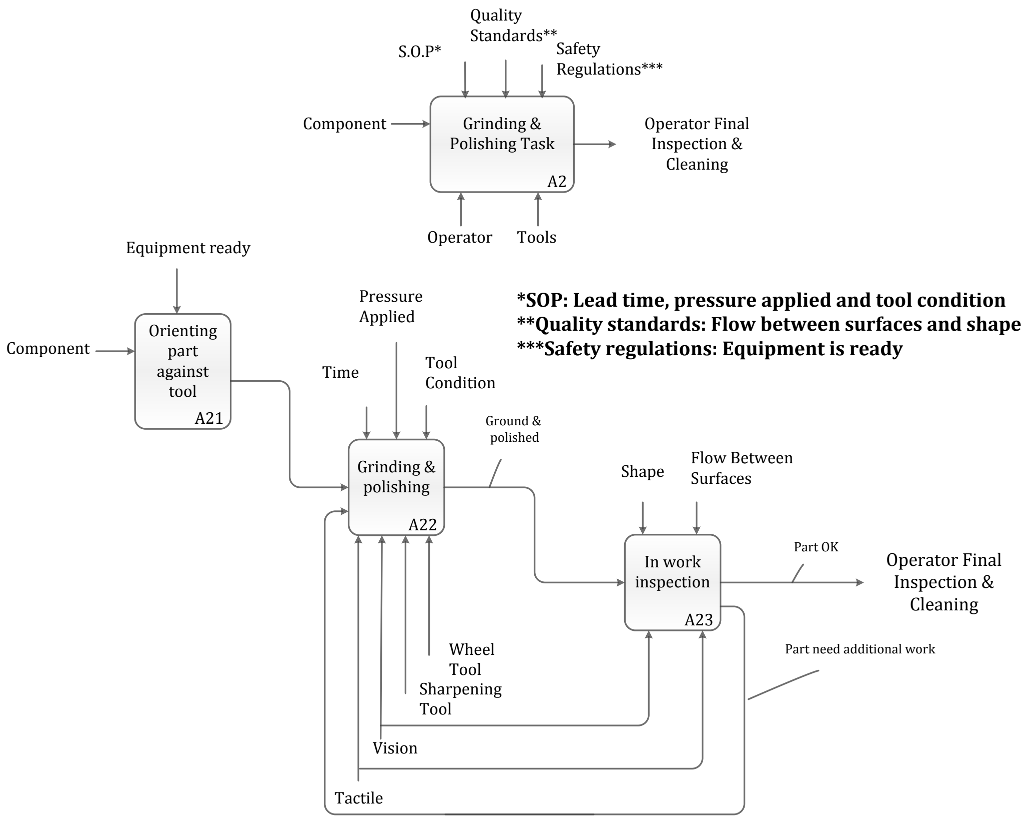
The IDEF0 diagram for the process of grinding and polishing is presented in Figure 4-3. There are seven different features that are processed during the process and all of them are treated using the same techniques and principles. Figure 4-3 represents the general working process: (a) represents the highest level of the process, also known as level A0 and (b) A1 level, (c) A2 level and (d) A3 level diagrams are its children.



a) IDEF0 Diagram from process. A0 Level

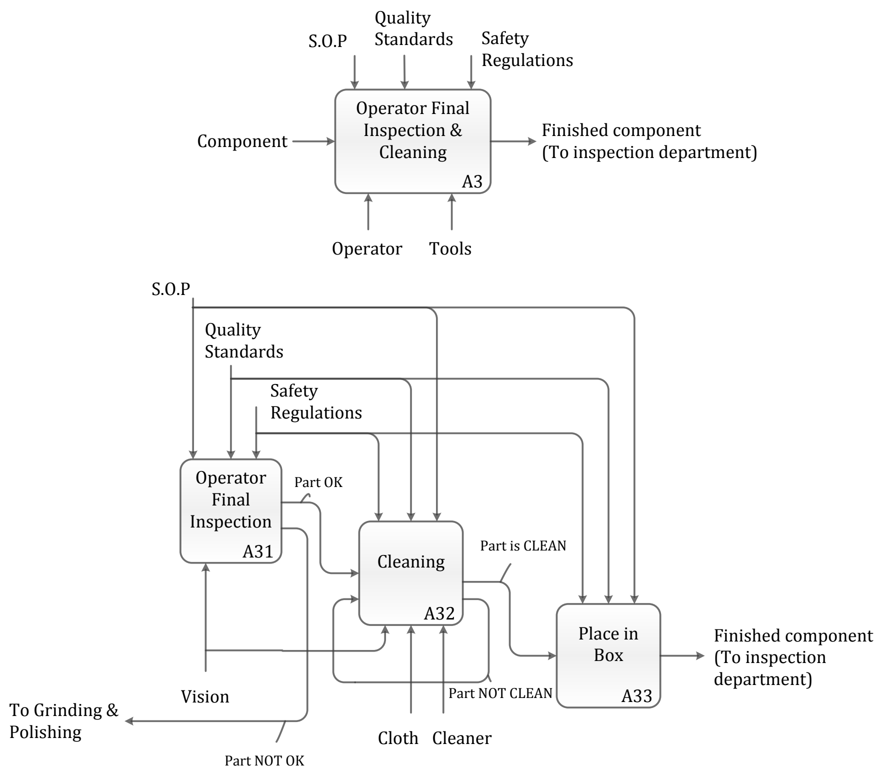


b) IDEF0 Diagram from process. A1 Level



***SOP: Lead time, pressure applied and tool condition**
****Quality standards: Flow between surfaces and shape**
*****Safety regulations: Equipment is ready**

c) IDEF0 Diagram from process. A2 Level



d) IDEF0 Diagram from process. A3 Level

Figure 4-3. IDEF0 diagram for grinding and polishing process and its children

Key Characteristics

In order to discern the key characteristics affected by variability, the method used is based on Key Characteristics (KCs) in Variation Risk Management (Thornton 2004). Different KCs can be found in a process, for example in the components, in the machines, tools and environmental. The interaction of operators with these KCs will determine whether workers are successfully eliminating or reducing this variability to acceptable levels.

In the grinding and polishing (Task A22) of the component, the Key Characteristics for variability identified are: time of grinding/polishing, pressure applied and tool condition (tool shape and tool's surface roughness). All these Key Characteristics are interdependent and the operators need to manage these interactions dynamically to achieve an optimum outcome in terms of customer requirements. Therefore, the operators are constantly controlling pressure applied, grinding time, and tool condition.

It was found that the operators followed the Standard Operating Procedures (SOP) but they responded to it personally, meaning that they vary the procedure slightly, for example by varying the sequence of actions. This was corroborated by visual inspection staff, as they can differentiate which operator has worked on the component by how it was “signed”. All the questions to visual inspectors can be found in Appendix 2.

-“I know who processed the part by the marks left in the part, it is like a signature”-
[Visual inspector 3]

-“I notice that different operators have different ways of proceeding”-
[Visual inspector 4]

-“Same errors are repeated by same operator”-
[Visual inspector 3]

-“You can see same differences over and over again”-
[Visual inspector 4]

The observation of both operators also confirmed that they proceeded differently. They do not grind and polish the features in the component in the same sequence. Table 4-4 shows the order of processing the different features constituting the process. The table only shows the sequence of features being processed for every tool replacement although it does not distinguish whether it is grinding or polishing. It does not discern if the tool is used more than once either, as the purpose is to prove that the procedure is different.

Table 4-4. Sequence of action followed by each operator

	Operator 1	Operator 2
Feature	Fin	Platform
	Platform	Fin
	Fin - Main Surface	Fin
	Fin	Fin
	Platform - Main Surface	Platform - Main Surface
	Platform -Main Surface	Fin
	Leading Edge	Fin
	Fin	Fin
	Fin	Platform - Main Surface
	Fin	Platform – Main Surface
	Fin	Platform – Main Surface
	Leading Edge & Trailing Edge	Platform - Main Surface
	Platform - Main Surface	Platform - Main Surface & Leading Edge & Trailing Edge
	Platform + Platform - Main Surface	Fin
	Platform - Main Surface	Fin
	Main Surface	Fin
	-	Main surface
	-	Platform - Main Surface
	-	Fin & Main surface

The different procedures adopted have no impact on the outputs, i.e. the components are equally acceptable at the end of the process. It was noted that “in process re-work” could be affected by the strategies adopted by the workers, influencing cycle time (productivity) but not the final product as finished components comply with the required standards. Moreover, cycle times of operators observed were similar, between 9.5 and 10 minutes per component which would imply a daily difference of 12 minutes maximum.

In order to successfully cope with variability, operators used visual and tactile cues together with rules and skills to act on those cues. Interviews suggested that they have certain consciousness of dealing with variability but they act with unconscious control and automated behaviours (Rasmussen 1983).

-“I notice differences in surface finish among parts”-
[Operators 1 and 2]
-“When tool starts degrading, I apply more pressure and keep grinding for longer”-
[Operators 1 and 2]

This was also verified through observation of operators where rapid movements and decisions were made with limited control or conscious attention following a stored rule, i.e. learning by training. This was corroborated by the answers in the interviews where generic guidelines, more similar to a “philosophy” rather than a working procedure for the process were described.

-“I always proceed in the same way, with all the parts” - [Operator 3]
-“I control flow between surfaces and shape” - [Operators 1 and 2]
-“I check my work all the time” - [Operators 1, 2 and 3]

For the component, Table 4-5 shows a summary of these findings.

Table 4-5. Parameters of the sources of variability

Sub-system KCs	Process KCs	Variability	Primary Senses	Source
Curvature Marks	Time of grinding	External (linked to dimensions, pressure applied and tool condition and shape)	Vision	Observations Interviews
	Pressure Applied	External (linked to time of operation, dimensions, vibrations in spinning machine and tool condition and shape)	Tactile	Observations Interviews
Tools	Shape	Internal (linked to operator)	Vision	Observations Interviews
	Surface Roughness	Internal (linked to operator) External (linked to tool and machine supplier)	Tactile & vision	Interviews

Time of grinding/polishing. The time the operator spent grinding or polishing a specific feature on the component varied depending on the feature dimensions, pressure applied in the operation and tool condition.

- If more material needed to be removed, then more time was required for grinding/polishing if other parameters stay constant.
- Pressure applied changed the rate of material removal but higher applied pressure introduced vibration and degraded the tool more quickly.
- Tool surface roughness and shape affected the rate of material removed. When the tool had been recently sharpened, the tool ground/polished more efficiently.

Pressure applied. Pressure applied by the operator was directly related to time of operation, vibration in the machine's axis, feature dimensions and tool shape and surface roughness.

- Time of operation. If the pressure was inadequate, the time spent in the operation increased. If the pressure was too great, the operator was not able to control the amount of material being removed; therefore the component may be ruined.
- Dimensions of features. The correct pressure applied will lead to a more accurate amount of material removed, hence complying with the dimensional requirements of the features. The dimensions of features varied from component to component.
- Vibration. When the pressure applied increases, there is more vibration in the machine axis making it more difficult to control.

Tool surface roughness and shape. In this case tool shape is directly related to the operator as operators sharpen their tools and give them the shape desired. Equally, operators reconditioned some of their tools so surface roughness of those tools than can be reconditioned depend on each individual. Tools that cannot be reconditioned are disposed after their life cycle.

- Pressure. The closer the tool is to its original shape and surface roughness, the less pressure needs to be applied.
- Surface roughness. The roughness of the surface wear depends on the way the operator works, the pressure applied and the time of operation.

All these Key Characteristics are interdependent and the operators need to manage these interactions dynamically to achieve an optimum outcome in terms of the customer specifications. Therefore, operators are constantly controlling the pressure applied, grinding time, tool shape and tool surface roughness.

The Key Characteristics (KC) diagram for the process is summarised in Figure 4-4.

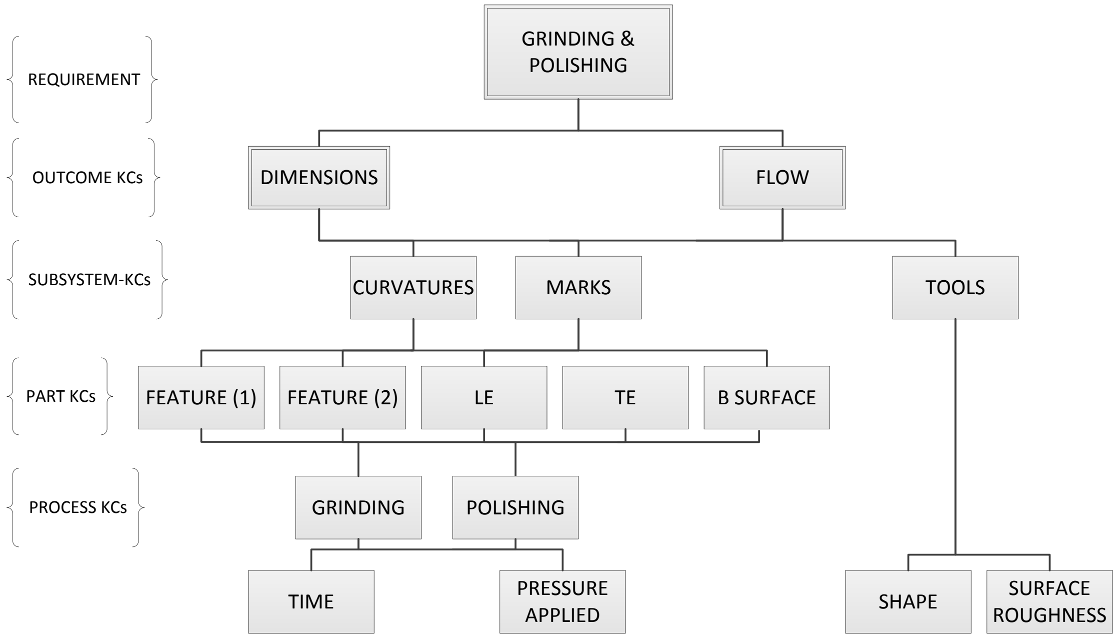


Figure 4-4. Key Characteristics diagram for variability in process of component

Parameters for framework

After the study and analysis of the grinding process, the potential parameters found to characterise variability are shown in Table 4-6. These parameters have been identified as a good fit to describe variability in the process and they have also been noted in literature regarding task complexity.

Table 4-6. Potential parameters identified in grinding process

Parameters from literature	In variability to describe
Number of elements	Number of inputs/outputs affected by variability
Number of information cues, information load	Number of inputs affected by variability
Number of products/outcomes	Number of outputs affected by variability
Variety/diversity of elements	Number of sources of variability in inputs/outputs
Uncertainty	Interval of variability in inputs/outputs
Connectivity/relationship	Interdependency
Number of paths/solutions	Number of alternatives
Number of alternatives	Number of alternatives
Number of operations/sub-tasks/acts	Number of actions to solve variability
Repetitiveness/non-routinely	Pattern
Concurrency	If sources of variability are managed at the same time
Time pressure	If time available is enough to solve variability
Difficulty	Physical/cognitive requisites
Cognitive demand	Cognitive requisites
Physical demand	Physical requisites

4.4 Summary

From the Standard Operating Procedure, drawings and measurement report provided by the company, observations and interviews, the key characteristics for variability identified were: tools and curvatures and marks in the components. These are transferred into the process parameters as: time of grinding/polishing, pressure applied when grinding/polishing, tool shape and tool surface roughness (during process and after being reconditioned by operator). As seen from Figure 4-3, the Key Characteristics of the process affect all the features of the component. Currently, the operators use their experience and skills to overcome the variability achieving the component requirements.

The study of this industrial process proved that operators are dealing with different sources of variability that are interrelated and these relationships vary over time. This implies a dynamic environment where the operators are successfully adapting due to their skills and experience.

From a final product point of view, it can be stated that workers are delivering outcomes that comply with the quality standards required. However, it was also found that procedures used by different operators may differ slightly although these changes do not affect the requirements to be met by the final product.

Although the study of variability introduced by operators is not part of the scope of this research, it can be said that this variability could be classified into two groups:

- Variability that is introduced by operators but its impact in the final product is neglected. For example, visual inspectors declared that different operators can be identified by the way they process the component. This unique “signature” has no impact in the product delivered as far as the visual inspector passes the component.
- Variability that is introduced by operators when processing but it is “self-corrected”. For instance, it was found that one of the operators decided not to sharpen a tool before to start grinding one of the features (he possibly thought that it had the proper shape for the feature). After one and a half seconds (very quick), he noticed that he needed to sharpen the tool so he did so.

- Variability that is introduced by operators when processing the component and which affects the outputs. For example, components are sent back to re-work by visual inspectors if they consider any feature was not properly processed.

Summarising, it can be concluded from this chapter that variability is a complex problem that implies managing dynamic relations among sources of variability, which requires use of different senses and cognitive skills (judgements, assessments and problem solving-thinking skills). At the same time, variability is difficult to characterise, both quantitatively and qualitatively. In order to reinforce these findings, another manufacturing process was studied. The study of another manufacturing process would allow the establishment of analogies between variability in both processes as well as determining which parameters to consider when variability needs to be characterised.

5. PROCESS STUDY: DE-BURRING OF HIGH END COMPONENTS

This process study is introduced as a continuation of the study of manufacturing processes that started with the grinding and polishing process described in Chapter 4. However, the study of a different manufacturing process was needed this time in order to reinforce those findings and establish some parameters to be used in the framework.

In this process study, manual de-burring of high-end components were observed. In order to acquire some previous knowledge about the de-burring process itself, some of the available documentation such as Standard Operating Procedures (SOP) and measurement data gathered from January to April during 2014 were studied. Additional data were collected through careful observation of the process as well as through interviews with the operator in charge.

This process was introduced to study the issue of variability in a de-burring process, understanding "variability" as the inherent deviation from design specifications. In addition to this, the process was investigated to determine how operators dealt with variability: firstly, identifying the sources, that is, where and how variability can appear and, secondly, how humans coped with it.

The following are the main objectives for this study:

- To detect and recognise variability in de-burring processes.
- To establish to what extent variability affects the Key Characteristics of the process.
- To identify strategies to deal with variability.

The same techniques as were employed in the grinding and polishing process study (Chapter 4) were used in the de-burring study.

5.1 Process and product description

To de-burr is defined as to *"neaten and smooth the rough edges or ridges of an object, typically one made of metal"* (Anon 2015) by the Oxford dictionary.

In this case, a raw material block is machined in order to create specific design features: holes, cavities, threads and surfaces with different inclinations and intersections. The components received in the manual work cell were derived from an automated machining process, but the pieces would need to be de-burred manually due to the speed of the machining. The process of de-burring is considered finished when the component is properly washed to eliminate any particles, which is then sent for measurement.

The general principle of de-burring process is "*to remove any sharp edges from the components, applying light pressure*". The aim of the process is to generate smooth transitions between surfaces on the component and the goal, according to the operator interviewed, is: "*to eliminate burrs without modifying the component's features at all*". Changes in the features of the components would adversely affect their functionality.

Company Background

The company is dedicated to design, manufacture, procurement, testing and support of engine control systems. The company has been in business since the 1940s, providing a high variety of Line-Replaceable Units (LRU) for aircraft use. A LRU is a modular component designed to be replaced quickly. It is usually a sealed component and therefore, when needed, it is replaced by a new one. Families of LRU manufactured by the company include: auxiliary power units (APUs), turbo-shafts and thrust fans.

The components being manufactured are high-end products which are required to comply with stringent standards and requirements. The company complies with AS9100 and ISO 14000 (S.A.E 1999; ISO 2004). AS9100 is a quality management system standardised for the industry and ISO 14000 is a family of standards related to environmental management to minimise effect of processes on the environment and to observe laws, regulations, and other requirements oriented to environment protection. The company also adopts the Six-Sigma and lean manufacturing principles in their processes. Six-Sigma is a methodology to improve the quality of process outputs. Lean manufacturing is a production philosophy that tries to eliminate anything that is not adding value to the product. In this case, value means anything that customers are willing to pay for.

Component

The process that was studied is the de-burring of a component which is part of an aircraft. These components come from previous machining processes, and present *burrs* on several features, are irregularly distributed through the *features* and may vary in size. For this reason, a manual de-burring process has been implemented to maintain the production volume and fully cover the component demand. This de-burring process is completely manual and a single worker spends from four to six hours per component. As little material as possible should be removed in order to keep the component's original form, and only experienced workers, with more than five years' experience, are in charge of de-burring this component in this company.

The component has different features i.e.: threads, surfaces, cavities, holes and intersections, which will require de-burring. These features vary in terms of size, ranging from millimetres to a few centimetres, for instance, in case of *holes* and *cavities*. Similarly, *threads* can have different dimensions and the component may also have different planar *surfaces*, *fillets* and *chamfers*. In addition, some of these features involve complications as the access for proper inspection can be difficult both visually and tactilely in the de-burring operations. A component with similar features to the one studied is shown in Figure 5-1 in an attempt to illustrate the component's complexity, as the actual component studied cannot be illustrated due to confidentiality.

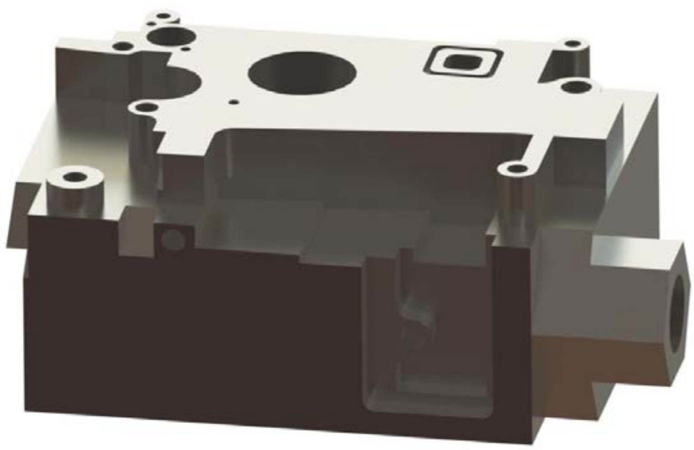


Figure 5-1. Representation of a complex component with similar features to the one studied

The number of processed components per day may differ from 4 to 6. Likewise, the de-burring process is a long process that includes working on different types of features (*threads, edges, cavities, holes* and *intersections)*. The operator may use up to three de-burring tool changes per feature, depending on the *burr* and the feature where the *burr* is found, and includes proper inspection and evaluation of the burr itself in order to select the appropriate tool in each case. Taken together these aspects increase the complexity of the process, and are the reason why only experienced operators carry out the process. Only three employees are trained to work on the component which is the subject of this study, one per work shift. According to managers, the operators can also de-burr other types of components, but working with the same component each time increases operational efficiency.

The process currently runs 24 hours a day, scheduled in three work shifts: the morning shift runs from 7 am to 3 pm, the evening shift from 3 pm to 11 pm, and the night shift is scheduled from 11 pm to 7 am. The night shift is always worked by the same operator, although employees working in the morning and afternoon shifts will alternate their shifts every two weeks. If a component has not been finished when the shift is over, the operator labels the component with his name and staff number and shelves it, to be completed next working day.

The work-cell for de-burring the component contains a set of tools: two air compressed tools (one rotational and one blower), a tiny torch with light intensity regulator, a magnifying glass and different types of emery cloth, coarse files, needle files and fettling tools. In addition to this, two tubular lights are employed to provide extra illumination to the cell work while the operator works sitting facing the station. Lastly, one working-cell is allotted to de-burr this component. The cell is shown in the following Figure 5-2.

Figure 5-2. Manual de-burring process working-cell

Figure 5-3 below shows tools and equipment used in the working cell during the process.

(a) Tool Box **(b) Fettlings and pneumatic tool** **(c) Torch and Second pneumatic tool**

Figure 5-3. Set of tools for de-burring process

Coarse files, fettlings, needle files and emery cloth shown in the pictures above (Figure 5-3), are used to remove *burrs*, although each has distinct levels of refinement, for instance, some of them are used to remove more material, while others a very small amount only.

Justification of the process selection

The company's desire to improve productivity by considering automation was a key factor in selecting this process. Furthermore, the company is aware of the difficulties implied when automating de-burring processes on the grounds that sizes and location of the burrs, differ from one component to another, which obliges the process to be manual in order to deal properly with this variability.

Additionally, the component's geometry contains a considerable number of *holes*, *threads*, *cavities*, *sloped surfaces* and their *intersections* that need to be de-burred, and thus a large number of different tools need to be used. More importantly, the specific process studied was selected owing to its complexity because it is dealing with a "high end" component that needs to be de-burred "right first time", due to the high production costs.

In addition to the procedure complexity, but also because of the high levels of concentration as well as visual and manual precision, which are both mentally and physically challenging for operators. It requires from eight to ten weeks of proper training, depending on the trainee's previous skills. Operators are trained on scrap components, constantly supervised, before working on real components that will be previously checked and approved by an experienced operator. For these reasons, it becomes crucial to find an alternative solution for de-burring processes, to reduce operator's specialisation and increase their flexibility.

5.2 Data Collection

The complete de-burring process can last up to 6 hours, but the observation lasted four hours. The four hours was sufficient because both techniques and principles employed are applicable to all features.

Documentation

The identification method starts by searching for the principal sources of variation in machines, materials, procedures and measurements. This information is found in manufacturing processes, quality reports, the functional structure of products, equipment documentation and product requirements.

Any components resulting from the de-burring process are measured by a coordinate measuring machine (CMM), generating a report. The reports and the number of components de-burred per month were not disclosed, due to confidentiality. Instead, monthly *non-conformity reports* from January to April 2014 were provided. During this period, twenty one of these components presented non-conformities, and 3 of them passed after re-work.

Non-conformity reports from January to April 2014 were analysed and a summary is shown in Table 5-1, displaying "number" and "type" of non-conformities as well as "condition" of *non-conformities* presented in those reports. According to the quality manager, some non-conformities were not related to de-burring processes but were on account of the previous machining process or the debris-cleaning process.

Table 5-1 has seven columns, representing different types of *non-conformity*: *bore, spigot*, *diameter*, *point*, *face* and *axis*. When a component presented different types of *non-conformities*, it was added to more than one column. However, if a component presented *non-conformities* of the same type, one *non-conformity* only would be added to its column. For instance, if a component had one *non-conformity* in *threads*, one *non-conformity in diameters* and one *non-conformity in points*, the component would have 3 *non-conformities*. On the other hand, if a component presents three non-conformities of the type *diameter*, it was considered as one *non-conformity* because they share the same type.

Moreover, the "*Confirmed*" label describes components with *non-conformities* considered as scrap material, or those that did not pass second dimensional measurements after have been being reworked. Lastly, the "OK after rework" label describes components which initially had one or more *non-conformities* which were eliminated after being reworked.

Table 5-1. Non-conformity type and condition

Non-conformities type						
Bore	**Spigot**	**Diameter**	**Thread**	**Point**	**Face**	**Axis**
2	4	10	7	7	2	1
Condition of Non-conformities						
OK after rework						**3**
Confirmed						**18**
Total number of components w/ non-conformities						**21**

Observations

The process was observed during two different days, although permission for video-recording was given on only one day. The same operator was observed for approximately four hours: one hour and a half during the first day, and two hours and a half the second day. Both observations started at 10 a.m.

Certain features are easier to identify and de-burr at first glance, for example, wide holes, wide cavities, or external edges. These features are easy to identify for a beginner who is not familiar with the component. However, others are extremely laborious to identify due to their location, requiring high tactile sensitivity to detect them. It would be unlikely that operators who are not familiar with the process could identify them.

The parameters identified during the observation are shown in Table 5-2.

Table 5-2. Parameters from literature found in the process of de-burring

Parameters	Found in	Variability to describe
Number of elements	Documentation, observations	Number of inputs/outputs affected by variability
Number of information cues, information load	Observations	Number of inputs affected by variability
Number of products/outcomes	Documentation, observations	Number of outputs affected by variability
Variety/diversity of elements	Not Observed	-
Presentation heterogeneity	Not observed	-
Uncertainty	Documentation, observations, interviews	Interval of variability in inputs/outputs
Connectivity/relationship	Observations	Interdependency
Number of paths/solutions	Interviews	Number of alternatives
Number of alternatives	Not Observed	-
Number of operations/sub-tasks/acts	Observations	Number of actions to solve variability
Structure/specification/clarity	Not observed	-
Repetitiveness/non-routinely	Observations	Pattern
Concurrency	Observations	If sources of variability are managed at the same time
Time pressure	Observations	If time available is enough to solve variability
Format/mismatch/inconsistency/compatibility	Not observed	-
Difficulty	Documentation, observations, interviews	Physical/cognitive requisites
Cognitive demand	Observations, interviews	Cognitive requisites
Physical demand	Observations, interviews	Physical requisites

Interviews

The interviewing process was carried out after the observation process. The interview was not recorded but transcribed. The same operator who was observed was interviewed. Only one person was interviewed in view of the fact that this process is performed by one person per shift. The person was remarkably communicative and helpful, responding to all the questions without hesitation. The operator gave a lot of information concerning the study; procedure, process, tools, working-station and principal discrepancies he finds in the components. He is trained to work on this specific component and has more than five years of experience in de-burring this component. A summary of the interview is presented in Table 5-3. The template of the interview can be found in Appendix 3.

Table 5-3. De-burring process interview

Question	*Answer*
Think about what you do when you De-burr. Can you break this task down into less than six, but more than three steps?	Inspection, removal of burrs from outside edges, inspection of internal bore, holes and cross-holes, removal of burrs from bore, holes and cross-holes and inspection again
Of the steps you have just identified which require difficult cognitive skills? By cognitive skills I mean judgements, assessments and problem solving-thinking skills	De-burring and inspecting to determine whether the burrs have been removed or not
Years working in the company?	6 years
Years working with this type of component?	5 years
Do you notice differences between components? What is the most common?	Yes. Burrs type and burrs location
How do you cope with these differences?	I inspect job thoroughly, before, during and after de-burring
What do you control when you are performing the task?	Removing burrs
Every how many seconds do you check the job?	All the time
How many different tools do you use in the whole process?	Between 15 and 20
Is the condition of the tool an issue for the job?	Yes, when is degraded, I change it and I use a new one
Do you work differently when you feel degradation in the tool? What do you change?	Yes, I have to apply more force to remove burrs. When tool in the previous process is degraded, there are more burrs and job takes longer
Do you customize your tools? What do you focus on when customizing?	Yes, shaping the tools to fit component's features.
What do you think are the main sources of variation?	Condition of cutting tool from machining (previous process)
What do you think is the most critical in order to comply with customer's standards?	Inspection
How do you think this variation could be reduced / eliminated?	Improving previous process and using better machines/tools.
How do you think your job could be improved?	Reducing burrs

The interviewed operator was aware of differences among components, mainly in the number of *burrs'* and their location. He was able to detect a degraded cutting tool that needed replacement in the machining process (previous process) as the components presented more burrs.

According to the operator, there are two tasks requiring cognitive skills, that is, removing *burrs* and inspecting them to determine whether *burrs* have been properly removed or not. During the process, up to 15 different tools per component can be used and eventually replaced when considered degraded or at the end of their use. The latter can occur after few minutes for emery clothes, or up to a year for needle files. In order to fit into certain features some tools are customised by the operator.

In relation to the process cycle time, it is highly dependent on how many *burrs* need to be removed from the component. Operators inspected every feature of the component and check them thoroughly before, during and after de-burring, which was corroborated by observation. According to the operator interviewed, the basic steps in the process are the following:

- Inspection and removal of burrs from outside edges, internal bores, holes and cross holes.
- Final Inspection

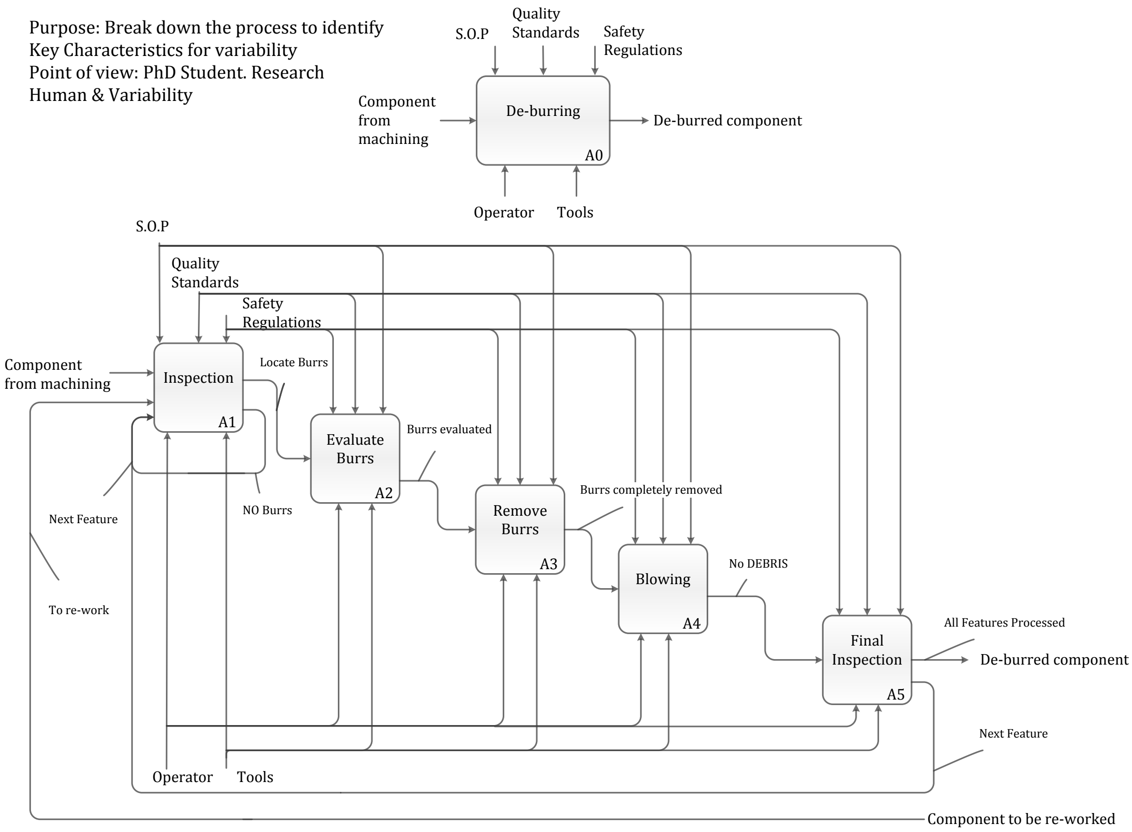
In addition, the operator interviewed suggested that some features never required the process of de-burring while others always did. Based on the operator's experience, the principal source of variability is originated in previous process *(machining processes)* and his opinion was that by refining this previous process, variability could be reduced as well as burrs in components.

Finally, when components with *marks* (not burrs) on the surface are found through tactile inspection, it must be reported immediately to the Quality department and the component will not be processed.

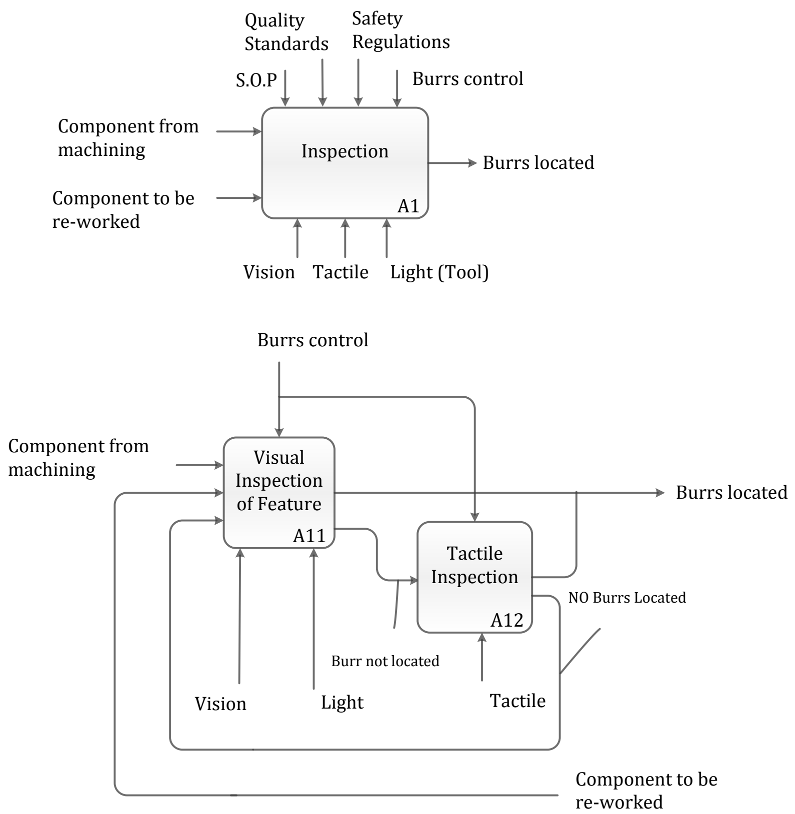
5.3 Analysis

Process decomposition (IDEF0 Diagram)

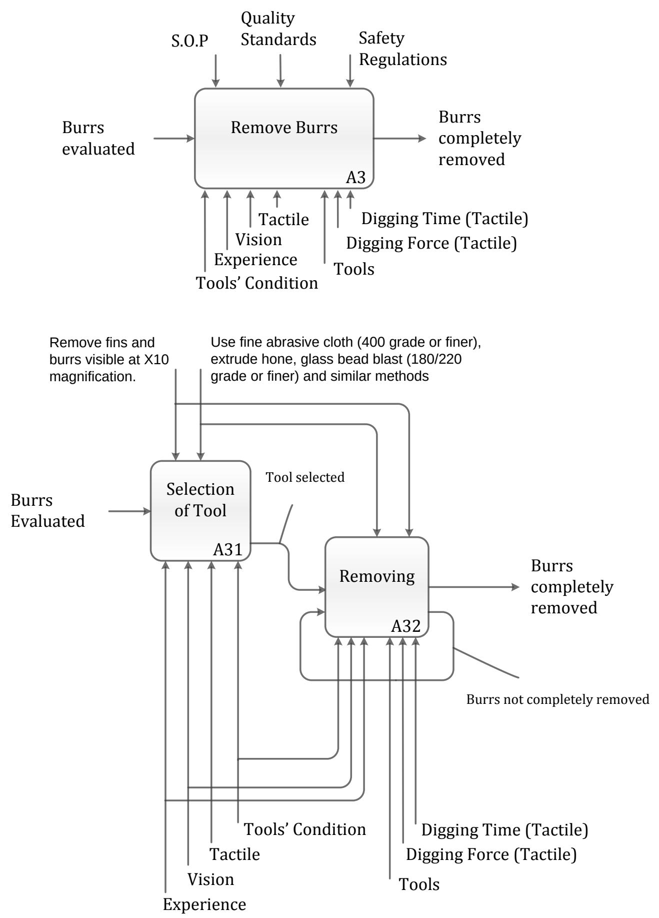
The decomposition of the process was developed from the SOP, observations and interview with the operator. There were five types of features that were worked in the component and all of them were processed using the same techniques and principles. This procedure is extremely fast and is repeated several times during the process, from two to five times per feature to achieve the expected outcomes. Figure 5-4 develops the tasks executed when de-burring one feature in the form of an IDEF0 diagram. Figure 5-4 (a) represents the general working process: (a) represents the highest level of the process, also known as level A0 and (b) A1 level, (c) A3 level and (d) A5 level diagrams are those children which can be further decomposed.



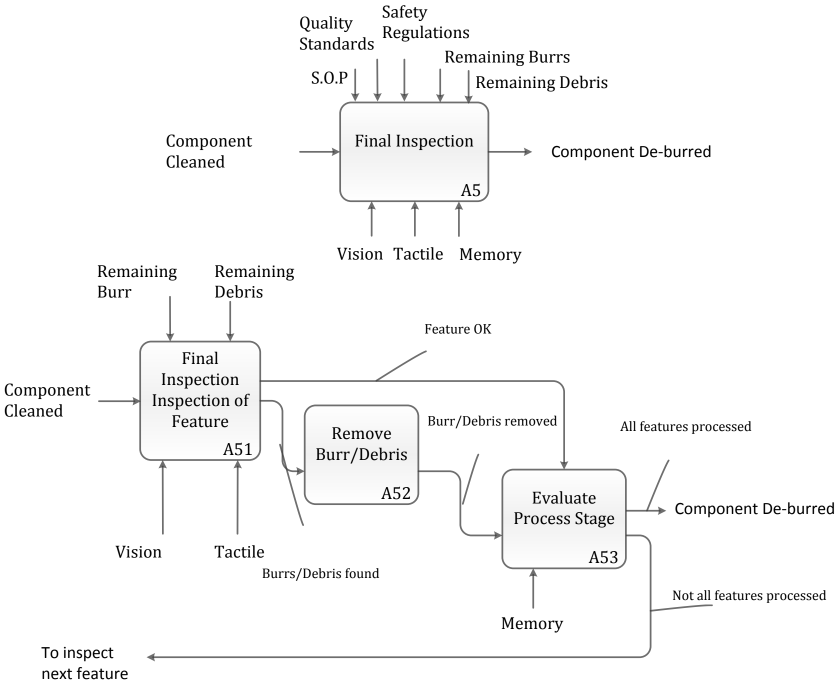
(a) IDEF0 Diagram from process. A0 Level



(b) IDEF0 Diagram from process. A1 Level



(c) IDEF0 Diagram from process. . A3 Level



(d) IDEF0 Diagram from process. A5 Level

Figure 5-4. IDEF0 diagram for de-burring process and its children

Key Characteristics

This section analyses the variability in the process. Data has been collected from documentation provided by the company, observations and interview.

Observations and video recording confirmed that Standard Operating Procedure (SOP) was generally followed by the operator, although a different order may apply by a different operator (according to the operator interviewed). In the operator's own words: *"We might be using a different sequence [of features checked] but obviously we cover all the features in the component"*. He also added that these changes did not affect the final product in any way.

Operators group features by properties in common, for instance, on the same surface, of the same size or of the same type. The operator was observed to start by checking the largest features, leaving the smallest to the end. According to the operator, there are three types of features depending on whether or not they need intervention, although which features belong to which category was not revealed. These features types are:

- Features that NEVER need to be de-burred.
- Features that ALWAYS are de-burred
- Features that at times are de-burred and at times not.

Although this classification of feature types was pointed out by the interviewed operator, observation confirmed that all features were checked regardless their classification.

In Figure 5-5, the Key Characteristics diagram for the process is presented. The Process KCs in the diagram shows variability sources that are dealt by the operator and how they influence the Outcome KCs for those key features.

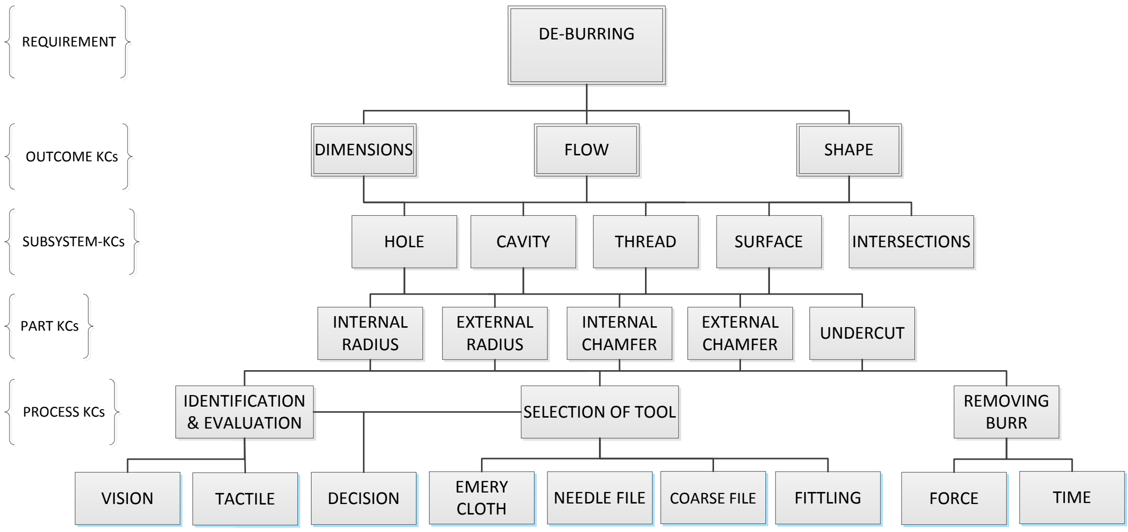


Figure 5-5. KCs for de-burring process

In order to overcome variability in all Key Characteristics, the operator used vision and tactile senses to perceive informational *cues*, together with "stored" rules and skills, previously acquired from both training and experience. Also, the operator showed absolute consciousness of the variability presented in the component. He pointed out: *"Main source of variation [in the component] is condition of tooling in machining process"*. He was also aware of: *"Variation [in the component] could be reduced / eliminated by improving previous process"*.

A summary of the results from this process study can be seen in the following Table 5-4.

Table 5-4. Summary of results from process study

Sub-system KCs	Process KCs	Variability	Human Sense implied	Source
Thread Surfaces Cavity Hole Intersections	Identification	External (Linked to previous process Internal (vision and tactile sense)	Tactile & vision	Observations Interviews
	Evaluation	Internal (Linked to identification and experience)	Decision process	Observations Interviews
	Tool Selection	Internal (Linked to operator experience)	Decision process & Vision	Observations Interviews
	Removing Burr	Internal (Linked to operator)	Tactile & vision	Observations Interviews

The main components' features associated to be de-burred are:

- Threads
- Surfaces
- Holes
- Cavities
- Intersections, especially holes and cavities' intersections between them and with flat surfaces, chamfers and surfaces' intersections.

The main Key Characteristics for variability identified in this processes are described in the following points:

- **Identification of the burr.** The operator identified burrs on a specific feature of the component. The existence of burrs and hence its identification depended on the machining process. This identification was directly related to operator visual and tactile perception.
- **Evaluation.** This is a mental process followed by operators, which determines the type of burr and the tool needed for elimination. Evaluation was directly related to operator experience and the identification task.
- **Tool Selection.** Tool selection was related to the operator's previous experience and was directly related to the evaluation task.
- **Removing Burrs.** Burrs should be efficiently eliminated.

- *Removing force*. With inadequate pressure, the burr will not be properly removed. If the force is significant, the component might be ruined as only a certain amount of material can be removed from the component.
- *Removing time*. Removing time is affected by removing force, more force applied, less time and vice versa. Too much time removing a burr will affect productivity.

Tool condition is identified as a potential source for variability but the operator replaces it when the task becomes difficult.

Parameters for framework

The two process studies have revealed some of the parameters which will be incorporated into the framework. These potential parameters are shown in Table 5-5.

Table 5-5. Potential parameters identified in de-burring and grinding process

Parameter	Grinding	De-burring
Number of inputs/outputs affected by variability	☑	☑
Number of sources of variability in inputs/outputs	☑	☑
Presentation Heterogeneity	☒	☒
Interval of variability in inputs/outputs	☑	☑
Interdependency	☑	☑
Number of alternatives	☑	☒
Number of actions to solve variability	☑	☑
Structure/specification/clarity	☒	☒
Pattern	☑	☑
If sources of variability are managed at the same time	☑	☑
If time available is enough to solve variability	☑	☑
Format/mismatch/inconsistency/compatibility	☒	☒
Physical/cognitive requisites	☑	☑
Cognitive requisites	☑	☑
Physical requisites	☑	☑

A framework is developed from these findings and the literature, which will be described in Chapter 6. Three parameters have been excluded from the framework, with more evidence, i.e. more processes studied, these parameters could be eliminated.

5.4 Discussion

Cleaning the component by blowing the debris away was identified as one of the primary causes of non-conformity by the quality manager, on the grounds that, if a burr debris remains on the component, the dimensional report will fail as this debris can adhere to the CMM touching sensor and contaminate the measurement.

The procedure depends greatly on both tactile and vision senses and the use of them interchangeably becomes crucial because, sometimes the *burr* cannot be seen but can be felt. Finally, the final inspection and evaluation of whether or not the *burr* has been completely removed is always made by using the tactile sense.

As pointed out by the operator, if the machining process could be improved fewer *burrs* would be found on the component, reducing considerably the time employed on each component and production costs. Therefore, more frequent replacement of the cutting tool in the machining process will potentially reduce *burrs* in the component. This is important because machining tool condition could be a vital cue to inform the de-burring process.

Given the process studied to identify process variability and how humans are dealing with this variability, it can be claimed that operators are fully aware of variability in components processed. Based the non-conformity reports provided, operators are successfully eliminating *burrs* in components. According to the interviewed operator, employees are trained to follow a specific procedure depending on the component; however, the order of checking the component features changes from operator to operator. For instance, some operators start the procedure checking the largest features first, while others would rather start checking all features of one face. Yet, the order of sequence to *de-burr* features does not modify the procedure itself or the final result.

The key tasks found were *identification and evaluation of burrs* in order to select the correct tool and to *remove the burr* because it demands concentration and outstanding visual and tactile skills. Evaluating burrs also requires cognitive skills, learned by experience. *Removing burrs* requires high dexterity in using tools. Operators have shown competence in identifying, evaluating, selecting the correct tool and removing *burrs* both promptly and effectively.

Although variability introduced by operators is not part of the scope of this research, it was found that this variability could be classified into three groups:

- Variability that is introduced by operators but its impact in the final product is neglected. For example, there are ranges of accepted radius and chamfer dimensions for corners after de-burring. Any measure falling within this range will be accepted. Figure 5-6 shows a graphical representation.

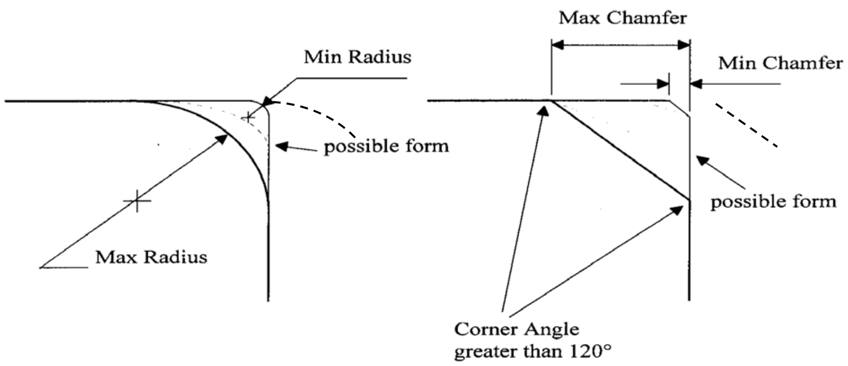


Figure 5-6. Acceptable external corner forms

- Variability introduced by operators that is corrected during the process, having no impact on outcomes. For example, it was observed that the removal stage is an iterative process where burrs are rarely eliminated "right first time".
- Variability that is introduced by operators when processing the component and which affects the outputs. It is documented that some components need re-work but the implication of the operators has not been further investigated.

In terms of limitations regarding studying processes, the generalisation of the findings in process studies is difficult as a process study involves the study of a group of people; the conduct of this group may or may not emulate the behaviour in other similar groups. Other limitations in this specific process study should be attributed to confidentiality issues. For instance, the observation process was limited in terms of timing and did not allow observation of the complete process, which would take up to 6 hours. In order to more precisely understand human strategy when dealing with variability in this process, it is critical to spend more time observing behaviours and decisions, in multiple operators, and during more than one work shift to both fully understand the process and draw more accurate conclusions.

5.5 Summary

Summarising, Chapter 4 and 5 have served the purpose of creating a structured procedure to identify variability in manufacturing processes, locate the tasks that are affected by variability and understand how operators deal with variability. The operators are found to manage dynamic relations among variability in the Key Characteristics effectively using different information cues, senses and cognitive skills (judgements, assessments and problem solving-thinking skills).

6. DECISION FOR AUTOMATION FRAMEWORK

The two industrial processes, studied so far (in Chapters 4 and 5), resulted in a significant amount of data on industrial manufacturing processes on which a procedure has been developed to identify variability within processes, and to characterise/describe the interactions of operators with variability. In this chapter, the findings from process studies and literature are combined to support the development of a framework to assist automation decisions. The aim is to consider variability during the decision-making process. The reason behind this is that, if variability in a process is not contemplated when automating a process, the automated solution might not be able to solve variability in the way it was overcome in the manual process. This can lead to an incomplete solution which might need changes to be introduced in the previous processes to eliminate variability, and potentially higher investments. It is known that variability affects manufacturing processes (Glodek et al. 2006; MacDonald 2003; Sandom & Harvey 2004) and this has been corroborated during the study of two different industrial processes (Chapters 4 and 5). However, there is no model with which to ponder process variability such that it can be included in the automation decision.

The framework is expected to take into account information about the variability in the process before deciding to automate. Other factors beyond variability that might affect automation decisions are not considered in this framework although they have been identified and briefly explained in Section 1.2. Through a set of parameters, the framework proposed will categorise variability in the process studied and, according to the results, a level of automation for the process will be suggested based on the values and states of the parameters. The parameters are further explained in Section 6.1.

6.1 Attributes and parameters used in the framework

The framework identifies five attributes of tasks in manufacturing processes that might be affected by variability. These attributes are: *inputs*, *outputs*, *strategy*, *time* and *requirements*. Two of the attributes have been selected to match those in the IDEF0 Function modelling method: inputs and outputs therefore, inputs and outputs have same meaning than in IDEF0. Additionally, "*strategy*", "*requirements*" and "*time*" has been introduced to include important parameters appearing in the literature. IDEF0 identifies four data and objects that interrelate functions or activities (represented by arrows) in a process: Inputs, Outputs, Mechanisms and Controls (ICOMs) and it was chosen for process analysis in this research (section 3.4).

For these five attributes: *inputs*, *outputs*, *strategy*, *time* and *requirements*, a set of parameters were chosen to describe variability. These parameters were derived from the process studies and corroborated through the literature review, confirming that they are mentioned by different authors when describing task complexity. There is no specific literature defining parameters to describe variability within tasks performed by humans, much less in manufacturing processes. However, variability has been identified in the literature as an attribute of complexity in manufacturing processes (Thornton 1999a; Doerr and Arreola-Risa 2000; Glodek et al. 2006; Antony, Hughes, and Kaye 2010; Wang, Sowden, and Mileham 2013) and tasks (Schwab & Cummings 1976; Gutenberg et al. 1983; Wood 1986; Lohse 1997; Liu & Li 2012) therefore the task complexity literature is the best benchmark for comparison.

Table 6-1 shows attributes and their parameters used in the framework and compare them to equivalent terms used in the literature. For example, in the literature different models describe “uncertainty” or “presentation heterogeneity” as parameters for complexity. The definition given to those parameters is equivalent to the definition given to “range or interval” of variability in the framework.

Table 6-1. Attributes and parameters from processes study and correspondences in literature

Attribute	Parameter	Equivalent in literature
Inputs/ Outputs	Quantity	**Number of elements** (Baccarini 1996; Rouse & Rouse 1979; Williams & Li 1999), **Number of information cues, information load** (Steinmann 1976; Simnett 1996; Hartley & Anderson 1983; Wood 1986; Bonner 1994; Asare & McDaniel 1996; Carey & Kacmar 1997; Zhang et al. 2009)
	Diversification	**Number of products/outcomes** (Wood 1986; Campbell 1988; Ho & Weigelt 1996; Harvey & Koubek 2000), **Variety/diversity of elements** (Gardner 1990; Ham et al. 2011)
	Interval or range	**Presentation heterogeneity** (Bonner 1994; Marshall & Byrd 1998) **Uncertainty** (Campbell 1988; Wood 1986; Carey & Kacmar 1997; Xiao et al. 1996; Williams 1999; Bell & Ruthven 2004)
	Interdependency	**Connectivity/relationship** (Rouse & Rouse 1979; Wood 1986; Campbell 1988; Bonner 1994; Baccarini 1996; Williams 1999; Boag et al. 2006)
Strategy	Number of alternatives	**Number of paths/solutions** (Campbell 1988; Bonner 1994; Harvey & Koubek 2000) **Number of alternatives** (Payne 1976; Kim & Khoury 1987; Payne et al. 1992)
	Number of actions	**Number of operations/sub-tasks/acts** (Wood 1986; Speier 2006; Xu et al. 2009; Zhang et al. 2009)
	Pattern	**Structure/specification/clarity** (Bonner 1994; Byström & Järvelin 1995; Harvey & Koubek 2000; Nadkarni & Gupta 2007; Mascha & Miller 2010; Skjerve & Bye 2011; Liu & Li 2012) **Repetitiveness/non-routinely** (Harvey & Koubek 2000; Schwarzwald et al. 2003)
Time	Concurrency	**Concurrency** (Xiao et al. 1996; Molloy & Parasuraman 1996; K. . Hendy et al. 1997; Skjerve & Bye 2011; Liu & Li 2012)
	Time availability	**Time pressure** (Payne et al. 1992; Skjerve & Bye 2011; Liu & Li 2012; Greitzer 2005; Svenson & Edland 1987; Klein 1993; K. C. Hendy et al. 1997)
Requirements	Sensorial	**Format/mismatch/inconsistency/compatibility** (Steinmann 1976; O'Donnell & Johnson 2001; Greitzer 2005; Liu & Li 2012)
	Cognitive requisite	**Difficulty** (Greitzer 2005; Liu & Li 2012) **Cognitive demand** (Campbell & Gingrich 1986; Campbell 1988; Sintchenko & Coiera 2003; Bailey & Scerbo 2007; Liu & Li 2012)
	Physical requisite	**Physical demand** (Campbell & Gingrich 1986; Campbell 1988; Sintchenko & Coiera 2003; Bailey & Scerbo 2007; Liu & Li 2012)

The attributes and parameters selected for the categorisation of variability are presented next.

Inputs and outputs

The four parameters used to measure variability in both *inputs* and *outputs* of a given task in a manufacturing process are: *quantity*, *diversification*, *range or interval* and *interdependency*. These parameters have been chosen based on the two processes studied previously which showed the need to count the sources of variability, the number of different inputs/outputs affected by variability, the interval or range of this variability (if known) and the relationships among sources of variability (whether they are dependent or not).

- ***Quantity***: identifying sources of variability implies quantify them, that is, to know how many of them are affecting inputs/outputs.
- ***Diversification***: *diversification* quantifies the number of different types of outputs/inputs affected by variability. One source of variability could affect different outputs/inputs. For example, two plates with different length but the same width and thickness are welded in a welding task. It has been noticed that both plates present variability in thickness when they are from different batches. In this case, although only one source of variability is introduced (thickness), there are two inputs affected so in *"diversification"* it should be counted as 2 and only 1 in *"quantity"*.
- ***Interval or Range of variability***: Ideally, if variability is identified, it should be delimited. Delimiting sources of variability will give the range of the inherent deviation and that will aid the automated solution by reducing uncertainty. For instance, if variability found in the position of a drill is always between -1.00 mm and +1.20 mm in the X axis of the defined coordinates by design, this will be the *range of variability* for this case (*interval of variability*: -1.00 mm to +1.20 mm).
- ***Interdependency***: Two sources of variability could be either *dependent* or *independent*. Therefore, a question arises: how does one source of variability affect another source of variability?
    - ***Dependent***: If both sources of variability are dependents, the effect could be either positive or negative:

        - ***Positive*** (reducing or eliminating one source of variability will reduce or eliminate the other source of variability).
        - ***Negative*** (reducing or eliminating one source of variability will augment the other source of variability).
    - ***Independent***: If sources of variability are *independent,* working on one source of variability will have no effect on other sources of variability.

Strategy

The strategy followed to complete the task comprises three further parameters to evaluate sources of variability affecting the task. These parameters are: *number of alternatives*, *number of actions* and *patterned actions.*

- ***Number of alternatives:*** number of alternatives refers to the number of different paths followed to complete a task where one alternative can be perfectly substituted by another one. In manufacturing processes, different alternatives can be used in order to achieve the same goal. (Patrick & James 2004). However, if the final goal is to automate a task, this divergence of alternatives is interpreted as different solutions solving the same problem. Thus, the higher the number of alternatives, the more difficult it is to select the optimum, adding difficulty to the automation decision.
- ***Number of actions***: in reference to how many actions are executed to overcome variability in a task. *Action* is defined in this research as every indivisible "event of doing something", which is absolutely necessary to successfully cope with variability. The number of actions will assist in determining the suitability of the task for automation if, for example, no variability is managed during its execution.
- ***Patterned actions***: the repeated actions during the task could follow a *pattern*. Subsequently, identifying those repeated actions will facilitate their classification into tasks, for automation purposes. Those most likely will differ from tasks described in SOPs as it was noticed in the two processes studied.

Time

Concurrency and *Time availability* are the two time parameters described below:

- ***Concurrency***: refers to how the sources of variability are introduced during the execution of the task with regards to "time". They will be *sequential*, if they are introduced in different actions. On the other hand, they can also be *coincident* or simultaneous when they are introduced during the same action and managed simultaneously, thus the former will be easier to resolve than the latter.
- ***Time availability***: this refers to the time allocated in the manual task to either eliminate variability, or to reduce it to an admissible range. If there is sufficient time to effectively reduce the variability up to an acceptable level, regardless of external conditions and operators, the "*state*" of *Time availability* would be "sufficient", as it has been allocated enough time to reduce/eliminate variability. Contrarily, if variability cannot be reduced or eliminated in the allocated time, it should be categorised as "insufficient".

Sensorial, Cognitive and Physical Requirements

- ***Sensorial***: the domain of sensorial features required to detect variability, i.e. sight, hearing, taste, touch and smell, in humans. The automated solution should use an equivalent to detect this variability.
- ***Cognitive requisite***: Cognitive requisite attempts to highlight any mental process required to evaluate and react to variability, such as *analysis*, *judgement*, *assessments* and *problem solving skills*. This is important to define the level of intelligence in the automation solution as it should successfully cope with variability.
- ***Physical requisite***: any physical attribute to deal with variability, for instance: accessibility, force, torque or, environmental conditions. Any operator will have to have the required physical capabilities to properly perform these tasks, without risking his/her health or the quality of the outputs. For any automated solution, these physical prerequisites should not exceed the capabilities of the equipment described by the manufacturer.

Table 6-2 summarises the parameters to characterise variability in tasks in manufacturing processes for each attribute.

Table 6-2. Framework: attributes and parameters

Attribute	Parameter
Output	Quantity → # sources of variability in outputs
	Diversification → # different outputs affected by variability
	Interval of variability → Determines whether the range of variability is delimited or not
	Interdependency → Acting on one source of variability doesn't affect other sources of variability
Inputs (parts, tools, stimuli, data, information cues, procedure)	Quantity → # sources of variability in inputs
	Diversification → # different outputs affected by variability
	Interval of variability → Determines whether the range of variability is delimited or not
	Interdependency → Acting on one source of variability doesn't affect other sources of variability
Strategy	Number of alternatives → # different ways to solve variability
	Number of actions → # different actions required to overcome the problem
	Pattern → Actions which follow a repeated pattern
Time	Concurrency → Sources of variability are presented in sequence or concurrently
	Time availability → Time available is enough to eliminate variability
Requirements	Sensorial → Domain of the sensorial features needed to cope with variability (visual, hearing, tactile…)
	Cognitive requisite → To solve the variation
	Physical requisite → To solve the variation (space, force, torque, etc...)

6.2 Framework for automation: considering the level of automation.

Prerequisites

Before the framework can be applied, there are some prerequisites that should be taken into consideration. The specific nature of the industry studied to design the framework (heavily regulated, highly manual, low production volume) should be noted. The potential application of the framework to other industries and therefore to other processes is discussed in Chapter 8. These prerequisites are:

Manual Process. Some of the tasks in the process are currently performed by operators due to variability and complexity that are not easily overcome requiring the operators to apply their knowledge and skills.

Sector. The proposed framework has been designed and validated in the high-value manufacturing industry. Its application to other manufacturing sectors needs further investigation.

Volume of production. There are no restrictions in the application of the framework to processes regarding the volume of production. However, due to the fact that variability is dealt by operators in those processes studied, the volume of production is usually low.

Established process. The framework should be applied only to tasks in established processes, established processes as those where both the outputs and the process constantly achieve the required quality and safety standards for the volume of production demanded.

Values assigned to the parameters: standardisation of the outcome

The parameters categorise variability in the task using *numerical values* and *states* accordingly. Therefore, a definition of these parameters will be accessible for those working with this framework with their corresponding *numerical values* or *states* to choose from. This will allow the users to set the value or state that each parameter takes, depending on the task being studied. For example, in a given task quantity (of sources of variability) in inputs could be two whereas in a different task it could be one.

As not all parameters have *numerical values*, those with *state* values are assigned *numerical values* in a second layer, helping to standardise parameters and later on, to suggest the level of automation.

A summary of numerical *values* and *states* are shown in Table 6-3 and explained afterwards.

Table 6-3. Parameter, values and states

Attribute	Parameter	States	Value
Output	Quantity	-	Not applicable (0) to 10
	Interval of variability	Not Applicable	0
		Known	0
		Unknown	10
	Diversification	-	Not applicable (0) to 10
	Interdependency	Not Applicable	0
		Dependent	5
		Independent	10
Inputs	Quantity	-	Not applicable (0) to 10
	Interval of variability	Not Applicable	0
		Known	0
		Unknown	10
	Diversification	-	Not applicable (0) to 10
	Interdependency	Not Applicable	0
		Dependent	5
		Independent	10
Strategy	Number of alternatives	-	Not applicable (0) to 10
	Number of actions	Not Applicable	Not applicable
		1 to 5 (low)	0
		6 to 15 (medium)	5
		More than 15	10
	Patterned actions	Not Applicable	0
		Some actions patterned	5
		No pattern	10
Time	Concurrency	Not Applicable	0
		Sequence	5
		Concurrent	10
	Time availability	Not Applicable	0
		Sufficient	0
		Insufficient	10
Requirements	Sensorial	-	1 to 5
	Cognitive requisite	Not Applicable	0
		No	0
		Yes	10
	Physical prerequisite	Not Applicable	0
		No	0
		Yes	10

***Quantity*:** this refers to the number of sources of variability detected either in *outputs* or *inputs* and might take values from *not applicable* (0) to theoretically *infinite*. However, it has been limited up to 10 in order to simplify the number of sources of variability available. Experience has determined that sources of variability ranges from 1 to 5 in the observed tasks, however, in the case that more than 10 sources of variability are found, the framework allows higher numbers to be represented.

***Interval of variability**:* interval of variability tries to define whether the variability is delimited or not. Hence, this parameter will be able to present three different states: *not applicable*, *delimited* or *unknown*.

- *Not applicable* is used when there is no variability (outputs or inputs) found in the attribute. *Not applicable* has an assigned value of 0.
- ***Delimited*** is when the range of variability is acknowledged by all sources of variability. It has a value of 0.
- ***Unknown*** when the range of variability remains unknown for a certain source of variability. It has a value of 10.

***Diversification*:** this defines the number of different type of *outputs* or *inputs* affected by variability. It has been limited to 10, although, as same as in *quantity,* it can be modified to introduce a higher value.

Interdependency*:* this has four different states: *not applicable, dependent positive, dependent negative* and *independent.*

- ***Not applicable*** is used when there is no variability found in the attribute (inputs or outputs) or only one source of variability is found; its correspondent value is 0.
- ***Dependent*** is selected when all sources of variability are inter-dependent, i.e. working on one of them will have an effect, either positive or negative as explained in Section 6.1.1, on the others. This has a value of 5.
- ***Independent*** is used when at least one source of variability found in the attribute, is independent of the others, as explained in section 6.1.1 (working on other sources of variability has no effect in this one). It has a numerical value of 10.

In literature it has been found that redundant and dependent actions in a task have a reduced complexity (Rouse & Rouse 1979; Wood 1986; Campbell 1988; Bonner 1994; Baccarini 1996; Williams 1999; Boag et al. 2006; Liu & Li 2012).

Number of alternatives: this describes how many different paths can be followed to reach the desired outcome. It has been limited to 10 yet, the same as in *quantity* and *diversification*; it can be modified to introduce a larger number.

Number of actions: this defines how many different actions (not repeated) need to be executed to overcome variability. It has three states: low, medium and high.

- ***Low*** is used when the number of actions is between 1 and 5. It has a value of 0.

- ***Medium*** is used when the number of actions is between 6 and 15. It has a value of 5.
- ***High*** is used when the number of actions is more than 15. It has a value of 10.

***Pattern*:** pattern tries to describe whether a set of actions are repeated during the task. It is defined by three states:

- ***Not applicable*** is used when there is no variability found in the task; its corresponding value is 0.
- ***Some actions patterned*** will be selected when a minimum of three actions are executed more than once and, in the same sequence during the task. For example, pick up (a nut), fasten it manually (on one free bolt) and, apply final torque (with provided tool), are series of repeated actions while assembling a car wheel. It has a value of 5.
- ***No pattern*** no pattern is selected when no patterned actions have been identified among actions in the task. It has a value of 10.

Concurrency: this can have three different states, *not applicable, sequence* and *concurrent*.

- ***Not applicable*** is used when there is no variability found in the task; its corresponding value is 0.
- ***Sequential*** occurs when sources of variability are introduced in the task, one after the other, in a sequence, in different actions. It has been assigned a value of 5.
- ***Concurrent*** describes when, at least two sources of variability, have to be managed in the same action. It has a value of 10.

Time availability: this parameter has three states: *not applicable, insufficient* and *sufficient*.

- ***Not applicable*** is used when there is no variability found in the task; its corresponding value is 0.
- ***Insufficient*** is chosen when the time available to successfully perform the task and hence, to overcome variability, is not enough for any given operator. It has a value of 10.
- ***Sufficient*** describes that the time allocated to perform the task and to deal with the variability in it is adequate. It has a value of 0.

Sensorial: The parameter *sensorial* counts the number of senses used during the execution of the task to surmount variability. Likewise, if it is applied to a potential automated solution, it will refer to technical characteristics that will be used to substitute human senses. For example, a laser sensor could be used to determine roughness of a surface instead of the tactile sense.

Cognitive requisite: cognitive requisite has three states: *not applicable*, *yes* and *no*.

- ***Not applicable*** is used when there is no variability found in the task; its corresponding value is 0.
- ***Yes*** describes mental processes where cognitive requisites, i.e. judgement, assessment and problem solving, are essential in order to successfully perform the task. It has an assigned value of 10. Supposing that a potential automated solution is assessed, Yes will define those capabilities which enable the solution for choosing the best option in response to a set of inputs, for instance, the system could use fuzzy logic, artificial neural networks or, any other machine learning algorithm.
- ***No*** describes those processes where no cognitive requisites are needed to successfully perform the task. It has a value of 0.

Physical prerequisite: this parameter also has three states: *not applicable, yes* and *no*.

- ***Not applicable*** is used when there is no variability found in the task; its corresponding value is 0.
- ***Yes*** defines some specific physical requirement in order to successfully perform the task. For example, lifting heavy parts weighting more than 25 Kg could be a physical prerequisite in the sense that not everybody can do it. This can also be applied to equipment and devices. In this case, the equipment/device limits (as in specifications) cannot be surpassed in working conditions. It has a value of 10.
- ***No*** describes when no special physical prerequisites are needed, that is, any operator could physically perform the task regardless his physical condition or physical attributes such as weight, height or body build. It has a value of 0.

Weights of the parameters

Outputs obtained through the application of the framework will be utilised to suggest the level of automation to implement therefore incorporating variability study into the making decision process. The framework assumes that the levels of automation will be inversely proportional to how well defined are both the process and the variability. In consequence, lower knowledge of process and variability will lead to lower levels of automation, i.e. more human implications in the execution of the tasks within the process.

In order to be able to compare variability and to provide a standardised value for the parameters described, a specific *weight* has been assigned to each of these parameters in the framework, in order to suggest the level of automation to apply. These weights have been calculated using the Analytic Hierarchy Process (AHP) (Saaty 1990). The AHP is a method applied in solving decision problems using a hierarchical structure of factors. It is based on comparing factors one-to-one with each of the other factors. The pairwise comparisons are arranged into a matrix A_{nxn}

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \text{ where n = number of parameters}$$

As an example, Table 6-4 shows these values proposed by an expert consulted. These values are represented in a table for better understanding.

Table 6-4. Table comparing factors one-to-one

Parameter	**Q**	**D**	**R**	**I**	**Al**	**Act**	**P**	**C**	**A**	**S**	**Cog**	**Phy**
Quantity (Q)	**1**	0.33	0.14	1	5	5	5	0.33	0.13	3	0.20	0.20
Diversification (D)	3	**1**	0.14	3	5	5	5	1	0.13	3	0.25	0.25
Range (R)	7	7	**1**	7	9	9	9	3	1	5	2	2
Interdependency (I)	1	0.33	0.14	**1**	1	1	1	0.33	0.13	0.50	0.13	0.13
# of alternatives (Al)	0.20	0.20	0.11	1	**1**	1	1	0.33	0.13	0.33	0.13	0.13
# of actions (Act)	0.20	0.20	0.11	1	1	**1**	1	0.33	0.13	0.33	0.13	0.13
Patterns (P)	0.20	0.20	0.11	1	1	1	**1**	0.33	0.13	0.33	0.13	0.13
Concurrency (C)	3	1	0.33	3	3	3	3	**1**	0.13	0.33	0.13	0.13
Time availability (A)	8	8	1	8	8	8	8	8	**1**	5	3	3
Sensorial (S)	0.33	0.33	0.20	2	3	3	3	3	0.20	**1**	1	1
Cognitive (Cog)	5	4	0.50	8	8	8	8	8	0.33	1	**1**	1
Physical (Phy)	5	4	0.50	8	8	8	8	8	0.33	1	1	**1**

This matrix contains "ones" on the diagonal and numbers ranging from 1/9 to 9 in the cells above the diagonal and their inverses in those cells below the diagonal. For example, if the cell $a_{15} = 5$, the cell $a_{51} = 1/5 = 0.20$. These numbers correspond to the comparison of the parameters against each other to evaluate the importance of each parameter. So, the cell a_{ij} will be the result of comparing the parameter i with the parameter j. For example, the cell a_{15} = 5 means that *Quantity* is 5 times more important than *number of alternatives* according to the person who filled out the cells.

In the next step of the AHP, these values are standardised into a "standardised matrix" B, where the values in each cell of matrix A are divided by the sum of all the values in the column.

$$B = \begin{bmatrix} b_{11} & \cdots & b_{1n} \\ \vdots & \ddots & \vdots \\ b_{n1} & \cdots & b_{nn} \end{bmatrix} \qquad \text{where} \qquad b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}$$

Therefore, the standardised values from the previous table are shown in Table 6-5.

Table 6-5. Standardised values for parameters' matrix

Parameter	**Q**	**D**	**R**	**I**	**Al**	**Act**	**P**	**C**	**A**	**S**	**Cog**	**Phy**
Quantity (Q)	0.03	0.01	0.03	0.02	0.09	0.09	0.09	0.01	0.03	0.14	0.02	0.02
Diversification (D)	0.09	0.04	0.03	0.07	0.09	0.09	0.09	0.03	0.03	0.14	0.03	0.03
Range (R)	0.21	0.26	0.23	0.16	0.17	0.17	0.17	0.09	0.27	0.24	0.22	0.22
Interdependency (I)	0.03	0.01	0.03	0.02	0.02	0.02	0.02	0.01	0.03	0.02	0.01	0.01
# of alternatives (Al)	0.01	0.01	0.03	0.02	0.02	0.02	0.02	0.01	0.03	0.02	0.01	0.01
# of actions (Act)	0.01	0.01	0.03	0.02	0.02	0.02	0.02	0.01	0.03	0.02	0.01	0.01
Patterns (P)	0.01	0.01	0.03	0.02	0.02	0.02	0.02	0.01	0.03	0.02	0.01	0.01
Concurrency (C)	0.09	0.04	0.08	0.07	0.06	0.06	0.06	0.03	0.03	0.02	0.01	0.01
Time availability (A)	0.24	0.30	0.23	0.18	0.15	0.15	0.15	0.24	0.27	0.24	0.33	0.33
Sensorial (S)	0.01	0.01	0.05	0.05	0.06	0.06	0.06	0.09	0.05	0.05	0.11	0.11
Cognitive (Cog)	0.15	0.15	0.12	0.18	0.15	0.15	0.15	0.24	0.09	0.05	0.11	0.11
Physical (Phy)	0.15	0.15	0.12	0.18	0.15	0.15	0.15	0.24	0.09	0.05	0.11	0.11
SUM	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**

Finally, the weight for each parameter (w_i) is calculated as:

$$w_i = \frac{\sum_{j=1}^{n} b_{ij}}{n}$$

The AHP transforms these one-to-one comparisons into a rank where these parameters are classified by weight (importance). In this example, parameters and its weights (as percentages for readiness) are shown in Table 6-6.

Table 6-6. Weights resulting from the example

Attribute	Parameter	Weight
Output/Inputs	Quantity	**5.1%**
	Diversification	**6.4%**
	Interval of variability	**20.1%**
	Interdependency	**2.1%**
Strategy	Number of alternatives	**1.7%**
	Number of actions	**1.7%**
	Patterned actions	**1.7%**
Time	Concurrency	**4.6%**
	Time availability	**23.4%**
Requirements	Sensorial	**5.8%**
	Cognitive prerequisite	**13.7%**
	Physical prerequisite	**13.7%**
	TOTAL	**100%**

The weights have been calculated from a survey of three engineers working in the aeronautical sector but not in process automation. These subjects have extensive experience in manufacturing process, more than five years in all cases. The experts were asked to evaluate each parameter against the others through a parameter matrix like the one shown in Table 6-4. The three matrices are shown in Table 6-7.

Table 6-7. Matrices comparing parameters

Expert 1												
Parameter	Q	D	R	I	Al	Act	P	C	A	S	Cog	Phy
Quantity (Q)	**1**	0.33	0.14	1.00	5.00	5.00	5.00	0.33	0.13	3.00	0.20	0.20
Diversification (D)	3.00	**1**	0.14	3.00	5.00	5.00	5.00	1.00	0.13	3.00	0.25	0.25
Range (R)	7.00	7.00	**1**	7.00	9.00	9.00	9.00	3.00	1.00	5.00	2.00	2.00
Interdependency (I)	1.00	0.33	0.14	**1**	1.00	1.00	1.00	0.33	0.13	0.50	0.13	0.13
# of alternatives (Al)	0.20	0.20	0.11	1.00	**1**	1.00	1.00	0.33	0.13	0.33	0.13	0.13
# of actions (Act)	0.20	0.20	0.11	1.00	1.00	**1**	1.00	0.33	0.13	0.33	0.13	0.13
Patterns (P)	0.20	0.20	0.11	1.00	1.00	1.00	**1**	0.33	0.13	0.33	0.13	0.13
Concurrency (C)	3.03	1.00	0.33	3.00	3.00	3.00	3.00	**1**	0.13	0.33	0.13	0.13
Time availability (A)	8.00	8.00	1.00	8.00	8.00	8.00	8.00	8.00	**1**	5.00	3.00	3.00
Sensorial (S)	0.33	0.33	0.20	2.00	3.00	3.00	3.00	3.00	0.20	**1**	1.00	1.00
Cognitive (Cog)	5.00	4.00	0.50	8.00	8.00	8.00	8.00	8.00	0.33	1.00	**1**	1.00
Physical (Phy)	5.00	4.00	0.50	8.00	8.00	8.00	8.00	8.00	0.33	1.00	1.00	**1**

Expert 2												
Parameter	Q	D	R	I	Al	Act	P	C	A	S	Cog	Phy
Quantity (Q)	**1**	1.00	0.13	0.50	3.00	3.00	5.00	0.33	0.13	3.00	0.25	0.50
Diversification (D)	1.00	**1**	0.13	3.00	5.00	6.00	5.00	0.20	0.13	3.00	0.25	0.33
Range (R)	8.00	8.00	**1**	7.00	9.00	9.00	8.00	6.00	0.50	7.00	5.00	7.00
Interdependency (I)	2.00	0.33	0.14	**1**	3.00	5.00	5.00	0.33	0.20	2.00	0.20	0.25
# of alternatives (Al)	0.33	0.20	0.11	0.33	**1**	2.00	1.00	0.33	0.13	2.00	0.20	0.25
# of actions (Act)	0.33	0.17	0.11	0.20	0.50	**1**	0.33	0.25	0.13	0.33	0.13	0.13
Patterns (P)	0.20	0.20	0.13	0.20	1.00	3.03	**1**	0.20	0.13	0.50	0.20	0.25
Concurrency (C)	3.03	5.00	0.17	3.03	3.03	4.00	5.00	**1**	0.20	3.00	1.00	2.00
Time availability (A)	8.00	8.00	2.00	5.00	8.00	8.00	8.00	5.00	**1**	8.00	3.00	5.00
Sensorial (S)	0.33	0.33	0.14	0.50	0.50	3.03	2.00	0.33	0.13	**1**	0.20	0.25
Cognitive (Cog)	4.00	4.00	0.20	5.00	5.00	8.00	5.00	1.00	0.33	5.00	**1**	3.00
Physical (Phy)	2.00	3.03	0.14	4.00	4.00	8.00	4.00	0.50	0.20	4.00	0.33	**1**

Expert 3												
Parameter	Q	D	R	I	Al	Act	P	C	A	S	Cog	Phy
Quantity (Q)	**1**	1.00	0.25	2.00	7.00	9.00	4.00	1.00	0.33	5.00	0.50	1.00
Diversification (D)	1.00	**1**	0.25	2.00	4.00	6.00	2.00	1.00	0.25	5.00	0.33	0.50
Range (R)	4.00	4.00	**1**	5.00	7.00	9.00	9.00	5.00	1.00	7.00	2.00	5.00
Interdependency (I)	0.50	0.50	0.20	**1**	4.00	5.00	1.00	0.50	0.25	1.00	0.33	0.33
# of alternatives (Al)	0.14	0.25	0.14	0.25	**1**	3.00	2.00	0.33	0.13	1.00	0.20	0.33
# of actions (Act)	0.11	0.17	0.11	0.20	0.33	**1**	0.50	0.33	0.13	0.33	0.13	0.20
Patterns (P)	0.25	0.50	0.11	1.00	0.50	2.00	**1**	0.33	0.14	2.00	0.13	0.17
Concurrency (C)	1.00	1.00	0.20	2.00	3.03	3.03	3.03	**1**	0.13	5.00	0.33	0.50
Time availability (A)	3.03	4.00	1.00	4.00	8.00	8.00	7.00	8.00	**1**	0.13	0.20	0.33
Sensorial (S)	0.20	0.20	0.14	1.00	1.00	3.03	0.50	0.20	8.00	**1**	0.20	0.33
Cognitive (Cog)	2.00	3.03	0.50	3.03	5.00	8.00	8.00	3.03	5.00	5.00	**1**	5.00
Physical (Phy)	1.00	2.00	0.20	3.03	3.03	5.00	6.00	2.00	3.03	3.03	0.20	**1**

After obtaining the *weights* from the experts, the definitive weights were obtained as an average. These weights for each parameter are shown in Table 6-8.

Table 6-8. Final weight utilised in the framework

Attribute	Parameter	Weight			
		Expert 1	Expert 2	Expert 3	**Average**
Output/ Inputs	Quantity	5.1%	4.3%	8.5%	**6.0%**
	Diversification	6.4%	5.7%	6.6%	**6.2%**
	Interval of variability	20.1%	25.0%	22.0%	**22.4%**
	Interdependency	2.1%	4.7%	4.1%	**3.6%**
Strategy	Number of alternatives	1.7%	2.3%	2.4%	**2.1%**
	Number of actions	1.7%	1.4%	1.3%	**1.5%**
	Patterned actions	1.7%	2.0%	2.4%	**2.0%**
Time	Concurrency	4.6%	8.6%	6.1%	**6.4%**
	Time availability	23.4%	24.8%	14.9%	**21.0%**
Requirements	Sensorial	5.8%	2.4%	5.8%	**4.7%**
	Cognitive prerequisite	13.7%	11.3%	17.0%	**14.0%**
	Physical prerequisite	13.7%	7.6%	9.0%	**10.1%**
	TOTAL	100%	100%	100%	**100%**

These weights are determined from experience and, because they are subject to the framework user's perception, different users have suggested different *weights*. These divergences could be related to the type of processes they are dealing with; expert 1 works in avionic systems, expert 2 in final assembly and expert 3 in tooling. Therefore, future framework users should determine their own weights prior to the application of the framework, based on their own contexts.

From the weights determined, it can be seen that *"interval of variability"*, *"time availability"* and *"cognitive requisite"* have the highest weights and therefore, in their most unfavourable *states "unknown"*, *"insufficient"* and *"yes"* respectively, higher levels of uncertainty will be found in the variability, therefore this variability will be more challenging to overcome, implying the suggestion of lower levels of automation. On the other hand, the parameters *"number of alternatives"*, *"number of actions"* and *"patterned actions"* have weights that show low influence meaning that, even if the number of different alternatives is high, for example twenty, its impact on the level of automation suggested would be smaller. Table 6-9 shows a summary of the parameters classified by degree of importance.

Table 6-9. Degree of importance of the parameters

Importance (Highest to Lowest)	Parameters	Weight
1	Interval of variability, Time availability	>20%
2	Cognitive requisite, Physical prerequisite	>10%
3	Quantity, Diversification, Concurrency	≥6%
4	Interdependency, Number of actions, Number of alternatives, Patterned actions, Sensorial	<5%

Level of automation

The level of automation is applied to a task level, in between the higher level "process" and lower level "action". Considering the level of automation as the number of automated actions performed without human intervention or supervision within a task, this level can vary from completely manual to fully automated. In order to suggest a level of automation suitable to deal with the variability presented, it is necessary to establish a scale capable of describing different automation levels. In this research, a 1 to 7 scale was chosen, similar to the scale proposed by Frohm et al. (Frohm et al. 2008), on the grounds that this work describes the level of automation in physical and cognitive tasks, therefore at a task level. Physical tasks refer to those tasks that imply physical activities, for example drilling, riveting, stamping or fastening and cognitive tasks make reference to the supervision, control and problem solving tasks, for example inspecting an assembly, deciding where to grind, evaluating a weld or responding to an alarm.

Although these levels of automation for physical and cognitive tasks can be assessed independently in Frohm's work, the level of automation suggested in this thesis will not differentiate between physical and cognitive tasks because from the processes studied, this differentiation is found in a lower level (actions) whereas at task level both physical and cognitive actions are present. This is a similar approach to that found in the literature, where most authors apply levels of automation to tasks (Kotha & Orne 1989; Billings 1997; Endsley & Kaber 1999; Parasuraman et al. 2000; Lorenz et al. 2002; Sauer et al. 2013) without making any distinction.

On the scale proposed, 1 corresponds to a completely manual task and 7 concurs with a full automation, that is, where no human intervention or supervision is needed. In the framework, the first two levels are discarded due to the fact that they apply to rudimentary systems not found in the type of processes studied in this research and therefore noted as “None” referring to level of automation null or neglected. The remaining five levels have been grouped into four categories: *low* (levels 3 & 4), *moderate* (level 5), *considerable* (level 6) and *high* (level 7). Table 6-10 shows both, levels of automation and their categories.

Table 6-10. Categories based on Level of automation in (Frohm et al. 2008)

Level of Automation		**Physical tasks**	**Cognitive tasks**
NONE	1.	**Totally manual**. Only muscular power is used, no tools. E.g. Manual fastening	**Totally manual**. The user evaluates the task, and applies a solution based on his/her previous experience and knowledge. E.g. A job interview
	2	**Simple tool**. Mostly manual with help of a simple tool. E.g. Hammer	**Applying decision**. The user gets information or is suggested on how the task in done. E.g. Filling out a document
LOW	3	**Flexible tool**. Mostly manual work with help of flexible tool. E.g. Adjustable spanner	**Instructing**. The user receives instruction on how to do the task. E.g. Standard Operating Procedure.
	4	**Automated tool**. Mostly manual work with help of automated tool. E.g. Electric drill	**Questioning**. The system asks what to do next. E.g. Installing software
MODERATE	5	**Simple machine**. Work done by a machine designed for this purpose. E.g. Welding machine	**Supervision**. The system requests an action from the user. E.g. Alarms
CONSIDERABLE	6	**Flexible machine**. Work done by a machine that is reconfigurable for other tasks. E.g. Robot	**Intervention**. The system acts independently, if an anomaly occurs. E.g. automatic working cell with proximity sensors
HIGH	7	**Totally automatic**. Automatic System works autonomously, solving variability by itself. E.g. Adaptive welding (Manorathna et al. 2014)	**Totally automatic**. All information and control is managed by the system. E.g. Full-automated warehouse system

The final value of each parameter is obtained by multiplying the initial value by the weight. The final score is the result of the sum of all the parameters scores. The maximum score that can be obtained in the framework is 8.35 (due to not rounding up weights) and the minimum is 0. The maximum value (8.35) would be the most unfavourable case to handle, meaning that variability remains mostly undefined and is high, with zero when no variability has been found in the task. Logically, the level of automation suggested will depend on the score obtained after evaluating all the parameters.

In order to allocate the level of automation suggested, this range (0 to 8.35) has been divided into four and so, when the score is between 0 and 2.1, the level of automation suggested is "*high*" because the variability is very low and somehow controlled. When the total sum is 6.25 or more, the level of automation suggested is "*low*", due to the poor knowledge of the variability. Lastly, in between these two extremes, another two levels of automation have been suggested; a "*considerable*" level of automation when the values' total sum is between 2.1<x≤4.2, and a "*moderate*" level of automation when the values' total sum remains 4.2<x≤6.25.

In any case, these values range are not fixed and final but an indication only, allowing changes at the users' discretion. Also, more insights will be obtained through careful study of the constituent parameter values.

Implementation of the framework

This section discusses how the framework should be implemented, including the tool used, method of using it, who can use it, in which cases and when it should be used.

The framework has been developed in a Excel® spreadsheet where the user only can modify a column called "results" where the information for each parameter is presented in a drop-down list and the user choose from the options displayed. Figure 6-1 shows a partial view of the framework, displaying the menu for the parameter "Interval of variability".

Characteristic	Results
Quantity → # sources of variability in outputs	Not Applicable
Interval of variability → Range of variability is delimited	Unknown Not Applicable Delimited Unknown
Diversification → # different outputs affected by variability	
Interdependency → Acting on one source of variability doesn't affect other sources of variability	Independent

Figure 6-1. Partial view of the framework' s spreadsheet

The user must filled out the column "Results" with one of the options available for each parameter and, when finished, the suggested level of automation will be displayed on the right side of the spreadsheet, as shown in Figure 6-2.

Results	Comments
Not Applicable	
Unknown	
10	
Independent	
3	
Delimited	
1	
Independent	

Levels of automation
Low. Levels 3 & 4
Moderate. Level 5
Considerable. Level 6
High. Level 7

Level of Automation recommended
Considerable

Figure 6-2. Partial view of the framework's spreadsheet showing suggested level of automation

Before applying the framework to the tasks in the process, it is necessary to identify the sources of variability, which can be achieved through *documentation*, *interviews* and *observation*. Later, it would be required to identify attributes affected by the specific variability. Hence, the IDEF0 process decomposition and Key Characteristics analysis should be applied to the process. Going through this analysis helps to explore and understand the process in greater detail, which will be useful when applying the framework. Once all the information has been collected and analysed, the framework can be applied. Figure 6-3 schematically represents how sources of variability are identified, allocated, and characterised with the framework.

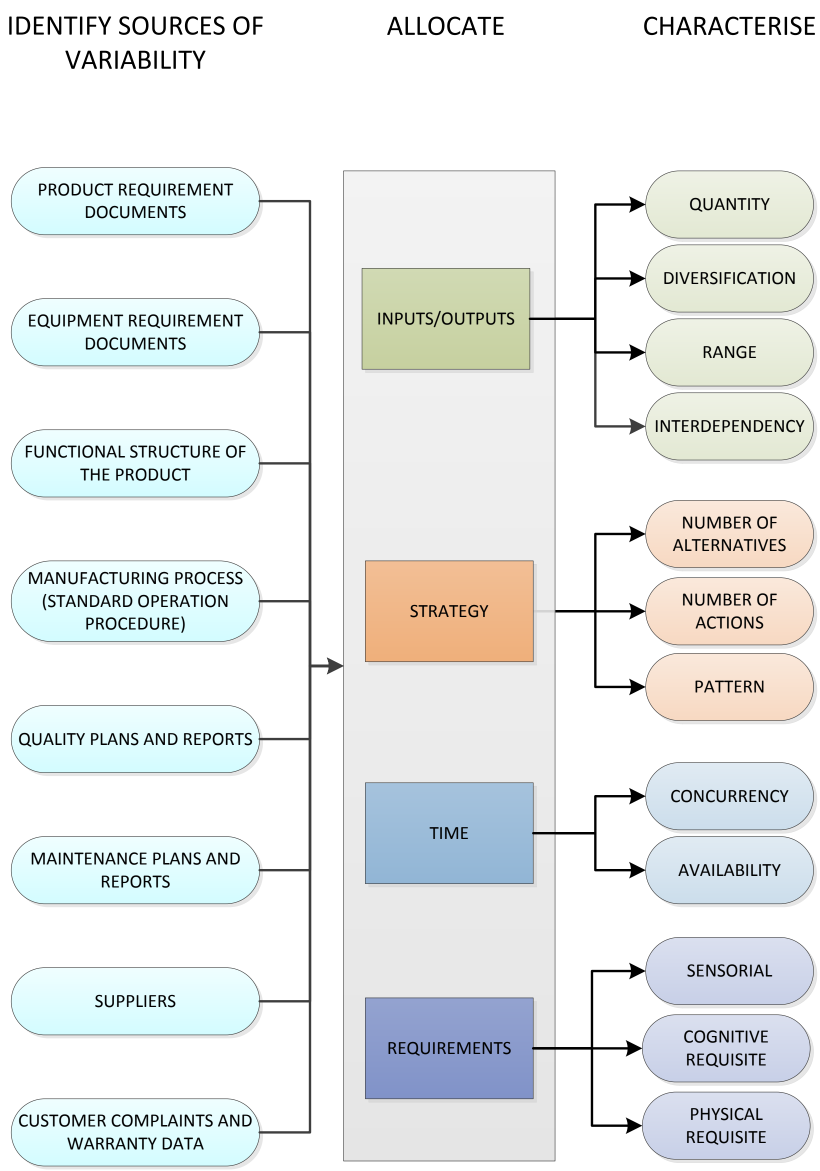


Figure 6-3. Inputs needed in the framework

In order to obtain a suggested level of automation, the framework has to be applied to a task level. This is because different tasks within the process could have different levels of automation. For example, if the framework is applied to the de-burring process presented in Chapter 5, it should be applied independently to each of the tasks identified in Figure 5-4: inspection, evaluation, removal, blowing and final inspection because each of these tasks will have different parameters values.

The framework should be applied for any person who is knowledgeable about the process. This knowledge might be acquired by working in the process (directly or as supervisor) or study of the process through documentation, observation and interviewing agents working in the process. This might include: operators, shift managers (line managers, shift supervisors, process supervisors and similar positions), engineers (production, manufacturing, industrial, quality engineers and similar positions). The decision of automation should include: Engineers, Top managers (Plant manager, Production manager, Chief of Engineering and similar positions), Chief Financial Officer (CFO), Chief Technology Officer (CTO) and Chief Executive Officer (CEO).

Figure 6-4 shows a flowchart of the framework application stages including the people which should be able to perform each of the stages.

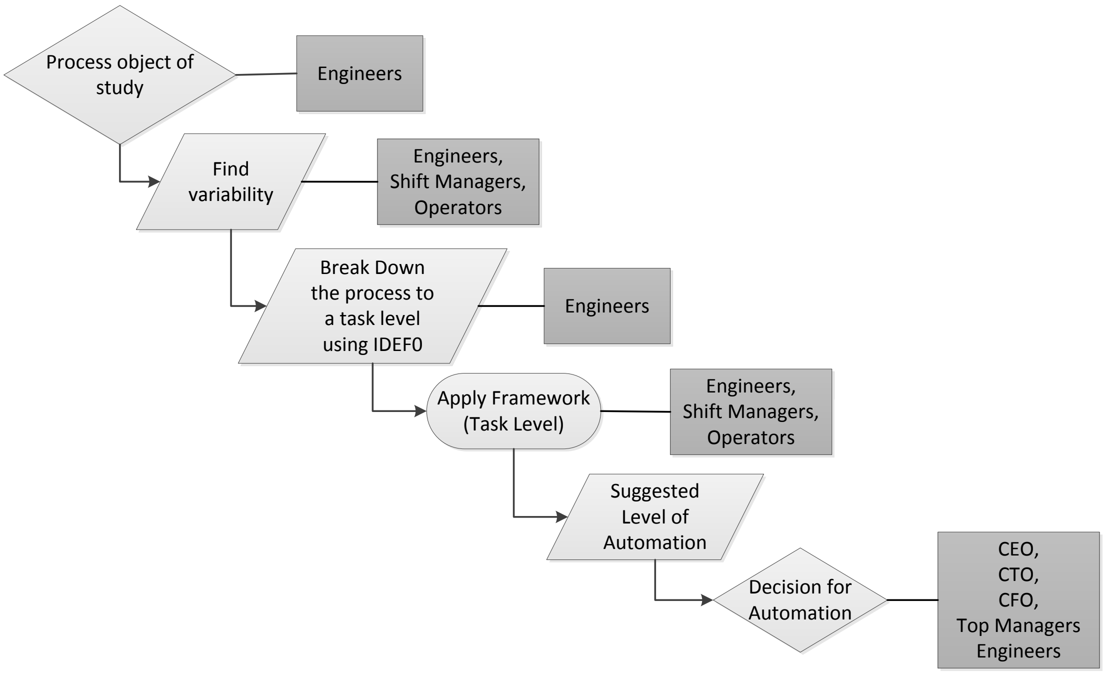


Figure 6-4. Framework application stages

6.3 Examples of framework application

Two different tasks in the processes studied in Chapters 4 and 5 are used as examples of the application of the framework.

The first task is “set up” in the grinding process. Figure 6-5 shows the IDEF0 diagram for this task. The sources of variability present in this task are: surface roughness and shape in the grinding tool.

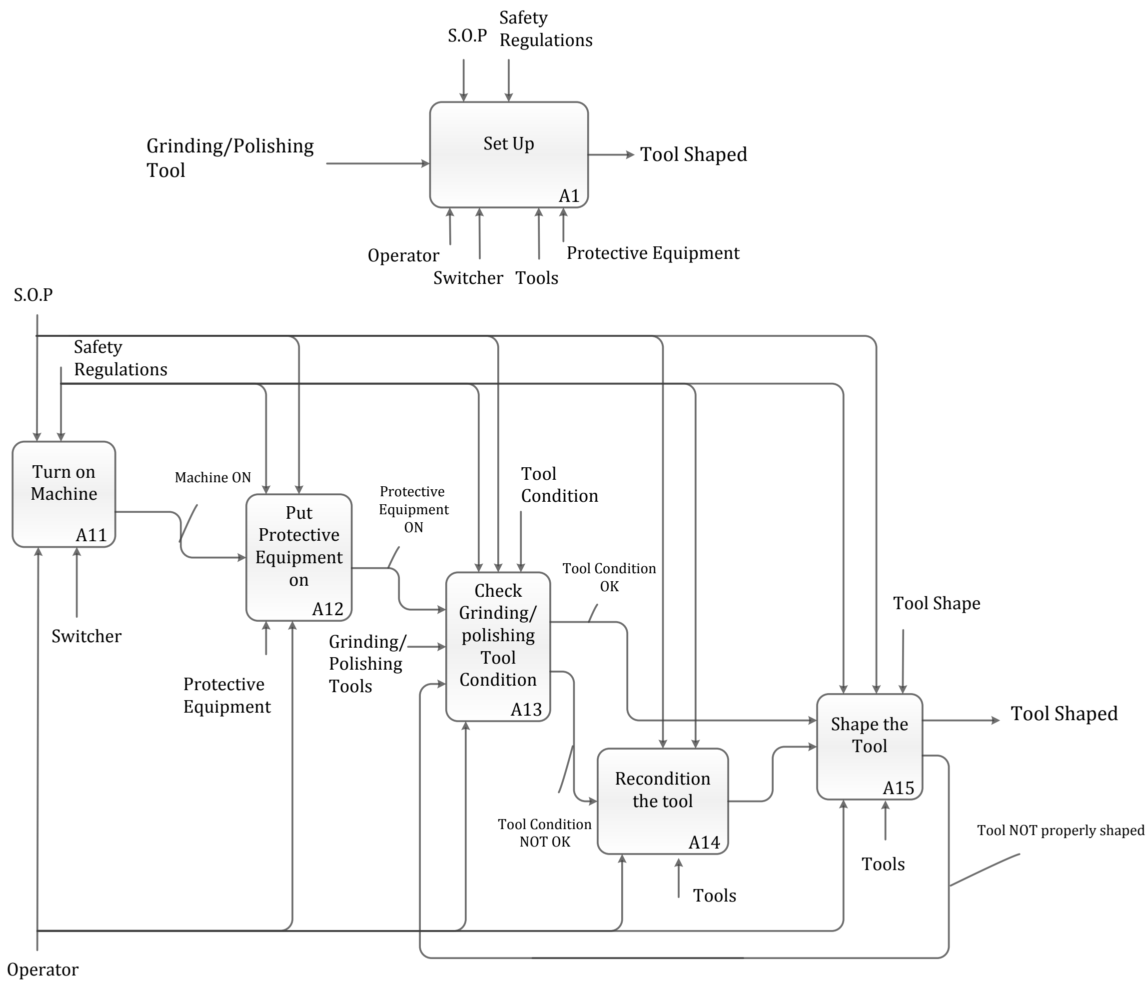


Figure 6-5. IDEF0 Diagram from task “set up” in grinding process

If the framework is applied, the result obtained can be seen in Table 6-11.

Table 6-11. Framework results for "set up" task in grinding process

Source of Variability	Parameter	Results	Comments
Output	Quantity	2	Surface roughness and shape
	Interval of variability	Unknown	It could not be measured
	Diversification	1	1 tool is set up at a time
	Interdependency	Independent	Surface roughness and shape of tool are independent of each other
Inputs	Quantity	2	Surface roughness and shape
	Interval of variability	Unknown	It could not be measured
	Diversification	1	1 tool is set up at a time
	Interdependency	Independent	Surface roughness and shape of tool are independent of each other
Strategy	Number of alternatives	2	2 Operators with slightly different ways to proceed
	Number of actions	3	Check tool condition, recondition tool, shape tool
	Patterned actions	Some actions patterned	
Time	Concurrency	Concurrently	Both sources managed simultaneously
	Time availability	Sufficient	
Requirements	Sensorial	2	Vision and tactile
	Cognitive requisite	Yes	Operator knows optimal tool condition and shape by experience
	Physical prerequisite	No	

The sources of variability in the outputs and inputs are surface roughness and shape which are independent; a tool might be brand new (roughness properties intact) and not shaped or it could have been recently shaped but presents some wear. The interval of variability of these sources was unknown as no data were disclosed. The two operators observed followed different sequence of actions when preparing the tool and some of their actions followed a pattern, i.e. check tool then shape tool, check tool again, shape again if necessary until the tool is shaped satisfactorily. The two sources of variability must be managed at the same time as the operators adapt to surface roughness wear and loss of grinding properties by applying more pressure and by reshaping the tool. The time available is enough as there is not any cycle time restriction. Finally, they rely on their visual and tactile sense to control tool surface roughness and tool shape, requiring cognitive requisites to evaluate the tool condition but the task does not require special physical requisites.

Based on the weightings in Table 6-8 (column “average”) and values in Table 6-11, the level of automation recommended is **moderate (Level 5)** for the “set-up” task because the interval of variability is unknown in inputs and outputs and some actions required cognitive skills. The current level of automation of this task is **low**, hence there is opportunity to increase automation. For example, the system could warn that tool life is coming to an end and need replacement.

The “removal” task in de-burring process has been chosen as the second example. Figure 6-6 shows the IDEF0 diagram for this task.

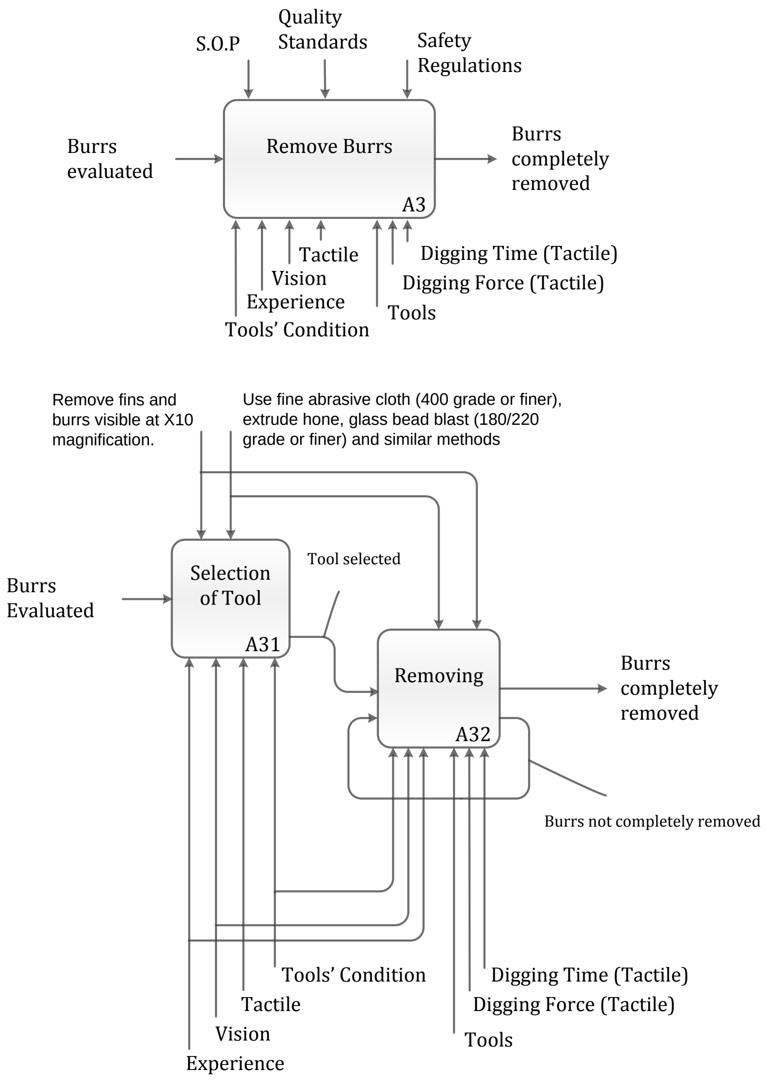


Figure 6-6. IDEF0 Diagram from task “removal” in de-burring process

If the framework is applied, the result obtained can be seen in Table 6-12.

Table 6-12. Framework results for "removal" task in de-burring process

Source of Variability	Parameter	Results	Comments
Output	Quantity	1	Component dimensions
	Interval of variability	Not Applicable	If component is accepted
	Diversification	1	1 type of component de-burred
	Interdependency	Not Applicable	
Inputs	Quantity	3	Tool, digging force and digging time
	Interval of variability	Unknown	It could not be measured
	Diversification	1	Working on one feature
	Interdependency	Dependent	Digging time and digging force depend on the tool selected
Strategy	Number of alternatives	3	Three Operators work in this component
	Number of actions	2	Selection of the tool and removal
	Patterned actions	No pattern	
Time	Concurrency	Concurrently	Selection of the tool is managed first, but digging force and digging time are managed simultaneously
	Time availability	Sufficient	Enough time available to perform the task
Requirements	Sensorial	2	Vision and tactile
	Cognitive requisite	Yes	Operator knows best tool depending on burr, digging force and digging time by experience
	Physical prerequisite	No	No special physical requisite found

The source of variability in the dimensions of the component can be caused either by previous machining process or by operator during the removal task. The sources of variability in inputs are digging force, digging time and type of tool which are dependent; tool selected will affect digging force and digging time. The interval of variability of these sources was unknown as they could not be measured. There are no evidence to support that different operators will select the same tool and apply the same digging force during the exact same time to remove the same type of burr, therefore it has been assumed that the three operators will proceed differently in the removal task (number of alternatives: 3). There are no room to patterned actions as this task only is composed of two actions. Digging force and digging time are managed at the same time and the tool is selected in the previous action. Time available is enough as there is no cycle time restriction. Finally they rely on their visual and tactile sense to apply the proper force during a period of time, requiring cognitive requisites to apply the correct force during the proper period of time but there are no special physical requisites.

Based on the weightings in Table 6-8 (column "average") and values in Table 6-12, the level of automation recommended is **considerable** for this task probably due to the fact that the interval of automation is unknown and the task requires cognitive skills together with the sum of the results from the other parameters. The current level of automation of this task is **moderate**, in the best case as a pneumatic machine might be used to remove burrs. Level of automation could be increased by, for example, adding a pressure sensor which can warn or disconnect the machine in case the pressure is higher than a certain value.

In both examples discussed, the level of automation recommended is dependent on the results scored in the framework. However, other factors explained in 1.2 will also influence the final decision. For example, in the removal task, a considerable level of automation could be implemented considering variability embedded in the task but it might be implemented a lower level of automation or none because the return of investment makes the upgrade unfeasible.

6.4 Summary

The proposed framework aspires to better characterise the variability in tasks in a given process. The framework considers twelve parameters: quantity, diversification, interval of variability, interdependency, number of alternatives, number of actions, pattern, time availability, concurrency, sensorial, cognitive requisite and physical requisite to characterise variability in the process of study. These parameters are assessed on the five attributes of the task: inputs, outputs, strategy, time and requirements. These parameters were chosen to characterise variability in two process studies.

The IDEF0 process decomposition is used to break down the process where the framework is applied to a task level. The variability found in the tasks is then described using different values and states that the parameters can take, depending on which the framework suggests a level of automation for the task, considering different weights for each parameters calculated from a survey with three experienced manufacturing engineers.

The level of automation suggested from the framework will need to be considered alongside other factors, as discussed in Section 1.2 when considering automating a process. Furthermore, both "*weights*" and "*values*" are parameters selected subjectively, therefore, they are subjected to revision due to limited exposition in different manufacturing processes, the constant evolution in the available technology, and the subjectivity implied when the framework is applied by a different user. The framework will be tested in the next chapter in one experiment and one manufacturing process, in order to evaluate its robustness, i.e. usability and coincidence of results among different users.

7. FRAMEWORK APPLICATION AND ROBUSTNESS

The framework was first tested in an experiment and an industrial process. The application of the framework to the experiment, considered here as a manual process, was intended to measure its competence in categorising the variability designed for the experiment. Therefore, it was designed to determine the relation, if any, among variability and the parameters utilised to define manual tasks. The variability was defined ideally in the experiment and human performance was quantified through three parameters: force of insertion, angles of insertion and trajectory. The framework was applied by a user different from the experiment's designer, to ensure an unbiased utilisation.

The industrial process was included to validate the framework outside of the laboratory, in real life conditions. The industrial process was selected by virtue of the documentation available regarding variability owing to its recent automation (one of the tasks in the process was automated by the company).

Finally, the framework was also contrasted through three different manual processes, to verify the convergence of the results obtained when applied by different people. The usability and robustness of the framework was tested, to corroborate whether or not the results obtained through the framework are similar regardless who is applying it. The selection of these three processes was based on the variability found in the process plus accessibility to people who have been studying the possibility of automating these processes.

The framework was also applied to the two process studies described in Chapters 4 and 5 and can be consulted in Appendix 9.

7.1 Experiment

Although inserting a peg into a hole is an assembly problem which does not present significant challenge to humans (Yun 2008), for an automated solution, if variability is found in the position of the hole, the peg or the clearance between peg and hole, the problem is challenging for automation. The experiment requires that subjects insert a peg into a hole, simulating a manual assembly process. The problem is well studied in the literature and involves different actions in the task: identify peg position, pick peg up, identify hole position, approach peg to hole, align peg and hole and finally apply the proper insertion force.

During the experiment, the insertion forces, peg trajectories and angles of insertion were measured. Ten subjects repeated the task (approaching, aligning and inserting) twice for each of the three pegs. The sampling technique was stratified, meaning that only subjects from one stratum were chosen (between 26 and 30 years of age, male and with no experience of the task), in an attempt to minimise the impact of physical human variability of the sample. The experiment was carried out in the EPSRC Centre for Innovative Manufacturing in Intelligent Automation, on two consecutive days, 1st and 2nd July 2015, starting at 14:50 and 14:30 respectively. The subjects were observed using a non-participant, direct, overt and structured observation and written consent was obtained from subjects to comply with regulations at Loughborough University. This type of observation is described and justified in Section 3.2 above. In addition, the experiment was video recorded for a more detailed observation afterwards.

Finally, interviews were carried out after the observation process. The interviews were semi-structured, combining closed and open questions. An elaborated description can be found in section 3.3 and the full interviews can be consulted in Appendix 4.

Objectives

The main objective of the experiment was to validate the applicability and robustness of the framework. Access to real industrial processes is limited and it is very difficult to obtain permission to collect data in industrial environments. The experiment therefore, replicates a manual process in controlled conditions which provides all the data that otherwise would be problematic to collect. The experiment was used to test the framework and help in refining the framework if necessary.

In addition, the experiment provided information regarding the relationships, if any, between sources of variability (inputs in this case) and strategies followed by the subjects. Firstly, the experiment was design to determine any relationship between trajectories and inputs (weight of pegs). A relationship between trajectories and weights would mean that subjects used different alternatives to solve variability in inputs (parts in this case). Secondly, the relationships between clearance (source of variability in inputs) and force of insertion (strategy) were determined. In addition, the measure of force of insertion would determine if any special physical force was required to perform the task of insertion. Thirdly, relationships between clearance (inputs) and angles of insertion (strategy) were determined, to prove whether or not three alternatives (angles of insertion) were used to overcome the source of variability (clearance).

Finally, the level of automation suggested by the framework was expected to be high/considerable from experience and literature (Chhatpar & Branicky 2001). The framework recommendation will be compared to this known level.

Components and experimental setup

The pegs had a cylindrical shape. Two were made of aluminium, weighing 42 g each, and the third was made of stainless steel weighing 122 g. Figure 7-1 shows a 3D drawing of the component with the tracking markers used to track trajectory.

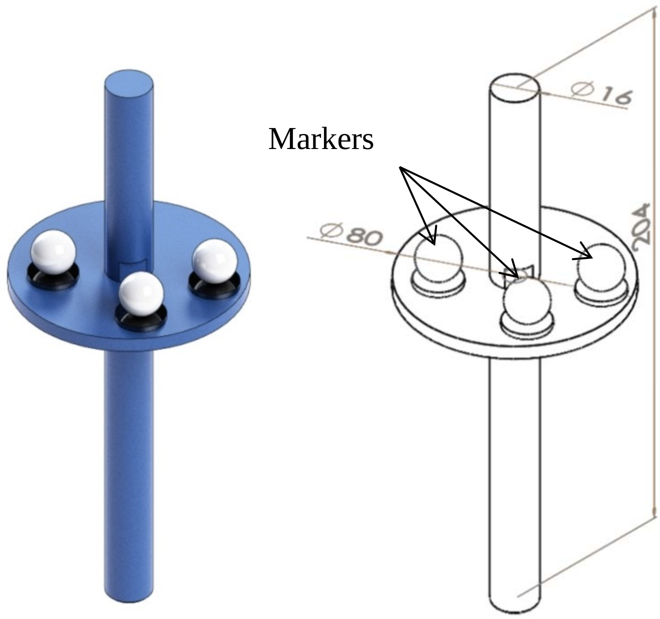


Figure 7-1. Peg 3D drawings (dimensions in mm)

Table 7-1 shows diameters, weights and materials of the three pegs. The main dimensions are in millimetres.

Table 7-1. Peg diameters, weights and materials

	Diameter (mm)	Weight (g)	Material
Peg 1	15.90±0.01	42±0.5	Aluminium
Peg 2	15.95±0.01	42±0.5	Aluminium
Peg 3	15.99±0.01	122±0.5	Steel

The component with a hole has a conical shape, weighed 358 g and was made of the same aluminium as two of the pegs. Figure 7-2 shows a 3D drawing of the component with main dimensions in millimetres. The hole has a diameter of 16.00±0.01 mm

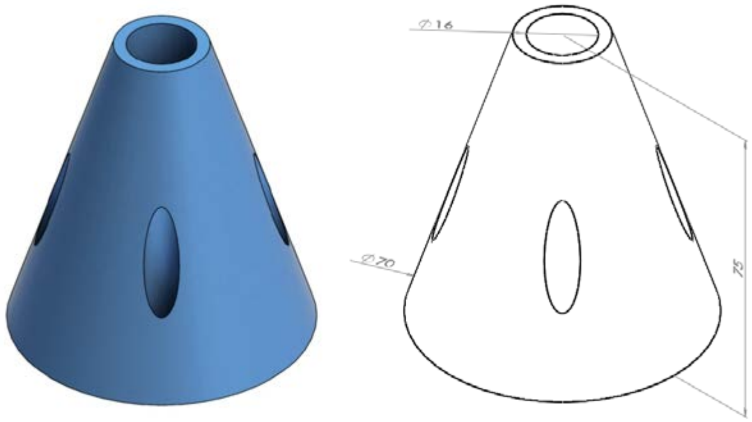
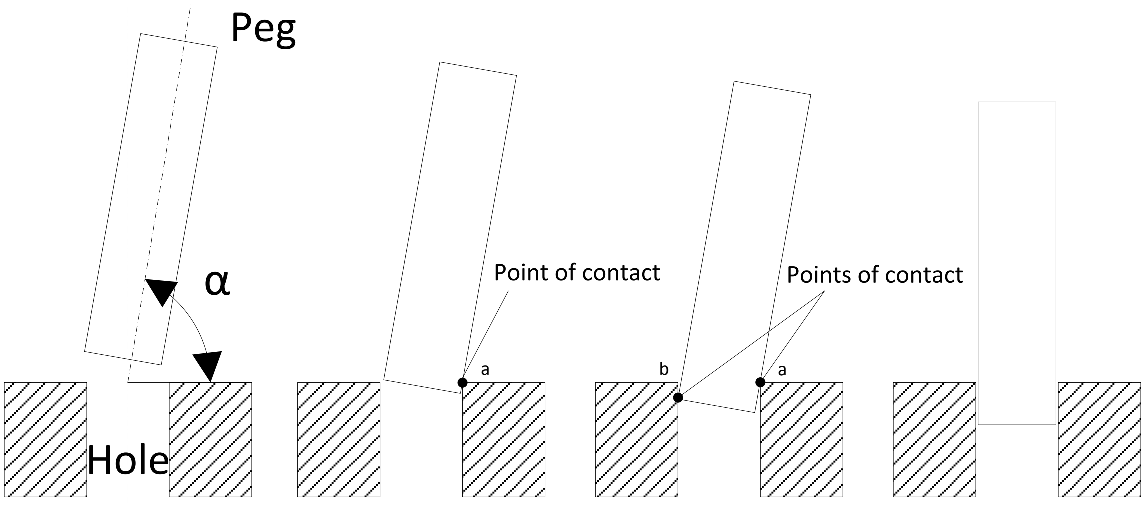


Figure 7-2. Component simulating hole to be rigidly fixed on table using 4xM10 bolts

The stages of mating pegs and holes can differ. In the case where the hole has no chamfer the stages are: approach, first contact, two-point contact and line contact (Whitney 2004). If the hole had a chamfer, there would be an additional stage between approach and first contact, called "chamfer crossing". Figure 7-3 shows the stages for non-chamfered holes.



(a) Approach **(b) First point contact** **(c) Two-point contact** **(d) Line contact**

Figure 7-3. Stages in mating pegs and holes, alpha is the angle of approach

The experiment was carried out in a 4m x 2.5m cell. The cell contained: a PC with two screens and a keyboard, two Vicon "Bonita" cameras, a torque and force sensor, a video camera, a table and the components. The components were placed on the table. The hole-component was fixed to the table and the pegs were place randomly but always in the same area of the table top right-hand edge (looking form subject's position). Figure 7-4 shows the set-up of the experiment in the cell as well as the position of the subject.

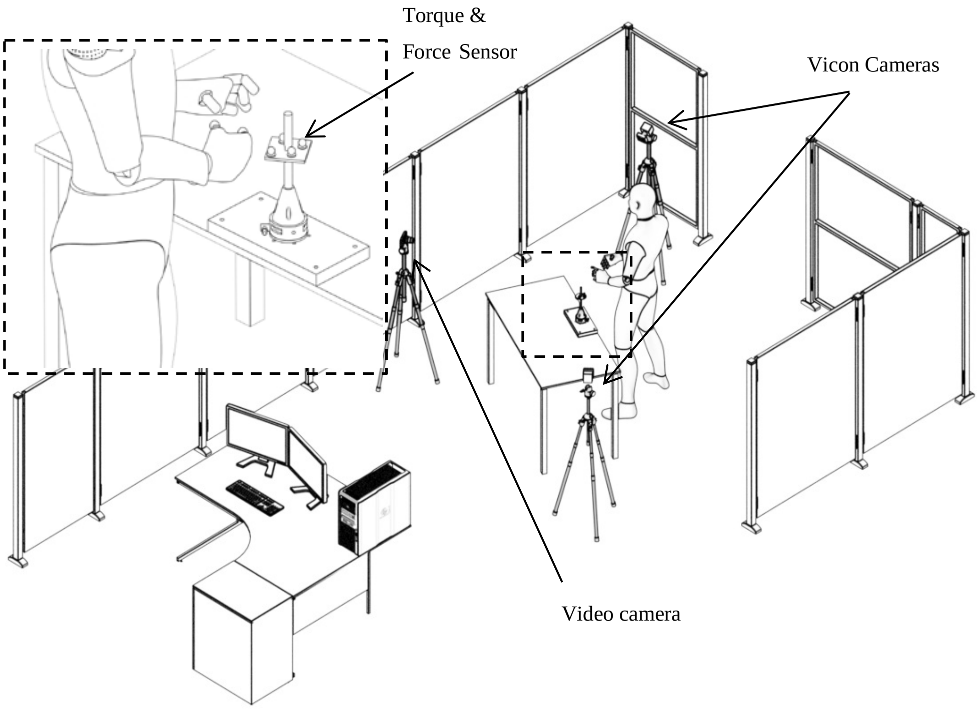


Figure 7-4. Peg in a hole experiment cell set-up

Data collection

a) Trajectories

Trajectories of the movement of the peg from initial position to insertion were tracked. For each peg, two tests were performed by each individual so a total of twenty trajectories were recorded per peg. Trajectories were fitted to a surface using Matlab©. Goodness of fit is represented by coefficient of determination, R-squared.

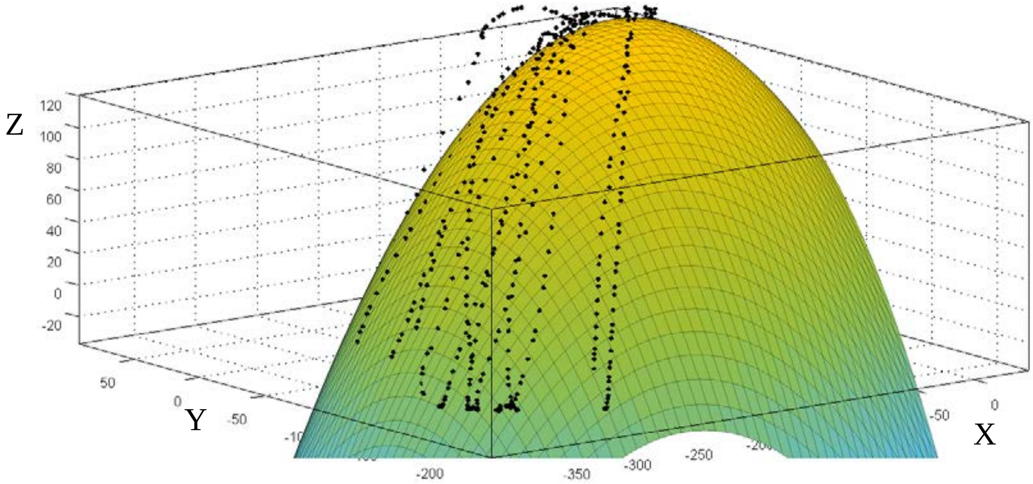
R-squared measures how successful the fit is in explaining the variation of the data. R-squared can take on any value between 0 and 1. For example, an R-squared value of 0.7934 means that the fit explains 79.34% of the total variation in the data about the mean.

Table 7-2 shows the quadratic polynomial equations of the fitted surfaces for each peg and their "goodness of fit" represented by R-squared and adjusted R-squared values. Increasing the order of the polynomial equations grade did not improve the "goodness of fit" substantially, and therefore a second order function was chosen.

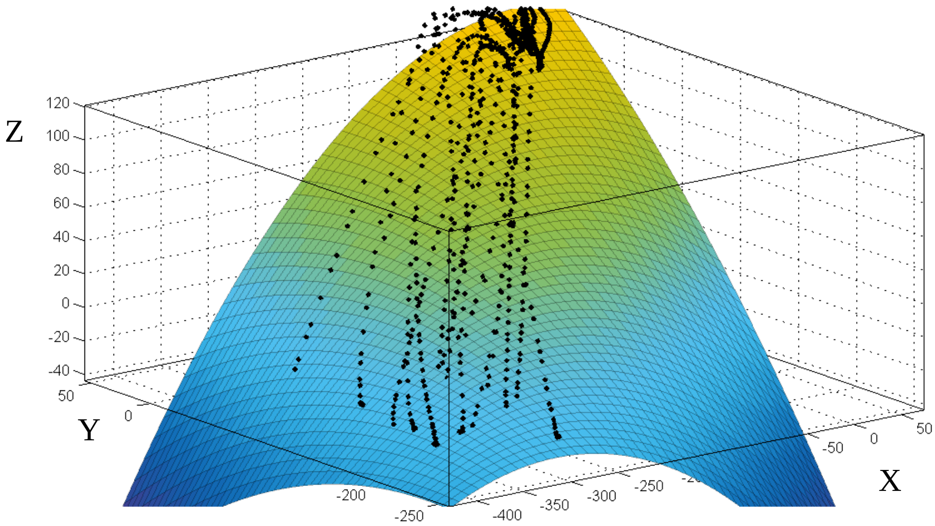
Table 7-2. Equations of fitted surface for Pegs

	Surface Equation	R-squared
Peg1	$F_1(x, y) = 126.2 + 79.17x + 17.87y - 78.99x^2 + 76.72xy - 74.21y^2$	0.9974
Peg2	$F_2(x, y) = 31.02 + 28.18x + 25.89y - 29.18x^2 + 43.66xy - 13.94y^2$	0.9959
Peg3	$F_3(x, y) = -1.475 + 37.09x + 12.65y - 10.17x^2 + 23.63xy - 5.569y^2$	0.9959

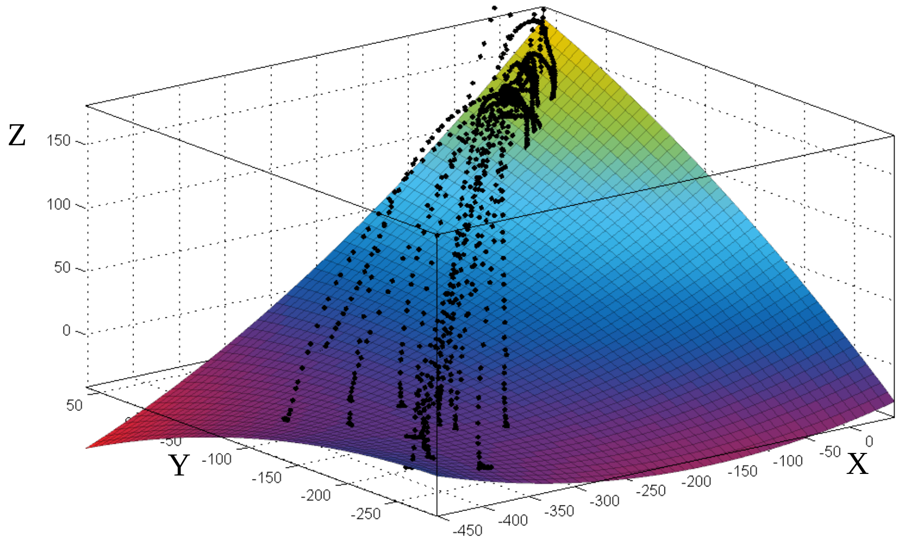
Figure 7-5 shows these surfaces graphically. (a), (b) and (c) display the fitting surfaces for Peg 1, Peg 2 and Peg 3 respectively and the point-clouds of trajectories.



a) Fitted curve for Peg 1



b) Fitted curve for Peg 2



c) Fitted curve for Peg 3

Figure 7-5. Fitted curves for three pegs in millimetres

Trajectories can be parametrised with any software like Matlab© and can be used as base model for programming optimal trajectories to be followed by the automated solution.

b) Force of insertion

The forces of insertion for each peg were also analysed Figure 7-6 shows the averages of the maxima, minima and the force of insertion per peg.

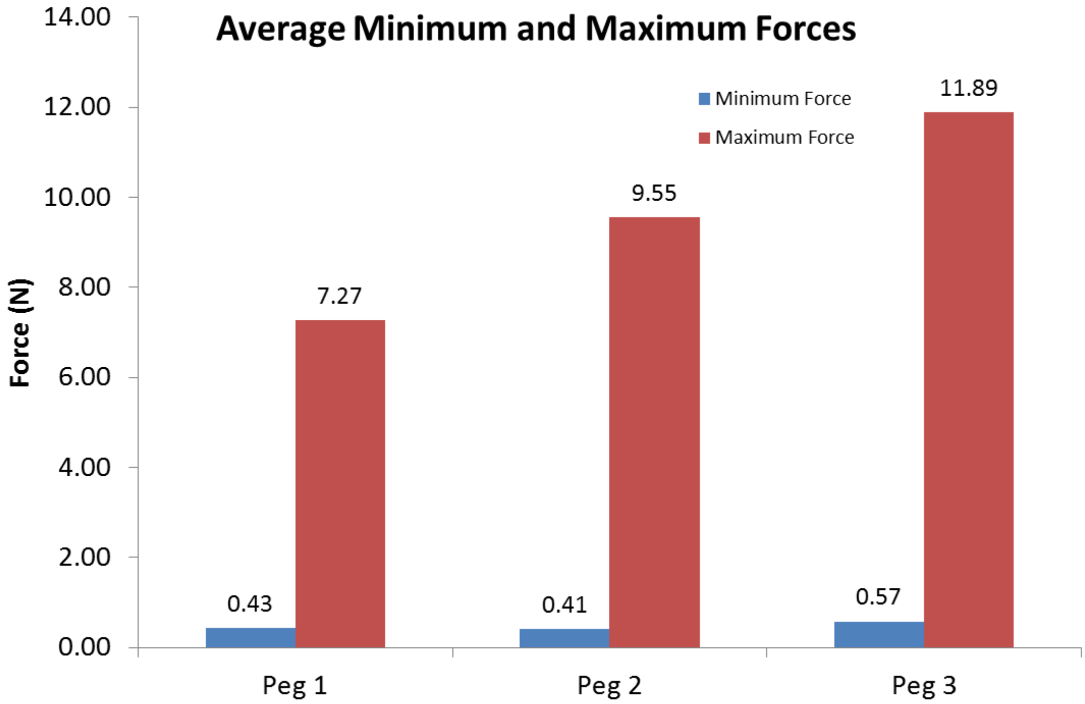


Figure 7-6. Forces of insertion per Peg

These values show that the average of the minima forces applied is slightly higher for peg 3 but they are similar for peg 1 and 2. Maxima forces behave as expected, presenting the highest value for peg 3 and the lowest for peg 1. The results also show that subjects applied higher force for tighter clearances as expected.

a) Angles of approach

Angles of approach were also measured. The angles of approach are defined in this experiment as the angles of rotation of the X, Y and Z axes with respect to the plane formed by YZ, XZ and XY respectively. These angles have been named as α, β and γ and they measure the rotation of the axis from the position X, Y, Z to the position X_1, Y_1 and Z_1 as can be seen graphically in Figure 7-7.

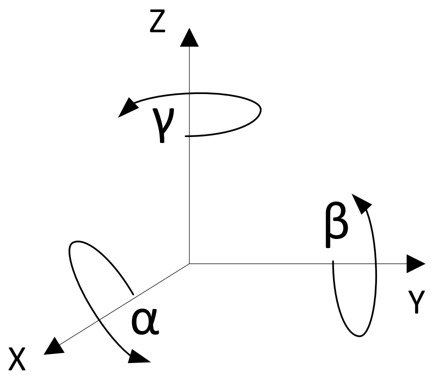


Figure 7-7. Rotation angles

The angle of axis Z (γ) is not displayed due to its null effect in the angle of approach problem, because rotation through axis Z does not correct peg inclination to align with the hole as its shape is circular. It would be different if the shape of the hole was polygonal as the rotation in Z would allow aligning the corners of the shape. Figure 7-8 shows an example of rotation with respect to axis Z when this rotation would be considered for insertion. The view is from a plane parallel to XY plane.

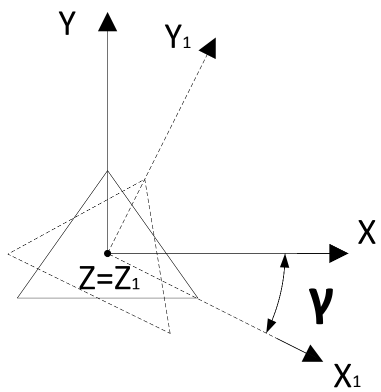
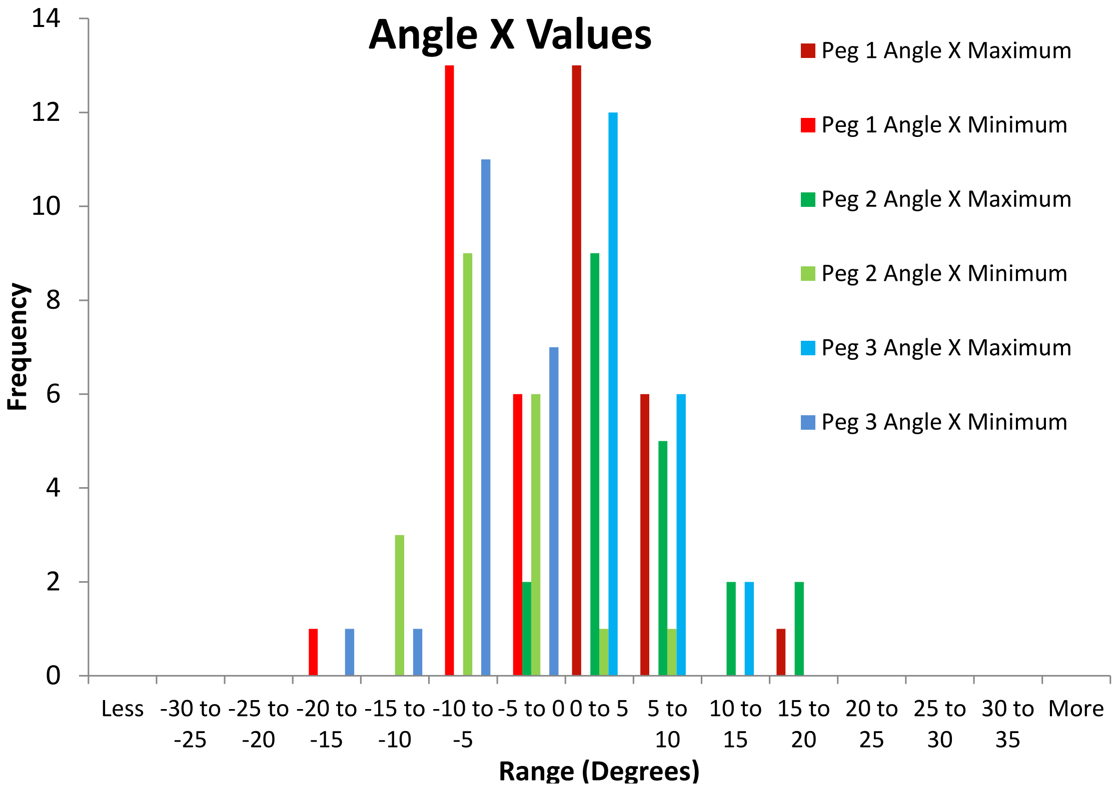
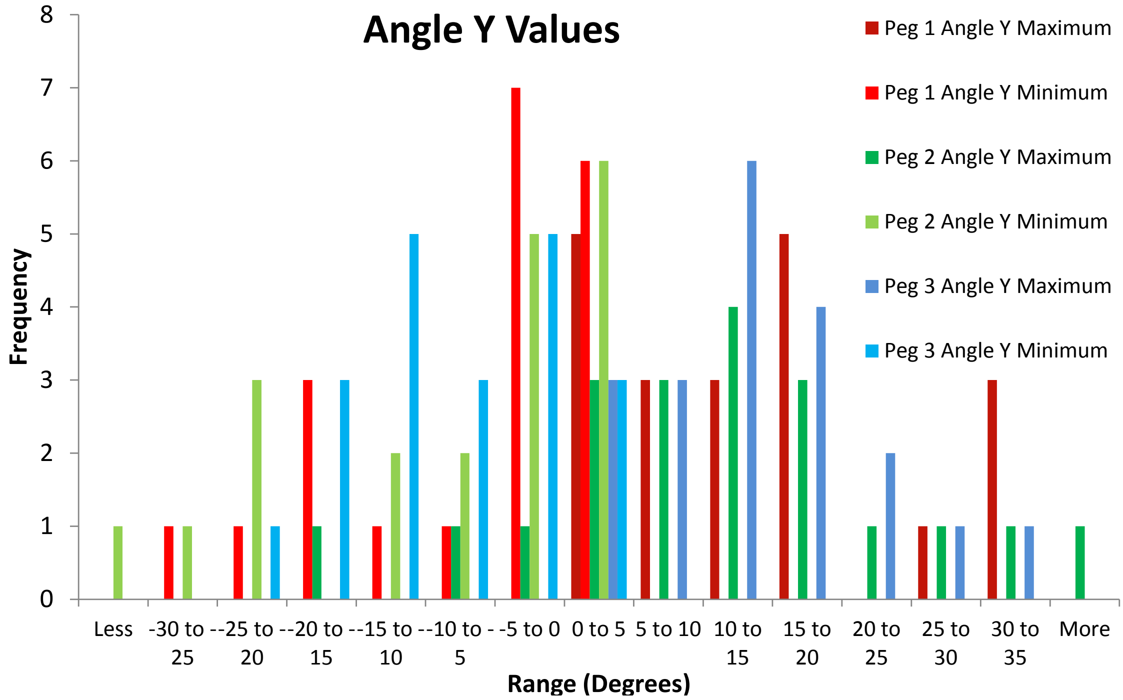


Figure 7-8. Rotation in Z axis

The results shown in Figure 7-9 are for the data obtained from 0.5 seconds before the first point of contact until contact is reached. After contact, the position of the peg is corrected to properly align with the hole, in order to complete the insertion. Figure 7-9 (a) count the number of maximum and minimum values of angles X falling into each band of degrees for the three pegs and (b) count the number of maximum and minimum values of angles Y falling into each band of degrees for the three pegs. Therefore, sixty values are represented per chart, two tests per subject. Raw data can be consulted in Appendix 5.



a) Histogram angles X



b) Histogram angles Y

Figure 7-9. Maximum and minimum Angles of insertion for Pegs

A high range of dispersion in the angles of approach was found which leads to the conclusion that:

- No common strategy is used by subject through different tests.
- No common strategy among subjects can be extracted from the experiment.

For Angle X, the histograms show a smaller dispersion, ranging from -20º to 20º for different pegs. For angle Y, the dispersion is bigger, ranging from -35º to 40º.

Lastly, Figure 7-10 represents the average of the maximum and minimum angles obtained from all subjects for Peg 1, Peg 2 and Peg 3. The results are analysed further for statistical significance in the next section.

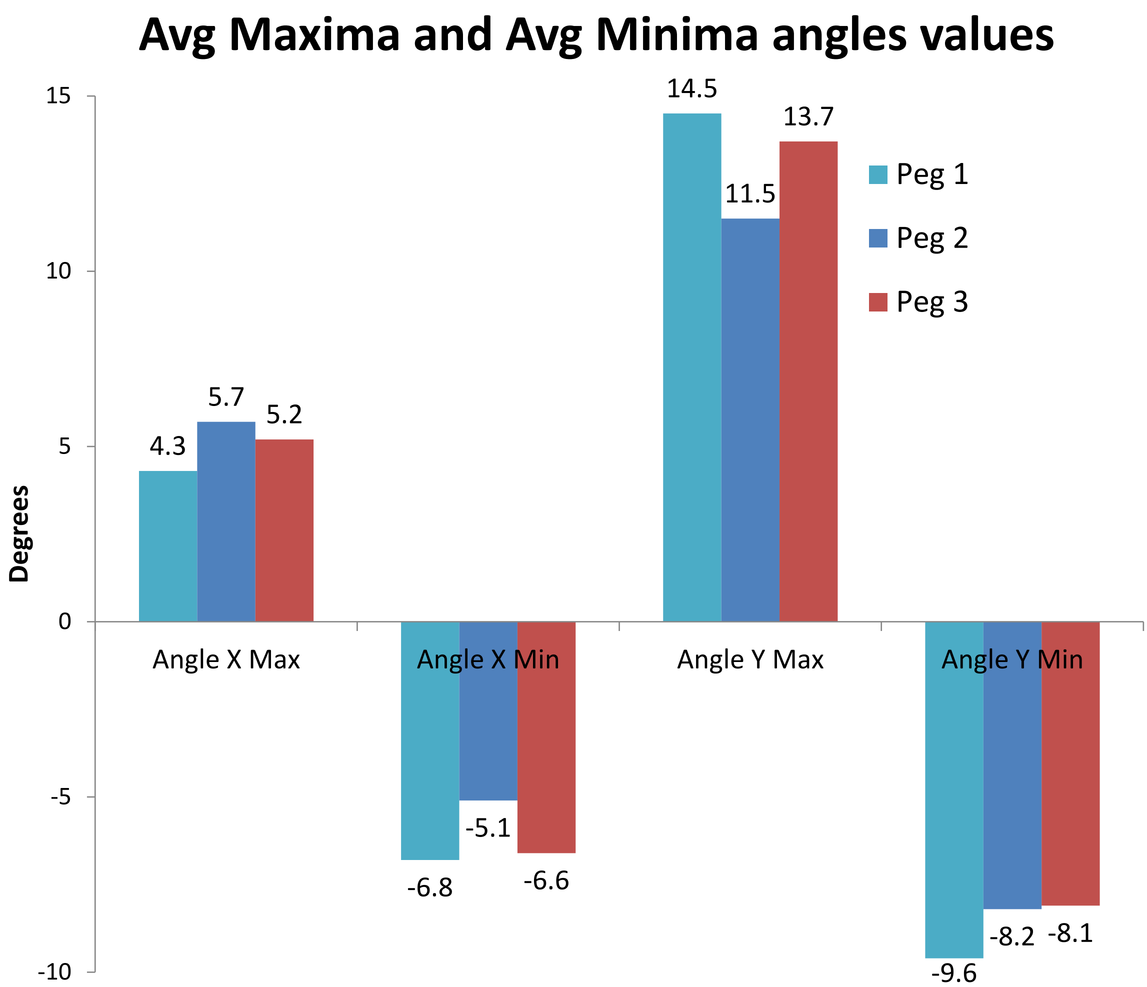


Figure 7-10. Average Angles for Peg 1, Peg 2 and Peg 3

Results analysis

A statistical analysis was conducted to determine if there was any correlation between angle of approach and insertion force. So far, a relationship between insertion force and variability in peg-hole clearance has been shown. However, it was not clear if there was a relationship between angles of approach and clearance. If a correlation between angles and insertion force were found, this would mean that angles of approach were correlated to clearances.

An analysis of variance (Anova) was conducted on *"angle X"*, *"angle Y"* and *"force of insertion"*. The results are shown in Table 7-3, (a), (b) and (c). Table 7-3 (a) shows values obtained when comparing variables *"angle X"* and *"angle Y"* with "force of insertion" in Peg 1 and (b) does the same comparison for Peg 2. Table 7-3 (c) shows values obtained when *"Angle X"* and *"Force of insertion"* are compared to *"Angle Y"* in Peg 3.

To interpret the results, “sum of squares” is the sum of squares due to each source, “d.f” is the degrees of freedom of each source, “mean squares” is the mean squares for each source (which is the ratio of sum of squares/degree of freedom), “F” is the *F*-statistic (which is the ratio of the mean squares) and “Prob>F” is the *p*-value (probability that the *F*-statistic can take a value larger than the computed test-statistic value).

For the purpose of this experiment, the important value was the “Prob>F” value, where the closer the value to 1 the highest the probability they were independent.

Table 7-3. Anova analysis for the peg in a hole experiment

Source	Sum of squares	d.f.	Mean Squares	F	Prob>F
Angle x Peg 1	1	5	0.19201	0.22	0.9541
Angle y Peg 1	0.3	5	0.05922	0.07	0.9968
Error	206.9	236	0.87650		

(a) Angle X & angle Y independency with respect to insertion force in Peg 1

Source	Sum of squares	d.f.	Mean Squares	F	Prob>F
Angle x Peg 2	0.0454	3	0.01512	0.03	0.9915
Angle y Peg 2	0.0048	1	0.00486	0.01	0.9169
Error	43.5	98	0.44411		

(b) Angle X & angle Y independency with respect to insertion force in Peg 2

Source	Sum of squares	d.f.	Mean Squares	F	Prob>F
Angle x Peg 3	12.2	67	0.18292	1.84e10	0
Force Peg 3	0	103	0	0	1
Error	0	1	0		

(c) Angle X & insertion force independency with respect to Angle Y in Peg 3

The results in Table 7-3 (a) and (b) proved that “force of insertion” was independent of the angles of approach. In addition, the results in Table 7-3 (c) revealed that angle X of approach is dependent from angle Y whereas force of insertion is independent from angle Y.

All the subjects were interviewed and a word map for the answers has been created. A word map is a graphic representation of the most repeated words in a text. It has been used because a word map is an easy way of visually understanding the words most used by subjects when answering the questions. Table 7-4 show these questions and the most repeated words in the answers, in brackets are the number of times each word is mentioned. The full interview can be consulted in Appendix 4.

Table 7-4. Questions and word maps of answers

Questions
Break this task down into less than six, but more than three steps
insert (10) pick (9) remove (5) align (4) initial (3) locate (3) position (2) reach (2) release (2) target (2)
Which require difficult cognitive skills
insertion (5) alignment (3)
Do you notice differences among parts? What is the most common?
dimensions (5) finishing (4) weight (3) colour (2)
How do you cope with these differences?
adjusting force (4) adjusting angle (2)
What do you control when you are performing the task
pressure applied (8) speed (6) **hole location (4)** insertion (3) angle(2)
What do you think are the main sources of variability?
Peg dimensions (4) position (3) weight (3) finish (2) initial (2)

The interviews showed that subjects were very good at finding the sources of variability, i.e. diameter (dimensions), weight, and position which are the most repeated words when asking about “main sources of variability”: peg dimensions (4), position (3) and weight (3) and when they were asked about “differences among parts”: dimensions (5), finishing (4) weight (3).

The actions performed were summarised in: **pick (9)**, **align (4)** and **insert (10)**, in line with expected sequence of actions in the task: identifying peg position, **pick peg up**, identifying hole position, approach peg to hole, **aligning peg and hole** and finally **applying the proper force of insertion**. Subjects recognised insertion (5) and alignment (3) as requiring cognitive skills. The most controlled variables according to subjects were: pressure applied (8), speed (6) and position (3) which can be interpreted as controlling force of insertion, speed of insertion and relative position between peg and hole.

The data showed that subjects adapted their force of insertion to variability (clearances and weights) but did not follow different trajectories or different angles of approach to adapt to variability.

The following results (Table 7-5) were obtained when applying the framework to the peg in a hole experiment.

Table 7-5. Results for experiment "peg in a hole"

Source of Variability	Parameter	Results	Comments
Output	Quantity	0	Considered all as "accepted component"
	Interval of variability	None	
	Diversification	0	Considered all as "accepted component"
	Interdependency	Not Applicable	
Inputs	Quantity	3	Diameter, Weight, Position
	Interval of variability	Delimited	Diameter: 15.9 to 15.99 mm Weight: 42g to 122g Position: any position in a $10cm^2$ area in the right top corner of the table
	Diversification	1	Peg (diameter, weight & position)
	Interdependency	Independent	
Strategy	Number of alternatives	1	No evidence were collected of different strategies among subjects
	Number of actions	2	Identify peg position Apply the proper force of insertion
	Patterned actions	No pattern	No actions patterned in one episode
Time	Sequentiality	Sequence	
	Restriction	Sufficient	
Requirements	Sensorial	2	Vision & Tactile
	Cognitive requisite	Yes	Force must be increased with tightness in insertion
	Physical prerequisite	No	No special physical prerequisite needed

The sources of variability in the inputs are diameter of the peg, weight of the peg and position of the peg with respect to the hole. These sources of variability are independent. The interval of variability of these sources is known. One alternative have been considered due to no significant differences were found in the trajectories, angles of approach or forces of insertion. No patterned actions were found as only two actions were executed to solve variability in the task: locate (peg) and insert (peg) which was corroborated by results in the experiment (alignment was independent from variability but force of insertion was adapted to clearance and the location of the peg differs slightly during the experiment). Position is managed first and afterwards diameter and weight. Time available is enough as there is no cycle time restriction. Finally the operators rely on their visual and tactile sense to locate the peg and apply the proper insertion force, requiring cognitive requisites to apply the correct insertion force but there are no special physical requisites.

Based on the weightings and values in Table 6-8 (column “average”) and values in Table 7-5, the level of automation recommended is **considerable** for this task. The suggested level of automation is aligned with the expected level of automation before commencing the experiment (Chhatpar & Branicky 2001).

7.2 Industrial MIG Welding process

An industrial case study was introduced to prove applicability and robustness of the framework. The process consisted of preparing, positioning and welding three components. The welding integrity will also be checked and components may be reworked if necessary. In the company, all these tasks were originally performed manually. The semi-automated solution was implemented in 2013, where the welding was automated but the preparation and positioning were still manually performed.

This process was selected owing to its unique status, considering that the manual and the automated processes coexist and can be compared. It is also important to mention that, because the process was semi-automated, the variability in the manual tasks (preparation and positioning) will be evaluated through the framework. The company is interested in evaluating the possibility of automating the manual tasks. Through the framework, a level of automation for these tasks will be suggested and discussed.

Process and component description

The product manufactured is a metallic product, composed of three metallic components: two halves and a pipe, the two halves have a complex shape. These two halves are placed in two fixtures and tightened, bringing both halves together to be welded. These components only need to comply with the process requirements as they will be disposed of afterwards. These requirements are overhang width, geometrical shape of chamfers and a constant gap between the two halves. The *final product* must be completely hermetically sealed when the welding is finished and a leaking test is performed for every *final product* to check for air tightness. The semi-automated as well as the manual welding processes were comprised of five tasks: preparation 1, positioning 1, preparation 2, positioning 2 and welding.

In the semi-automated process, preparation 1 consisted of unloading and assessing the *part* welded in previous cycle, and checking and cleaning fixtures for positioning. Positioning 1 comprised loading and adjusting the position of the components in the fixtures and clamping fixtures. Preparation 2 is where edges are trimmed to a constant overhang of 12 mm, planished[1] and chamfered at the corners. A constant gap between the two halves of 0.2 mm has to be maintained and finally, burrs need to be removed and overall *part* condition assessed before the welding. Positioning 2 loaded and properly positions the *"bottom half component"* into the *"pipe welding fixture"*, loads the *"pipe"* and starts the auto-welding sequence. Lastly, welding includes two different welding operations: in the first, the *"pipe"* is welded to the *"bottom half component"*, creating a *"pipe-bottom half subassembly"* and in the second, a "*pipe-bottom half subassembly*" (welded in the previous process) and the "*top half component*" are welded to create a *"final product"*.

The manual process differs in some of the actions performed in preparation 1, positioning 1, preparation 2 and positioning 2. Welding task is performed manually (with MIG welding equipment). Table 7-6 shows these differences between manual and semi-automated processes. It also includes tools utilised for each action.

[1] **Planish** is a technique consisting of finishing a metal surface by finely shaping with a hammer or slapper file

Table 7-6. Task and actions in the MIG welding process.

Tasks	Actions	Automated	Manual	Tools
Preparation 1	Enter cell.	✓	✗	
	Unload welded final product assembly.	✓	✓	
	Visually assess final product weld.	✓	✓	
	Endorse batch card	✓	✗	
	Check final product condition and cleanliness.	✓	✓	
	Check panel ID against batch card.	✓	✗	
	Check previous operations completed.	✓	✓	
	Check welding fixture condition.	✓	✓	
	Clean welding fixture.	✓	✓	Wipe and Isopropanol
	Remove *"pipe-bottom half subassembly"* welded	✓	✓	
	Visual inspect *"pipe-bottom half subassembly"* weld	✓	✓	
Positioning 1	Load *"pipe-bottom half subassembly"* into *"bottom half fixture"*	✓	✓	
	Load *"component"* into *"pipe-bottom half subassembly"*	✓	✓	
	Load *"top half component"*	✓	✓	
	Position *"top half fixture"*	✓	✓	Lifting hoist
	Unhook lifting hoist and slide to home position	✓	✓	
	Clamp the two halves of the welding fixture	✓	✓	Pneumatic torque, socket wrench and bolts
Preparation 2	Trim final product edges	✓	✗	Trimming shears, trimming guides, manual tin snips and steel rule
	Planish final product edges at corners	✓	✗	Fixture blocks and hammer
	Tap out gaps between components	✓	✓	Hammer and slip gauges
	Visual assess components edge condition and remove burrs	✓	✗	
Positioning 2	Load *"bottom half component"* onto *"pipe welding fixture"*	✓	✓	
	Load *"pipe"*	✓	✓	
	Exit cell and engage interlocks	✓	✗	
	Start Auto-welding sequence	✓	✗	

Data collection

First, the sources of variability in the process were identified. In addition, the processes were observed, a non-participant, direct, overt and structured observation was conducted and written consent was obtained from operators to comply with regulations at Loughborough University. This type of observation was described and justified in Section 3.2.

Secondly, interviews were carried out after the observation process. These interviews were semi-structured, combining closed and open questions. A full description of these interviews can be found in Section 3.3. Questions were divided into groups: work experience, procedure and tools.

a) Observations

The manual process was observed during one day, for one hour and it was not video-recorded. One operator was observed completing a whole process. Observation started at 11:20 a.m. The semi-automated process was observed for two hours in one day and partially video-recorded by the company (six minutes in total). Two operators were observed for a whole cycle each, i.e. preparation 1, positioning 1, preparation 2, positioning 2 and automated welding. Observations started at 11 a.m.

Operators followed SOP and trimming overhang was observed to be difficult in the semi-automated process as the fixtures have two reinforcement pillars interfering with trimming, and the areas behind the pillar must be trimmed manually. In addition, it was observed that corners have to be chamfered in the semi-automated process but not in the manual one, corroborating what was indicated by managers in order for automated welding to be successfully completed. Finally, it was also observed that there was a more conscientious adjustment of the gap between the two halves in the semi-automated as pointed out by the managers and operators interviewed.

Observations confirmed those notes from managers and operators; positioning and preparation tasks are less meticulously performed for manual welding due to the higher flexibility of operators with respect to the automated welding solution.

b) Interviews

In the first meeting held, the managers showed the manual process and responded to questions about it. According to the managers, the process has variability in: dimensions of parts, position on fixture, overhang for welding, gap, material thickness and chamfer shape.

It was not possible to interview those operators working on the manual process. Two operators working on the semi-automated process were interviewed, they completed a cycle each and then they were interviewed. The questions and answers are summarised in Table 7-7.

Table 7-7. Questions and answers from operators working in semi-automated welding process

Question	***Operator 1***	***Operator 2***
Think about what you do during the process. Can you break this process down into less than six, but more than three tasks?	Pipe, assembling, final product & component, trimming final product, blocking certain areas in the final product, check & repair	Bring parts, loading & positioning, trimming, weld preparation and leak check
Of the tasks you have just identified which require difficult cognitive skills?	Understanding the cell when is wrong. Some preparation process have to match automated process	Trimming and weld preparation
Years working in the company?	35	10
Years working with this process?	1.5[2]	2[2]
Do you notice differences between components? What is the most common?	Yes. Shape in the components	Yes, shape and bend
How do you cope with these differences?	Welding and reworking	I don't
What does the cell control when welding?	One edge of the halves	Weld speed, feed, amperage, tracking beam (only certain points)
How many different tools are used in the process?	Hammer, blocking tool, torque gun	Torque gun, crane, snips, setting blocks, hammer and filled
Do you notice any difference among tools or equipment?	Yes. Torque gun and trimming snips	I don't know
Is tools' condition an issue for the job?	Yes	Yes, snips
Has the overhang to be more constant dimensionally than in the manual process?	Yes, because of the camera	Very accurate
Has the overhang to comply with any requirement?	Yes, it has to be 12 mm width	Yes, 12 mm
Has the gap to be more constant dimensionally than in the manual process?	Yes	Yes
Has the gap to comply with any requirement?	Yes. It has to be 1.5 mm maximum	Yes, 1.5 mm maximum
Do you check the torque applied?	Yes	Yes
How often is the dynamometric tool calibrated	3 months	3 months
How does the chamfer affect to the welding process?	It was created to keep position of the robot correctly	I don't know
Do you notice any external factor affecting the weld?	No	No
What do you think are the main sources of variability?	Components.	Final product, component's shape and operators
How do you think this variability could be reduced / eliminated?	I don't think it can be reduced	It cannot be reduced
How do you think your job could be improved?	I don't know	Right first time

[2] Operators helped in the testing and adjustment stages.

c) Outputs and right first time data

The company could not provide any data from the manual process because it was not monitored. The reason was that the *"final product"* was a sacrificial component, and so it is only checked for airtightness and, if the test finds any leak, the component is welded again in the re-work area. However, due to the recent implementation of the semi-automated process, the performance of the cell was monitored, providing number of outputs produced, number of "right first time" outputs and percentage of "right first time" over total. Figure 7-11 shows those trends graphically since the implementation of the process (week 1) until week 18. Those weeks not shown (weeks 5, 6, 7 and 10) were non-productive weeks; the reason why the cell did not operate during these weeks was not disclosed. The values have been omitted for confidentiality.

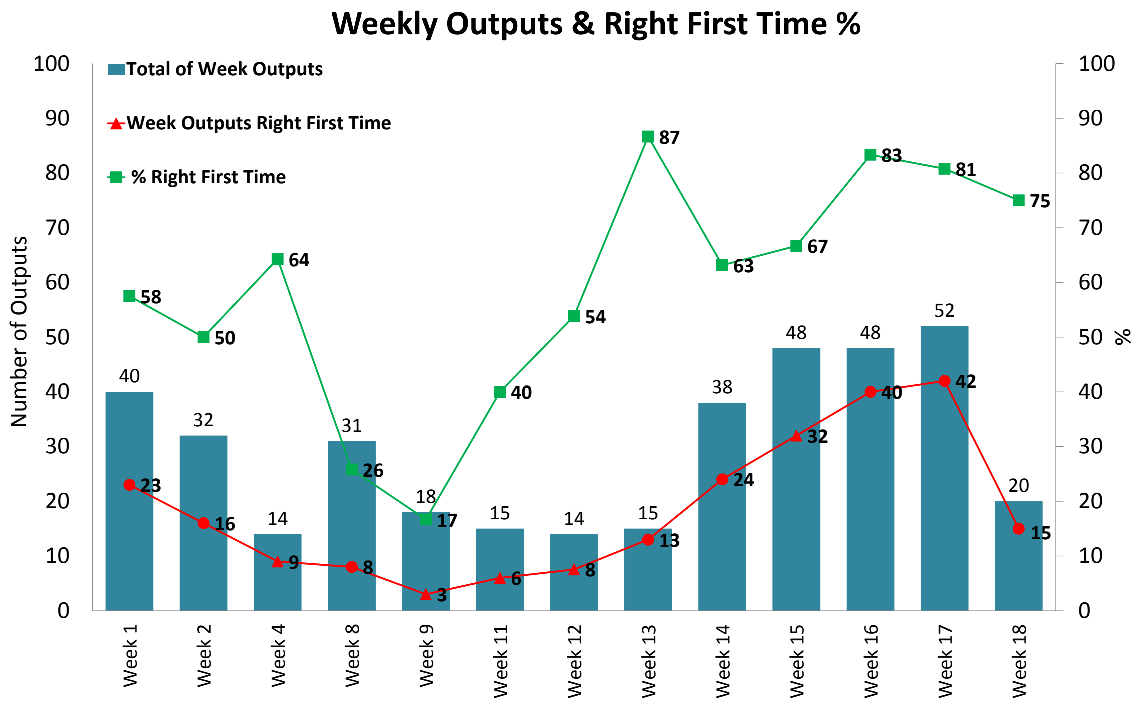


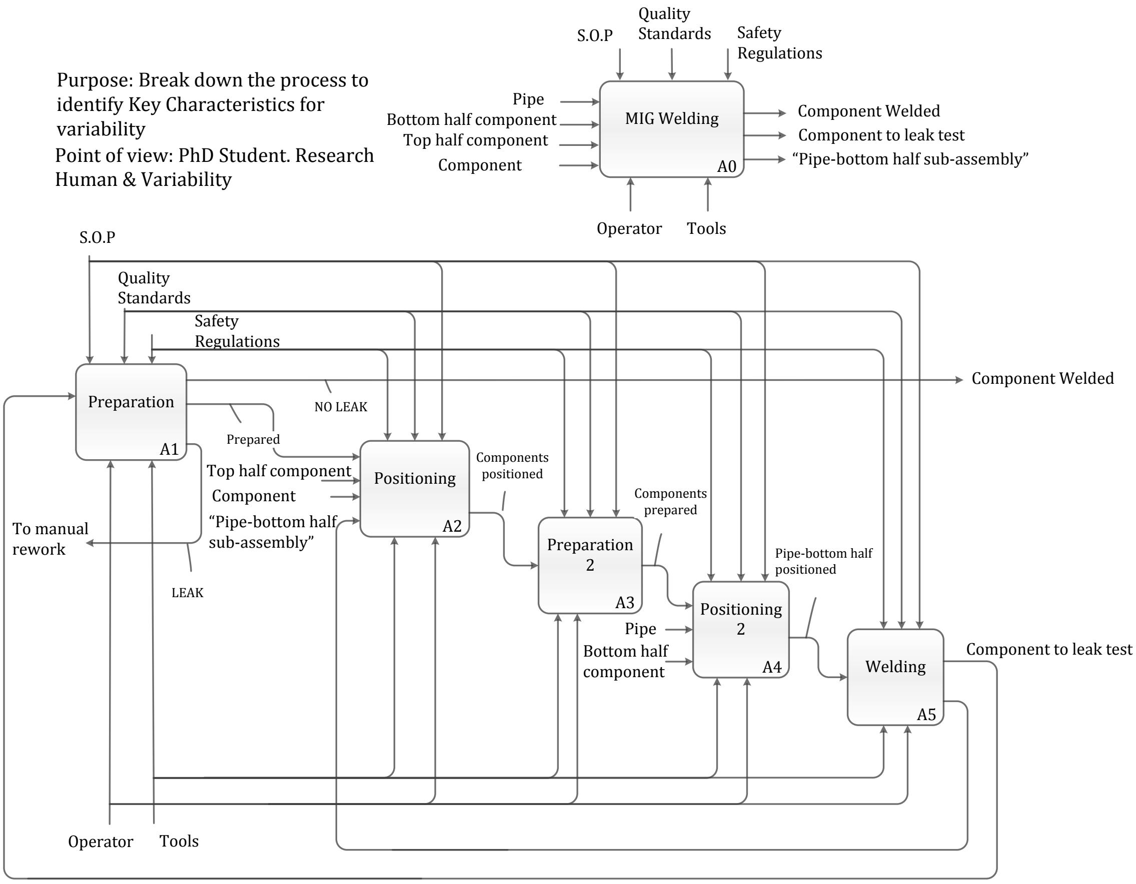
Figure 7-11. Weekly number of outputs

These numbers show inconsistency of outputs made right first time, although it seems there are an increase in "right first time" percentage in the last 6 weeks.

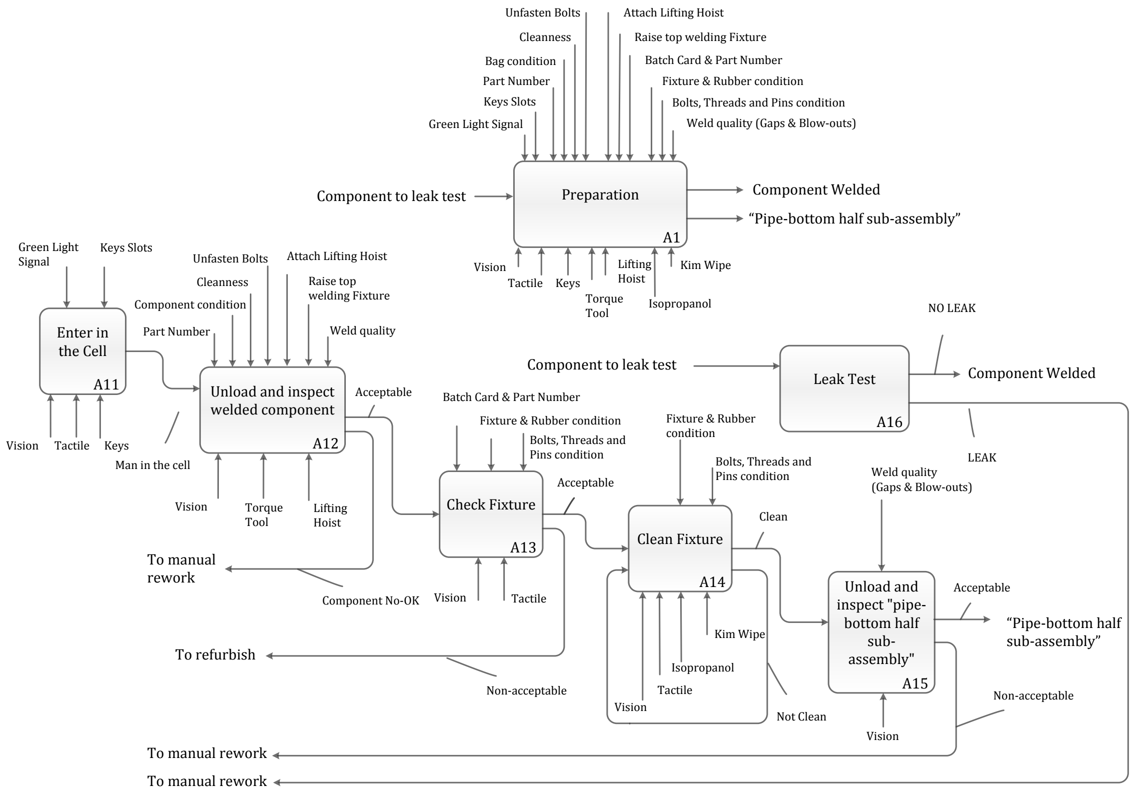
No information was available for the percentage of right first time for the manual cell, however, the percentage of "right first time" in the manual cell might be higher according to managers. This is because the operators can evaluate the characteristics of the weld and correct for them during the process.

Data analysis

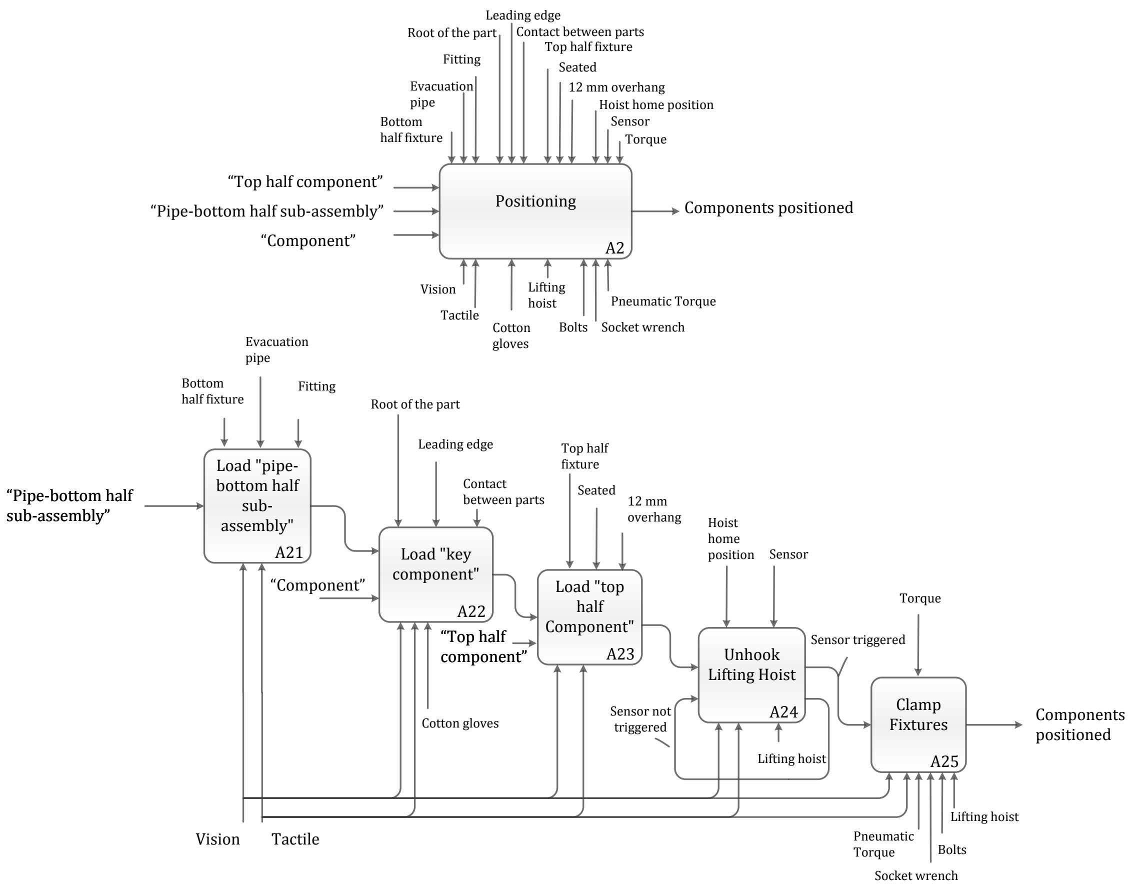
The MIG welding process has been represented using IDEF0. The diagram shows where variability is introduced and handled by operators. Figure 7-12 represents the semi-automated welding process: (a) represents the highest level of the process, also known as level A0 and (b) A1 level, (c) A2 level, (d) A3 and (e) A4 level diagrams are its children.



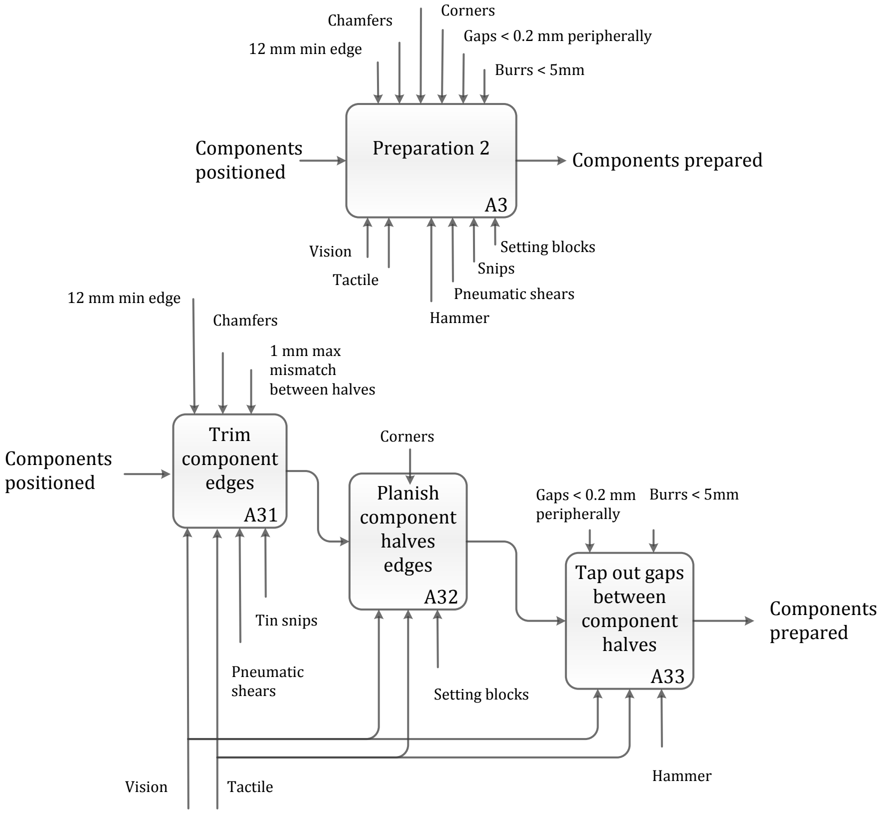
(a) IDEF0 Diagram from process. A0 Level



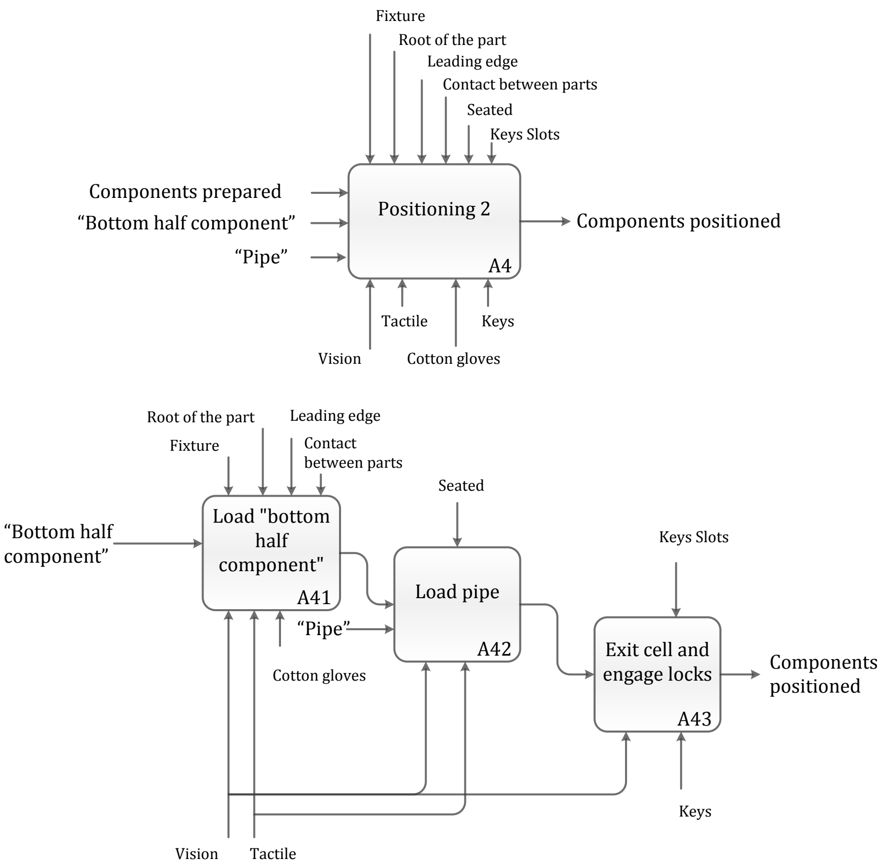
(b) IDEF0 Diagram from process. A1 Level



(c) IDEF0 Diagram from process. A2 Level



(d) IDEF0 Diagram from process. A3 Level



(e) IDEF0 Diagram from process. A4 Level

Figure 7-12. IDEF0 diagram for the semi-automated MIG welding process and its children

The Key Characteristics for variability within the process are shown in Figure 7-13.

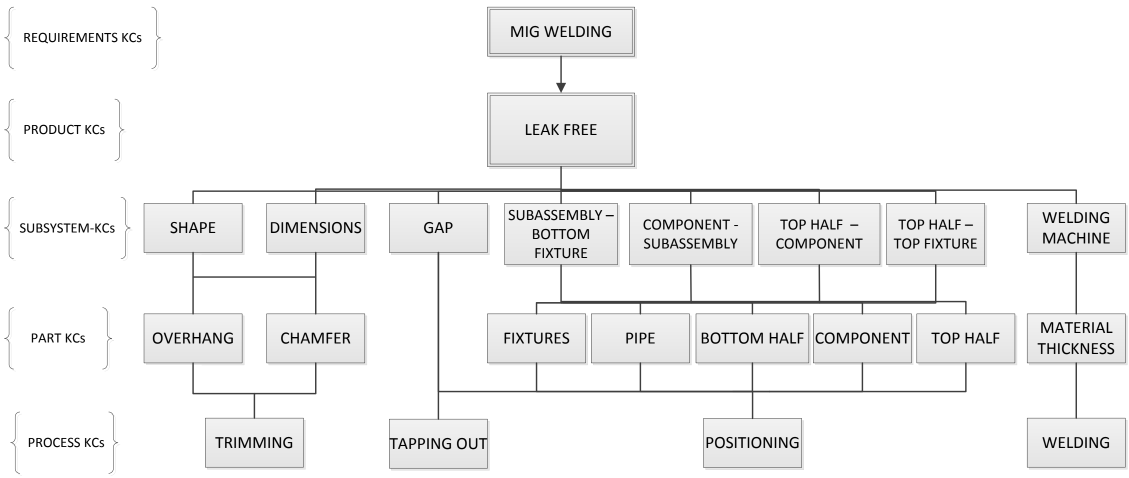


Figure 7-13. Key Characteristics for variability in semi-automated MIG Welding Process

Trimming is affected by the dimensions and shape of the two halves and by the operator executing it. A constant overhang of 12 mm and a mismatch between halves less than 1 mm must be left around the two halves and it has to be very precise as the scanner mounted in the automated solution takes the edge as the reference for welding. On the other hand, this overhang does not need to be as precise for manual welding as operators adapt the weld beam to the edge constantly. In addition, chamfers are affected by the shape of two halves and the operators' dexterity. Setting blocks and manual snips are used to trim the corners around the periphery of the two halves. This is a critical operation in the automated welding as the solution cannot weld right angles. However, for the manual process, chamfering is not needed as operators are able to weld right angles.

The gap was found to be another source of variability. The gap is affected by the torque applied, which was not disclosed, but a C_{pk} value of 1.33 was given for torque. C_{pk} is the "Process Capability Index" and measures the process performance for 6 sigma where C_{pk} = 1.33 means that 63 times out of a 1000000 the torque applied is out of specifications. Tapping is related to positioning as a good position of the components will lead to an easier adjustment of the gap. For the automated solution, the gap must be kept to 0.2 mm throughout the perimeter meanwhile, in the manual process, as reported by operators, they are able to weld gaps bigger than 0.2 mm, although this could not be corroborated by observation.

Figure 7-14 shows graphically maximum mismatch and gap allowed.

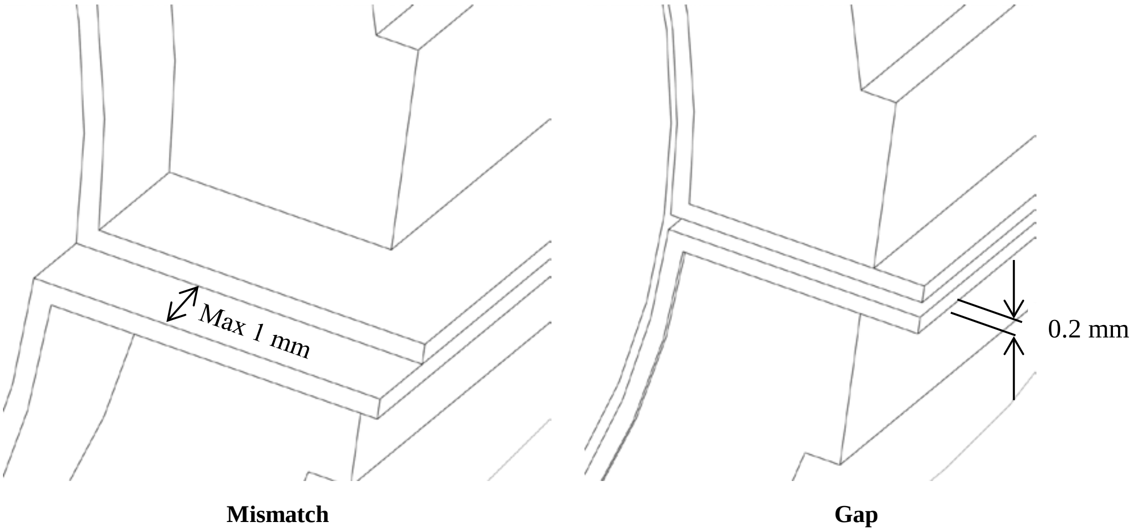


Figure 7-14. Maximum mismatch and gap values allowed

Positioning was affected by components (two halves, pipe and key component) and fixtures. New fixtures were provided for the semi-automated process which, according to managers, are better finished providing a finer and faster adjustment of fixtures and components. Proper positioning of the parts was identified by operators as requiring cognitive skills.

Welding parameters could be influenced by material thickness. Material thickness was identified by managers as one source of variability which could affect the characteristics of the weld, as the welding parameters were fixed and cannot be dynamically controlled.

After the previous analysis of collected data, the framework was applied. The results for preparation 1 task and welding tasks are shown in Table 7-8. The framework for positioning 1, preparation 2 and positioning 2 can be consulted in Appendix 6. Recall that welding is the only automated task in the process and the level of automation is high.

Table 7-8. Manual tasks in welding process: framework results and levels of automation recommended

PREPARATION 1			
Source of Variability	**Parameter**	**Results**	**Comments**
Outputs	Quantity	0	Thickness (not dealt in this task)
	Interval of variability	Not Applicable	Unknown but not dealt in this task
	Diversification	0	Pipe-bottom half subassembly
	Interdependency	Not Applicable	
Inputs	Quantity	0	Thickness (not dealt in this task)
	Interval of variability	Not Applicable	Unknown but not dealt in this task
	Diversification	0	Pipe-bottom half subassembly
	Interdependency	Not Applicable	
Strategy	Number of alternatives	2	Two operators working in the automated cell
	Number of actions	0	No variability is reduced/eliminated in the task
	Patterned actions	No pattern	
Time	Sequentiality	Not Applicable	Thickness is not managed in this task
	Restriction	Sufficient	
Requirements	Sensorial	2	Visual, tactile
	Cognitive requisite	No	
	Physical prerequisite	No	

WELDING			
Source of Variability	**Parameter**	**Results**	**Comments**
Outputs	Quantity	1	Leak
	Interval of variability	Delimited	
	Diversification	1	
	Interdependency	Not Applicable	
Inputs	Quantity	1	Thickness
	Interval of variability	Delimited	
	Diversification	2	Pipe-bottom half subassembly & top half part
	Interdependency	Not Applicable	
Strategy	Number of alternatives	1	Automated Task
	Number of actions	1	Welding perimeter
	Patterned actions	Not Applicable	
Time	Sequentiality	Not Applicable	
	Restriction	Sufficient	
Requirements	Sensorial	2	Visual, hearing
	Cognitive requisite	Yes	Follow edge to weld
	Physical prerequisite	No	

Table 7-9 show a summary of the levels of automation suggested for the four manual tasks of the semi-automatic MIG welding process.

Table 7-9. Summary of level of automation suggested for MIG welding process

Tasks	Level of Automation suggested
Preparation 1	High
Positioning 1	Moderate
Preparation 2	Moderate
Positioning 2	Moderate
Welding	High

The application of the framework to the five tasks of the semi-automatic welding process suggested a **high** level of automation for the welding task which corresponds to the level of automation implemented. The control of the variability through the previous tasks permitted to reach a high automation of the task.

The framework also suggested a **high** level of automation for the preparation 1 task which is reasonable taken into consideration that the actions to be performed are not dealing with variability, not requiring cognitive skills and there are enough time allocated to perform the task. Most of these actions are movements (enter cell, unload welded final assembly, remove “pipe-bottom half subassembly” welded, endorse batch card, clean welding fixture). If the task is to be automated, the action of “entering the cell” will not be needed anymore.

In the other three tasks, positioning 1, preparation 2 and positioning 2, a **moderate** level of automation is suggested due to the fact that unknown interval of variability in inputs (22.35% weight). Considering that interval of variability is available or may be obtained by the company, the level of automation suggested may be higher.

In addition, cognitive requisite has a high impact on level of automation (13.99% weight) therefore, leading to lower level of automation suggested. For example, in the positioning 1 task, the actions of positioning “pipe-bottom half subassembly”, “key component”, “top half component” requires cognitive skills. For the preparation 2 task, all actions “trim components edges”, “planish components edges at corners”, “tap out gaps between halves”, and “remove burrs” and “visually assess components edge condition” also required cognitive skills. Finally, the positioning 2 task, the actions of positioning “bottom half component” and “pipe” into fixture require cognitive skills and are dealing with variability.

The main challenge faced by the company when the welding task was automated was the need to reduce variability in gap and overhang and eliminate right angles. The gap of 0.2 mm has to be kept constant for the automated welding but not for manual welding –in manager’s words – *“in the automatic weld, this gap is critical while in the manual welding this gap can be adjusted when welding”* –. Similarly, the overhang must be 12 mm with a mismatch no greater than 1 mm and it is also critical for automated welding because the automated solution uses the edge as reference. The conditions in preparation and positioning in manual process are less strict than the ones for the automated welding, operators do not rely on the edge to weld and they can weld gap bigger than 0.2 mm. The solution was to change the SOP to specifically maintain a constant overhang and gap, to introduce new fixtures for better positioning and to eliminate right angles, introducing fixtures to trim corners to a chamfer shape.

After studying the process, it was noticed that variability in final outputs was not critical (but must achieve its function, i.e. no leakage) considering that the *final product* is sacrificial at the end of the manufacturing process. The process has five sources of variability: overhang, position on fixture, gap between halves, chamfers (only for automated process) and halves’ thickness. This variability is accommodated by operators in manual cells but, for the automated process, some of them were reduced to acceptable ranges that can be managed by the automated solution.

The four changes introduced to automate the welding task; new fixtures, constant 12 mm overhang, constant 0.2 mm gap and new corners shape brought longer cycle time for preparation and positioning tasks. As a consequence, although the process is faster given that operators can position and prepare in one cell while the other cell is welding automatically, these tasks are more time consuming in the automated cell that in the manual cells.

In this research, lower levels of automation have been suggested due to the fact that the intervals of variability were not disclosed. Nonetheless, the company might be able to delimit these intervals before pondering further automation. Secondly, although dimensions, position and gap are dependent, it was concluded that chamfer, overhang and thickness are independent which will favour lower levels of automation. Finally, positioning and preparation were identified as tasks requiring cognitive skills, consequently suggesting lower levels of automation. These parameters are the main contributors to equivocalness in variability and they should be properly addressed if full automation is implemented.

7.3 Framework Usability

In Sections 7.1 and 7.2, the framework has been applied to an experiment and an industrial manufacturing process. In this section, the robustness of the framework has been tested by comparing the outputs obtained by different people applying the framework. Three “processes” were chosen: grinding and polishing, “peg in a hole” experiment and MIG welding. These three processes have been previously described in this thesis (Chapter 4, Sections 7.1 and 7.2, respectively). The framework was applied to a selected task within the process by two different people, the researcher and a volunteer with substantial knowledge about the process. The volunteers were:

- Grinding and polishing. A PhD student who visited the company and studied the process for automation purposes.
- Peg in a hole experiment. A PhD student who knew about the experiment as he used it for automation purposes.
- MIG welding. A Research Engineer who visited the company and is researching adaptive automation of welding processes.

The subjects received written instructions on how to use the framework. Instructions can be found in Appendix 7. No extra information was provided about the process as the objective was to test the framework without any external influence other than their understanding of the process and tasks through their experience and points of view.

Grinding and polishing process

As mentioned in Chapter 4, the grinding process is an industrial process carried out by skilled and experienced operators. After applying the framework only to the “set up” task in grinding process (A1 in Figure 6-5), the outcomes for both individuals are shown in Table 7-10.

Table 7-10. Framework comparative different subjects in "set up" task

Source of Variability	Parameters	Results	
		Volunteer 1	**Researcher**
Output	Quantity	2	2
	Interval of variability	Unknown	Unknown
	Diversification	1	1
	Interdependency	Independent	Independent
Inputs	Quantity	2	2
	Interval of variability	Unknown	Unknown
	Diversification	1	1
	Interdependency	Independent	Independent
Strategy	Number of alternatives	**1**	**3**
	Number of actions	**2**	**3**
	Patterned actions	Some actions repeated	Some actions patterned
Time	Sequentiality	Concurrently	Concurrently
	Restriction	Sufficient	Sufficient
Requirements	Sensorial	2	2
	Cognitive requisite	Yes	Yes
	Physical prerequisite	Yes	No

It can be seen that both subjects reached same results for most of the parameters. Discrepancies are encountered in the number of alternatives and the number of actions. Table 7-11 shows the comments for two parameters.

Table 7-11. Comments in divergent parameters

Parameter	Comments	
	Volunteer 1	**Researcher**
Number of alternatives	Operator follows SOP (techniques may vary from operator to operator) and focus only where finishing is needed	2 Operators with slightly different ways to proceed
Number of actions	1) inspect the tool, 2) shape only where required	Check tool condition, recondition tool, shape tool

Regarding the number of alternatives, although the subject distinguished only one path followed, in the comments he wrote "*Operator follows SOP (techniques may vary from operator to operator)*" meaning that he identified that different operators may follow different paths. In the researcher's response, three paths were noted, one path per operator (3 operators can process this component, see section 0 for details). Here, the discrepancy seems to come from different points of view of both subjects applying the framework.

Discrepancy in the number of actions could be attributed to consider recondition as a “shaping action” (volunteer) or not (researcher). This might open to a deeper debate but for this case, it is a different in the point of view.

Comments for all parameters can be consulted in Appendix 8.

Peg in a hole experiment

The results for both individuals are shown in Table 7-12. In this case, both subjects reached similar results for most of the parameters. The only disparity found was in the number of alternatives. The volunteer stated two different alternatives, substituting alternative by “paths” in the comments, giving the following explanation *“1) Pick & place* ***path*** *(rough motion, user dependent). 2) Insertion* ***path*** *(it’s constrained by environment)*”. Meanwhile, the researcher described one different “paths” as no evidence was found of different trajectories, angles of approach of force of insertion among subjects. This discrepancy is due to the interpretation given to the definition in the instructions. The instructions define the parameter as *“Number of alternatives refers to the number of different paths that can be applied to complete the group of tasks comprising the process. It is expected that different people may use different strategies to achieve the same goal. In a manufacturing process, as far as these alternatives lead to the achievement of same outputs, it is permitted”* and the volunteer interpreted it as quantity of different paths (literally) the trajectories can be split in; one “rough movement” from initial position to hole and “insertion path” which would be the final insertion trajectory, constrained by physical contact between peg and hole. However, the intended meaning for path in the instruction was “course or direction of action, conduct, or procedure”, not path as “route, course, or track along which something moves”. This ambiguity can be eliminated by defining the number of alternatives more accurately.

Table 7-12. Framework comparative different subjects in peg in a hole experiment

Source of Variability	Parameter	Results	
		Volunteer 2	Researcher
Output	Quantity	0	0
	Interval of variability	None	None
	Diversification	0	0
	Interdependency	Not Applicable	Not Applicable
Inputs	Quantity	3	3
	Interval of variability	Delimited	Delimited
	Diversification	1	1
	Interdependency	Independent	Independent
Strategy	Number of alternatives	**2**	**1**
	Number of actions	2	2
	Patterned actions	No pattern	No pattern
Time	Sequentiality	Sequence	Sequence
	Restriction	Sufficient	Sufficient
Requirements	Sensorial	2	2
	Cognitive requisite	Yes	Yes
	Physical prerequisite	No	No

Comments for all parameters can be consulted in Appendix 8.

MIG Welding process

The results for both individuals are shown in Table 7-13. The preparation 2 task was the one analysed.

Table 7-13. Framework comparative different subjects in MIG welding process

Source of Variability	Parameter	Results	
		Volunteer 3	**Researcher**
Output	Quantity	1	1
	Interval of variability	Unknown	Unknown
	Diversification	1	1
	Interdependency	Not Applicable	Not Applicable
Inputs	Quantity	2	2
	Interval of variability	Unknown	Unknown
	Diversification	2	2
	Interdependency	**Dependent Positive**	**Independent**
Strategy	Number of alternatives	2	2
	Number of actions	**2**	**2**
	Patterned actions	No pattern	No pattern
Time	Sequentiality	Sequence	Sequence
	Restriction	Sufficient	Sufficient
Requirements	Sensorial	2	2
	Cognitive requisite	Yes	Yes
	Physical prerequisite	No	No

Again, for both subjects, the results presented are similar with some disparities. These disparities are encountered in: *diversification* and *interdependency* (inputs). Comments are shown in Table 7-14 and explained afterwards.

Table 7-14. Comment for Welding process

Parameter	Comments	
	Volunteer 3	**Researcher**
Interdependency	Cutting force is affected by thickness and dimensions of the sample, Impact force and impact direction is affected by thickness and surface/edge quality	Position on Fixture is independent from thickness
Number of Actions	Double checking the alignment of samples Double checking the gap between the sheets	Load “bottom half component” onto “pipe welding fixture” Load “pipe”

In the case of interdependency, a possible interpretation of the discrepancy could be because the volunteer confused sources of variability with inputs. In effect, as the volunteer pointed out "cutting force is affected by thickness and dimensions of the halves, impact force and impact direction are affected by thickness and surface/edge quality" but again, these inputs were not identified by operators as being influenced by sources of variability.

In the case of number of actions although it is two in both cases, there are a discrepancy in the actions defined by each individual. This discrepancy might come from the definition of action. The two "actions" identified by the volunteer *"double check the alignment of halves and double check the gap between the halves"* are among the actions needed to complete the preparation and positioning tasks. For example, *"double check the alignment of halves"* describes position of the two halves and *"double check the gap between the halves"* is equal to *"Tap out gaps between components"* but these actions belong to other tasks in the process. The reason behind is the fact that the volunteer did not have the SOP.

A table with all comments is found in Appendix 8.

7.4 Discussion

The framework was applied to an experiment and an industry process study and, in addition, to the two process studies described in Chapters 4 and 5 (the outcomes can be consulted in Appendix 9. From the experiment, the sources of variability were characterised. However, in the three industrial processes studied, variability could not be delimited and therefore, it affected the level of automation suggested. This was a limitation for this research but, if this information is disclosed by the company, the interval of variability would be known and possibly a higher level of automation would have been suggested.

The other parameters related to inputs/outputs were easy to determine in all cases: quantity of sources of variability, interdependency of those sources and diversification (number of inputs/outputs affected). Moreover, it was also easy to assess those parameters related to time and requirements: sequentiality and restrictions as well as cognitive and physical requirements.

Regarding the parameters related to strategy, it was relatively easy to determine whether there are patterns of actions which can be grouped but the determination of the number of alternatives and the number of actions was more challenging. The number of alternatives needed careful observation of the processes studied and seems to be subjective to the observer. Regarding the number of actions, it was found difficult to discern which of the actions were executed to handle variability from those which were executed to achieve the final goal, i.e. transform inputs into outputs. The former actions are interesting from the point of view of handling the variability but all actions should be considered if the decision is to automate the process.

The results suggest that the framework is reasonably robust when applied by different subjects to various processes with 89.6% consistency. This was calculated by

$$\%\ Consistency = \frac{n_t - n_d}{n_t} * 100$$

Where n_t = Total number of parameters compared
Where n_d = Total number of discrepancies

Therefore, $\%\ Consistency = \frac{(16+16+16)-(2+2+1)}{(16+16+16)} * 100 = 89.6\%$

Disparities were found in two parameters of the *“preparation 2”* task, in the welding process evaluation, two in the *“set up”* task in the grinding process and one in the peg-in-a-hole task. These discrepancies were due to the different interpretations of the instructions given. The definitions given in the instructions were not refined because the results showed a high consistency in this first interaction. The instructions will be improved by defining the parameters unequivocally. Additionally, the framework was found effective when characterising variability present in the processes where it was applied.

However, the more in depth analysis made by the researcher including process decomposition, interviews and observations, allowed a more exhaustive study. This is why it is important that anyone applying the framework should carry out an in depth process analysis to fully capture all the information.

8. CONCLUSIONS AND FUTURE WORK

The aim of this research was to establish a framework to categorise variability in manufacturing processes to support the decision-making in the automation of processes. The results provided by the framework will support the decisions on allocating tasks between operators and machines, depending on variability. Variability is one of the main causes of lack of robustness in production processes and in general, increases the cost of automation. In the context of high value manufacturing, this variability is eliminated or reduced by experienced operators. These processes require a tacit knowledge which is difficult to transfer and therefore the training of new operators is difficult and time consuming. Moreover, the adeptness of these operators make them hard to replace and less flexible for working in other processes.

The research started with the study of two industrial processes. The analysis of these industrial cases allowed the identification of the sources of variability, the key characteristics for variability and, to a reasonable extent, an understanding of how variability is managed by operators. It also served to select those parameters to describe different aspects of variability which were used in the design of the framework.

The procedure comprised the collection of information about the process, the observation and interview of operators performing the process, the analysis of the process (when and where variability is introduced and the key characteristics of variability) and the application of the designed framework to determine the extent and limits of knowledge attained regarding variability within the process.

The framework was designed to better describe the variability embedded in manual manufacturing processes, categorising it through a set of parameters which provide additional information if the process is being considered for automation. These parameters were chosen from industrial process studies and in alignment with similar parameters used to model task complexity in the literature. The framework also delivers a guide for the level of automation which should be implemented depending on the level of knowledge acquired through the study of the process and the extent of the variability implicated.

The application of the framework by different users showed reasonable consistency in the results and its application to different processes reflected the capacity to describe variability effectively.

8.1 Discussions

The hypothesis in this thesis stated that variability in manufacturing processes can be characterised and this information might be used to support the decision of automating the process. The study of two manual manufacturing processes in addition to literature was used to create a framework with twelve parameters to characterise variability. Furthermore, the framework suggests a level of automation for each task performed to complete the process. This characterisation can be used prior to automation, providing information regarding variability embedded within the process. The framework was applied to three industrial processes, and the information obtained is being used to support deciding the level of automation.

This framework can be used in combination with other methods or frameworks to study manual processes which are being considered for automation. For example, Cognitive Task analysis (Militello & Hutton 2000; Schaafstal et al. 2000; Clark et al. 2008) used to extract human knowledge, Characterisation of Adaptive Solutions (Feigh et al. 2012) utilised to find key characteristics (triggers) to determine when to employ an adaptation, the duration of this adaptation, and when to cancel the adaptation or Ecological Interface Design (Burns & Hajdukiewicz 2004) which is a framework for the design of human-machine interfaces. Other research fields such as ergonomics, psychology, robotics (machine learning, quantum computing, internet of things) or material science, among others will contribute to the automation of those process which are difficult to automate.

8.2 Contributions to Knowledge

The novelty of this research lies in the establishment of a procedure to identify variability and the creation of a framework to categorise this variability in manufacturing processes. Moreover, to connect the study of variability to automation, the framework evaluates this variability, proposing a level of automation depending on the values the parameters take.

The main questions addressed in this research were: how can be the extent of the variability identified and how can this variability be characterised. This research has established a method where process variability can be identified through a well-defined process, including collection of relevant information, observation and interviews with operators performing the process, process decomposition and key characteristics for variability. The variability found can be characterised through the application of the framework at a task level, to determine whether or not the task should be automated and the level of this automation is suggested depending on the variability extent and knowledge.

The framework uses five attributes of tasks; inputs, outputs, strategy, time and requirements and twelve parameters (quantity, range or interval of variability, interdependency, diversification, number of alternatives, number of actions, patterned actions, concurrency, time restriction, sensorial domain, cognitive requisite and physical requisites) to categorise variability inherent in the task. The level of automation suggested is obtained through a system of scores and weights for each parameter. The weights were calculated using Analytical Hierarchical Process (AHP).

8.3 Implications

The framework may be applied by any person with a previous knowledge about the process and automation capabilities, and with a willingness to know more about variability involved in the tasks performed during the execution of the process. The study of variability and the application of the framework would be introduced in the planning stage of the project, before the requirements for the process are fully defined. The aim is a “right first time” automation solution, avoiding iterative refinement e.g. changing inputs specifications or redesigning previous processes.

The framework will characterise variability present in a task, to suggest a level of automation and therefore assisting in determining the suitability of the task to be automated, helping to find flexible and intelligent solutions capable of adapting and solving this variability. Some processes may involve semi-automated solutions where some tasks are performed by machines, other tasks by humans and others in a collaborative manner where automation aids operators. For example if it has been found that all the sources of variability present in a process are managed in two task (out of five) maybe the level of automation for this two tasks should be low, but the other three tasks in the process could be automated, heading to a semi-automated solution.

This research has not fully considered this human-machine collaboration. However, there are research taking place in this area including: system’s effectiveness, productivity, safety, ease of performance as well as optimizing the work load and enhancing the operators’ well-being and quality of life (Karwowski 2005; Nachreiner et al. 2006). Additionally, adaptive automation will deal with function allocation, responsibility and authority (human or machine) (Feigh et al. 2012). Although humans may not be responsible of a certain task, such autonomous action implementations have to assure safety (Inagaki 2006).

It is important to involve the operators in the design and implementation stages of the automated solutions. Successful automation will require interaction with operators during the development process (Kofman et al. 2009). Therefore, operators’ knowledge, feedback and implication in the project are fundamental for the acceptance and consummation of the solution.

In addition, operators’ motivation and morale can be influenced by the automated solution and its effectiveness. The motivational issue associated with supervisory control and the development of bad habits, through too much automation, has been recently identified as a crucial concern (Marras et al. 2010; Turner & Arif 2012). This is supported by (Monfared & Sharples 2011) who claimed in their study that a lack of control over tasks was the cause of dissatisfaction among subjects. Consequently, a balance between operators’ control and supervisory tasks and automation is needed.

8.4 Future work

Process studies

Although the information collected from the industrial collaborators during the study of the industrial processes was substantial there are some limitations due to confidentiality. For example, SOP and measurement data such as tool wear were not accessible in some cases.

It was a long process to arrange visits to the companies. The permissions for observing and video recording the processes were agreed but limited time was granted. More time observing would have allowed the observation of unusual situations as well as other operators. A continuous presence in the facilities for several days would have made the researcher into a familiar face and develop trust with the operators. In order to fully understand human strategies when dealing with variability in processes, it is critical to spend enough time observing their behaviours and be able to observe more than one operator and more than one shift.

Framework

The case studies were derived only from high-end manufacturing processes. The suitability of the framework in other manufacturing environments such as automotive, heavy machinery, electronics, etc. can be further studied. The special characteristics of the high end components industry, such as being safety critical and heavily regulated, make it different from other business where automated processes are more extensively implemented. However, it is envisaged that the application of the framework in other manufacturing environments should be possible. This affirmation should be corroborated by further investigation of additional processes.

The framework could be subjected to further improvement. As it is applied to new processes, it could potentially include other parameters to describe other variability Parameters not found in the processes analysed.

The framework could be extended to potentially automatable processes in other industries. The procedure used as well as the framework parameters do not present peculiarities which make them only applicable to high end components industry, therefore its application in processes in other industries would be the next natural step. This could reveal additional requirements and characteristics which are not present in the sources of variability in the analysed processes. Application of the framework in different processes and industries would strengthen it as well as extend its application field.

The framework could be complemented by a database with more process studies. Hence, the database would contain information from general to specific: industry, company, process, product, documentation, transcripts of interviews, process video-recordings, sources of variability identified and outcomes from the framework. This would help to classify processes and tasks by different categories and therefore, identify similarities and patterns. For example, two tasks could share same source of variability and that which was implemented successfully in a task could be applied to a different situation or at least, this information might be used as benchmark to make a better decision or to select a better solution.

This database would be open, inviting engineers from different industries to add new studies and consult those already submitted, eliminating any confidential reference to processes, to stimulate network externality of the database (network externality means that the more users the database has, the more valuable it becomes for other users, in the same way that mobile phone networks or social networks behave).

Finally, the database may also monitor all the processes studied, examining the long-term performance of the automated solutions implemented, the level of automation employed and tasks automated. In addition, it would encompass productivity ratios, breakdowns, cycle time, quality issues and inconsistencies generated by the new automated tasks. Furthermore, it might include operators' productivity and levels of satisfaction, motivation, responsibility and acceptance of their new roles.

PUBLICATIONS

This research has generated a list of publications that are numbered below:

Sanchez-Salas, A, Y.M Goh, and K Case. 2016. “A framework to support the decision of automation when dealing with variability in manufacturing processes” to be submitted.

Sanchez-Salas, A, Y.M Goh, and K Case. 2016. “Study of process variability in a manual finishing process” to be submitted.

Sanchez, A, Y.M Goh, and K Case. 2014. “Study of Humans coping with variability in a complex manual manufacturing process for automation purposes”. In the *III EPRSC Manufacturing the Future Conference*, Glasgow

Sanchez, A, S Mat, Y.M Goh, and K Case. 2013. “Human Variability, Task Complexity and Motivation Contribution in manufacturing.” In *The 11th International Conference on Manufacturing Research*, 325–331. Cranfield.

REFERENCES

Agah, A., 2000. Human interactions with intelligent systems: research taxonomy. *Computers & Electrical Engineering*, 27(1), pp.71–107.

Anon, 2015. deburr. *Oxford Dictionary*. Available at: http://www.oxforddictionaries.com/definition/english/deburr [Accessed August 10, 2015].

Antony, J., Hughes, M. & Kaye, M., 1999. Reducing manufacturing process variability using experimental design technique: a case study. *Integrated Manufacturing Systems*, 10(3), pp.162–170.

Apley, D.W. & Shi, J., 2001. A Factor-Analysis Method for Diagnosing Variability in Mulitvariate Manufacturing Processes. *Technometrics*, 43(1), pp.84–95.

Asare, S.. & McDaniel, L.., 1996. The effects of familiarity with the preparer and task complexity on the effectiveness of the audit review process. *Accounting Review*, 71(2), pp.139–159.

Association, I.E., 2016. Ergonomics. *International Ergonomics Association*. Available at: http://www.iea.cc/whats/index.html [Accessed April 5, 2016].

Baccarini, D., 1996. The concept of project complexity—a review. *International Journal of Project Management*, 14(4), pp.201–204.

Backs, R.W. & Boucsein, W., 2000. *Engineering psychophysiology: issues and applications*, CRC.

Bailey, N.R. & Scerbo, M.W., 2007. Automation-induced complacency for monitoring highly reliable systems: the role of task complexity, system experience, and operator trust. *Theoretical Issues in Ergonomics Science*, 8(4), pp.321–348.

Bell, D.J. & Ruthven, I., 2004. Searcher 's Assessments of Task Complexity for Web Searching. In *Advances in Information Retrieval*. Springer Berlin Heidelberg, pp. 57–71.

Billings, C., 1997. *Aviation Automation: The Search for a Human-Centered Approach.*, Mahwah, New Jersey, USA.: Lawrence Erlbaum Associates.

Boag, C. et al., 2006. An analysis of relational complexity in an air traffic control conflict detection task. *Ergonomics*, 49(14), pp.1508–1526.

Boff, K., 2006. Revolutions and shifting paradigms in human factors and ergonomics. *Applied ergonomics*, 37(4), pp.391–399.

Bonner, S.E., 1994. A model of the effects of audit task complexity. *Accounting Organizations and Society*, 19(3), pp.213–234.

Boot, W.R. et al., 2010. Transfer of skill engendered by complex task training under conditions of variable priority. *Acta psychologica*, 135(3), pp.349–357.

Braarud, Ø., 2011. Task Complexity: What Challenges the Crew and How Do They Cope. In *Simulator-based Human Factors Studies Across 25 Years*. Springer London, pp. 233–251.

Britten, N., 1995. Qualitative Research: Qualitative interviews in medical research. *British Medical Journal*, 311(6999), pp.251–253.

Burns, C.. & Hajdukiewicz, J., 2004. *Ecological Interface Design*, CRC Press.

Byrne, E.A. & Parasuraman, R., 1996. Psychophysiology and adaptive automation. *Biological psychology*, 42(3), pp.249–68.

Byström, K. & Järvelin, K., 1995. Task complexity affects information seeking and use. *Information Processing & Management*, 31(2), pp.191–213.

Campbell, D.., 1988. Task Complexity: A Review and Analysis. *The Academy of Management Review*, 13(1), pp.40–52.

Campbell, D.. & Gingrich, K.., 1986. The interactive effects of task complexity and participation on task performance: A field experiment. *Organizational Behavior and Human Decision Processes*, 38(2), pp.162–180.

Carey, J.. & Kacmar, C.., 1997. The Impact of Communication Mode and Task Complexity on Small Group Performance and Member Satisfaction. *Computers in Human Behavior*, 13(1), pp.23–49.

Chandrasekaran, M. et al., 2009. Application of soft computing techniques in machining performance prediction and optimization: a literature review. *The International Journal of Advanced Manufacturing Technology*, 46(5–8), pp.445–464.

Chen, J., 2009. Concurrent performance of military tasks and robotics tasks: Effects of automation unreliability and individual differences. In *Human-Robot Interaction (HRI), 4th ACM/IEEE International Conference on*. pp. 181–188.

Chhatpar, S. & Branicky, M., 2001. Search strategies for peg-in-hole assemblies with position uncertainty. In *Proceedings 2001 IEEE/RSJ International Conference on Intelligent Robots and Systems. Expanding the Societal Role of Robotics in the the Next Millennium*. pp. 1465–1470.

Chmiel, N., 2008. *An introduction to work and organizational psychology: a European perspective*, John Wiley & Sons.

Clark, R.E. et al., 2008. Cognitive Task Analysis. In *Handbook of research on educational communications and technology*. pp. 577–593.

Clarkson, P.J. & Hamilton, J.R., 2000. “Signposting”, a parameter-driven task-based model of the design process. *Research in Engineering Design - Theory, Applications, and Concurrent Engineering*, 12(1), pp.18–38.

Corrêa, H.L., 1996. The Flexibility of Technological and Human Resources in Automotive Manufacturing. *Integrated Manufacturing Systems*, 5(1), pp.33–40.

Dai, W. & Yang, J., 2011. Decision-making in process design based on failure knowledge. In *IEEE International Conference on Industrial Engineering and Engineering Management*. Ieee, pp. 1505–1509.

Deb, S. & Dixit, U.., 2008. Intelligent machining: computational methods and optimization. In *Machining: fundamentals and recent advances*. Springer London, pp. 329–358.

Digiesi, S. et al., 2009. The effect of dynamic worker behavior on flow line performance. *International Journal of Production Economics*, 120(2), pp.368–377.

Dixit, P.. & Dixit, U.., 2008. *Modeling of metal forming and machining processes: by finite element and soft computing methods*, London: Springer Science & Business Media.

Dixon, S. & Wickens, C., 2006. Reliability in automated aids for unmanned aerial vehicle flight control: Evaluating a model of automation dependence in high workload. *Human Factors*, 48, pp.474–486.

Doerr, K. & Mitchell, T.R., 2002. Heterogeneity and variability in the context of flow lines. , 27(4), pp.594–607.

Doerr, K.H. & Arreola-Risa, A., 2000. A worker-based approach for modeling variability in task completion times. *IIE Transactions*, 32(7), pp.625–636.

Dorigo, M., Maniezzo, V. & Colorni, A., 1996. The ant systems: optimization by a colony of cooperative agents. In *IEEE Transactions on Man, Machine and Cybernetics-Part B*. pp. 29–41.

Endsley, M.. & Kaber, D.., 1999. Level of automation effects on performance, situation awareness and workload in a dynamic control task. *Ergonomics*, 42(3), pp.462–492.

Eppinger, S.D. & Browning, T.., 2012. *Design structure matrix methods and applications.*, Vancouver: MIT press.

EPSRC Centre for Innovative Manufacturing in Intelligent Automation, 2014. EPSRC Centre for Innovative Manufacturing in Intelligent Automation. Available at: http://www.intelligent-automation.org.uk/ [Accessed April 9, 2016].

Feigh, K.M., Dorneich, M.. & Hayes, C.., 2012. Toward a Characterization of Adaptive Systems: A Framework for Researchers and System Designers. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 54(6), pp.1008–1024.

Feldmann, C., 2013. *The practical guide to business process reengineering using IDEFO*, Addison-Wesley.

Ferdows, K., 2006. Transfer of changing production know-how. *Production and Operations Management*, 15(1), pp.1–9.

Fitts, P.M., 1951. Human Engineering for an Effective Air-Navigation and Traffic-Control System. *Air Navigation development board*.

Fletcher, S.. R., Baines, T.. S. & Harrison, D.. K., 2006. An investigation of production workers' performance variations and the potential impact of attitudes. *The International Journal of Advanced Manufacturing Technology*, 35(11–12), pp.1113–1123. Available at: http://link.springer.com/10.1007/s00170-006-0793-y [Accessed May 7, 2013].

Frohm, J. et al., 2008. Levels of Automation in Manufacturing. *International Journal of Ergonomics and Human Factors*, 30(3), pp.1–28.

Gardner, D.., 1990. Task complexity effects on non-task-related movements: A test of activation theory. *Organizational Behavior and Human Decision Processes*, 45(2), pp.209–231.

Glodek, M. et al., 2006. Process Robustness. *Pharmaceutical Engineering (Online Exclusive)*, 26(6), pp.1–11.

Goh, Y.M., Booker, J.D. & McMahon, C. a, 2003. Evaluation of Process Modelling Approaches to Support Probabilistic Design Analysis. In *International Conference of Engineering Design*.

Goldberg, D.., 1989. *Genetic Algorithms in Search, Optimization, and Machine Learning*, Addison-wesley.

Goodrich, M.. et al., 2007. Managing Autonomy in Robot Teams: Observations from Four Experiments. In *ACM/IEEE International Conference on Human-Robot Interaction*. pp. 25–32.

Gregoriades, A. & Sutcliffe, A., 2008. Workload prediction for improved design and reliability of complex systems. *Reliability Engineering & System Safety*, 93(4), pp.530–549.

Greitzer, F.L., 2005. Toward the development of cognitive task difficulty metrics to support intelligence analysis research. In *Fourth IEEE Conference on Cognitive Informatics*. pp. 315–320.

Griffiths, J., James, R. & Kempson, J., 2000. Focusing customer demand through manufacturing supply chains by the use of customer focused cells: An appraisal. *International Journal of Production Economics*, 65(1), pp.111–120.

Groover, M.P., 2007. *Automation, production systems and computer-integrated manufacturing*, Prentice Hall Press.

Gutenberg, R.L. et al., 1983. Moderating effects of decision-making/information-processing job dimensions on test validities. *Journal of Applied Psychology*, 68(4), pp.602–608.

Ham, D.., Park, J. & Jung, W., 2011. A Framework-Based Approach to Identifying and Organizing the Complexity Factors of Human-System Interaction. *IEEE Systems Journal*, 5(2), pp.213–222.

Ham, D.H., Park, J. & Jung, W., 2012. Model-based identification and use of task complexity factors of human integrated systems. *Reliability Engineering & System Safety*, 100, pp.33–47.

Hartley, A.A. & Anderson, J.W., 1983. Task complexity and problem-solving performance in younger and older adults. *Journals of Gerontology*, 38(1), pp.72–77.

Harvey, C.M. & Koubek, R.J., 2000. Cognitive, social, and environmental attributes of distributed engineering collaboration: A review and proposed model of collaboration. *Human Factors and Ergonomics in Manufacturing*, 10(4), pp.369–393.

Hendy, K.., Liao, J. & Milgram, P., 1997. Combining time and intensity effects in assessing operator information- processing load. *Human Factors*, 39(1), pp.30–47.

Hendy, K.C., Liao, J. & Milgram, P., 1997. Combining Time and Intensity Effects in Assessing Operator Information-Processing Load. *The Journal of the Human Factors and Ergonomics Society*, 39(1), pp.30–47.

Ho, T.H. & Weigelt, K., 1996. Task complexity, equilibrium selection, and learning: An experimental study. *Management Science*, 42(5), pp.659–679.

Inagaki, T., 2006. Design of human-machine interactions in light of domain-dependence of human-centered automation. *Cognition, Technology and Work*, 8(3), pp.161–167.

International Ergonomics Association, 2000. What is Ergonomics. *http://www.iea.cc/01_what/What%20is%20Ergonomics.html*. Available at: http://www.iea.cc/.

ISO, 2004. ISO 14000 - Environmental management. Available at: http://www.iso.org/iso/home/standards/management-standards/iso14000.htm [Accessed August 27, 2015].

Jamshidi, J. et al., 2010. Manufacturing and assembly automation by integrated metrology systems for aircraft wing fabrication. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 224(1), pp.25–36. Available at: http://dx.doi.org/10.1243/09544054JEM1280.

Kahya, E., 2007. The effects of job characteristics and working conditions in work performance. *International Journal of Industrial Ergonomics*, 37(6), pp.515–523.

Kara, S. & Kayis, B., 2004. Manufacturing flexibility and variability: an overview. *Journal of Manufacturing Technology Management*, 15(6), pp.466–478. Available at: http://www.emeraldinsight.com/10.1108/17410380410547870 [Accessed May 25, 2013].

Karwowski, W., 2005. Ergonomics and human factors: the paradigms for science, engineering, design, technology and management of human-compatible systems. *Ergonomics*, 48(5), pp.436–463.

Kennedy, J., 2010. Encyclopedia of Machine Learning. In C. Sammut & G. I. Webb, eds. Boston, MA: Springer US, pp. 760–766.

Kihlman, H., 2005. *Affordable Automation for Airframe Assembly Development of Key Enabling Technologies*.

Kim, C. & Khoury, M., 1987. Task complexity and contingent information processing in the case of couple's decision making. *Journal of the Academy of Marketing*

Science, 15(3), pp.32–43.

Klein, G. et al., 1996. Decision Making in Complex Naval Command-and-Control Environments. *The Journal of the Human Factors and Ergonomics Society*, 38, pp.220–231.

Klein, G., 1993. Sources of error in naturalistic decision making tasks. In *Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting*. pp. 368–371.

Kofman, A. et al., 2009. Roles, rights, and responsibilities: Better governance through decision rights automation. In *Proceedings of the 2009 ICSE Workshop on Software Development Governance*. pp. 9–14.

Kotha, S. & Orne, D., 1989. Generic manufacturing strategies: A conceptual synthesis. *Strategic Management Journal*, 10(3), pp.211–231.

Krüger, J., Lien, T.K. & Verl, A., 2009. Cooperation of human and machines in assembly lines. *CIRP Annals - Manufacturing Technology*, 58(2), pp.628–646.

Lamberts, K. & Shanks, D., 2013. *Knowledge Concepts and Categories*, Psychology Press.

Levinthal, B.R. & Wickens, C.D., 2006. Management of Multiple Uavs with Imperfect Automation. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. pp. 1941–1944.

Liu, P. & Li, Z., 2012. Task complexity. A review and conceptualization framework. *International Journal of Industrial Ergonomics*, 42(6), pp.553–568.

Lohse, G.L., 1997. The role of working memory on graphical information processing. *Behaviour & Information Technology*, 16(6), pp.297–308.

Loose, J., Zhou, S. & Ceglarek, D., 2008. Variation Source Identification in Manufacturing Processes Based on Relational Measurements of Key Product Characteristics. *Journal of Manufacturing Science and Engineering*, 130(3).

Lorenz, B. et al., 2002. Automated fault-management in a simulated spaceflight micro-world. *Aviation space and environmental medicine*, 73(9), pp.886–897.

MacDonald, W., 2003. The Impact of Job Demands and Workload on Stress and Fatigue. *Australian Psychologist*, 38(2), pp.102–117.

Manorathna, R.P. et al., 2014. Feature extraction and tracking of a weld joint for adaptive robotic welding. In *13th International Conference on Control Automation Robotics & Vision (ICARCV)*. pp. 1368–1372.

Mantripragada, R. & Whitney, D.., 1999. Modeling and Controlling Variation Propagation in Mechanical Assemblies. *IEEE Transactions on Robotics and Automation*, 15(1), pp.124–140.

Manzey, D., Reichenbach, J. & Onnasch, L., 2008. Performance Consequences Of Automated Aids In Supervisory Control: The Impact Of Function Allocation. In *Human Factors and Ergonomics Society Annual Meeting*. SAGE Publications Ltd., pp. 297–301.

Marras, W. et al., 2010. Bored beyond belief: How automation is boring us to distraction. In *Human Factors and Ergonomics Society 54th Annual Meeting*. p. 758.

Marshall, T. & Byrd, T., 1998. Perceived task complexity as a criterion for information support. *Information & Management*, 34(5), pp.251–263.

Mascha, M.. & Miller, C.., 2010. The effects of task complexity and skill on over/under-estimation of internal control. *Managerial Auditing Journal*, 25(8), pp.734–755.

Maskell, B.H., 1991. *Performance measurement for world class manufacturing: a model for American companies*, Cambridge, Massachussets: Productivity Press.

Middleton, P. & McCollum, B., 2001. Management of process improvement by prescription. *Journal of Systems and Software*, 57(1), pp.9–19. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-0035957819&partnerID=tZOtx3y1.

Militello, L. & Hutton, R., 2000. *Applied cognitive task analysis (ACTA): a practitioner's toolkit for understanding cognitive task demands*, Task Analysis.

Molloy, R. & Parasuraman, R., 1996. Monitoring an Automated System for a Single Failure: Vigilance and Task Complexity Effects. *The Journal of the Human Factors and Ergonomics Society*, 38(2), pp.311–322.

Monfared, I.G. & Sharples, S., 2011. Occupants' perceptions and expectations of a green office building: a longitudinal case study. *Architectural Science Review*, 54(4), pp.344–355.

Montgomery, D., 2008. *Introduction to Statistical Quality Control*, John Wiley & Sons.

Mosier, K.L. et al., 2007. What You Don't Know Can Hurt You: Factors Impacting Diagnosis in the Automated Cockpit. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 49(2), pp.300–310.

Mulhall, A., 2003. In the field: notes on observation in qualitative research. *Journal of advanced nursing*, 41(3), pp.306–13.

Muthard, E.K. & Wickens, C.D., 2003. Factors That Mediate Flight Plan Monitoring and Errors in Plan Revision: An Examination of Planning Under Automated Conditions. In *12th international symposium on aviation psychology*. Dayton, OH.

Nachreiner, F., Nickel, P. & Meyer, I., 2006. Human factors in process control systems: The design of human–machine interfaces. *Safety Science*, 44(1), pp.5–26.

Nadkarni, S. & Gupta, R., 2007. A task-based model of perceived website complexity. *MIS Quarterly: Management Information Systems*, 31(3), pp.501–524.

National Institute of Standards and Technology, 2016. National Institute of Standards and Technology. Available at: http://www.nist.gov/ [Accessed April 17, 2016].

Nembhard, D.A. & Osothsilp, N., 2002. Task complexity effects on between-individual learning-forgetting variability. *International Journal of Industrial Ergonomics*, 29(5), pp.297–306.

O'Donnell, E. & Johnson, E.N., 2001. The effects of auditor gender and task complexity on information processing efficiency. *International Journal of Auditing*, 5(2), pp.91–105.

O'Hare, D. et al., 1998. Cognitive task analyses for decision centred design and training. *Ergonomics*, 41(11), pp.1698–1718.

Ogle, R., Morrison, D. & Carpenter, A., 2008. The relationship between automation complexity and operator error. *Journal of hazardous materials*, 159(1), pp.135–41.

Osman, M., 2010. Controlling uncertainty: a review of human behavior in complex dynamic environments. *Psychological bulletin*, 136(1), pp.65–86.

Parasuraman, R., Sheridan, T.B. & Wickens, C.D., 2000. A model for types and levels of human interaction with automation. *IEEE transactions on systems, man, and cybernetics. Part A, Systems and humans : a publication of the IEEE Systems, Man, and Cybernetics Society*, 30(3), pp.286–97.

Park, J., Kim, J. & Jung, W., 2004. Comparing the complexity of procedural steps with the operators' performance observed under stressful conditions. *Reliability Engineering & System Safety*, 83(1), pp.79–91.

Park, S.H. & Woldstad, J.C., 2000. Multiple two-dimensional displays as an alternative to three-dimensional displays in telerobotic tasks. *Human factors*, 42(4), pp.592–603.

Patrick, J. & James, N., 2004. Process tracing of complex cognitive work tasks. *Journal of Occupational and Organizational Psychology*, 77(2), pp.259–280.

Pavkovic, N., Marjanovic, D. & Dekovic, D., 2001. Object-oriented modelling of the design process. In *International Conference of Engineering Design*. Glasgow.

Payne, J.W., 1976. Task complexity and contingent processing in decision making: An information search and protocol analysis. *Organizational Behavior and Human Performance*, 16(2), pp.366–387.

Payne, J.W., Bettman, J.R. & Johnson, E.J., 1992. Behavioral decision research: A constructive processing perspective. *Annual Review of Psychology*, 43(1), pp.87–131.

Qiao, L.A., Kao, S.A. & Zhang, Y.B., 2011. Manufacturing process modelling using process specification language. *International Journal of Advanced Manufacturing*

Technology, 55(5–8), pp.549–563.

Rasmussen, J., 1983. Skill, rules and knowledge: Signals, signs, and symbols, and other distinctions in human performance models. *IEEE Transactions on Systems, Man, and Cybernetics*, (3), pp.257–266.

Reichenbach, J., Onnasch, L. & Manzey, D., 2011. Human performance consequences of automated decision aid in states of fatigue. *The Journal of the Human Factors and Ergonomics Society*, 53(6), pp.717–728.

Reveliotis, S.A., 1999. Production planning and control in flexibly automated manufacturing systems: current status and future requirements. In *IEEE International Conference on Robotics and Automation*. pp. 1442–1449.

Rhodes, C., 2014. Manufacturing : statistics and policy. *House of Commons Library*, 13.

Rhodes, C., Hough, D. & Ward, M., 2015. *The UK aerospace industry : statistics and policy*,

Robinson, P., 2001. Task Complexity, Task Difficulty, and Task Production: Exploring Interactions in a Componential Framework. *Applied Linguistics*, 22(1), pp.27–57.

Röttger, S., Bali, K. & Manzey, D., 2009. Impact of automated decision aids on performance, operator behaviour and workload in a simulated supervisory control task. *Ergonomics*, 52(5), pp.512–523.

Rouse, W.B. & Rouse, S.H., 1979. Measures of complexity of fault diagnosis tasks. *IEEE Transactions on Systems, Man and Cybernetics*, SMC-9(11), pp.720–727.

Rovira, E., McGarry, K. & Parasuraman, R., 2007. Effects of imperfect automation on decision making in a simulated command and control task. *Human factors*, 49(1), pp.76–87.

S.A.E, 1999. Quality Systems - Aerospace - Model for Quality Assurance in Design, Development, Production, Installation and Servicing.

Saaty, T.L., 1990. How to make a decision: The analytic hierarchy process. *European Journal of Operational Research*, 48(1), pp.9–26.

Sandom, C. & Harvey, R., 2004. *Human Factors for Engineers*, London : Institution of Electrical Engineers.

Satchell, P., 1998. *Innovation and Automation*, Ashgate.

Sauer, J., Nickel, P. & Wastell, D., 2013. Designing automation for complex work environments under different levels of stress. *Applied ergonomics*, 44(1), pp.119–27.

Schaafstal, A., Schraagen, J.M. & van Berlo, M., 2000. Cognitive Task Analysis and Innovation of Training: The Case of Structured Troubleshooting. *The Journal of the Human Factors and Ergonomics Society*, 42(1), pp.75–86.

Schraagen, J.M., Chipman, S.F. & Shalin, V.L., 2000. *Cognitive Task Analysis*, Psychology Press.

Schwab, D.P. & Cummings, L.L., 1976. A Theoretical Analysis of the Impact of Task Scope on Employee Performance. *The Academy of Management Review*, 1(2), pp.23–25.

Schwarzwald, J., Koslowsky, M. & Ochana-Levin, T., 2003. Usage of and Compliance with Power Tactics in Routine Versus Nonroutine Work Settings. *Journal of Business and Psychology*, 18(3), pp.385–402.

Shingo, S., 1989. *A study of the Toyota production system from an industrial engineering viewpoint*, CRC Press.

Shingo, S., 1986. *Zero Quality Control: Source Inspection and the Poka-yoke System*, Productivity Press.

Simnett, R., 1996. The effect of information selection, information processing and task complexity on predictive accuracy of auditors. *Accounting, Organizations and Society*, 21(7–8), pp.699–719.

Sintchenko, V. & Coiera, E., 2003. Which clinical decisions benefit from automation. A task complexity approach. *International Journal of Medical Informatics*, 70, pp.309–316.

Skjerve, A.B. & Bye, A., 2011. *Simulator-based Human Factors Studies Across 25 Years*, Springer London.

Slack, F. et al., 2001. Observation : Perspectives on Research Methodologies for Leisure Managers. *Management Research News*, 24, pp.35–42.

SMMT, 2014. The Society of Motor Manufacturers and Traders Motor Industry Facts 2014.

Speier, C., 2006. The influence of information presentation formats on complex task decision-making performance. *International Journal of Human-Computer Studies*, 64(11), pp.1115–1131.

Steinmann, D.O., 1976. The effects of cognitive feedback and task complexity in multiple-cue probability learning. *Organizational Behavior and Human Performance*, 15(2), pp.168–179.

Svenson, O. & Edland, A., 1987. Change of preferences under time pressure: choices and judgements. *Scandinavian Journal of psychology*, 28, pp.322–330.

Thornton, A., 1999a. A Mathematical Framework for the Key Characteristic Process. *Research in Engineering Design*, 11(3), pp.145–157.

Thornton, A., 2000. Quantitative Selection of Variation Reduction Plans. *Journal of Mechanical Design*, 122(2), pp.185–193.

Thornton, A., 2004. *Variation Risk Management: focusing quality improvements in product development and production*, John Wiley & Sons.

Thornton, A., 1999b. Variation Risk Management Using Modelling and Simulation. *Journal of Mechanical Design*, 121(2), pp.297–304.

Thornton, A., Donnelly, S. & Ertan, B., 2000. More than Just Robust Design: Why Product Development Organizations Still Contend with Variation and its Impact on Quality. *Research in Engineering Design*, 12(3), pp.127–143.

Turner, N. & Arif, M., 2012. BREEAM excellent: Business Value vs Employee Morale. *Journal of Physics: Conference Series*, 364(1), p.12116.

U.S. Department of Commerce, 1993. FIPS PUB 183: Integration Definition for Function Modeling (IDEF0). , p.120.

United Nations Statistics Division, 2013. GDP and its breakdown at current prices in US Dollars. *Main Aggregates Database*.

Vakkari, P., 1999. Task complexity, problem structure and information actions: Integrating studies on information seeking and retrieval. *Information Processing & Management*, 35(6), pp.819–837.

Wang, H., Lewis, M., et al., 2009. How search and its subtasks scale in N robots. In *Proceedings of the 4th ACM/IEEE international conference on Human robot interaction*. p. 141.

Wang, H., Chien, S.Y., et al., 2009. Human teams for large scale multirobot control. In *Conference Proceedings - IEEE International Conference on Systems, Man and Cybernetics*. pp. 1269–1274.

Wang, L., Jamieson, G. & Hollands, J.G., 2009. Trust and reliance on an automated combat identification system. *Human factors*, 51(3), pp.281–291.

Wang, Q., Sowden, M. & Mileham, A., 2013. Modelling human performance within an automotive engine assembly line. *The International Journal of Advanced Manufacturing Technology*, 68(1–4), pp.141–148.

Whitney, D.E., 2004. *Mechanical Assemblies*, Oxford University Press.

Wiker, S.F., Schwerha, D.J. & Jaraiedi, M., 2009. Auditory and Visual Distractor Decrement in Older Worker Manual Assembly Task Learning : Impact of Spatial Reasoning , Field Independence , and Level of Education. *Human Factors and Ergonomics in Manufacturing & Service Industries*, 19(4), pp.300–317.

Williams, T.J. & Li, H., 1999. PERA and GERAM—Enterprise reference architectures in enterprise integration. *Information Infrastructure Systems for Manufacturing II*, pp.3–30.

Williams, T.M., 1999. The need for new paradigms for complex projects. *International Journal of Project Management*, 17(5), pp.269–273.

De Winter, J.C. & Dodou, D., 2011. Why the Fitts list has persisted throughout the history of function allocation. *Cognition, Technology & Work*, 16(1), pp.1–11.

Wood, R.. E., Mento, A.. J. & Locke, E.A., 1987. Task complexity as a moderator of goal effects: A meta-analysis. *Journal of Applied Psychology*, 72(3), pp.416–425.

Wood, R.E., 1986. Task complexity: Definition of the Construct. *Organizational Behavior And Human Decision Processes*, 37(1), pp.60–82.

Xiao, Y. et al., 1996. Task Complexity in Emergency Medical Care and Its Implications for Team Coordination. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 38(4), pp.636–645.

Xu, S. et al., 2009. Influence of step complexity and presentation style on step performance of computerized emergency operating procedures. *Reliability Engineering & System Safety*, 94(2), pp.670–674.

Yun, S., 2008. Compliant manipulation for peg-in-hole: Is passive compliance a key to learn contact motion? In *IEEE International Conference on Robotics and Automation*. pp. 1647–1652.

Zhang, Y. et al., 2009. A spaceflight operation complexity measure and its experimental validation. *International Journal of Industrial Ergonomics*, 39(5), pp.756–765.

Zheng, L.Y. et al., 2008. Key characteristics management in product lifecycle management: a survey of methodologies and practices. *Journal of Engineering Manufacture: Proceedings of the Institution of Mechanical Engineers, Part B*, 222(8), pp.989–1008.

APPENDIX 1

WORKSHOP

Work

How long have you been working at -----?

- Less than 10 year
- 10 to 15 years
- 15 to 20 years
- More than 20 years

How long have you been working in this specific part/component?

- Less than 5 year
- 5 to 10 years
- 10 to 20 years
- More than 20 years

Could you please tell me what part/component are you currently working on?
Please Specify (Part number, Component's name) ___________________________

Job procedure

Do you notice differences between parts? What is the most common?

- No
- Yes, dimensions
- Yes, radii
- Yes, surface finish (pitting, scratches,…)
- Yes, other. Please specify ____

Do you notice differences between batches? (tick as many as you need)

- No
- Yes, dimensions
- Yes, surface finish (pitting, scratches,…)
- Yes, other. Please specify ____

How do you cope with these differences?

- I do not, I always proceed in the same way, with all the parts
- I work on the part only after visual inspection send it for rework
- I spend time eliminating the defect/anomaly
- I just report to quality

What do you control when you are performing the task?

- Dimensions
- Flow between surfaces
- Radii
- Any other. Please specify ____

Every how many seconds do you check the job? Worst and best case scenario

Dimensions	Flow between surfaces	Radii	Other
1 sec	1 sec	1 sec	1sec
3 to 5 secs	3 to 5 secs	3 to 5 secs	3 to5secs
More than 5 sec	More than 5 sec	More than 5 sec	More than 5 sec

Tools Wear

Do you notice when wheel tool is degraded (wear in tool)? How often? (worst case scenario)

No

Yes, every ____

Do you work differently when you feel degradation in the tool? What do you change?

No

Yes, I apply more pressure

Yes, I keep grinding/polishing for longer time

Yes, other. Please specify ____

Who prepare and recondition the tools? How long does it take?

I do ____

There are someone doing it ____

Do you customize your tools? What do you focus on when customizing?

No

Yes, mainly sharpness

Yes, mainly edge's shape

Any other. Please specify ____

Other questions

What do you think are the main sources of variation?

Please specify ____

What do you think is the most critical in order to comply with ----- standards?

Please specify ____

How do you think this variation could be reduced/eliminated?

Improving prior processes

Redesigning procedures

Better machines/tools

Any other. Please specify

____

How do you think your job could be improved?

Reducing Vibrations

Reducing the number of action in the process (working with semifinished parts)

Reducing rework

Any other. Please specify ____

Additional Comments

Thank you for your participation!

APPENDIX 2

Loughborough University

My name is *Angel Sanchez*. I am a PhD student at the Loughborough University. I am conducting this interview as part of my research.

The interview involves answering some general questions about your job. The purpose of the survey is to understand how people are able to adapt and minimize external variability in manufacturing processes. Your participation is completely voluntary, and your responses will be completely anonymous. The data I collect will be analyzed at the group level only. You do not have to answer any question you'd rather not answer.

The results of my research will be available after March 2014. If you would like a copy of the results of my research or have any questions, please contact me at a.sanchez@lboro.ac.uk

Work

How long have you been working at -----?

Less than 1 year

1 to 5 years

5 to 10 years

More than 10 years

How long have you been working in visual inspection?

Less than 6 months

6 to 12 months

1 to 2 years

More than 2 years

Could you please tell us what part/component are you currently inspecting?
Please Specify (Part number, Component's name) ____

Job procedure.

Do you notice differences between operators?

No

Yes, dimensions

Yes, radii

Yes, surface finish (pitting, scratches,…)

Yes, other. Please specify____

Do you notice differences between parts in the same operator? (tick as many as you need)

- No
- Yes, dimensions
- Yes, radii
- Yes, surface finish (pitting, scratches,…)
- Yes, other. Please specify____

In your opinion, what is the most common "non-conformity" issue in parts (answer as many as you want)

- Excess/Defective removed material
- Dimensions
- Surface finish (pitting, scratches,…)
- Other. Please specify ____

In your opinion, what is the less common "non-conformity" issue in parts (answer as many as you want)?

- Excess/Defective removed material
- Dimensions
- Surface finish (pitting, scratches,…)
- Other. Please specify ____

Rework Parts

What is the part number with the highest rework rate?____

- Less than 10%
- 10% to 50%
- 50% to 75% parts
- 75% to 100%

What is the part number with the lowest rework rate?____________________________________

- Less than 10%
- 10% to 50%
- 50% to 75% parts
- 75% to 100%

Are there any operators with an unusual rework rate?

- Yes, low rework rate
- Yes, high rework rate

In your opinion, what are operators' most common mistakes?

____
____

In your opinion, is same operator repeatedly making the same mistakes?

- Yes, same operator make same mistake______________________________________
- No, they vary ____

Additional Comments

Thank you for your participation!

APPENDIX 3

Loughborough University

My name is *Angel Sanchez*. I am a PhD student at the Loughborough University. I am conducting this interview as part of my research.

The interview involves answering some general questions about your job. The purpose of the survey is to understand how people are able to adapt and minimize external variability in manufacturing processes. Your participation is completely voluntary, and your responses will be completely anonymous. The data I collect will be analyzed at research level only. You do not have to answer any question you'd rather not answer.

The results of my research will be available after June 2014. If you would like a copy of the results of my research or have any questions, please contact me at a.sanchez@lboro.ac.uk

Procedure

Think about what you do when you Deburr. Can you break this task down into less than six, but more than three steps?

____
____
____
____

Of the steps you have just identified which require difficult cognitive skills? By cognitive skills I mean judgements, assessments and problem solving-thinking skills

____
____
____

Work

How long have you been working at -----?

- Less than 10 year
- 10 to 15 years
- 15 to 20 years
- More than 20 years

How long have you been working in deburring -----?

- Less than 5 year
- 5 to 10 years
- 10 to 20 years
- More than 20 years

Job procedure

Do you notice differences between parts? What is the most common?

No

Yes, dimensions

Yes, burrs type

Yes, burrs location

Yes, other. Please specify

____
_

How do you cope with these differences?

Please specify

____

What do you control when you are performing the task?

Dimensions

Removing burr

Edge's Shape

Depth

Any other. Please specify

____

Every how many seconds do you check the job? Worst and best case scenario

Dimensions	Removing Burr	Edge's Shape	Depth
5 sec	5 sec	5 sec	5 sec
10 to 15 secs	10 to 15 secs	10 to 15 secs	10 to 15 secs
More than 15 sec	More than 15 sec	More than 15 sec	More than 15 sec

Tools

How many different tools do you use in the whole process?

Is tools' condition an issue for the job?

No

Yes, every ____

Do you work differently when you feel degradation in the tool? What do you change?

No

Yes, I apply more pressure

Yes, I keep removing burrs for longer time

Yes, other. Please specify ____

Do you customize any of your tools? What do you focus on when customizing?

No

Yes, ____

Other questions

What do you think is the most critical in order to comply with standards?

Please specify

____

How do you think this variation could be reduced/eliminated?

Improving prior processes

Redesigning procedures

Better machines/tools

Any other. Please specify ____

How do you think your job could be improved?

Reducing deburring applied

Reducing the number of actions in the process (splitting the process into smaller processes)

Improving environment conditions (light, noise, working position)

Redesigning procedure

Any other. Please specify ____

Additional Comments

__Thank you for your participation!__

APPENDIX 4

Experiment interviews

	Subject									
Procedure	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Break this process down into less than six, but more than three steps	1. Grab the peg 2. Approach to the hole 3. Push down until reach the bottom 4. Release & Rest 5. Extract	1. Pick up the shaft & move it near to the hole 2. Align shaft w/ hole & insert it 3. Remove shaft & move near to the initial position 4. Leave the shaft at the initial position	1. Object pick up 2. Hole location & identification 3. Reaching the hole w/ the object 4. Initial insertion into the hole 5. Final insertion	1. Place the component in the hole & inspect 2. Remove it 3. Remove base shaft from component 4. Screw the new base 5. Repeat steps 1 to 4	1. Move to pick up the shaft 2. Hold it 3. Move to the hole 4. Insert it 5. Release	Grab item Insert it in hole	1. Pick up rod 2. Move close to hole 3. Touch to guide insertion 4. Complete insertion	1. Locate rod 2. Pick up rod 3. Align w/ hole 4. Insert it 5. Remove it 6. Replace on table top	1. Pick up 2. Move toward target 3. Align 4. Hit target	1. Pick up 2. Locate receptacle 3. Move to hole 4. Check orientation/ alignment 5. Insert 6. Remove
Which require difficult cognitive skills	Push down until reach the bottom	All of them but judgments and problems to be solved are different for each step	Initial breakthrough involves force/torque feedback to achieve it	Placement of the shaft on the table Centring the shaft to the table	The part w/ minimum tolerance requires a bit of cognitive judgment for insertion		Touching the hole area w/ the rod to initially guide the insertion	Alignment and insertion required the most fine adjustments	Align	Check orientation/alignment of the pin vs pin hole
Task procedure										
Do you notice differences between parts? What is the most common?	Dimensions	Finishing	Dimensions Finishing	Weight Material, Colour	Dimensions	Just colour	Finishing	Dimensions	Weight	Dimension Finishing Shape (not sure if one had a tapper) Weight
How do you cope with these differences?	By adjusting force applied and angle	It's just a visual difference that helps me to identify which shaft goes first, second and third	A little adjustment before insertion	By more attention when a part is difficult to place	There are a sligh difficulty in insertion w/ different parts	I just notice that it is a different one	By feeling the resistance while inserting the rod	Apply more force for a higher fit. Also finer adjustments to angle	Increase power to compensate in order to reach the target	Adjust pressure when inserting pin closer observation of positional accuracy

What do you control when you are performing the task?	Dimensions, hole location, pressure applied and speed	Pressure applied and speed	Pressure applied	Hole location Speed	Hole location	Pressure applied Speed Inserting time	Finding the hole visually Pressure applied	Pressure applied Insertion angle	Pressure applied (unconsciously) Speed	Pressure applied Speed Entry angle. Time taking to judge insertion alignment
Every how many seconds do you check the job?	Dimensions. Just one Hole location. 5 s Pressure applied. All the time Speed. All the time	Dimensions. <15 s Hole location. 10s<t<15 s Pressure applied. All the time Speed. All the time	Dimensions. <15 s Hole location. <5 s Pressure applied. All the time Speed. All the time	Dimensions. <5 s Hole location. 10s<t<15 s Pressure applied. ,15s Speed. All the time	Dimensions . All the time Hole location. All the time Pressure applied. <5 s Speed. <5s	Dimensions. <15 s Hole location. <5 s Pressure applied. All the time Speed. All the time	Dimensions. <5 s Hole location. <5 s Pressure applied. All the time Speed. <5s	Dimensions. <15 s Hole location. <5 s Pressure applied. All the time Speed. All the time	Dimensions. <15 s Hole location. 10s<t<15 s Pressure applied. <15 s Speed. 10s<t<15 s	Dimensions. <5 s Hole location. t<5 s Pressure applied. All the time Speed. All the time
Other questions										
What do you think are the main sources of variation?	Dimensions (Clearance), starting point, weight of pegs	Movement to go from initial position and final position	Object dimensions	Dimensions, weight, material, speed of operation	Parts diameter	Hand positioning accuracy and inserting time	The orientation of the rod as it initially maker contact	Inaccurate location of the peg	Weight Finish	Peg dimensions and surface finish
What do you think is the most critical in order to complete the task?	Clearance	Align shaft w/ hole & placing shaft vertically back on table	Distinction of pressure applied during insertion	Speed of operation and placement of object in centre	Hole detection	Persistence	Force sensing	Fine adjustment of insertion angle	Weight	Dimension
How do you think this variation could be reduced/ eliminated?	By force/tactile feedback & minor visual feedback	Constant and programmed speed	By monitoring force/torque applied	By speed control and close monitoring	Parts' diameter and material finish		Using a fixed/programmed path to insert the rod exactly in the same way	A jig to guide the peg into the correct angle	Same weight	Ensure part is correct size
How do you think the task could be improved?	Keep the starting tilted angle for chamfer crossing in a small angle Gradually pushing the peg		A compliance in holding the components will be useful for inserting different dimension components	By better and improved mechanical design	Parts' diameter and material finish	Could put jigs into place to reduce my focusing need	Better force and visual sensing	Make sure that the plate can't fall on the floor!	Bring peg closer to target before insertion to reduce error	

APPENDIX 5

		Peg 1				Peg 2				Peg 3			
		Angle X		Angle Y		Angle X		Angle Y		Angle X		Angle Y	
Subject	**Test**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**
1	1	3.6	-2.4	31.6	1.2	10.0	7.0	-19.5	-21.8	13.6	-9.5	34.1	1.2
	2	3.4	-7.6	39.4	0.7	5.5	-4.3	29.1	-0.8	9.6	-7.8	29.0	1.3
2	1	3.2	-8.0	15.0	0.3	-1.2	-8.4	10.0	1.8	1.0	-5.9	13.8	-13.1
	2	1.9	-7.2	15.4	0.8	2.3	-6.4	16.1	0.3	1.5	-5.2	11.7	-2.8
3	1	7.2	-7.2	35.2	0.7	0.7	-10.3	9.5	0.8	5.1	-10.7	17.3	-5.7
	2	1.9	-9.4	9.0	-2.6	-1.6	-8.8	12.5	-0.3	4.0	-9.5	20.4	-4.5
4	1	0.8	-9.0	18.5	-4.4	7.6	-4.8	24.8	2.5	13.5	-3.3	7.0	-15.3
	2	1.5	-0.5	2.1	1.3	11.9	4.3	-2.3	-29.0	0.7	-17.6	16.0	-13.3
5	1	0.8	-9.0	18.5	-4.4	4.1	-1.9	-7.9	-12.5	9.8	-3.9	7.1	-17.1
	2	2.1	-8.3	15.5	-7.5	8.8	-5.4	4.7	-8.7	7.7	-7.8	10.9	-14.8
6	1	1.5	-4.6	4.4	-19.8	1.3	-5.5	4.7	-2.7	4.4	-8.9	4.7	-15.8
	2	1.8	-7.5	4.4	-16.7	3.1	-8.7	5.9	-21.4	3.9	-6.2	11.2	-21.0
7	1	7.0	-8.6	1.1	-33.2	2.0	-10.9	30.1	3.2	0.7	-2.2	1.0	-3.2
	2	0.1	-7.2	1.8	-4.8	1.2	-8.3	3.9	-32.7	3.0	-8.8	20.5	-3.8
8	1	6.7	-3.3	12.9	-2.6	10.4	-7.8	13.1	-11.4	3.9	-2.1	4.1	-11.2
	2	8.3	-8.2	11.0	-4.2	17.9	-0.8	39.6	-1.7	7.1	-3.2	12.8	-5.7
9	1	5.4	-5.9	10.9	-11.8	2.4	-10.9	11.5	-5.0	1.2	-5.3	12.1	-3.7
	2	4.0	-17.3	6.7	-18.0	6.1	-6.5	10.3	-5.0	3.3	-8.0	15.5	-6.5
10	1	16.8	-1.7	5.8	-54.6	18.7	-1.8	17.5	-24.3	2.3	-2.7	18.7	3.1
	2	8.6	-2.2	29.7	-1.3	2.8	-2.3	17.1	3.8	8.6	-4.3	6.4	-10.2

APPENDIX 6

POSITIONING 1			
Source of Variability	**Parameter**	**Results**	**Comments**
Outputs	Quantity	4	Overhang, Gap, chamfer dimensions (only for automated process), thickness
	Interval of variability	Unknown	
	Diversification	2	Pipe-bottom half subassembly & top half
	Interdependency	Independent	
Inputs	Quantity	5	Overhang, Gap, chamfer dimensions (only for automated process), thickness and position on fixture
	Interval of variability	Unknown	
	Diversification	2	Pipe-bottom half subassembly & top half
	Interdependency	Not Applicable	
Strategy	Number of alternatives	2	Two operators working in the automated cell
	Number of actions	6	Load "pipe-bottom half subassembly" into "bottom half fixture" Load "key component" into "pipe-bottom half subassembly" Load "top half component" onto "key component" Position "top half fixture" Unhook lifting hoist and slide to home position Clamp the two halves of the welding fixture
	Patterned actions	No pattern	
Time	Sequentiality	Sequence	Only position on fixture-managed
	Restriction	Sufficient	
Requirements	Sensorial	2	Visual, tactile
	Cognitive requisite	Yes	Positioning
	Physical prerequisite	No	Heavy part are moved with hoist help

Levels of automation

Low. Levels 3 & 4

Moderate. Level 5

Considerable. Level 6

High. Level 7

Level of Automation recommended

Moderate

PREPARATION 2			
Source of Variability	**Parameter**	**Results**	**Comments**
Outputs	Quantity	1	Thickness.
	Interval of variability	Unknown	
	Diversification	2	Pipe-bottom half subassembly & top half
	Interdependency	Not Applicable	
Inputs	Quantity	4	Overhang, Gap (0.2 mm), chamfer dimensions (only for automated process), thickness
	Interval of variability	Unknown	
	Diversification	2	Pipe-bottom half subassembly & top half
	Interdependency	Independent	
Strategy	Number of alternatives	2	Two operators working in the automated cell
	Number of actions	4	Trim components edges Planish components edges at corners Tap out gaps between components Visual assess components edge condition and remove burrs
	Patterned actions	No pattern	
Time	Sequentiality	Sequence	Overhang, chamfer and gap are solve in sequence
	Restriction	Sufficient	
Requirements	Sensorial	2	Visual, tactile
	Cognitive requisite	Yes	Trimming & Tapping out
	Physical prerequisite	No	Tools used are small

Levels of automation

Low. Levels 3 & 4

Moderate. Level 5

Considerable. Level 6

High. Level 7

Level of Automation recommended

Moderate

POSITIONING 2			
Source of Variability	**Parameter**	**Results**	**Comments**
Outputs	Quantity	1	Thickness
	Interval of variability	Unknown	
	Diversification	1	Pipe-bottom half subassembly
	Interdependency	Not Applicable	
Inputs	Quantity	2	Position on fixture, thickness.
	Interval of variability	Unknown	
	Diversification	1	Bottom half component and pipe
	Interdependency	Independent	Position on Fixture is independent from thickness
Strategy	Number of alternatives	2	Two operators working in the automated cell
	Number of actions	2	Load “bottom half component” onto “pipe welding fixture” Load “pipe”
	Patterned actions	No pattern	
Time	Sequentiality	Sequence	Only position on fixture considered
	Restriction	Sufficient	
Requirements	Sensorial	2	Visual, tactile
	Cognitive requisite	Yes	Positioning pipe and bottom half component
	Physical prerequisite	No	Not heavy components to be positioned

Levels of automation

Low. Levels 3 & 4

Moderate. Level 5

Considerable. Level 6

High. Level 7

Level of Automation recommended

Moderate

APPENDIX 7

Introduction

The following instructions will show how to use the framework. This framework has been designed to characterise the sources of variability present in manufacturing processes and affecting any of the components of the process. It is out of the scope of this framework the categorisation of any source of variability which is not affecting any of the components of the process. It is also out of the scope of this framework the study of the variability introduced by humans, although it must be identified when considering in automating the process. For instance, the temperature of the room, if varies, should not be included in this framework unless it has been noticed that is affecting the process (any property of a component, speed of equipment, viscosity of a refrigerant, dimensions of a gauge, to name some examples)

It is very important to say that, before the framework can be used, the sources of variability need to be identified. If the sources of variability have not been identified, the framework will not be able to be applied.

Framework

The framework divides the process into five different components of the processes that could be potentially affected by variability: inputs, outputs, strategy, time and requirements.

Outputs.

Output refers to those goods that underwent a transformation during a task. This refers to those goods coming out of the task whether or not they comply with the requirements. For example, those sent to rework or scrap are outputs although they are not final outputs. Here are defined the parameters affecting the outputs of the manufacturing process object of study: quantity, diversification, range and interdependency.

- Quantity. Quantity will enumerate how many sources of variability are affecting the outputs. Ex: 3 sources of variability have been identified.
- Diversification. Diversification quantifies the number of inputs affected by variability. One source of variability could affects different inputs or a single input. Ex: let say that in a working station an operator is welding joints to obtain

two different components. If the thickness of the weld varies in one component but is constant in the other, just only one component would be affected by variability.

- Range or Interval of variability. It would present the range of the variability. For example, finding that variability in the diameter of a hole varying from 15.95 mm to 16.04 mm. In this case, if the nominal diameter is 16 mm, it can be said that variability goes from -0.05 mm to +0.04 mm.
- Interdependency. Interdependency refers to the interdependency of the different sources of variability. Therefore, how acting on one source of variability will affect another source of variability. If both sources of variability are dependents, the effect could be positive (reducing or eliminating one source of variability will reduce or eliminate the other source of variability) or negative (reducing or eliminating one source of variability will augment the other source of variability). If they are independents, acting on one source of variability will have no effect in the other source of variability.

Inputs

Inputs: inputs apply to *parts*, *tools*, *data*, *stimuli*, *information cues* or *instructions* needed to perform the *task*. Therefore, they are also introduced to achieve the desired outputs in processes.

- *Part* defines any of physical components constituting the expected output.
- *Tools* are instruments utilised to perform a specific task.
- *Data* refers to quantitative information presented to the operators and it is required to complete a task satisfactorily. For this reason, the operator, according to previous experience or training received, would need to interpret data in order to complete the task
- *Stimulus* is a sensorial perception which helps to evaluate an action within a task, supporting the manner in which the task is performed.
- *Information cue*: is is a piece of information used by the subject to make decisions during the completion of a task(Wood 1986). To differentiate *information cues* from *data*, the former should be considered as “supporting information” used to conceive a decision. Moreover, *information cues* could be presented as qualitative information. For example, welding experts rely on the noise made by the weld to check if the welding has been done properly.

The parameters affecting the inputs are those that are affecting the outputs: quantity, diversification, delimitation and interdependency and their definitions are similar.

Strategy (procedure)

The strategy followed by the person to complete the process comprises other three parameters used to define the sources of variability affecting the process. These parameters are: Number of alternatives, Number of actions and patterns.

- Number of alternatives refers to the number of different alternatives that can be used to complete the group of tasks comprising the process. It is sufficiently known that different people use different strategies to achieve the same goal. In a manufacturing process, as far as these alternatives lead to the achievement of same outputs, it is permitted.
- Number of actions gives a measure of how many actions are executed in the completion of the process. In this framework, action is defined as every individual verb used to describe the fact of doing something that is absolutely necessary to successfully finish the process.
- Patterned actions. Those actions that are repeated during the process could follow a pattern. For example, in a grinding process, the action of grinding is followed by the action of checking progress. These two actions are performed several times when grinding a component. Therefore, there is a pattern grouping these actions that is repeated during the process: "grind-check".

Time

Time parameters are two: concurrency and availability.

- Sequentiality. Sequentiality has relation to how the sources of variability are presented during the process. Sources of variability will be sequential when they are managed in a different period of time. On the contrary, they will be coincident or simultaneous when they are presented at the same time. For example, if a welder has to control a variable gap and a variable thickness of the components to be welded, these sources of variability will be simultaneous. On the contrary, if the welder is welding components with variable gap but constant thickness and s/he is asked to weld other two components with a different thickness, s/he will adjust the welding parameters to the new components and afterwards, s/he will deal with the variable gap. In this case, the sources of variability are presented in sequence.

- Time restriction. Availability names the time designated to accommodate the variability. If this time has been proven to be enough to effectively reduce the variability to an acceptable levels regardless external conditions and operators, it can be asseverated that time for variability is “sufficient”. Contrarily, if variability in inputs cannot be reduced or eliminated in the time allocated for the process, in order to deliver acceptable outputs, time should be catalogued as “insufficient”.

Requirements

- Sensorial. Sensorial specifies the domain of the sensorial features (sight, hearing, taste, touch and smell in the case of humans) or technical characteristics in the case of equipment needed to overcome variability.
- Cognitive prerequisite. Cognitive prerequisite attempts to highlight any mental process effectuated to solve variability within the process. A machine might reproduce a cognitive process but due to certain limitations, could not be implemented (space, investment, technology maturity, accuracy and precision).
- Physical prerequisite. Physical prerequisite deals with any physical attribute necessary to overcome the variability (accessibility, force, torque, environmental conditions, etc…). For manual processes it is supposed that any operator working in a specific process will have the physical capabilities to properly perform it, without risking his /her health or to the quality of the outputs. In this case, it should be noted “lift 1 up to 1 Kg”, “stand up for 40 min”, “use of two hands”, “able to listen under 20 dB (normal hearing)”, etc. For any automated solution, these physical prerequisite should not exceed the capabilities of the equipment described by the manufacturer.

APPENDIX 8

Comments for “set up” task in grinding/polishing process

Parameters	Comments	
	Volunteer 1	Researcher
Quantity	1) abrasive tool wear/geometry	Surface roughness and shape
Interval of variability	Surface texture/geometry/dimension of the abrasive tool wear is identified but not measured	It could not be measured
Diversification	1 tool	1 tool is set up at a time
Interdependency	Quality of the part and the tool are affecting the work independently	Surface roughness and shape of tool are independent of each other?
Quantity	1) abrasive tool wear/geometry	Surface roughness and shape
Interval of variability	Surface texture/geometry/dimension of the abrasive tool wear is identified but not measured	It could not be measured
Diversification	1 tool	1 tool is set up at a time
Interdependency	Quality of the part and the tool are affecting the work independently	Surface roughness and shape of tool are independent of each other?
Number of alternatives	Operator follows SOP (techniques may vary from operator to operator) and focus only where finishing is needed	Two Operators
Number of actions	1) inspect the tool, 2) shape only where required	Turn on machine, Put protective equipment, check tool condition, recondition tool, shape tool
Patterned actions	Same strategy is followed until the surface quality is satisfactory	
Sequentiality	1) frequent visual inspection, 2) adapt strategy during operation	Both sources managed simultaneously
Restriction	none (the operator is carrying out the operation one part at a time)	
Sensorial	1) visual feedback, 2) tactile feedback (and dexterity)	Vision and tactile
Cognitive requisite	Adapt strategy to the part and surface requirement (using previous experience and training). Flexibility: must be able to work at different stage of the finishing process	Operator knows optimal tool condition and shape by experience
Physical prerequisite	A) Hand dexterity to change force/speed, keep the part perpendicular and compensate for torque and vibrations. B) Resistance to fatigue and vibration. C) Good sight to locate defect(s) and monitor operation in real time	

Comments for peg in a hole task

Parameters	Comments	
	Volunteer 1	Researcher
Quantity		Considered all as “accepted component”
Interval of variability		
Diversification		Considered all as “accepted component”
Interdependency		
Quantity	Diameter, Weight and Position	Diameter, Weight, Position
Interval of variability	15.9 to 15.99, 42g to 122g, 1500mm x 750mm	Diameter: 15.9 to 15.99 mm Weight: 42g to 122g Position: any position in a 10cm2 area in the right top corner of the table
Diversification	Insertion force	Peg (diameter, weight & position)
Interdependency	Force is uncorrelated with position	
Number of alternatives	1) Pick & place path (rough motion) (user dependant). 2) Insertion path (constrained by environment)	No evidence were collected of different strategies among subjects
Number of actions	Pick & place, fine motion (insertion)	Position: any position in a 10cm2 area in the right top corner of the table
Patterned actions	1) Gross motion pattern: move object from A to B in workspace 2) Fine motion: constrained motion	Identify peg position Apply the proper force of insertion
Sequentiality		
Restriction	No time restriction	Vision & Tactile
Sensorial	Gross motion: Visual Fine motion: Tactile	Identify peg position
Cognitive requisite	1) Object recognition, 2) Adjustable grasp force, 3) Adjust insertion force	Force must be increased with tightness in insertion
Physical prerequisite		No special physical prerequisite needed

Comments for “positioning 2” task in MIG welding process

Parameters	Comments	
	Volunteer 1	Researcher
Quantity	Thick	Thickness
Interval of variability		
Diversification	Subassembly	Pipe-bottom half subassembly
Interdependency		
Quantity	Thickness, alignment	Position on fixture, thickness
Interval of variability		
Diversification	Half part and pipe	Bottom half and pipe
Interdependency	Cutting force is affected by thickness and dimensions of the sample, Impact force and impact direction is affected by thickness and surface/edge quality	Position on Fixture is independent from thickness
Number of alternatives	2 Operators working in automated process	Two operators working in the automated cell
Number of actions	Double checking the alignment of samples, Double checking the gap between the sheets	"Load “bottom half component” onto “pipe welding fixture” Load “pipe”
Patterned actions	1) Alignment of sheets 2) Cutting edges	
Sequentiality		Only position on fixture considered
Restriction	No time restriction	
Sensorial	Visual: gap between sheets, alignment Tactile: edge preparation Tactile/visual: surface formless	Visual, tactile
Cognitive requisite	1) Formless recognition 2) Adjustable impact force 3) Adjust cutting force 4) Adjust alignment	Positioning pipe and bottom half
Physical prerequisite	Apply cutting force, Align the coffin, apply impact force	Not heavy components to be positioned

APPENDIX 9

Case study. Grinding and polishing

Source of Variability	Characteristic	Results	Comments
Inputs	Quantity	4	Grinding Time, Pressure applied, Tool Shape & Tool surface roughness
	Interval of variability	Unknown	Not allowed to take measurement onsite
	Diversification	3	Grinding, component, tool
	Interdependency	Independent	Grinding time and pressure applied depend on tool shape and tool roughness. Grinding time and pressure applied are independent
Strategy	Number of alternatives	3	3 Operators with slightly different ways to proceed
	Number of actions	2	Grinding & Checking
	Patterned actions	Some actions patterned	Grinding & checking is repeated along the entire process
Time	Sequentiality	Concurrently	All the sources of variability must be managed at the same time
	Restriction	Sufficient	
Requirements	Area	3	Visual, Tactile and hearing
	Cognitive requisite	Yes	Long training needed
	Physical prerequisite	Yes	Handling Small parts

Levels of automation

Low. Levels 3 & 4

Moderate. Level 5

Considerable. Level 6

High. Level 7

Level of Automation recommended

Low

Case study. De-burring

Source of Variability	Characteristic	Results	Comments
Output	Quantity	Not Applicable	
	Interval of variability	Not Applicable	
	Diversification	Not Applicable	
	Interdependency	Not Applicable	
Inputs	Quantity	4	To identify the location of burrs To evaluate those burrs To select the proper tool for the job To remove the burrs
	Interval of variability	Unknown	Not allowed to take measurement onsite
	Diversification	2	Component and tools
	Interdependency	Independent	Locate burrs is independent. Select tool depends on evaluate burrs. Remove burrs depends on selected tool therefore depends on evaluate burr
Strategy	Number of alternatives	3	3 Operators w/ slightly different ways to proceed
	Number of actions	4	Inspection, evaluation, selection of tool and removal
	Patterned actions	Some actions patterned	These 4 actions are repeated per each feature and a few times in the same feature
Time	Sequentiality	Sequence	First location, then evaluation, after that selection of tool, and finally removal of burrs
	Restriction	Sufficient	Enough time allocated to remove burrs
Requirements	Area	2	Visual & Tactile
	Cognitive requisite	Yes	Evaluation and removal requires cognitive skills.
	Physical prerequisite	Yes	Locations of some burrs are in difficult to access areas.

Levels of automation

Low. Levels 3 & 4

Moderate. Level 5

Considerable. Level 6

High. Level 7

Level of Automation recommended

Moderate