CRANFIELD UNIVERSITY

USUE ALIENDE URRUTIA

DEVELOPMENT OF A METHODOLOGY FOR IMPROVING THE AIRCRAFT SYSTEMS INSTALLATION PROCESS

SCHOOL OF AEROSPACE, TRANSPORT AND MANUFACTURING

PhD
Academic Year: 2012 - 2015

Supervisor: Professor Philip Webb
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This thesis is submitted in partial fulfilment of the requirements for the degree of PhD

ABSTRACT

In the aviation industry, competition to be the market leader is intense; Airbus must differentiate from its rival Boeing by applying the most innovative solutions. Building aircraft faster and cheaper, without affecting the quality has continued to grow in importance. It is not enough to apply the traditional lean manufacturing philosophy developed by Toyota; in fact, this philosophy does not include other perspectives unrelated to production specific to aircraft build.

It has also become increasingly difficult to ignore, the problems which occur in the production; more specifically in the installation of systems such as fuel, bleed air and electrics. These issues, which could be from ergonomic challenges due to the traditional build of the aircraft wings or visibility or access restrictions due to the structural complexity, can represent a significant proportion of the cost and time involved in wing manufacture.

The research so far has concentrated on individual manufacturing and assembly technologies, whereas this project seeks to take a more global view of the systems installation process.

This thesis presents a solution for the mentioned gap: a 3-step continuous improvement methodology which provides a structured approach to identify improvement opportunities on the existing system installation process by capturing shop-floor operator’s perspective, but also gathers the basic knowledge for initiating a Design-for-System-Installation approach of designing future aircraft systems.

The developed improvement methodology, which evaluates shop-floor operators’ “perception of work” and presents results to identify opportunities, utilises a questionnaire which has been designed for this specific purpose. It has been successfully implemented in three industrial case-studies measuring and quantifying the ease of installation, and providing feedback to improve the product, process, people and technology aspects of the system installation.

Keywords: *Continuous improvement, lean manufacturing, aircraft system installation, complex assembly process*.

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In regards to the first stages of my research, the collaboration of Airbus employees has been essential. Employees involved at the initial assessment of the system installation process have helped me understand the system installation process, obtain a snapshot of the challenges they were facing in different programmes, and determine what would be the focus of my project. In addition, employees from the Research & Technology department have also collaborated providing me useful background information on future trends in the aerospace business.

During the development stage, I attended several courses at the Doctoral Training Centre at Cranfield University which improved not only my technical skills, but also my writing and presentations skills. Additionally, being able to attend international conferences and poster competitions has provided me the chance to network with other professionals in the field as well as enhance my personal skills a little further.

The methodology implementation stage would not have been possible without the collaboration of the Research & Technology department (especially Andy Roberts and Jon Cashin) and the 17 shop-floor employees from Airbus' site in Broughton, Wales. Throughout these two months in the production site, employees showed a keen willingness to get involved in the project as well as invest their time in talking to me and going through never-ending questionnaires.

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
CI	Continuous Improvement
DfA	Design-for-Assembly
DfM	Design-for-Manufacture
DfMA	Design-for-Manufacture-and-Assembly
DfQ	Design-for-Quality
DfSI	Design-for-System-Installation
DfV	Design-for-Variety
DfX	Design-for-X
DMAIC	Define, Measure, Analyse, Improve and Control
EMA	Electro-mechanical actuator
FMEA	Failure Mode-Effect Analysis
IO	Improvement Opportunity
IOI	Improvement Opportunity Idea
IT	Information Technology
JIT	Just In Time
KF	Key Factor
MEA	More Electric Aircraft
PoW	Perception of Work
QFD	Quality Function Deployment
SIP	System Installation Process
SMED	Single-Minute Exchange of Dies
SS	Six Sigma
TPM	Total Productive Maintenance
TQM	Total Quality Management
VSM	Value Stream Mapping

1 INTRODUCTION

1.1 Statement of the Problem

In the aviation industry, competition to be the market leader is intense; Airbus must differentiate from its rival Boeing by applying the most innovative solutions. Building aircraft faster and cheaper, without affecting the quality has continued to grow in importance. It is not enough to apply the traditional lean manufacturing philosophy developed by Toyota; in fact, this philosophy does not include other perspectives unrelated to production specific to aircraft build.

It has also become increasingly difficult to ignore, the problems which occur in the production; more specifically in the installation of systems such as fuel, bleed air and electrics. These issues, which could be from ergonomic challenges due to the traditional build of the aircraft wings or visibility or access restrictions due to the structural complexity, can represent a significant proportion of the cost and time involved in wing manufacture.

Aircraft wings are designed with particular attention to weight: a small reduction in a component's weight would result in cost savings and an improvement in the performance of an aircraft (Kaufmann, 2008). Manufacturing times and costs are also becoming important drivers which may highlight one design over its alternative. However, to consider the ease of assembly as another one of these drivers would only benefit the sponsoring company, reducing as well time and cost.

In simple terms, the current design of a commercial aircraft wing is composed of a box-shaped structure with the skins comprising the top and bottom and spars which form the sides. Skins are assembled first, and then, attached to the spars. Once the main structure is built and the fuel tank tests carried out, components belonging to the fuel, hydraulic, electrical and pneumatic systems are installed inside the aircraft wing through the manholes in the bottom skin. Most of the time, the space available for both installation and access is very limited, and has corresponding safety constraints. These restrictions are the ones responsible for a challenging system installation process.

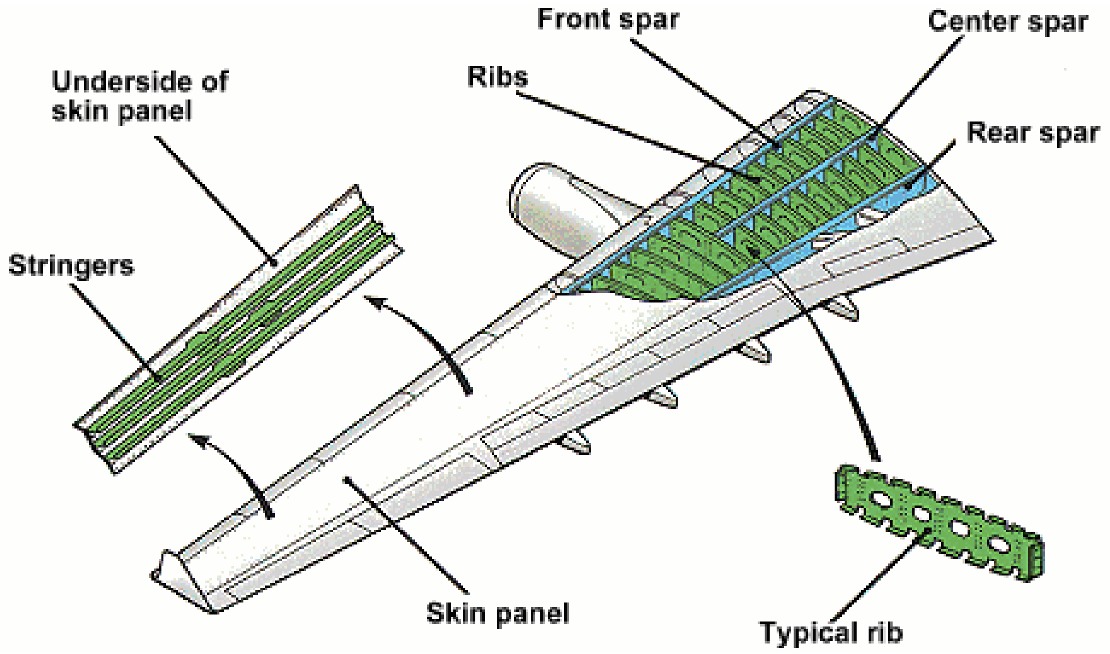


Figure 1-1: Aircraft Wing Structure (SAE International Website, 2015)

The installation of systems has to be highly accurate in order to meet strict aerospace restrictions, and as the process is mainly manual at the moment, shop-floor employees face many installation challenges. For instance, the fuel system is located internally without extra space for the installer to access. Limited access and visibility, awkward ergonomic position, accuracy issues, unnecessary repetitions, safety constraints, and space available are examples of these challenges which could increase the lead-time of the aircraft wing production considerably, and consequently, the total cost.

Cranfield University's Centre for Advanced Systems in the School of Aerospace, Manufacturing and Transport, has been working with Airbus for several years to find innovative ways of enhancing the process of systems installation. However, the work so far has concentrated on individual manufacturing and assembly technologies, whereas this PhD project seeks to take a more global view of the systems installation process.

1.2 Aim and Objectives

The aim of the project is to develop a methodology to evaluate and codify the current actual aircraft system installation process and support continuous improvement initiatives.

In order to do so, this solution provides a critical shop-floor assessment of the current system installation process to inform the development of future wing architectures, currently aircraft cost and weight predominantly drive design.

Nonetheless, providing lessons learnt, insights, perceptions, judgement, knowledge and experience from shop-floor employees, the methodology eases complex processes by avoiding late and recurring design changes and mistakes. It is a systematic and structured way to measure and quantify the shop-floor perception of work (PoW) related to the critical aspects mentioned earlier, to identify potential improvement areas, and to measure and visualise their effect on future architectures.

The main objectives of the research project are:

1. To develop a methodology that measures and quantifies the perception of work from the shop-floor employee’s perspective in complex assembly processes.
2. To provide a systematic approach to formulating and understanding problems, and identify possible continuous improvement solutions for the systems installation process.
3. To avoid recurrent system installation problems by facilitating the capture of knowledge and lessons learnt.
4. To identify and understand which factors facilitate or challenge the system installation process from the product, process, people and technology perspective.
5. To gather raw information to be able to inform the design department about the challenges in the shop-floor environment due to the current designs.

6. To validate the above by implementing the developed methodology in three case-studies for a specific wing configuration within Airbus.

The proposed solution is a methodology that provides a full analysis of the ease of installation into a structure by analysing Key Factors (explanation and definition on section 3.3) of a product and its building process. The solution is generic enough to be applied in other similarly complex assembly processes for multiple industries with few modifications. It provides support to managers in understanding the current challenges in the system installation process by monitoring certain factors that would ease the complex process.

In this PhD project, the methodology has been customised to be implemented in the aircraft SIP. The more systems the methodology is applied to, the better and more complete feedback it will provide. Ideally, the methodology should be applied for every single system installed in the wing. However, given that the product itself is a complex set of sub-systems, the methodology has been applied to specific key projects of the aircraft wing configuration: a partial installation of the fuel system, and in selected areas of the wing movables (due to the connection with other Cranfield projects).

1.3 Summary of Novelty

This PhD project describes the development of a methodology in the form of a questionnaire specifically designed to capture the shop-floor perspective of certain critical factors in complex assembly processes such as the aircraft system installation process. It aims at providing the shop-floor perception of work to assess current aircraft architectures and to continuously identify improvement opportunities.

The novelty of this methodology is that it provides a continuous improvement methodology which takes a global view of the aircraft system installation process instead of focusing on individual projects to improve only certain parts of the process. Additionally, this solution offers an approach to improve the aircraft system installation process by analysing and understanding the challenges directly from the parties affected (shop-floor employees).

1.4 Structure of Thesis

The thesis is divided into six chapters:

- Chapter 1 presents the statement of the research problem, aim and objectives as well as explaining the knowledge gap this PhD thesis aimed to fill.
- Chapter 2 states the literature survey of the research area. Research in aircraft system installation process, continuous improvement methodologies and Design-for-X (DfX) methodologies is presented in this chapter In addition to this, there is further information available relevant to the understanding of the background in Appendix A.
- Chapter 3 describes the 3-stage methodology development process, provides an explanation of each stage and introduces the concept of “Key Factor”. In addition, it proposes the most suitable methods to capture knowledge for the methodology, and describes the output reports in detail.
- Chapter 4 provides a detailed description of the three case-studies used to validate the methodology, two projects currently in production and a future project, and describes challenges faced when implementing it.
- Chapter 5 presents the validation to confirm by examination and to provide objective evidence of the suitability of the developed methodology.
- Chapter 6 highlights the most important discoveries as a conclusion, describes the challenges faced, explains how this project covers the gaps in the knowledge, and determines the actions to take as future work.

The document also includes appendices from A to E for further reading and references.

2 REVIEW OF THE LITERATURE

This following chapter gives an overview of the Literature Review, related published research, and identifies knowledge gaps on several topics.

Furthermore, it offers research on the process aimed at improving: the aircraft systems and their installation. It also provides an overview on the *complex assembly process* concept followed by an analysis of the existing continuous improvement methodologies. Additionally, there is also an examination of the DfX methodologies, as well as an overview of the most successful knowledge management techniques for similar applications.

The hypothesis to investigate is that "*it is possible to continuously improve current aircraft manufacturing processes through the capture and analysis of real experience-based knowledge from shop-floor employees, and estimate improvements or challenges with potential to inform future aircraft design changes*".

The following subsections, together with the background literature, provide information to understand whether the hypotheses are correct or not.

2.1 Aircraft System Installation Process

This PhD aims at enhancing the aircraft SIP. In section A.2, there is some background information on the research around different systems which is essential to learn what aircraft systems imply and what the current research on aircraft systems focuses on. However, the background presented in that section shows that the research on aircraft systems is mainly focused on improvement of the current technology as well as component characteristics. However, little research work has been found on the actual installation process of system components, which is the aim of this project.

Webb (2014) has published a conference paper describing how the assembly of system installation and equipping processes advance in civil aircrafts, and collaborated in a research suggesting human-robot cooperation to ease the system installation process in cases like this process, where conventional automation (Walton et al., 2011) has been another focus to improve the system installation process.

Additionally, Boothroyd et al. (2011, p.133) provided guidelines and an assessment process for electrical system installation design. The main focus of this work is to identify different electrical connections in order to provide Design-for-manucturing and Assembly feedback on aspects such as preparation times and securing. Even though the document provides extensive technical design information, it does not make a clear reference to aircraft manufacturing and therefore, clearly solve the challenges shop-floor operators face in this sector.

The closest document identified related completely to the aircraft system installation process itself was released in 1970, and mentions the electrical system installation only. Blake (1970) published an informal article providing tips for simpler electrical system installation. Focusing on the maintenance, the mentioned author stated that electrical wires should be fastened to the structure by friction tape rather than having a mess of loose wires, for instance.

However, besides this low reliability article, no formal peer-reviewed publication has been identified to support the SIP but concentrated on individual manufacturing and assembly technologies instead of taking a more global view, which creates a gap in the knowledge.

Therefore, it is important to highlight that the existing research has concentrated on individual manufacturing and assembly solutions rather than taking a more global view of the improvement of the system installation process in its entirety.

2.2 Research on Continuous Improvement (CI) Tools, Techniques and Methodologies

In order to gain long-term competitive strategy, companies worldwide have been introducing Kaizen philosophy, or continuous improvement, into their work methods in order to get “*big results from many small changes accumulated over time”* (Imai, 1991). Since then, organisations aimed at identifying root causes of problems to improve processes to improve the business.

This section aims at identifying whether current continuous improvement techniques are suitable for improving the aircraft system installation process and overcome the challenges shop-floor operators face.

2.2.1 Continuous Improvement (CI) Cycle

The four-step quality model, also known as Deming or Shewhart Cycle, is the most widely used tool to implement continuous improvement (Shewhart, 1939; Deming, 1950). The following steps are used to coordinate continuous improvement effort with a careful planning (Sokovic, 2009):

- **Plan:** Identify an opportunity and plan for change.
- **Do:** Implement the change on a small scale.
- **Check/Study:** Use data to analyze the results of the change and determine whether it made a difference.
- **Act:** If the change was successful, implement it on a wider scale and continuously assess your results. If the change did not work, begin the cycle again.

Nonetheless, the mentioned cycle is commonly used to monitor current processes and implement small scale changes. Even though the aircraft system installation would benefit from small scale changes, the aim is not only to improve the current system installation process but also to identify root-causes, and propose improvements for future aircraft configurations learning from past mistakes.

2.2.2 CI Tools

There are plenty of tools in the CI methodology and in this section the most widely used tools are discussed whether they are suitable for this specific project or not.

The **SMED** technique, or “Single-Minute Exchange of Dies”, refers to a system for dramatically reducing the set-up times, originally changeover of die, clamping and unclamping of work piece/die on the machine (Singh, 2015). This concept is credited to Shingeo Shingo, one of the main contributors to the consolidation of the Toyota Production System. The essence of the SMED system is to convert to “external” as many changeover steps as possible in order to simplify and streamline the remaining steps (Shingo, 1985).

In the aircraft assembly process, the changeover steps are minimum. Therefore, this methodology is not ideal for this specific case. However, there are multiple activities happen in the same wing, which challenge the access to the assembly point and visibility. Even though this technique is not suitable to implement AS-IS, the essence could be incorporated to the SIP.

There is another approach called **Total Productive Maintenance** (TPM) which establishes a preventive maintenance to the equipment throughout its working life. It empowers shop-floor employees to initiate preventive and corrective maintenance activities, and maintains and improves the integrity of production and quality systems (Nakajima, 1988). The concept is attributed to Nippondenso, a company supplying parts for Toyota. However, Seiichi Nakajima has made numerous contributions to the topic that is considered the father of TPM. In this specific industrial case, there is not much automated equipment used to install systems and even though the maintenance is important, the application of this methodology would not represent a significant improvement in the SIP.

A more widely known and used CI tool is **Kanban**. It is a scheduling system for continuous improvement and just-in-time manufacturing. It controls the inventory with a specially designed box containing a Kanban card in it, which moves from workstation to store on requirement bases (Ohno, 1988). Taiichi Ohno, an industrial engineer at Toyota, developed Kanban to improve manufacturing efficiency and to reduce the work-in-progress inventory.

The aircraft manufacture follows a pull process, which means that there is no much inventory in the production unless when it is needed. Complex kits of parts are used and they are supplied directly to the line. Additionally, the number of products is low and they are built to order, not to stock. For that reason, implementing Kanban would not provide significant benefit in the SIP.

Another methodology for CI is focused on an efficient organise workplaces and it is called **5S** (derived from 5 Japanese words: seiri, siton, seise, seiketsu and shitsuke). It was Sakishi Toyoda as well as Toyota engineer Taiichi Ohno who developed the 5S methodology (Ohno, 1988). 5S incorporates standardised procedures to improve the process by sorting, setting in order, shining, standardising and sustaining the workplace. This tool improves quality, reduces costs, improves safety, creates more reliable deliveries, and improve availability of plant equipment (Naslund, 2008). Nowadays, the methodology has evolved into Lean 6S, adding an extra step for safety.

This particular tool focuses on both people and technology aspects of the production and it could be an efficient tool to indirectly improve the SIP. However, the sponsoring company has already incorporated the 5S tool to sort and standardise equipment in the production line and therefore, it would not provide significant extra benefit to review it.

Poka-yoke, on the other hand, is a mechanism to mistake-proof an entire process by ensuring a proper condition before executing a process step as a prevention mechanism for defects. This methodology was also part of the Toyota Production System (Ohno, 1988). It should be applied at every aspect of the production starting from the design to the assembly of parts. It has been identified that certain aircraft system components have introduced the poka-yoke technique into their design. However, the feedback from production whether this technique in fact provides a mistake-proof mechanism is missing.

In this project, the author has decided to incorporate an analysis on the poka-yoke technique providing an assessment to know whether it eases or challenges the System Installation Process (SIP) for the shop-floor operator.

There is another CI tool which brings the process under control by reducing variation. This is called **Standardised Work**, which eradicates wastages and increases the productivity. This concept the foundation for Kaizen and one of the most powerful but least used lean tools (Spear and Bowen, 1999). If efficiently implemented, it should allow virtually anyone to perform the work without any variance in the desired output. In order to automate a process, a work should be a succession of properly structured activities to ensure efficiency (Singh, 2015).

The author sees this approach challenging to implement in aircraft SIP because the process varies from product to product. Depending on product specifications, which are determined by the client, the process will add/remove certain operations. This is one of the facts making the process difficult to automate. Additionally, the restricted access and visibility to the assembly point as well as having manual operations requiring highly skilled professionals, this approach is very difficult to successfully accommodate. The level of standardization of the process is another factor to consider in the industrial case-study analysed in this thesis, and therefore the author has decided to incorporate this into consideration.

Value Stream Mapping (VSM) is another CI technique widely spread in the industry and it is assumed it was developed by Toyota (Ohno, 1988). The tool provides a visual representation of the activities required to bring a product from raw materials to delivery to the customer. It highlights the waste in the process and identifies activities adding value to the final product. The tool aims at eliminating 7 waste types in manufacturing operations such as overproduction, waiting time, transporting, inventory, over processing, motion and production defects.

For the SIP, it is essential that non-value-adding operations are deleted or reduced to maximum. Therefore, the VSM is a valid approach to understand where the waste is and what operations should be targeted for elimination. In fact, the author has incorporated an approach similar to VSM to identify and target non-value-adding system operations. However, this tool should be combined other tools to overcome not only waste but also other SIP challenges.

Quality Function Deployment (QFD) is a structured method to translate the voice of the customer into product specifications. It was invented in Japan by Yoji Akao in 1966 but was first implemented in the Mitsubishi’s Kobe shipyard in 1972. It is a way to design aiming at satisfying the customer and to develop better quality products (Akao, 1990; Moskowitz and Kim 1997). QFD has been used in product development but also in business, site and test planning, and problem solving as well in many markets such as aerospace, manufacturing, software and IT, defense, government, healthcare and service industries. It is a critical method to reduce the product development cycle, design lead time and customer complaints as well as to increase customer satisfaction.

This approach might sound far away from the scope of this project as customers and designers are not directly involved in the system installation process. Nonetheless, if shop-floor operators are considered “customers”, this tool’s essence could be to translated into this case-scenario where shop-floor operators needs are linked not only with product features but also the building process, and some other factors such as machinery and ergonomic aspects. This project gathers the necessary information to link product features with shop-floor operator’s satisfaction. That said, the designer’s view could not be translated into the picture as no designer has been directly involved in this process, leaving this aspect pending for the future.

Total Quality Management (TQM) refers to a managerial approach for long-term customer satisfaction by creating a participation culture within an organization to improve products, processes, and services. The system relies on the involvement of all employees in continuous improvement ideas always fact-based. The TQM ensures that “h*appy employees will to a better job, i.e. better products and services which will satisfy more customers*” (Naslund, 2008) which is also one of the drivers for this project.

As mentioned in QFD, the customer of the final product is not involved in the system installation process and therefore. Nonetheless, as with the QFD, if shop-floor operators are referred as customers, the approach would be applicable for system installation process by involving them to improve the process, product, and services for their own benefit. In fact, this project proposes a fact-based approach to suggest continuous improvements which is also required in the TQM system. Nevertheless, factors such as ergonomy and technology have been left out from the definition of TQM which make the methodology not entirely applicable for this case.

Failure Mode and Effects Analysis (FMEA) was one of the first highly structured, systematic approaches to failure analysis. It was developed by reliability engineers in the late 1950s to study problems that might arise from malfunctions of military systems, and was further developed by the aerospace and automotive industries. A successful FMEA activity helps to identify potential failure modes based on experience with similar products and processes (SAE, 1994). The aim of this project is exactly anticipating to potential challenges in SIP by understanding the factors that influence it based on shop-floor operators' experience. Therefore, even though this project does not aim at identifying potential failures, similarities with this approach could be identified and implemented in the SIP continuous improvement methodology.

2.2.3 Other Improvement Methodologies

Apart from CI tools and methodologies, organisations have been implementing similar methodologies to ensure continuous improvement is embedded into their working environment. Some of the most important ones are explained in the following subsections and discusses about the suitability for this specific project.

2.2.3.1 Six Sigma

The Six Sigma (SS) methodology provides organisations a methodology with a set of tools aiming to improve business processes. The term “Six Sigma” is credited to a Motorola engineer Bill Smith while working for the company in 1986. By reducing defects, the methodology increases performance and decreases process variation (Adams et al., 2003). The methodology uses a control chart to indicate that a process is well controlled if it limits +-3s from the center line.

The Six Sigma methodology follows a DMAIC cycle (Sokovic, 2009):

- **Define**: improvement of project goals, goals based on customer needs and wants
- **Measure:** current process and establish metrics to monitor the path to achievement of goals
- **Analyse:** current process to understand problems and their causes

- **Improve**: process by identifying and piloting solutions to problems
- **Control**: improved process with standardization and ongoing monitoring.”

SS methodology goes beyond the improvement tools because it requires an intelligent use of data, it is a structured methodology and emphasizes in statistical analysis. (Sokovic, 2009)

The elimination or reduction of defects is slightly of scope for the system installation process. The main objective of the project is not to reduce defects in the final product but to reduce challenges in SIP. Therefore, this methodology is not suitable to be implemented in this project.

However, as SS is considered to be the approach to quality improvement (Gershon), it is important to say that improved working conditions might lead to better quality that could then be measured with Six Sigma. Additionally, its DMAIC approach with the steps mentioned above could be beneficial to this project. The steps are very coherent for this project too, although it would require some modification (for example, control phase).

2.2.3.2 Lean Manufacturing

Henry Ford defined the concept of “lean manufacturing” as a system of techniques and activities to systematically eliminate all non-value-adding activities and waste from his business. It is marketed as a new organizational change and improvement method as a cost reduction mechanism (cited at (Naslund, 2008)) to increase competitiveness in the market by increasing efficiency, decreasing costs incurred due to elimination of non-value adding activities. (Naslund, 2008)

The concept extended not only being applicable to the manufacturing process but also the entire value stream or supply chain taking the term “lean enterprise” (http://asq.org/learn-about-quality/lean/overview/overview.html).

The lean approach is based on mapping and analyzing activities to define a value stream, a flow of necessary activities to produce the final product. It is primarily based on identifying activities that add value to the final product (muda) but also finds waste in all activities, which are identified to eliminate or reduce. (Naslund, 2008)

The lean manufacturing approach is interesting for the system installation process. The aerospace manufacturing process is already a pull system as products have a buyer the moment they are being developed. There is no product which does not have an owner during the product development process and this fact matches perfectly with the lean manufacturing approach. Besides, the people and technology aspects are also embedded into the lean manufacturing environment.

Nonetheless, lean also means cost reduction and this project is not aiming at directly reducing cost. It is more a holistic approach to identify issues and propose improvements that could eventually reduce costs and time.

2.2.3.3 Just in Time

Just-in-Time (JIT) is a methodology introduced by Toyota (Ohno, 1988) which primarily reduces flow times as well as response times from suppliers and customers. The ideas is that the production meets customer demands exactly, in time, quality and quantity, by implementing a zero-based inventory policy. Entra inventories, capacities, and time is a waste which JIT is focusing on reducing. The JIT manufacturing methodology includes tools such as Kanban, Jidoka and Andon to identify waste and ensure a “pull system”. Some researchers consider the Lean as an updated version of JIT methodology. (Naslund, 2008).

As mentioned above, the aerospace production is already a pull system as products have a buyer the moment they are being developed.

2.2.3.4 Lean Six Sigma

Six Sigma and Lean Manufacturing concepts together created a hybrid relatively new methodology called Lean Six Sigma. This methodology maximises shareholders value by achieving the fastest rate of improvement in customer satisfaction, cost, quality, process speed, and invested capital. (Singh,

2015) It addresses important issues that are overlooked by SS and Lean Manufacturing individually such as the steps in the process, the order in which they should be applied and the extend of the cost, quality and lead times of the proposed improvements. As for the SS approach, this methodology's aim is to reduce defects. However, in this project, the aim is to eliminate challenges in the SIP and to understand which factors influence positively or negatively in the process. The Lean SS will be considered in this project but not directly applied.

2.2.3.5 Re-Engineering

Re-engineering refers to a holistic approach for business management strategy focused on the analysis and design of workflows and business processes within an organisation. It encouraged organisations to rethink how they used to work to dramatically change their working environment by focusing on the ground-up design of their business processes (Davenport, 1990).

Re-engineering is a business management strategy, which is very far from the scope of this project. The system installation process could be re-engineered as a holistic approach, the efficiency improved and the most common challenges avoided to design a better system installation process. However, this approach is business focused and the management is not involved. Therefore, it is not the appropriate methodology to approach this industrial case-studies.

2.2.3.6 Lean Thinking

Lean Thinking is a methodology that aims to provide a new way of thinking about the entire business, not only the production. It has the Toyota Production System as the essence although it has been largely extended to other sections of the organization. The aim is to create a lean enterprise, aligning customer satisfaction with employee satisfaction, encouraging to create innovative product and solutions.

The methodology is being absorbed by many industries. Originally, it was popular in the automotive industry although recent researches also implemented it in sectors such as the construction industry for performance improvement Having more than 50% wasted time in the construction industry

(Aziz and Hafez, 2013), it seems to be the right industry to focus on. This includes a clear set of objectives for the delivery process aiming at maximizing performance of the delivery process, concurrent design, construction, and the project management throughout the life cycle of the project.

Womack, the Founder of Lean Enterprise Institute, has recently expressed that Lean Thinking is an opportunity for today's aerospace sector (http://planet-lean.com/womack-why-lean-is-an-opportunity-for-today-s-aerospace)

According to Womack, it's time for "*really exciting lean transformations in aerospace"* which *"might be at the operating level, working backwards from the needs of the customer rather than starting in manufacturing or engineering" (Ref).* Engaging and empowering operational employee's is key to ensure a lean enterprise and benefiting customers while eliminating waste and continuously improving the process throughout every step of the aircraft development process.

The assembly line is one of the places where continuous improvement has been most assiduously practiced and demanded. Many of those improvements are being made by paying attention to the details, such as ergonomics, the way humans interface with the tasks they must accomplish in assembling a vehicle (Sawyer, 2015).

As an example of applying lean thinking in the product design, Al-Ashaab et al. (2013) had carried out an aerospace case-study on lean environment and analised how product development process is transformed with a concurrent engineering design process. Firstly, they incorporated the principles of set-based concurrent engineering, a methodology that considers a solution as a combination of a number of feasible solutions for all parts, into the design phase. And then, produce the best solution with the tools associated to the methodology.

Nonetheless, any of the continuous improvement techniques will require investment in people, mind growing, having a strong leadership, and motivating employees (Bigelow, E., 2015; Jurburg et al., 2016)

2.3 Design-for-X Methodologies

Initially, the author of the thesis believed that developing a Design-for-X (DfX) methodology could be an interesting approach explains the evolution of DfX methodology and why these existing DfX methodologies are not entirely applicable for aircraft systems.

2.3.1 Introduction

In a market with intense competition, applying the most innovative solutions is a must for companies to differentiate themselves from their rivals and produce faster and cheaper product without affecting the quality. In order to achieve this goal, many corporations have introduced ‘Design-for-X’ methodologies into their working environment.

‘Design-for-X’ (DfX) is a modern terminology for a methodology which increases efficiency at the early design stage by addressing particular issues affecting the X characteristic of a product.

Traditionally, the first X characteristic a DfX methodology aimed at improving was the assembly (Leany and Wittenberg, 1992). The objective of the Design-for-Assembly (DfA) methodology was to feedback certain knowledge from the late phases of product development (assembly, in this case) into the early phases of product development (design). In such a way, designers would take the assembly perspective and develop products that are easier to assemble.

DfA methodology was followed by ‘Design-for-Manufacture’ (DfM), whose aim was to bring knowledge from the manufacture perspective (Boothroyd and Alting, 1992). As a combination of both techniques, ‘Design-for-Manufacture-and-Assembly” (DfMA) methodology arose, a methodology that simultaneously considered both manufacturing and assembly costs (Boothroyd, 1994).

Over the years, these DfX methodologies have evolved and begun to consider previously overlooked perspectives of the product (i.e. obsolescence, maintainability, disassembly, quality, reliability, etc.), the system (i.e. supply chain, network, etc.), and the eco-system (remanufacturing, life-cycle, recycle, etc.), classification done by Chiu and Okudan (2010).

Depending on the X characteristic aiming to improve, each methodology measures certain specific aspects of the product and its development process. These aspects, which as yet do not have specific terminology in the literature, are called “Key Factors” (KF) by the author of this document.

When thoroughly analysing the KFs of the most important DfX methodologies in the literature, the author has realised that there are some critical factors impacting on complex assembly processes which have been overlooked. In the next section, an extensive explanation of the evolution of DfX methodologies is provided to conclude and specifically determine the aspects that current DfX methodologies do not take into account.

The area of research regarding DfX methodologies has been active over the years. Nonetheless, the research focused only on the assembly and manufacturing areas in the first few years after Boothroyd’s concept whereas at the moment, other concepts such as ecology and recycle have increased its activity. Its implementation always involved a change in the ways of working and this has represented a challenge for the success of most of these methodologies.

2.3.2 Evolution of DfX methodologies

This section provides a description and evolution of the most relevant DfX methodologies in the literature, largely focusing on the assembly perspective, but also including other perspectives relevant to complex assembly processes.

The majority of DfA methodologies originated at private companies (Ohashi et al., 2002). Nevertheless, non-corporate researchers have likewise investigated this research topic and provided very useful inputs.

The terminology ‘Design-for-Assembly’ was introduced around 1980 by Professor Geoffrey Boothroyd to describe a methodology that would bring the assembly perspective into the design phases (Leany and Wittenberg, 1992).

However, the first industrial step towards assembly process improvement was made by Hitachi (Warnecke and Bassler, 1988). The company developed an internal tool called '*Assembly Evaluation Method'*, whose objective was to rate a process according to its ease for assembly and provide the product designer with some early feedback. Leany and Wittenberg (1992) claim that the Hitachi and the Boothroyd methodologies are the only quantitative assembly analysis techniques developed as a result of independent empirical and analytical work, and that all others are derivatives of these.

Boothroyd continued researching and, together with Alting, developed a methodology which mainly aimed at minimising product costs by reducing the number of components (Boothroyd and Alting, 1992). By combining components, the methodology claimed assembly cost and time would be reduced.

Despite the fact that reducing the number of parts eliminates operations, and as claimed by Boothroyd and Alting, reduces assembly cost and time, authors realised that it was not enough to focus on the assembly perspective. It was identified that a larger system of combined components would make the component more challenging and costly to manufacture. Therefore, the existing methodology could not be applied in isolation, and manufacturing costs should also be considered. Design-for-Manufacture-and-Assembly (DfMA) methodology was therefore developed (Boothroyd, 1994), and incorporating changes to Hitachi's original *Assembly Evaluation Method*, the *Extended Assemblability Evaluation Method* was developed (Ohashi et al., 2002), allowing a wider variety of use.

A third and significant methodology arose in the UK from collaborative work between Lucas Corporation and the University of Hull. Lucas Corporation developed a methodology which followed Boothroyd and Dewhurst's philosophy of reducing the number of components to minimise costs, but also included a mechanism for evaluating product designs explicitly for automated assembly (Leany and Wittenberg, 1992). For the first time, human interaction was identified as an influential aspect, and value addition considered.

After the development of the 3 most relevant methodologies, other researchers and corporations continued refining existing methodologies and adding previously unconsidered perspectives which would address other types of challenges encountered in the product development process. Sony Corporation (La Trobe-Bateman and Wild, 2003) incorporated Lucas Methodology principles into their own methodology called 'Design-for-Assembly Cost Effectiveness'. This methodology would classify factors for evaluation of each operation into 30 keywords displayed in a user-friendly diagram. They managed to find a way to visually identify the simplicity of each operation, and determine the efficiency of the assembly system.

In order to redesign a product for ease of both manual and automatic assembly, General Electric Corporation (Maczak, 1984) conducted a total of 42 DfA workshops, from which the output was utilised to develop specific guidelines for designers. A similar solution was proposed by Miles (1989), who provided a list of 14 principles to define good product DfA practices.

Parallel to the three most important methodologies, Warnecke and Bassler (1988) described their own vision of an evaluation method for suitability of products for assembly. Starting from setting up functional structure, they could determine the assembly sequence, expenditure and values of measuring the suitability for assembly with the aim of identifying technical problems during assembly. However, the authors did not include the manufacturing perspective in their methodology.

Who in fact did add the manufacturing perspective was Fabricius (1994), introducing a procedure to determine the manufacturability of the current product with other similar products on the market by evaluating parameters in design ideas, and selecting the best option according to the DfM objectives.

Van Vliet and van Luttervelt (2004, p.225) developed a DfM methodology which has the principle of '*design coordination and continuous design evaluation*'. They proposed a more practical definition of DfM by selecting the best combination of material geometry and their manufacturing methods, carrying a continuous evaluation which would constantly be improving the design.

Stoll (1988) preferred to use checklists to represent a systematic way to identify whether DfM practices were followed. Molloy et al. (1991) identified certain important aspects that both DfA and DfM were lacking: direct analysis on design, reflection of users' manufacturing concerns, qualitative analysis without providing design recommendations, and no mechanisms to capture manufacturing rules and decisions. As a result of this investigation, a computer-aided methodology was developed which would integrate DfA practices into the CAD systems.

Aliende-Urrutia et al. (2014) extracted a total of 167 aspects from published works that defined these DfX methodologies, and classified them according to the level of analysis, type of analysis, and their nature. From this work, it is apparent that researchers have adapted the original DfA and DfM methodologies in many different ways, and reflected specific perspectives always from the product structural build point of view. There are several characteristics that have not been taken into account yet that are critical for complex assembly processes such as segregation distances, access and visibility to the assembly point, and the human ergonomic factor.

In the past few years, there has been some research around redesign activities in the aerospace sector (Nounu, 2017). The author proposes a tool to identifies the impact of obsolescence and a holistic operation difficulty assessment for redesign projects, and compares the results with strategical business decisions.

Similarly, Zong and Mao (2015) had been investigating how to optimise design based on the manufacturing and assembly costs. Instead of using the traditional approach which aims at simply minimizing manufacturing costs, authors identify the nonlinear relationship between design and cost introducing tolerance as a critical factor to improve design quality.

The general conclusion on DfX methodologies is that the existing methodologies could not be directly used on complex assembly processes and there is potential to develop a different solution based on the DfM and DfA approach. However, the experience tells that it is still very challenging to incorporate a successfully implement a methodology created around 20 years ago in the aerospace business due to the complexity of the final product.

2.4 Gaps in the Knowledge

Previous research topics have identified several gaps in the literature where the following conclusions have been extracted and this PhD project presents a solution which addresses the following gaps:

1. The literature compiled on research around aircraft system installation confirms that the efforts had concentrated on individual manufacturing and assembly technologies so far rather than taking a more global view of the installation process. Therefore, this thesis investigates whether the system installation process could become more efficient with a more overall analysis of the production.
2. Even though there are plenty of methodologies to continuously improve the production, they concentrate on only a few of the challenges faced in the aircraft system installation process, almost independently. In fact, there are some challenges existing in the system installation process which have not been investigated by any continuous improvement methodology. As the system installation process challenges should not be investigated individually, the author suggested developing a continuous improvement methodology simultaneously analysing all the aspects challenging the system installation process.

Originally, the hypothesis (on page 6) included the Design-for-X approach as the best way to go. The aerospace business seemed to forget about the shop-floor when designing an aircraft and the author would like to bring this knowledge back to the initial stages of a product development process. However, the literature review on section 2.3 suggests that the successful implementation of such techniques in the aircraft manufacturing has not been straight-forward, limiting its usage of DfM manuals and consultant manufacturing experts. Therefore, the author decided that capturing raw information from shop-floor could be utilised as a first step toward a Design-for-System-Installation methodology.

3 METHODOLOGY DEVELOPMENT

3.1 Objective of Methodology

In order to fill the gaps exposed in the previous section, the author has developed a continuous improvement methodology for this specific application domain. It aims to improve the SIP by utilising a structured procedure to drive the improvement process and to ease with which systems are installed. A questionnaire assesses the ease with which systems are installed by analysing certain critical aspects identified from the literature from the shop-floor operator’s perspective. The issues, which could be from ergonomic challenges due to the traditional build of the aircraft wings or visibility or access restrictions due to the structural complexity, can represent a significant proportion of the cost and time involved in wing manufacture. These critical factors are either not fully considered in existing continuous improvement methodologies nor DfX methodologies, or in best case-scenarios, only few of them. With minimum modifications, the questionnaire could also be applied in similar installation process such as the automotive, engine manufacture or ship building industries.

In addition, this methodology also identifies improvement opportunity ideas (IOI) areas from the shop-floor perspective, not only to enhance an easier-to-install system design, but also to provide insight into recommendations based on shop-floor employees’ feedback. With this feedback, the methodology could improve the current installation process from the product, process, people and technology perspective and could also gather some raw knowledge from production which could potentially be utilised in the design department to avoid SIP challenges by modifying the design.

3.2 Initial Assessment of the System Installation Process

With the intention of increasing understanding of the challenges in the SIP as well as identifying first-hand how this PhD could help the sponsoring company, an initial assessment of the current practices in system installation was carried out.

In this initial assessment of the SIP, the author conducted several informal meetings with approximately 50 key stakeholders who are involved in the SIP in many different capacities; from shop-floor employees to project managers, designers or manufacturing engineers. These casual conversations provided the author enough information to understand the current challenges in the SIP from many perspectives and scope down the solution to develop.

The initial assessment of the SIP led to a clear conclusion: inter-departmental communication is key for a successful installation process and any continuous improvement proposal in this regard will ease the current way of installing systems. The sponsoring company is a large transnational business, communication among teams could be improved. For instance, the lack of communication between system designers and installers has a direct impact on the system installation process. In addition, systems and their ease of installation is not yet considered as a requirement as a potential variable to continuously improve the current process. Therefore, the gap was identified from an industrial application point of view.

In conclusion, the author decided to fill the communication gap by developing a systematic approach to gather the shop-floor perspective in order to continuously improve the SIP by identifying challenging aspects and collecting improvement opportunities.

3.3 What is a “Key Factor”?

A Key Factor (KF) is the specific aspect of the product and its development that DfX methodologies analyse to improve the X characteristic. This concept brings attention to the fact that the KFs on existing methodologies do not entirely cover critical aspects of complex assembly processes. The conference paper published by the author (Aliende-Urrutia et al., 2014) provides a deep analysis of KFs extracted from existing methodologies, and suggests developing a new methodology that could suit the process of system installation more accurately. From 167 KFs analysed and classified from the literature, the methodology incorporates some of the existing KFs, discards some others, proposes adapting others for the specific case of system installation, and suggests incorporating a few KFs that have not been mentioned before.

Therefore, the methodology described in this document analyses a total of 51 KFs critical to complex assembly processes which have been down-selected by comparing the literature review with the challenges identified in the initial assessment of the SIP (refer to section 3.2). The list has also been validated with industry experts when finalised.

3.3.1 Key Factors Divided into 4 Distinctive Groups

The literature reveals that there are three essential elements for a successful organisational transformation: process, people and technology. Due to the nature of the challenges in the aircraft system installation, a forth element (product) was incorporated to group the previously mentioned 51 Key Factors:

- **Product** group, for aspects of the product, subassemblies, components and their design.
- **Process** group, for aspects of the building sequence and operations.
- **People** group, for aspects of the human resources, ergonomics, training and experience.
- **Technology** group, which focuses on the technology and its characteristics.

Below, is a list of KFs in each of the four groups whose reasons for addition are explained in the following section:

- (01) **Product:** *type of system, material, shape of component, size of component, weight of component, flexibility of component, symmetry or exaggerated asymmetry, fragility, fit for purpose, identification of component, connection taxonomy, application of poka-yoke technique, quality certification, safety zone, and maintenance*.
- (02) **Process**: *value-addition, pre-/post- operations, level of automation, building sequence, duration, repetition, accuracy, level of stability, area of work, position of sub-assembly, tolerances and segregation distances, and precision*.

- (03) **People**: *number of operators, position of body, number of hands, position of arm, arm utilisation, position of head, level of visibility, level of access, training, experience, safety measures*.
- (04) **Technology**: *number of tools, passive/active classification, type of active tool, type of passive tool, type of operation, size of tool, weight of tool, level of innovation, power source/activation method, training requirement, experience requirement, efficiency of utilisation, technology share*.

Table 3-1: List of Key Factors in Methodology

KEY FACTORS			
01 PRODUCT	02 PROCESS	**03 PEOPLE**	**04 TECHNOLOGY**
01-01 Type of System	*02-01 Value Addition*	*03-01 Number of Operators*	*04-01 Number of Tools*
01-02 Material	*02-02 Pre/Operation/Post*	*03-02 Position of Body*	*04-02 Passive/Active*
01-03 Shape of component	*02-03 Manual/Semi/Auto*	*03-03 Number of Hands*	*04-03 Type of Active Tool*
01-04 Size of component	*02-04 Building Sequence*	*03-04 Position of Hands*	*04-04 Type of Passive Tool*
01-05 Weight of component	*02-05 Duration*	*03-05 Utilisation of Arm*	*04-05 Type of Operation*
01-06 Flexibility	*02-06 Repetition*	*03-06 Position of Head*	*04-06 Size of Tool*
01-07 Symmetry/Asymmetry	*02-07 Accuracy*	*03-07 Visibility*	*04-07 Weight of Tool*
01-08 Fragility	*02-08 Stability*	*03-08 Accessibility*	*04-08 Innovation Level*
01-09 Fit for purpose	*02-09 Area of Work*	*03-09 Training*	*04-09 Power Source/Activation*
01-10 Identification	*02-10 Position of Subassembly*	*03-10 Experience*	*04-10 Training Requirement*
01-11 Connection Taxonomy	*02-11 Tolerances and Segregation Distances*	*03-11 Safety Measures*	*04-11 Experience Requirement*
01-12 Poka-Yoke Technique	*02-12 Precision*		*04-12 Utilisation Efficiency*
01-13 Quality Certification			*04-13 Technology Share*
01-14 Safety Zone			
01-15 Maintenance			

For further information on each of these Key Factors, refer to A.5.

3.4 Short Description - Stages of Methodology -

The outcome of this project is a methodology that comprises of 3 stages aiming at creating a systematic procedure to assess the level of ease of which systems are installed and to capture improvement opportunities from the shop-floor perspective.

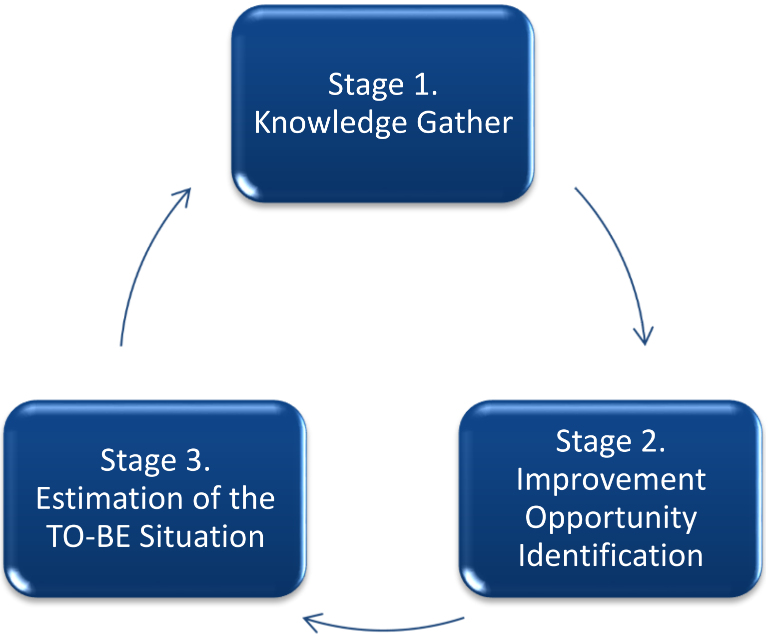


Figure 3-1: Stages of the Methodology

As represented in Figure 3-1, this approach is a circular model based on continuous refinement of the case-study process, and could be iterated around the cycle to improve and extend the results even further.

The following subsections describe each stage in greater detail.

3.4.1 Stage 1: Knowledge Gathering (AS-IS)

This first stage of the methodology is the most significant step as it aims at converting intangible concepts such as the shop-floor perception of the process into measurable and quantifiable indicators. The methodology provides a systematic approach to analyse a number of “key factors” (refer to section 3.3 for further information) and to identify which one’s influence in the ease or difficulty of the system installation process. The systematic approach is achieved with questionnaire (refer to section 3.5.1 for further information) which helps the capture of explicit and tacit knowledge.

In other words, the questionnaire guides the researcher who analyses the process by incorporating lean manufacturing and kaizen principles, by evaluating the value added in the process, and by analysing the current building sequence within the methodology. Along 51 questions (which correspond to the 51 Key Factors explained in section 3.3), the essence of these continuous improvement approaches is measured and quantified together with the influence of these 51 Key Factors into the SIP.

The knowledge gathering is carried out in two parts: Part A of the questionnaire gathers explicit knowledge on the system installation process (see attachment C.1) whilst Part B gathers tacit knowledge (refer to attachment C.2). Answers captured at Stage 1 of the methodology, as well as the comments that originated from each question, are stored in a database in a structured way and they contribute towards the generation of an AS-IS report.

It is important to remember that the questionnaire is not only a form to complete but also it provides the opportunity for the employee to expand upon their explanations, to have second thoughts about issues, or to learn from past mistakes. All this information will provide enough information to understand whether the Key Factors negatively or positively impact on the system installation process.

3.4.2 Stage 2: Improvement Opportunity Identification

With the AS-IS report generated with the replies in Stage 1, the methodology can facilitate identifying KFs positively impacting on the system installation process but more importantly, the ones which are most critical for their negative impact.

In general terms, the rule is that any KF scoring below 3 means that this specific KF is challenging (or negatively impacting) the system installation, and above 3 would mean that it eases (or positively impacting) the process. However, the rule is not applicable on many occasions without a correct interpretation of the comments and results.

The methodology identifies aspects of potential improvement and together with the involvement of the shop-floor operators, the researcher will be able to find improvement opportunity ideas (IOIs). These IOIs must be gathered directly from the shop-floor participants and, therefore, this stage also requires the collaboration of shop-floor employees.

On the basis that "*no idea is a bad idea*", every improvement opportunity is captured and stored in a database for a down selection in the next stage.

3.4.3 Stage 3: Estimation of the TO-BE situation

This stage of the methodology aims at measuring and quantifying the influence of selected IOIs would have to the perception of the *TO-BE situation* if they were to be implemented. In other words, amongst the improvement ideas captured and stored at the previous stage, some would be selected as improvement opportunities with a customised Project Selection technique based on the widely-spread Risk Management bubble diagram technique (Appendix D). Once selected, the methodology would guide the researcher to estimate the effect these changes would have if they would ever be implemented.

It is an exercise of estimating an inexistent future situation based on the experience, expertise and knowledge of the participant, and therefore, it is not an exact science. However, it would allow feeding back the knowledge, reacting in advance to challenges that might occur if similar changes were implemented, and also identifying which changes would bring further benefits to the system installation process.

Then, the methodology automatically creates a TO-BE report comparing both situations: AS-IS versus TO-BE. The effect of the selected IOIs are visualised and quantified in the new report, which again should be interpreted as appropriate.

3.5 Knowledge Gathering

The methodology utilises a questionnaire specifically designed for this methodology to capture information from the shop-floor employees. The questionnaire is divided into 2 parts: first one to capture explicit knowledge whilst the second one captures tactic knowledge (further information on section A.4.2). Nonetheless, the knowledge capturing techniques to fill this questionnaire are not the same in both parts of the questionnaire. The sections below present an in-depth description of the questionnaire, as well as the knowledge capture techniques utilised in each part.

3.5.1 Description of Questionnaire

The questionnaire has been designed to support and systematically guide the knowledge capture process. It has been designed to be as user-friendly and straight-forward as possible.

The questionnaire is divided into two parts: Part A (Appendix C.1) aims to capture explicit knowledge, and Part B (Appendix C.2) the tacit knowledge.

Although the questionnaire mostly consists of closed-ended questions in form of multiple-choice, it has a secondary intention of encouraging a sincere and trustworthy conversation between the author and participant, and gathering extensive information rather than simply getting a "*tick in a box*".

Nonetheless, questions are closed-ended as these are easier and quicker to answer, and also limit the answers, making it possible to treat data statistically. Most questions have been developed in the form of multiple-choice with only one possible answer. Nonetheless, depending on the nature of the KF, there are some exceptions where check-all-that-apply, multiple-choices, yes/no questions, or numerical answers are applied.

Part A: Explicit Knowledge Capture Questionnaire is the part of the questionnaire to capture explicit and measurable data. It has to be customised to suit each particular case-scenario. The data captured in this section is measurable and quantifiable. (Refer to 3.5.2 for explicit knowledge capture techniques utilised).

Part B: Tacit Knowledge Capture Questionnaire is a standard part of the questionnaire, same for all case-scenarios. It aims at capturing the subjective “perception of work” (PoW) of the shop-floor employee in a quantifiable manner (Refer to 3.5.3 for tactic knowledge capture techniques utilised).

It consists of closed-ended questions with ordinal scale answers ranked on a Likert scale (Likert, 1932). There are 5 answer options gradually ranked from 1 to 5, where, in terms of ease of installation, 1 is the worst case-scenario, and 5 the ideal case-scenario:

Answer 1. The KF under analysis *significantly challenges* the SIP.
Answer 2. The KF under analysis *slightly challenges* the SIP.
Answer 3. The KF under analysis *neither eases nor challenges* the SIP.
Answer 4. The KF under analysis *slightly eases* the SIP.
Answer 5. The KF under analysis *significantly eases* the SIP.

The participant must choose the option that best describes their reality.

In the following table, there is a summary of the types of question in each part of the questionnaire:

Table 3-2: Classification of Questions within Questionnaire

	Part A: Explicit Knowledge Capture				***Part B: Tacit Knowledge Capture***			
	Product	**Process**	**People**	**Techno.**	**Product**	**Process**	**People**	**Techno.**
Multiple-choice:	*4*	*6*	*9*	*10*	*1*	-	-	-
Check-all-that-apply:	*1*	-	*1*	-	-	-	-	-
Yes/No:	*5*	-	-	*1*	*1*	*1*	-	-
Numerical:	*2*	*1*	*1*	*1*	-	-	-	-
Likert Scale:	*1*	-	-	-	*10*	*8*	*10*	*10*
SUM	**13**	**7**	**11**	**12**	**12**	**9**	**10**	**10**

As observed in Table 3-2, Part A of the questionnaire has more varied questions than Part B. However, the answers to A are more objective and quantifiable than those in Part B, where the methodology is extracting the subjective perception. Except on rare occasions, the questions in Part B have been designed to follow the Likert scale. Other types of questions have been utilised whenever Likert scale questions did not make sense for the purpose of the KF.

It is possible to appreciate in Table 3-2, as well as in the questionnaire template (Appendix C), that sometimes there is no question for certain KFs. On some occasions, the question is not relevant or applicable to the context. For instance, the *appropriateness of design* KF cannot be captured from the explicit perspective, nor can the *value-addition* KF from the tacit perspective. For these cases, the PoW had to be calculated following a different procedure (refer to Section 3.6.2).

3.5.2 Explicit Knowledge Capture

Explicit knowledge capture has been carried out using three methods to be able to complete the questionnaire: *documentation, on-site observation* and *one-to-one storytelling.*

Documentation: most of the data was directly extracted from the sponsoring company's internal documentation dedicated to illustrate and describe the product and the production line. It was stored in a structured way following the part of the questionnaire dedicated to explicit knowledge capture.

Nonetheless, if there was information required not available in documents, it was obtained with **on-site observation** (Young, 2010). It is a process which involves observing, recording and interpreting the expert's knowledge while it takes place. The author observed the participant in his/her natural environment and captured the data to complete the questionnaire.

In addition, **one-to-one storytelling** (Young, 2010) had been used to capture further explanations directly from the shop-floor employees. It is a way of helping experts to date back to the origin of the failure or challenge.

3.5.3 Tacit knowledge capture

3.5.3.1 Selection of Participants

Participants collaborating in tacit knowledge gathering were a sample of shop-floor employees performing operations belonging to the SIP as well as their managers. After studying the nature of the process, the author realised that the participants' sample could not be selected randomly (when participants are chosen entirely by chance) or systematically (when participants are selected from a systematic sampling, i.e. equal-probability) for many reasons. On the one hand, there is a low number of employees dedicated to this process, and with a random or systematic selection of a sample, some experienced and knowledgeable participants could be missed. For that reason, it was decided to collaborate with as many participants as possible for each case-study to gather a better understanding of challenges.

The most appropriate collaborating participants were selected by their managers, in most cases including all employees involved in the installation process. However, all employees responsible for the installation of the systems in each case study engaged with the implementation. In short, a total of **22 employees** collaborated across three case-studies. These 22 employees were highly skilled production operators dedicated to install systems with varied level of experience and training.

3.5.3.2 Description of Tacit Knowledge Capture Techniques

Tacit knowledge was captured using a one-to-one structured interview on-site. This structured interview involved asking questions from a questionnaire to capture knowledge while the operator was on-site rather than in a meeting room. Most participants were interviewed individually face-to-face while performing their everyday tasks. The questionnaire, specifically developed for the methodology, ensured anonymity and confidentiality to all participants.

During the interview, the author asked each question from the questionnaire, taking notes of the selected answer, and allowing the participant to expand upon their responses if required. In some cases, participants provided examples and further explanation, which was also documented. This method of knowledge gathering also provided the opportunity to gather even more information through on-site observation and storytelling (Young, 2010).

The questionnaires were filled by the author as the participants were working at the exact moment the knowledge gather took place. Then, the complete questionnaire was shared with the participant, who had to agree with and own everything stated in it. This provides a structured way of capturing, measuring and analysing each of the KF from the participant’s point of view without interfering with their work.

Storytelling (Young, 2010) technique has been used to obtain a deeper understanding of participants’ perception of the work. They explore the main challenges of the SIP and the reasons why they occur. Interviews should be informal and take place during conversations to fill the questionnaire mentioned above.

Completion of the tacit knowledge gathering questionnaire took approximately 1 hour for each participant and operation. However, feedback from similar operations could be gathered simultaneously which reduces the overall capture duration considerably.

3.5.4 Modifications of the Questionnaire

In certain cases, the questionnaire must be modified to suit either the case-study or the information available within the company. Appendix C.3 includes two tables to describe some of the most probable modifications to Part A of the questionnaire, which is the *customisable questionnaire*. Table 6-1 includes the modifications normally required by the specific characteristics of a certain case-study such as type of connection, position of body or area of work, whereas Table 6-2 presents possible modifications used when information is not available within the company (for instance, dimension or weight of component).

3.5.5 Methods to Capture Improvement Opportunities

The stage of capturing IOs from participants (Stage 2) is probably the most important yet most challenging if the methodology is to capture first-hand the feedback from the shop-floor. The success of the whole systems depends on the quality of the IO captured and the ability to encourage creativity from the participants. Therefore, it is important to create a comfortable environment during the interviews, following the suggestions captured in the literature review so that they provide as much and high quality IO as possible.

This stage captures the shop-floor perspective on how they would personally improve their own situation by providing their own views and for their own benefit. This way, the process under analysis would be simplified, and the feedback from the shop-floor considered.

Once improvement areas are identified, the methodology again requires participant collaboration in order to learn of methods to improve the SIP from their perspective.

For each area of concern identified in the AS-IS report, the IO capture process should start with an open question, i.e.:

"*If you could do anything to the design of the component, what change would you incorporate that would allow you to improve the PoW of the SIP?*"

The success of this stage leans on the creativity and out-of-the-box thinking of the participant, as well as the skills of the interviewer in creating a suitable environment to allow participants to feel inspired and provide worthwhile feedback. If participants are unable to think of any recommendation, more specific questions must be asked, making reference to the four distinctive groups as well as specific KFs or operations within the process, i.e.:

"*Is there anything you'd change in the product/process/people/technology that could improve your perception of work?"*

or

"*How do you think the perception of the visibility KF could be improved in operation number 0150?"*

The interviewer must bear in mind that there is no useless IO. Every single IO must be captured at this stage, and stored in the database, even if it contradicts a previously captured IO. Each and every IO could lead to a new IO that was not previously considered and, therefore, none should be discarded.

The methodology provides a template to efficiently store IO within the database in an organised way. The template requires certain information that must be introduced for each of the IO (see example in Appendix E).

Data such as the objective of the IO (delete, modify, add), and the aspect they are improving (product, process, people, technology) will be required to fully understand the IO. Additionally, the participant needs to estimate the benefits of the IO as well as the negative impacts of introducing the change (last two columns). It must be as specific and rigorous as possible, considering as many KFs as conceivable, from both explicit and tacit perspectives. These estimations will be used to assess the effect of selected IO for future configurations.

The information obtained at this stage is confidential and anonymous, but if necessary, a code system can identify the creator of the IO. This information is to be destroyed once the selection of IOs is done.

3.6 Data Analysis and Calculation

3.6.1 How is the Data Analysed?

The explicit knowledge and tacit knowledge captured through the questionnaire are analysed differently. Answers from *Part A: Explicit Knowledge Capture Questionnaire* group operations according to the answers received. Answers from *Part B: Tacit Knowledge Capture Questionnaire* are utilised to calculate averages to determine the PoW.

Once both explicit and tacit knowledge are incorporated into the methodology, it automatically classifies operations, components or tools accordingly to the ratings obtained in the Tacit Knowledge Capture Questionnaire. It also calculates average PoW for each answer received in the explicit knowledge capture questions, and presents results from each KF in user-friendly diagrams. In this manner, the methodology aims at identifying IOIs by creating new knowledge based on how participants perceive the work. For an accurate analysis of results, user knowledge and interpretation is key.

3.6.2 How is the “Perception of Work” Calculated (Tacit Knowledge Capture Questionnaire)?

For each operation, shop-floor participants are asked to select the most appropriate answer to the tacit knowledge capture questions. Out of 5 possible options, they must select the one that best represents reality. This number corresponds to the perception of the participant towards the specific KF analysed in each question.

Ideally, the methodology should receive a homogeneous set of data. In order to do so, each participant is required to complete the one questionnaire in full for every operation under analysis. Depending on the magnitude of the case-study, it might not be possible to get answers within the time-scale. Some participant's answers might be missing, or some operations might not have received an equal amount of replies. Essentially, if complete homogeneity cannot be achieved, the appropriate action would be to obtain an equal amount of responses for each operation, and take it into consideration when interpreting results.

3.6.2.1 Calculating Perception of Work (PoW)

Operational Level

The operation level analysis refers to the type of analysis which looks at operations independently. With the responses received, the methodology calculates arithmetical averages for each KF with the answers received.

For confidentiality reasons, this section contains synthesised results to show how the calculations were done. For example, Table 3-3 summarises the answers selected by 6 individual participants regarding 3 questions (or Key Factors) for a particular operation.

Table 3-3: Synthesised Results (operational level)

	Question 1 (KF1)	Question 2 (KF2)	Question 3 (KF3)	Question 4 (KF4)
Participant 1	4	3	4	3
Participant 2	4	2	5	3
Participant 3	3	2	5	3
Participant 4	5	2	4	4
Participant 5	3	4	3	3
Participant 6	1	1	3	2

Perception of Work (PoW) for each question (KF) is be calculated with an arithmetical average:

(3-1) $$PoW_{KF_N} = \frac{1}{n}\sum_{i=1}^{n} P_i$$

where,
N: number of key factor
n: number of participants
P: perception of work

$$PoW_{KF1} = \frac{4+4+3+5+3+1}{6} = 3.33$$

$$PoW_{KF2} = \frac{3+2+2+2+4+1}{6} = 2.33$$

$$PoW_{KF3} = \frac{4+5+5+4+3+3}{6} = 4$$

$$PoW_{KF4} = \frac{3+3+3+4+3+2}{6} = 3$$

In cases where participants agree on how they perceive the work, the answers do not differ very much (rating 4, 5 or even 3). If the contrary happens, participants disagree on how they perceive the work, then the answers could be completely opposed. In order to identify disagreements, the methodology calculates variance as well, as it is an excellent measure of variability of responses:

$$s^2 = \frac{\sum(X_i - X)^2}{n-1}$$

KF1 → $s^2 = \frac{(4-3.33)^2+(4-3.33)^2+(3-3.33)^2+(5-3.33)^2+(3-3.33)^2+(1-3.33)^2}{6-1}$=1.867

KF2 → $s^2 = \frac{(3-2.33)^2+(2-2.33)^2+(2-2.33)^2+(2-2.33)^2+(4-2.33)^2+(1-2.33)^2}{6-1}$=1.067

KF3 → $s^2 = \frac{(4-4)^2+(5-4)^2+(5-4)^2+(4-4)^2+(3-4)^2+(3-4)^2}{6-1}$=0.8

KF4 → $s^2 = \frac{(3-3)^2+(3-3)^2+(3-3)^2+(4-3)^2+(3-3)^2+(2-3)^2}{6-1}$=0.4

A larger variance reflects a greater spread in the underlying data, which means that participants have not scored similarly and further investigation is needed to understand the reasons.

Once averages for each KF are calculated and the weighting system determined (refer to section 3.6.3 for further information on weighting system), the methodology automatically calculates PoW with a weighted arithmetic mean for the product, process, people and technology groups.

For instance, to calculate the PoW for the group *Product,* weights would be applied to calculate the average. Below, there is an example of results and its calculation assuming there are 4 questions in total for the Product KFs:

Table 3-4: Synthesised Results (Weighted PoW Calculation for Product)

	Question 1	Question 2	Question 3	Question 4
PoW each Question in Product	3.33	2.33	4	3
Weight of each Product KF	50%	20%	20%	10%

$$\overline{PoW}_{Product} = 3.33 * 0.5 + 2.33 * 0.20 + 4 * 0.20 + 3 * 0.10 = 3.231$$

The same calculation is done for the Process, People and Technology questions. The total PoW for an operation is also calculated the same way, taking into account the group PoW as well as the weights for each of them (further information on weight system on section 3.6.3):

Table 3-5: Synthesised Results (Weighted PoW Calculation for Case-Study)

	Product	Process	People	Techn.
PoW averages for Groups	3.23	3.16	1.25	4.79
Weight of each Group	50%	25%	15%	10%

$$\overline{PoW}_{Operation} = 3.23 * 0.5 + 3.16 * 0.25 + 1.25 * 0.15 + 4.79 * 0.10 = 3.07$$

Key Factor Level

The KF level analysis refers to the type of analysis that captures the evolution of the PoW of each KF throughout the operations under analysis. As shown in the equation (3-2), an arithmetical average is calculated, taking into consideration all the individual PoW to obtain the total average for each KF.

For confidentiality reasons, this section contains synthesised results to show how the calculations were done. For example, the table below summarises the average PoW calculated for a process involving 6 operations and 4 questions.

Table 3-6: Synthesised Results (key factor level)

	Question 1 (KF1)	Question 2 (KF2)	Question 3 (KF3)	Question 4 (KF4)
Operation 1	3.33	2.33	4.00	4.79
Operation 2	4.10	2.34	5.00	1.25
Operation 3	3.35	2.10	4.79	2.68
Operation 4	5.00	2.05	4.67	1.99
Operation 5	3.84	4.16	3.07	4.80
Operation 6	1.95	1.85	3.00	4.58

Overall PoWs for each KF are be calculated with an arithmetical average:

(3-2) $$PoW_{KF} = \frac{1}{N}\sum_{i=1}^{N} PoW_i$$

$$PoW_{KF1} = \frac{3.33 + 4.10 + 3.35 + 5.00 + 3.84 + 1.95}{6} = 3.59$$

$$PoW_{KF2} = \frac{2.33 + 2.34 + 2.10 + 2.05 + 4.16 + 1.85}{6} = 2.47$$

$$PoW_{KF3} = \frac{4 + 5 + 4.79 + 4.67 + 3.07 + 3}{6} = 4.09$$

$$PoW_{KF4} = \frac{4.79 + 1.25 + 2.68 + 1.99 + 4.80 + 4.58}{6} = 3.35$$

In addition, minimum and maximum PoW values are tracked for each KF (highlighted in table) and variance are also calculated to identify KFs whose perception has scored inconsistently.

$$s^2 = \frac{\sum(X_i - X)^2}{n-1}$$

KF1 → $s^2 = \frac{(3.33-3.59)^2+(4.10-3.59)^2+(3.35-3.59)^2+(5-3.59)^2+(3.84-3.59)^2+(1.95-3.59)^2}{6-1}$=1.02

KF2 → $s^2 = \frac{(2.33-2.48)^2+(2.34-2.48)^2+(2.10-2.48)^2+(2.05-2.48)^2+(4.16-2.48)^2+(1.85-2.48)^2}{6-1}$=0.72

KF3 → $s^2 = \frac{(4-4.09)^2+(5-4.09)^2+(4.79-4.09)^2+(4.67-4.09)^2+(3.07-4.09)^2+(3-4.09)^2}{6-1}$=0.78

KF4 → $s^2 = \frac{(4.79-3.35)^2+(1.25-3.35)^2+(2.68-3.35)^2+(1.99-3.35)^2+(4.8-3.35)^2+(4.58-3.35)^2}{6-1}$=2.48

3.6.2.2 Exceptions

Previous sections have mentioned that in some cases logic does not apply, and it makes no sense to analyse the KF from the explicit or tacit perspective. These cases are exceptions, and the PoW is calculated differently.

Part B of the questionnaire (People) has a separate part which aims at capturing the participants feeling from 10 different perspectives: *challenge, boredom, ease, complexity, satisfaction, fatigue, monotony, annoyance, comfort,* and *motivation*. Participants select from 1 to 5 (1 being minimum; 5 being maximum) how they perceive the mentioned aspects within each specific operation, and the average is utilised to calculate the PoW for the exceptions previously mentioned.

When calculating averages, it is important to note that a 5 of boredom, for instance, means that the participant perceives the operations as extremely boring but the answer does not represent the *ideal case-scenario.* Therefore, for *boredom, complexity, fatigue, monotony* and *annoyance,* averages must be calculated inversely.

3.6.3 Weighting System

In previous sections, a weight in the KFs has been mentioned. It seemed sensible to assume that some KF have more influence than others on the ease of the SIP. Furthermore, in the initial assessment carried out, the need for a weighting system was identified.

Formal multi-criteria analysis techniques usually provide an explicit relative weighting system for the different criteria, and for this specific type of processes, there are several reasons why a weighting system should be incorporated:

1. The nature of process under analysis determines importance of each criterion such as Product, Process, People and Technology, as well as of each key factor.
2. Substantial changes in the Product, Process, People and Technology in the process under analysis might affect the weight system initially determined.
3. Advances in the technology might have a greater effect in the process than the people performing operations
4. Experts' collaboration is necessary to determine the weight system. A consensus between several experts with different view could be translated into compromises in the weighting system different to what originally anticipated.

In order to take this influence into account, a weighting system is applied to KFs when calculating the PoW. However, the weighting system was incorporated by experts' consensus, knowledge and experience carefully selected for this purpose.

Different weighting methods have been considered to be applied in this thesis such as Analytic Hierarchy Process (AHP), which has a particular application in group decision making. This approach requires decision makers to evaluate by comparing two elements (Key Factors) at a time (Saaty, 2008). When having 51 elements to compare, this approach was discarded for being too time-consuming. Other group decision making techniques include Delphi Method, which insulates group members from the undue influence of others (Helmer, 1967). This was considered as a good approach for this specific case where professional interests would probably have influence in the weighting system.

The author finally decided that a combination of the traditional Decision Matrix with numerical weighting system would be the most convenient approach to determine the weighting system. However, the suggested insulation of group members described at the Delphi Technique was also done to determine the preliminary individual weightings.

The Decision Matrix, also called Pugh matrix or criteria-based matrix, attributes a maximum of 10 points among the criteria by consensus or discussion (Pugh, 1981). For this specific case, the author has decided to follow the steps below:

1. Researcher to Identify Key Factors
2. Experts to rate Key Factors' weights
3. Researcher to calculate overall weights for Key Factors

Influencing Key Factors had been identified and described in sections A.5 and 3.3.1. For the second step, the author has carefully selected certain stakeholders to independently rate the weighting system. These stakeholders were already familiar with the methodology as well as had both manufacturing and research perspectives. A workshop was carried out with each of them for this purpose. The final weighting system has been calculated at the third step, which is a unified weighting system taking into consideration all stakeholders' perspectives.

In general terms, experts agreed in most weights (refer to Appendix B). Even when they were brought together to discuss the final weights as suggested in Delphi Technique, they discussed and accepted them. In the few cases of discrepancies, the author referred to the initial assessment and introduced the weight suggested.

3.7 Outputs of Methodology

3.7.1 Description of the AS-IS Report

The AS-IS Report is a document where results from the knowledge gathering stages are visually presented in a user-friendly. It also allows the researcher to identify improvement areas within the process under analysis. Additionally, with the correct interpretation of results, it might also create new knowledge.

The report is created automatically once data is introduced to the methodology database, and provides a multi-level analysis, starting at a high level and going into further detail as it progresses. Firstly, there is a visual representation of the overall PoW for the whole case-study. A second diagram represents the average PoW for each of the four groups. Then, there are four subdivisions where KFs for each group are individually illustrated. Finally, a diagram provides detail of a selected operation.

The types of diagrams used in the AS-IS report have been carefully selected to provide as much information as possible in the simplest way. There are a variety of diagrams, which are described below, and with correct interpretation and understanding of the methodology, the user will be able to obtain very useful conclusions and improve the process under analysis.

The different types of diagrams included in the AS-IS report are described in the following subsections.

3.7.1.1 Bar Diagram

The vertical axis of the bar diagram shows the specific categories being compared, and the horizontal axis has been fixed with values starting from 1 to 5 as it represents the PoW. They provide a very clear visual representation of the current PoW, but do not present the root-cause of the issue, which is obtained with other diagrams.

Bar diagrams represent the PoW obtained for each KF as well as the Product, Process, People and Technology groups. These diagrams highlight Key Factors which negatively influence the SIP when the bar (towards number 1) is short but also when positively influence them when the bar is long (towards number 5)

The first bar diagram in the AS-IS report presents the whole project as well as individual average PoW for the product, process, people and technology (Figure 3-2).

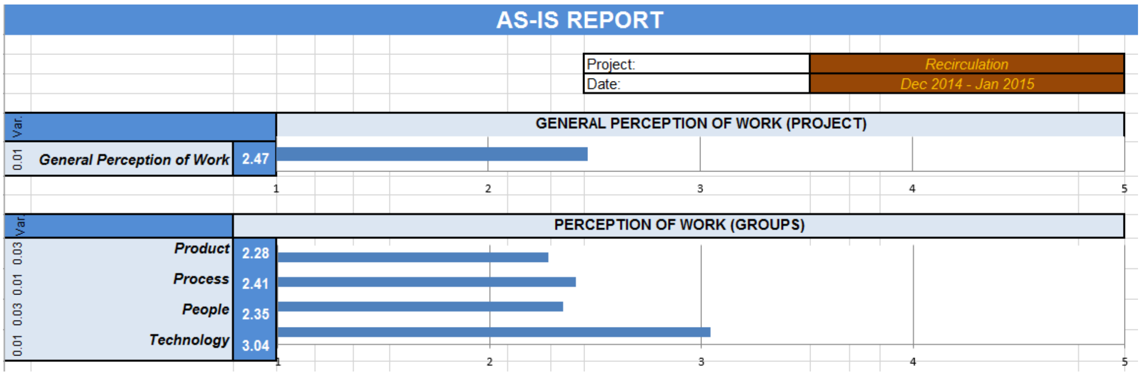


Figure 3-2: Bar Diagram (1)

Additionally, bar diagrams are used to present average PoW of all KF in each of the four groups. Each of the four groups has a bar diagram which comprises as many bars as KFs within the group (refer to Figure 3-3 as an example).

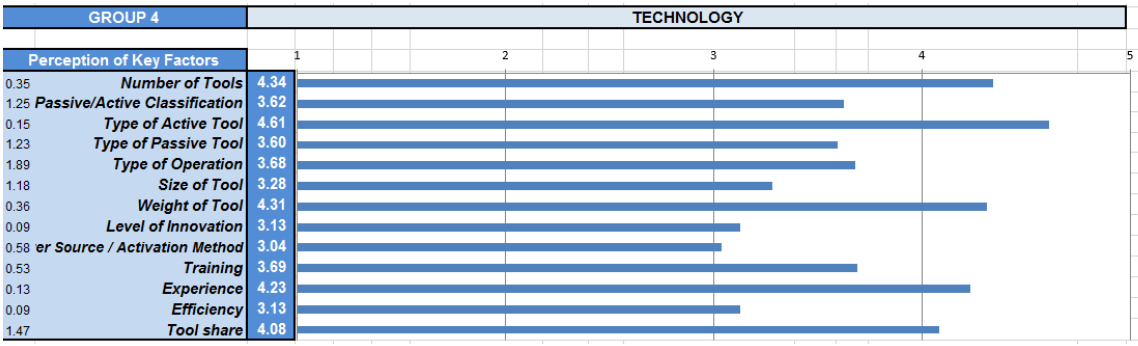


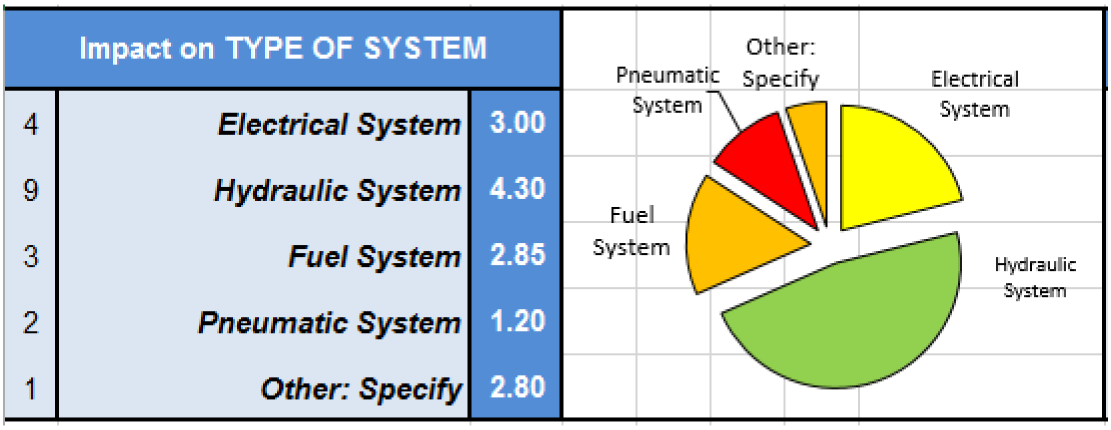
Figure 3-3: Bar Diagram (2)

The general guideline for interpreting these diagrams is as follows: any bar scoring lower than 3 will need further analysis whereas the closer to 5, the better perception it has received from participants.

On the left part of the graph, the variances had been introduced.

3.7.1.2 Pie Chart

Pie charts are utilised to provide a representation of results for each individual KF. It shows more in-depth information than bar diagrams because they classify possible responses in Part A (explicit knowledge) and calculates PoW received for each of the options. From a pie chart, the root-causes of issues can be identified.



Impact on TYPE OF SYSTEM		
4	*Electrical System*	3.00
9	*Hydraulic System*	4.30
3	*Fuel System*	2.85
2	*Pneumatic System*	1.20
1	*Other: Specify*	2.80

Figure 3-4: Pie Chart Example

For instance, Figure 3-4 represents the answers received for Questions A01.01 and B01.01. The column on the left represents how many responses were received for each of the answers (4 electrical system components; 9 hydraulic system; 3 fuel system components; 2 pneumatic system; 1 other). The column on the right calculates the average of the PoW received when participants have answered a particular option. The pie chart is a way to represent all the information in a visual way. The left column is translated into the arc length of a slice in the pie whereas the PoW is translated into the pie chart with its respective colour.

For the methodology, a colour system has been incorporated into the pie chart slices to provide additional information which otherwise would not be represented (PoW). The colour key is as follows:

Figure 3-5: Colour Key

The general guideline for interpreting these diagrams is as follows: any red piece-of-pie will further analysis and improvement whereas the greener it is, the better perception it has received from participants. Additional attention must be paid to the size of the piece-of-pie as it represents the frequency.

3.7.2 Description of the TO-BE Report

The TO-BE Report is a document where results from the AS-IS report are visually compared to the estimations captured in the previous stage (TO-BE). Additionally, this report can determine whether a selected IO does in fact improve the PoW of the process under analysis, or even if it indirectly affects other KFs. It is also an influential document in quantifying the benefits of incorporating certain re-design suggestions which could be used to improve the current system installation process but also to give some insights of how to solve shop-floor challenges in the future.

The document is automatically created once the benefits and negative impacts of selected IO are introduced to the methodology database. It also provides a multi-level analysis, starting at a high level and progressing into further detail, similar to the AS-IS report.

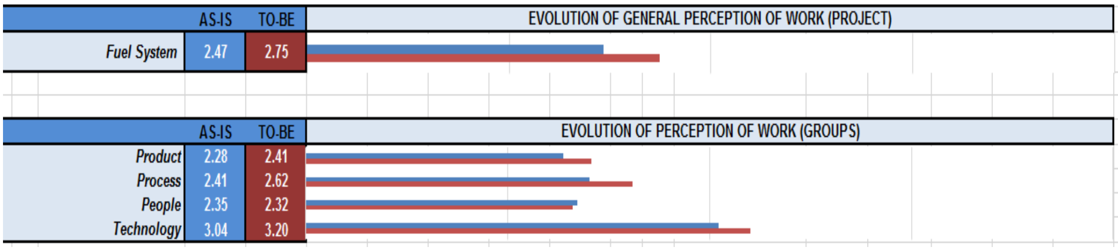
The type of diagram used in the TO-BE report has been carefully selected to provide as much information as possible in the simplest way. Only one type of diagram was most commonly used (described below), and with a correct interpretation and the right understanding of the methodology, the user will be able to obtain very useful conclusions.

3.7.2.1 Clustered Bar Diagram

Clustered bar diagrams are a modified version of the traditional bar diagrams described in 3.7. Instead of presenting one bar per category, it presents bars clustered in groups of two; one representing the AS-IS (blue), and the other representing the TO-BE (red).

Clustered bar diagrams provide a very clear visual comparison of both AS-IS and TO-BE perceptions and they in fact represent the impact that a selected IO would have on the current product development process.

The first clustered bar diagram in the report presents the whole project as well as individual average PoW for the product, process, people and technology (refer to Figure 3-6) for both AS-IS and TO-BE situations.



	AS-IS	TO-BE	EVOLUTION OF GENERAL PERCEPTION OF WORK (PROJECT)
Fuel System	2.47	2.75	

	AS-IS	TO-BE	EVOLUTION OF PERCEPTION OF WORK (GROUPS)
Product	2.28	2.41	
Process	2.41	2.62	
People	2.35	2.32	
Technology	3.04	3.20	

Figure 3-6: Clustered Bar Diagram (1)

Additionally, clustered bar diagrams are also used to present average PoW of all KF in each of the four groups (refer to Figure 3-7). Each of the four groups has a bar diagram which comprises of as many bars as KF within the group.

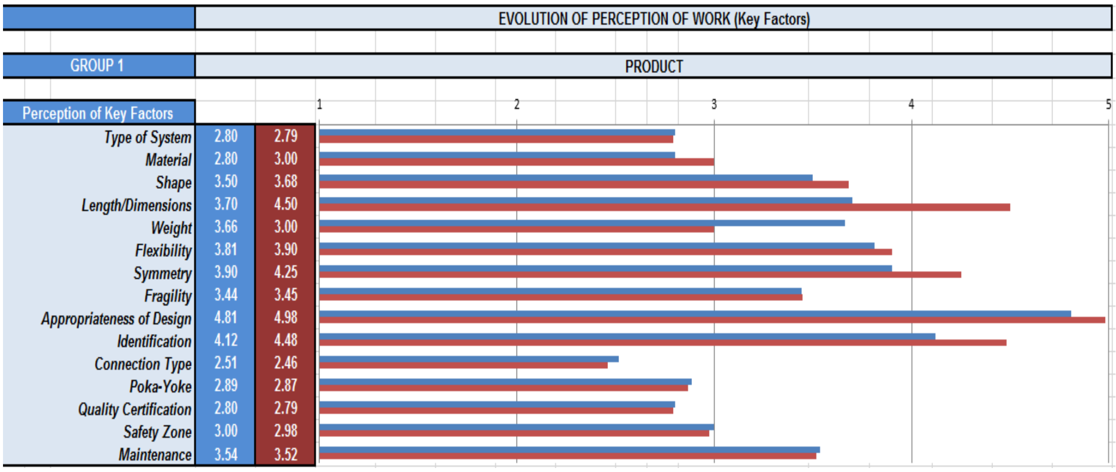


Figure 3-7: Clustered Bar Diagram (2)

Unlike in the AS-IS report, pie charts have been eliminated from the TO-BE report, as this particular report does not aim to identify the root-cause but only to present and to compare both situations. Therefore, the detailed level analysis in the TO-BE report is also represented by clustered bar diagrams (Figure 3-8).

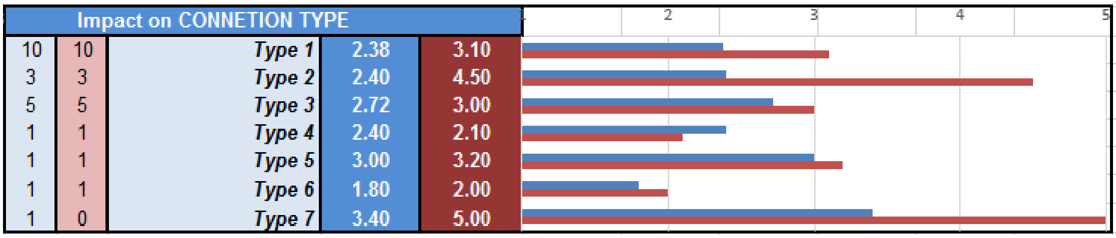


Figure 3-8: Clustered Bar Diagram (3)

The general guideline for interpreting these diagrams is as follows: any red bar scoring lower than the blue bar next to will need further analysis. If the opposite happens, it means the incorporated IO improves the perception of the KF directly or indirectly.

3.8 Insights of the Methodology Development Phase

The development of the methodology was more time consuming than expected. There was a continuous feedback between the author and the industrial stakeholders when selecting the Key Factors. This helped ensure that the selected Key Factors were the right ones to include within a System Installation focused methodology.

Also, the questionnaire development planned had also been extended in order to make sure the right wording was selected and correction where required during initial interviews to suit the case-scenarios more appropriately.

Whilst these challenges introduced significant delay in this stage of the research, the overall outcome justified the extra time dedicated to the development of the methodology.

Nonetheless, regardless of these challenges, the author has achieved a methodology which takes a more global view of the aircraft system installation by analysing and understanding challenges and improvement opportunities directly from the affected parties: the shop-floor employees. The following section 4 presents the results of implementing this methodology in 3 case-studies together with its interpretation to certify the last statement.

4 METHODOLOGY IMPLEMENTATION

The methodology has been tested and evaluated in three real case-studies of a leading aerospace company. Two were industrial case-study projects that are currently in production: a partial installation process of the fuel system, and the installation of flap beams. The third case-study, which is a process of incorporating a technology in research state, incorporates an important technological improvement suggested by many participants in the flap beam installation, and has been in research for several years.

Below is a description of the implementation process of all three case-studies.

4.1 Case-studies on Projects Currently in Production

In this section, the implementation of two case-studies has been described on projects that are currently in production; the first one refers to a partial installation process of the fuel system (4.1.1), and the second case-study analyses the installation process of the flap beams (4.1.1.4.2).

4.1.1 Case-study 1: Fuel System

The first case-study to implement and test the methodology was a partial installation of the fuel system. Fuel system components, as well as the rest of systems, are installed within the aircraft wing once the structure is finalised. Therefore, the space available to access the assembly point is very limited, and in some cases, it requires the operator to squeeze into the structure to install the component. Thus, the process involves some ergonomic challenges positions due to the limited access and visibility to the assembly point, amongst other factors.

The participant sample included **7 shop-floor employees** involved in the fuel SIP of varying experience, skill and age.

4.1.1.1 Preparation for Methodology Implementation

The case-study's **boundaries** have been defined by the author and stakeholders from the sponsoring company. Both agreed that this specific partial installation of the fuel system would clearly highlight many of the challenges shop-floor employees face.

The sponsoring company's internal documentation included 34 operations as part of this case-study, from which only 24 referred to systems (4 electrical system; 20 fuel system).

Technologies under analysis were described in the sponsoring company's internal process documents, although the author incorporated information not included in the official documentation by observing the production line.

The **building sequence** has also been extracted from the sponsoring company's internal documentation. The intention was to identify if there is a re-sequencing opportunity in the current building process.

4.1.1.2 Stage 1: Knowledge Gathering

4.1.1.2.1 Explicit Knowledge

Explicit knowledge gathering has been carried out as described in section 3.5.2: obtaining the required information from internal documents and reports.

However, the author faced various challenges during this process due to the limited access of the author to some of the sponsoring company's internal documents, it has been challenging to get some reports where the required information was described (*shape of component, area of work, repetition, value addition, weight and dimensions of component, size and weight of tools, etc.*). Therefore, the missing information had been obtained directly from the production line, by physical measurement or interviewing knowledgeable employees.

In addition, the questionnaire had to be modified to suit the specific case-study of fuel system installation. Questions A01.11, A02.09 and A03.02, for example, required modifications (refer to attachment).

- Question A01.11 – *Type of Connection*: the types of connectors in each case-study is vary, and therefore the answer options had to be modified to reflect the most common connection types in the fuel system. The question now includes *connector, adaptor, clamps, brackets, mounting block,* and *deflector plate* as answer options.

- Question A02.09 – *Area of Work*: the area of work varies depending on the system being installed, therefore, answer options had to be modified to cover all the areas within the sub-assembly where operations take place. The question now includes *away of the wing* and several different *inside the wing* options to choose from.
- Question A03.02 – Position of Body: answers for this question, as well as for any other ergonomic aspect-related questions, had to be modified to cover all ergonomic positions that take place within the installation process. The question now includes *sitting on a chair, sitting on the floor,* and several different *standing up* positions.

In the attachment C.3, there is a list of questions that are likely to require modification. Additionally, the template questionnaire can be located in Appendix C.

4.1.1.2.2 Tacit Knowledge

Tacit knowledge gathering has been carried out by applying the methods described in section 3.5.3 and interviewing participants following Part B of the questionnaire.

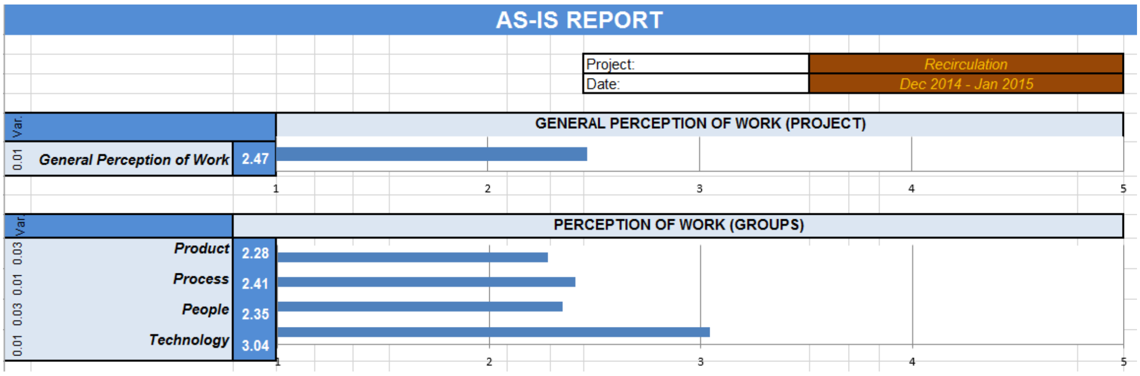
On some occasions, it was difficult to interview participants in their usual working environment, and due to the nature of the process, it proved easier to measure the impact of KFs by comparing operations to each other rather than analysing operations individually. Therefore, participants were individually interviewed in a quiet area, and the questionnaire was followed comparing the PoW between similar operations.

Nonetheless, Part B of the questionnaire did not involve any modification for this specific case-study.

4.1.1.2.3 AS-IS Report: Interpretation of Results

This section is an overview of the AS-IS report for the fuel system installation CS, which highlights the main areas of concern as well as providing a discussion on the results obtained.

The initial part of the AS-IS report shows that this project has obtained an overall PoW of 2.47.


AS-IS REPORT

Project: Recirculation

Date: Dec 2014 - Jan 2015

Figure 4-1: CS1 Overall PoW (AS-IS)

A similar conclusion can be extracted from the product, process and people groups, all scoring slightly below 2.50. The technology group is the exception. It scored a 3.04 PoW, showing that designers are aware of the importance of some KFs in the tools.

The AS-IS process also provides a deeper analysis into the KFs in each group, which is essential to justify the scores and to understand the root causes of the challenges faced by operators.

4.1.1.2.3.1 Product Analysis

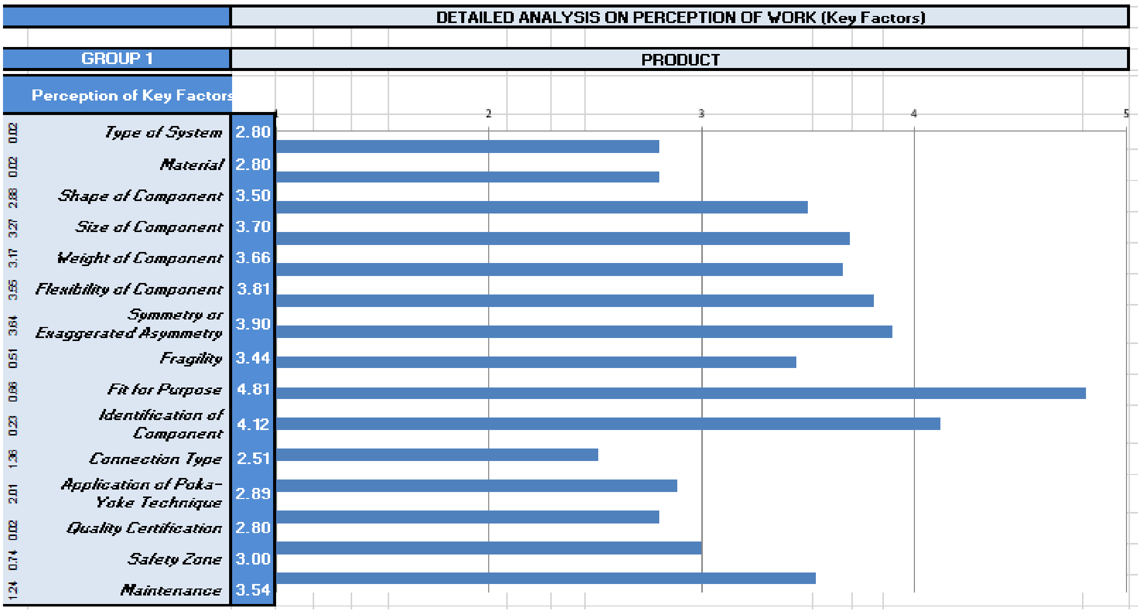
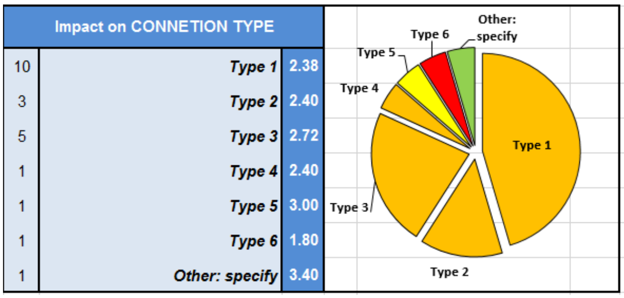


Figure 4-2: CS1 Product PoW (AS-IS)

Figure 4-2 provides a high level analysis of each KF in the product group, highlighting the areas of concern as well as positive utilisation of factors. The column on the left presents the variances for each KF.

On the positive side, *fit for purpose* (4.81) as well as *identification of component* (4.12) obtained high PoW, meaning that these aspects ease the SIP, both with low variances. Components are perceived as appropriately designed and well identified, and therefore, participants do not feel the need to modify them to ease the installation. On the negative side, the diagram highlights *type of connection* (2.51) and *poka-yoke application* (2.89) as areas of concern. However, both obtained high variances. In order to understand the root cause of those areas of concern, the AS-IS report must be analysed in more depth.

The **detailed analysis** section offers some interesting conclusions. A KF which scored significantly high PoW was the fact of applying *symmetry or exaggerated asymmetry* in a component's design. Although the difference in PoW is not remarkable (3.75 symmetric components; 3.88 asymmetric components), the results conclude that neither designers nor participants feel that symmetric or exaggeratedly asymmetric components should be implemented in aircraft systems in order to ensure safety and prevent human installation errors in the installation.



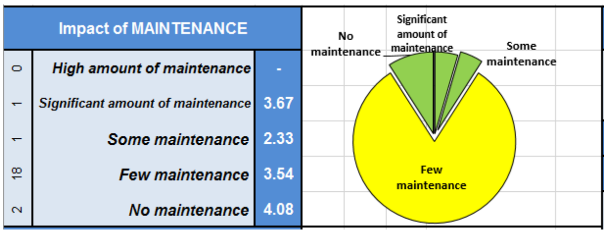
	Impact on CONNETION TYPE	
10	*Type 1*	2.38
3	*Type 2*	2.40
5	*Type 3*	2.72
1	*Type 4*	2.40
1	*Type 5*	3.00
1	*Type 6*	1.80
1	*Other: specify*	3.40

Figure 4-3: CS1 Connection Type (AS-IS)

Interesting conclusions were also extracted from KF scoring low. *Connection type*, for instance, shows that the PoW obtained for each of the various types of connection diverges (refer to Figure 4-3). Some connection types are perceived more possitively than others, highly recommending a design change in the connection types 1, 2, 3, 4 and 6.

Results obtained from the application of the *poka-yoke technique* (2.89) have been classified as not representative since participants are not familiar with the Japanese technique, and are not able to say with a high level of accuracy whether a component was error-proven or not.

Some additional interesting conclusions were also identified regarding the following factors:

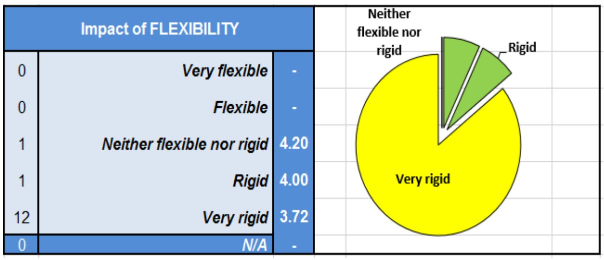


	Impact of MAINTENANCE	
0	*High amount of maintenance*	-
1	*Significant amount of maintenance*	3.67
1	*Some maintenance*	2.33
18	*Few maintenance*	3.54
2	*No maintenance*	4.08

Figure 4-4: CS1 Maintenance (AS-IS)

According to the results, participants generally perceive with more regard the installation of electrical system components (2.87) than fuel system components (2.79) both with low variances (0.33 and 0.10 respectively). Additionally, new knowledge was created when observing that operations needing *some maintenance* scored lower PoW than operations requiring a *significant amount of maintenance* (refer to Figure 4-4). It is very interesting to see that when more maintenance operations are required, the more participants feel it eases the SIP.

Moreover, Figure 4-5 shows that the installation of *very rigid* components is perceived more positively than *rigid* or *neither rigid nor flexible* components. These discoveries provide the company very useful feedback



	Impact of FLEXIBILITY	
0	*Very flexible*	-
0	*Flexible*	-
1	*Neither flexible nor rigid*	4.20
1	*Rigid*	4.00
12	*Very rigid*	3.72
0	*N/A*	-

Figure 4-5: CS1 Flexibility (AS-IS)

4.1.1.2.3.2 Process Analysis

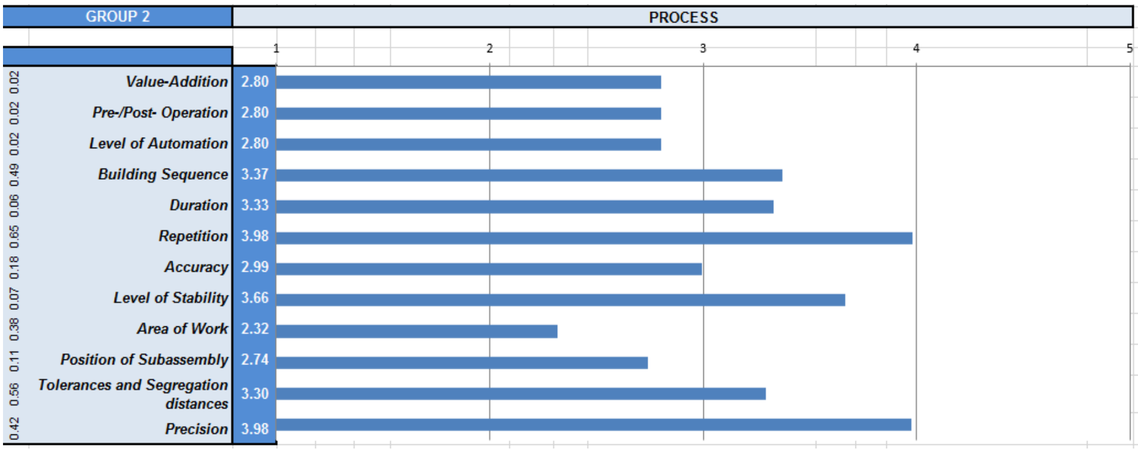
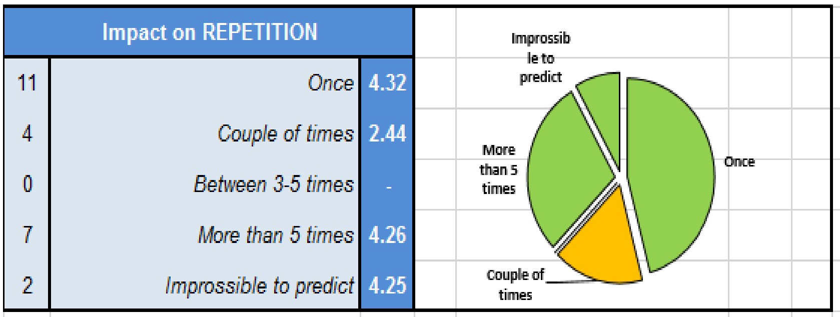


Figure 4-6: CS1 Process PoW (AS-IS)

Figure 4-6 manifests how well participants perceived the factors of *precision* and *repetition* of operations, scoring slightly below 4. Nonetheless, a correct interpretation of results together with a more detailed analysis identifies both factors as main areas of concern.

Building sequence (3.37), *duration* (3.33), *stability* (3.66) and *tolerances* (3.30) are KFs which obtained modest PoW, suggesting those aspects enhance the SIP. They also obtained low variance which means that participants rated similarly. The main areas of concern were, however, *area of work* (2.32) and the *position of the sub-assembly* (2.74). In order to understand the root cause of those areas of concern, the AS-IS report must be analysed in more depth.

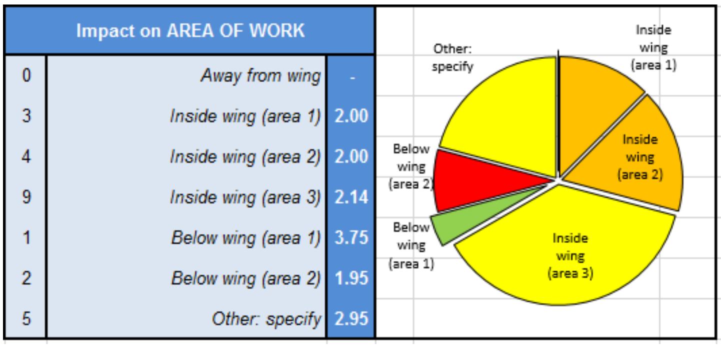
The **detailed analysis** section provides details on why the *repetition* results are not consistent (Figure 4-7). It is interesting to see that participants feel more confident repeating the operation *more than 5 times* (4.26) rather than just twice (2.44). It is also curious that the operations whose repetition times are impossible to predict affects other operations downstream. Therefore, it is safe to say that the high perception of repetition is due to the familiarisation of participants with the process rather than identifiying repetition of operations as a factor that eases the installation process.



	Impact on REPETITION	
11	*Once*	4.32
4	*Couple of times*	2.44
0	*Between 3-5 times*	-
7	*More than 5 times*	4.26
2	*Impossible to predict*	4.25

Figure 4-7: CS1 Repetition (AS-IS)

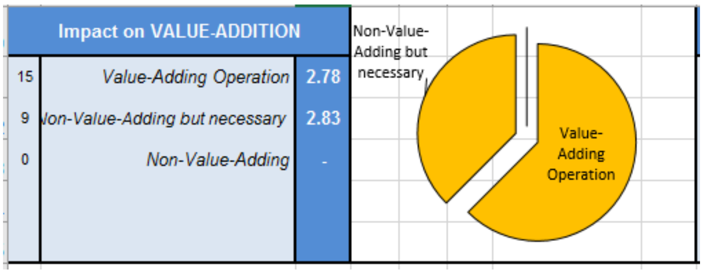
The fact that some KF scored lower PoW also provides interesting insights. The classification according to *area of* work, for instance, shows areas which are perceived more positively than others (Figure 4-8). It is interesting to highlight that participants find that *below the wing* is the most challlenging and easy area at the same time. When working *inside the wing* (between 2.00-2.14), however, participants agreed that this area needs to be a focus of improvement.



	Impact on AREA OF WORK	
0	*Away from wing*	-
3	*Inside wing (area 1)*	2.00
4	*Inside wing (area 2)*	2.00
9	*Inside wing (area 3)*	2.14
1	*Below wing (area 1)*	3.75
2	*Below wing (area 2)*	1.95
5	*Other: specify*	2.95

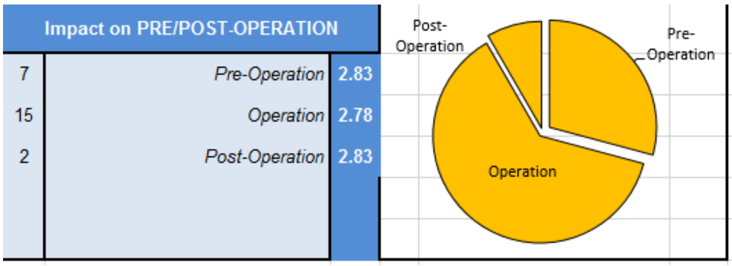
Figure 4-8: CS1 Area of Work (AS-IS)

The methodology identifies *value-addition* and *pre-/post- operations* as challenging. In fact, unexpectedly high PoW were obtained for *non-value-adding activities* (2.83) compared to *value-adding operations* (2.78) and, consequently, *pre- and post- operations* also obtained an unexpected 2.83 (Figure 4-9 and Figure 4-10). Nonetheless, the focus in this case-study is to delete as many non-value-adding operations as possible.



	Impact on VALUE-ADDITION	
15	Value-Adding Operation	2.78
9	Non-Value-Adding but necessary	2.83
0	Non-Value-Adding	-

Figure 4-9: CS1 Value-Addition (AS-IS)



	Impact on PRE/POST-OPERATION	
7	Pre-Operation	2.83
15	Operation	2.78
2	Post-Operation	2.83

Figure 4-10: Pre-/Post- Operations

The *level of automation* also provided some very interesting conclusions. The more automated the operation is, the better PoW scored. However, *semi-automatic* or *completely automatic* operations are either very few or non-existant and, therefore, this is an area which needs further automation improvements.

4.1.1.2.3.3 People Analysis

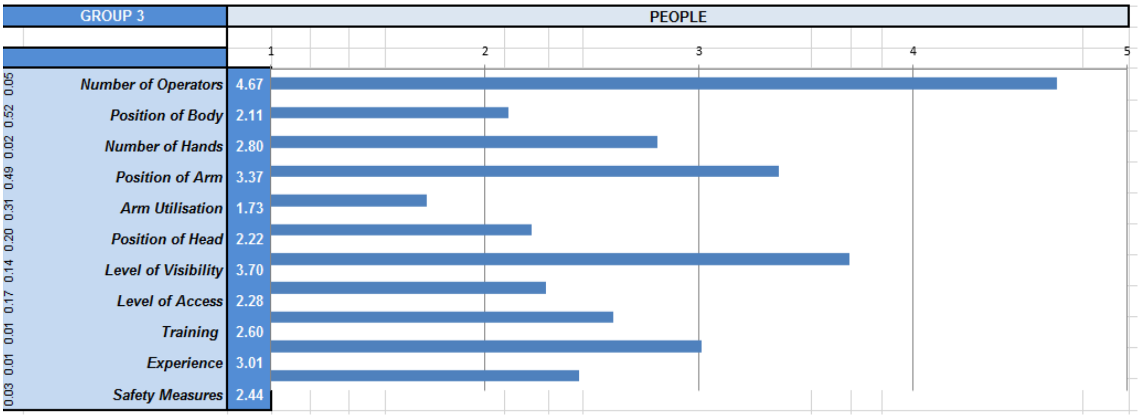


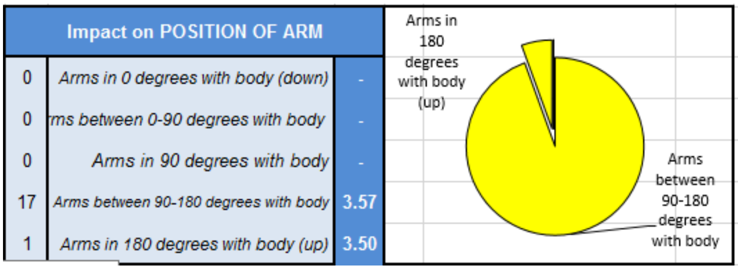
Figure 4-11: CS1 People PoW (AS-IS)

Figure 4-11 displays that the best results were scored in the *number of operators* KF*.* The impressive PoW (4.67) shows the number of operators involved in the operations is close to ideal. Other KFs scored above 3, such as *position of arm (*3.37) and *visibility* (3.70). It is interesting to see that, even though most operations are performed inside the wing where visibility is very limited, it has been perceived quite positively. On the negative side, *arm utilisation* (1.73), *position of body* (2.11), *position of head* (2.22) and *access* (2.28) are identified as the most challenging factors. The remaining of factors, also challenging, scored between 2.40-3, and also need further attention.

The AS-IS report provides a more **detailed analysis** of the KF related to people. Regarding the *number of operators,* it is clear that participants feel that the amount of operators currently involved in each operation significantly eases the SIP, regardless whether it is just one or two. In fact, participants feel more comfortable when operations involve one person (4.74) compared to two people (4.40). As a result, the methodology identifies that reducing the involvement of operations might be benefitial for fuel system installation.

As mentioned before, both *level of visibility* and *position of arm* scored high PoW but further analysis and interpretation of results is crucial. It is important to understand that the majority of the operations are performed inside the wing using an aid to improve visibility. Withouth this aid, the PoW would probably have scored considerably lower results, and therefore, current results are not strictly conclusive.

Regarding the position of arms, Figure 4-12 provides interesting results: some positions of the arm (*arms up*) are only slighlty less comfortable than others (*arms 90-180 degrees with body*), when common sense would expect the difference in the perception of comfort would be more significant.

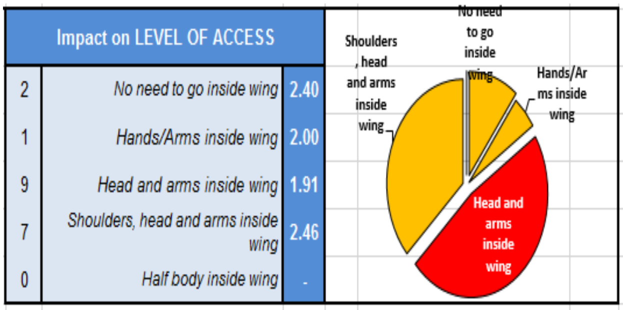


Impact on POSITION OF ARM		
0	*Arms in 0 degrees with body (down)*	-
0	*rms between 0-90 degrees with body*	-
0	*Arms in 90 degrees with body*	-
17	*Arms between 90-180 degrees with body*	3.57
1	*Arms in 180 degrees with body (up)*	3.50

Figure 4-12: CS1 Position of Arm (AS-IS)

Additionally, results suggest that the fuel system was not originally intended to ease either the ergonomic aspect or access to the assembly point. Even though both results were low, participants selected a significantly higher PoW (2.40) in operations where they use *the thumb and fingertips* rather than the *wrist* (1.52), for instance. Also, participants perceived the work to be slighlty easier when *standing up* (1.96) than *sitting down* (1.93) with a variance of 0.66 and 1.50 respectively. This might be a results of inappropriate seating being utilised for specific highly challenging ergonomic positions. For instance, participants felt *looking slightly up* to be more comfortable (2.20) than *slightly looking down* (2.01), which is also interesting. All the above aspects and findings should prompt designers to consider them during the early stages of development.

Another interesting discovery is related to the *level of access* (Figure 4-13). The methodology identifies issues with it, especially when both *head and arms are inside the wing* (1.91), and even more when only *arms and hands* are inside the wing



Impact on LEVEL OF ACCESS		
2	*No need to go inside wing*	2.40
1	*Hands/Arms inside wing*	2.00
9	*Head and arms inside wing*	1.91
7	*Shoulders, head and arms inside wing*	2.46
0	*Half body inside wing*	-

Figure 4-13: CS1 Level of Access (AS-IS)

(2.00). Curiously, when there is enough space to also introduce the *shoulders*, the PoW increases to 2.46, and the perception is also very low when participants do not need to go *inside the wing* (2.40).

If these ergonomic results are compared with the RULA (Rapid Upper Limb Assessment) tool (Ergonomics Plus Inc., -), which is a tool to evaluate upper extremity risk factors, there are certain results (such as working with arms up or slightly looking up) which would be considered as risk factors whereas the participants feel more comfortable than in any other position.

4.1.1.2.3.4 Technology Analysis

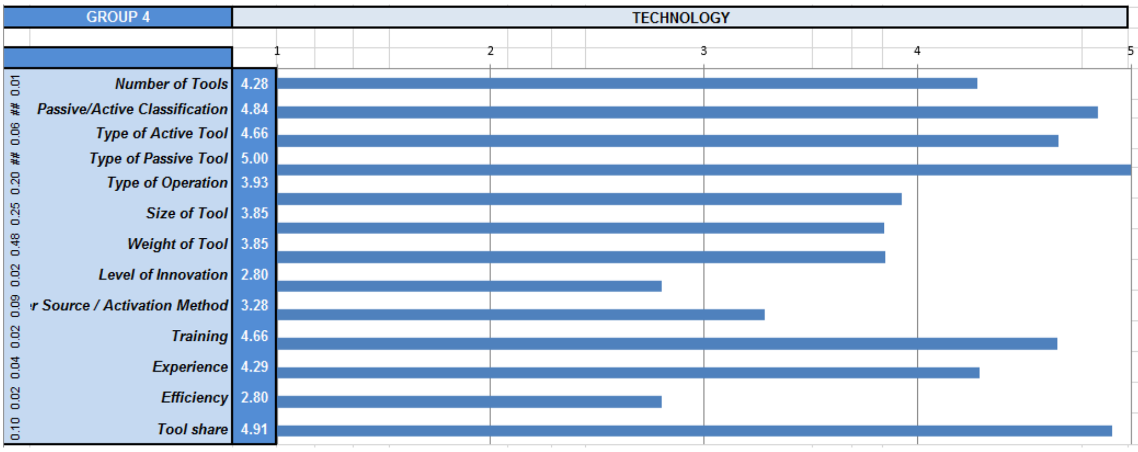


Figure 4-14: CS1 Technology PoW (AS-IS)

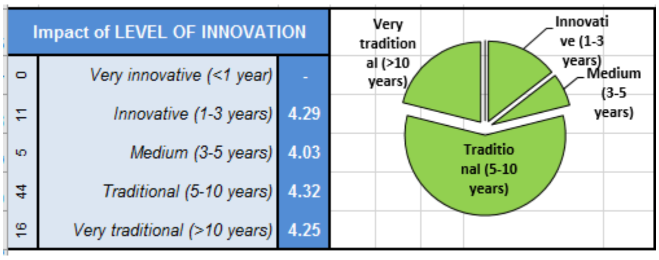
Figure 4-14 shows the results from all KF, highlighting *passive tools* (5.00) and *active tools* (4.66) as the best perceived. Apparently participants mentioned that both types of tools significantly ease the SIP. Participants also find *technology share* (4.91) and *training* (4.84) above average, both with very similar low variances. Nonetheless, factors such as *innovation level* and *efficiency* (both 2.80) are the main areas of concern with a consensus between participants.

The more **detailed analysis** section in the AS-IS report provides further information on both positively and negatively impacting KFs. As mentioned before, both the *type of passive* and *active* tools scored high PoW. Amongst the active tools utilised, the *vacuum cleaner* and *transport tools* (both 5.00) obtained the highest PoW, whereas tools to *apply paint or sealant* (4.25) obtained lower scores. Nevertheless, it is important to mention that most tools are traditional, and therefore participants might be accustomed to using them.

Additionally, participants find an operation more challenging when they *do not need to share the tool* (4.99) compared to those operations where tools *are shared* (4.98). There was, however, a greater disagreement between participants with shared tools (variance 2.14) than not sharing (0.55). The difference is, however, insignificant, and discards *technology share* as a factor to improving fuel system installation.

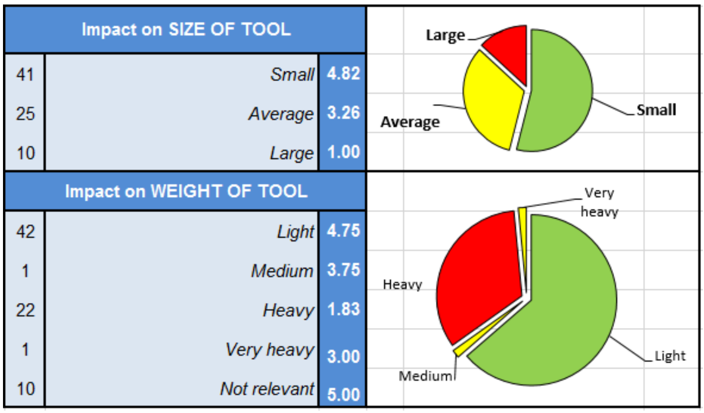
Among the KFs obtaining negative results, the *efficiency* showed interesting conclusions. Curiously, tools used with a *60-80% efficiency* have lower PoW (2.78) than those which are used more (2.80) or even less often (2.83 with a *40-60%* efficiency; 2.95 with a *20-40%* efficiency).

Additionally, the *level of innovation* (Figure 4-15) of most tools is *very traditional* (4.25) or *traditional* (4.32), and the PoW is expectedly higher than that of tools that are more *innovative* (4.03). This result reflects that participants are either not familiar with the metrology assisted technology selected for this case-study, or that the solution is not suitable for the application.



	Impact of LEVEL OF INNOVATION	
0	*Very innovative (<1 year)*	-
11	*Innovative (1-3 years)*	4.29
5	*Medium (3-5 years)*	4.03
44	*Traditional (5-10 years)*	4.32
16	*Very traditional (>10 years)*	4.25

Figure 4-15: CS1 Level of Innovation (AS-IS)



Impact on SIZE OF TOOL		
41	*Small*	4.82
25	*Average*	3.26
10	*Large*	1.00

Impact on WEIGHT OF TOOL		
42	*Light*	4.75
1	*Medium*	3.75
22	*Heavy*	1.83
1	*Very heavy*	3.00
10	*Not relevant*	5.00

Figure 4-16: CS1 Size & Weight of Tool (AS-IS)

Moreover, the *size* and *weight* of the technology utilised are the most questionable factors. Results highlight that *large* (1.00) and *heavy* (1.83) tools scored lower PoW than *average* (3.26) or *small* (4.82) tools. However, unexpected results were obtained in *very heavy* tools, which achieved 3.00 PoW. Therefore, further investigation is needed to identify *very heavy* tools, and investigate the reasons why it was perceived this way in order to be able to suggest IOs.

4.1.1.3 Stage 2: Capture Improvement Opportunities

The AS-IS report identified certain areas to focus. From those, a total of 59 IOs have been extracted from participants, most of them aiming at improving the PoW of the technology (32) but also the product (11) or process (13). Very few suggestions were captured from the people perspective (3). It was also identified that the majority are focused on modifying the current situation (50) rather than adding a new innovation (5) or deleting a solution that does not work anymore (3).

These have been stored in a predefined table (see template in attachment Appendix E). In addition, in cases where the IO did not directly involve a re-design to improve the perception, participants were asked to modify the IO so that it could provide useful for continuous improvements of the current SIP but also give insights of the challenges faced in the shop floor in order to avoid them in future aircrafts.

For instance, one participant believes that a specific mechanical tool they currently utilise is too heavy and long to handle it with ease inside the wing. Therefore, the IO extracted from that area of concern is to incorporate a new tool which is lighter and shorter, without losing its technical capabilities.

However, this IO provides feedback for manufacturing engineers instead of the design department, and so becomes redundant for this methodology. Thus, the guideline for designers extracted from this IO is "*make sure that in critical areas of the wing, there is enough access, visibility and space to be able to install components using only one operator and with the technology available*", covering that area of concern from the design perspective.

Due to company confidentiality, captured improvement opportunities could not be listed in this thesis.

4.1.1.4 Stage 3: Estimation of the TO-BE Situation

For each IO, participants have determined to what extent it benefits the PoW of the SIP and has also estimated the negative impact following the procedure described in Section 3.5.5. Then, the TO-BE Report was interpreted.

4.1.1.4.1 Selecting IO and Estimating Improvement

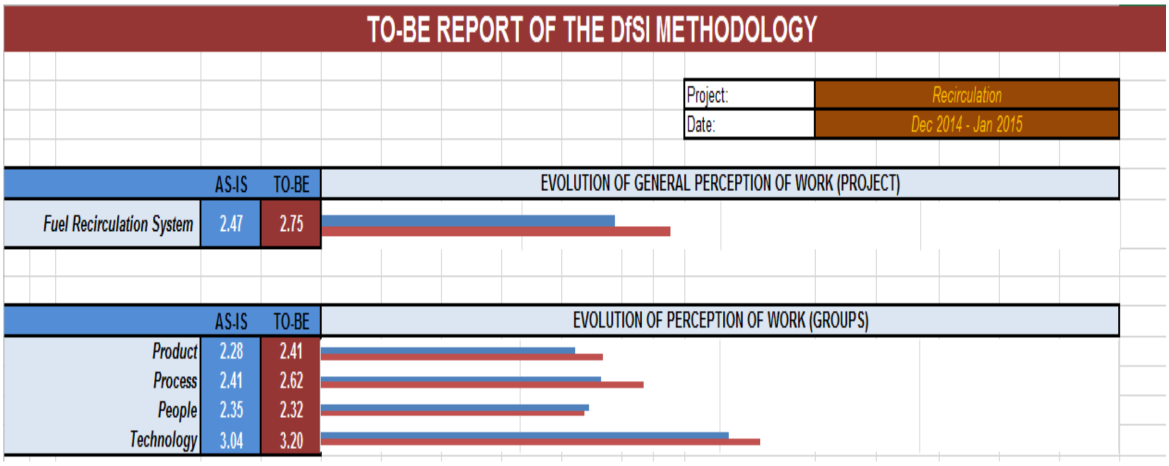
Among all IO identified, participants have selected 32 IO to visualise and measure the effect of the selected re-design changes and technology incorporations in the current project. Due to confidentiality, these improvement opportunities cannot be detailed. However, the estimated benefits and negative impacts of each of the selected IO has been incorporated into the methodology database, and the results have been illustrated in the TO-BE report. Additionally, a list with guidelines for designers have been created as an outcome from this stage (refer to Section 4.1.1.4.2).

4.1.1.4.2 TO-BE Report: Comparing AS-IS and TO-BE situations

In Stage 3 of the methodology applied to this particular case-study, participants identified 59 IOs, from which 32 have been selected with the bubble diagram technique (Appendix D) as potentially implementable in the future.

Amongst changes to incorporate into the current product development, there are suggestions to modify the current product design in several areas, improving identification of connectors as well as their design, remove operations, modify the building sequence in specific applications, modify methodology used to perform one operation, formally add an extra operator in certain operations, increase the number of tools, and improve current technology to fit the access and space limitations of the design.

The TO-BE report described below highlights the benefits and inconveniences of incorporating these 32 suggestions.



TO-BE REPORT OF THE DfSI METHODOLOGY

Project: Recirculation
Date: Dec 2014 - Jan 2015

	AS-IS	TO-BE	EVOLUTION OF GENERAL PERCEPTION OF WORK (PROJECT)
Fuel Recirculation System	2.47	2.75	

	AS-IS	TO-BE	EVOLUTION OF PERCEPTION OF WORK (GROUPS)
Product	2.28	2.41	
Process	2.41	2.62	
People	2.35	2.32	
Technology	3.04	3.20	

Figure 4-17: CS1 Overall PoW (TO-BE)

If the previously mentioned 32 IO are incorporated, participants have estimated several improvements: the number of operations within the fuel system installation would be reduced from 24 to 22, and the duration of the process would be reduced by 17%. These IOs would increase the overall PoW for the case-study as well as product, process and technology. As a downside, the people PoW would drop slightly, as shown in Figure 4-17.

An analysis on the **product** (Figure 4-18) shows the several changes that would take place in this new situation:

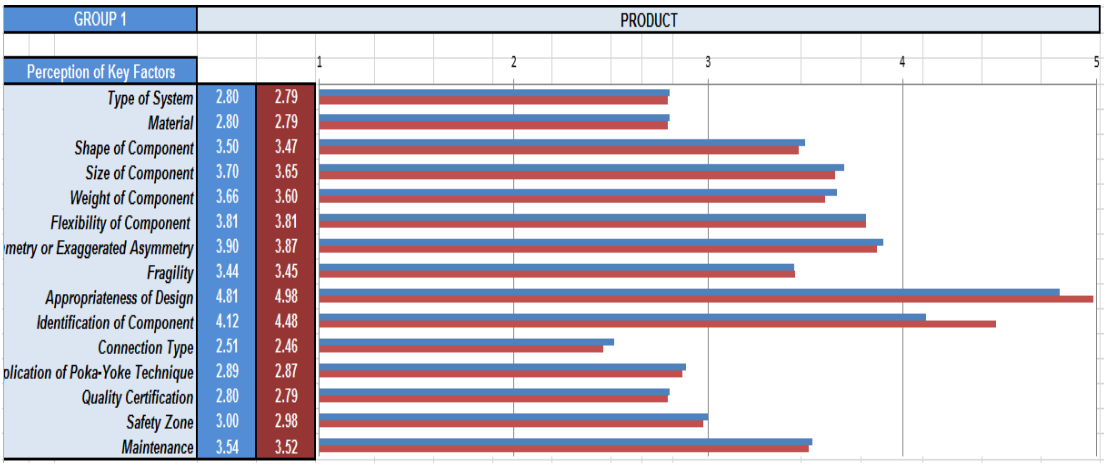


Figure 4-18: CS1 Product PoW (TO-BE)

KF which obtained high PoW in the AS-IS situation would also increase in the TO-BE situation, some more considerably than others. As a downside, KFs that scored lower PoW would decrease slightly. This highlights the tendency of participants to improve KF that have already scored acceptable PoW instead of focusing on those KF which need further improvement. For instance, participants have not identified any IOs in KFs which scored low PoW before, nor have they proposed any re-design suggestions in this regard. Two conclusions can be extracted from these results: either the AS-IS perception of those KF was wrongly captured, or participants do not consider that these KF could improve the SIP at all. Both alternatives would require further research.

Regarding the **process** (Figure 4-19), several changes would take place:

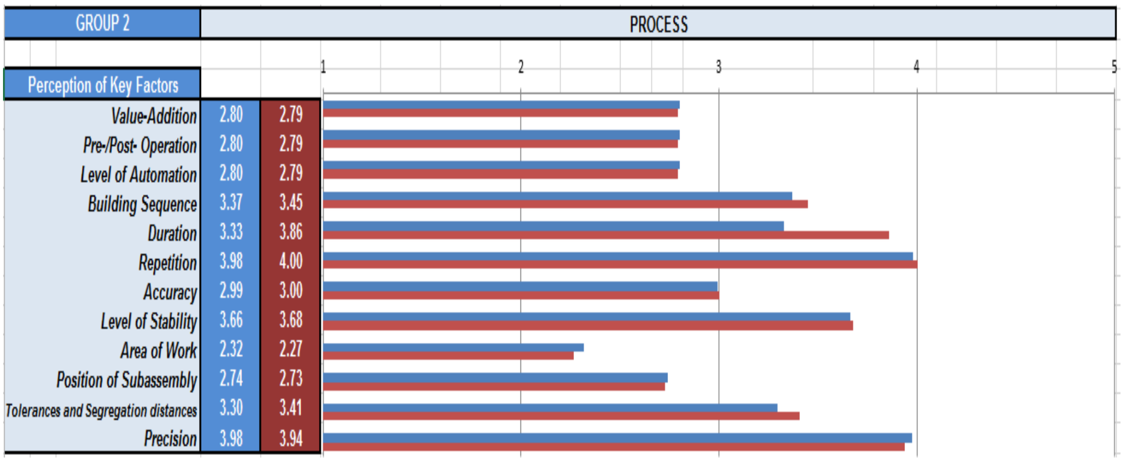


Figure 4-19: CS1 Process PoW (TO-BE)

KF that have obtained high PoW in the AS-IS situation would continue increasing with the implementation of IO. KF such as *repetition* and *stability* would reflect significant improvements, and previously unmentioned KFs such as *segregations*, *building sequence* and *duration* would also improve participant perception.

Nevertheless, as in the product analysis, KFs which had previously obtained low PoW would maintain the same score (or decrease slightly), probably because participants are not aware of any potential solution that could improve these KFs.

Regarding **people** (Figure 4-20), several changes would take place in this new situation.

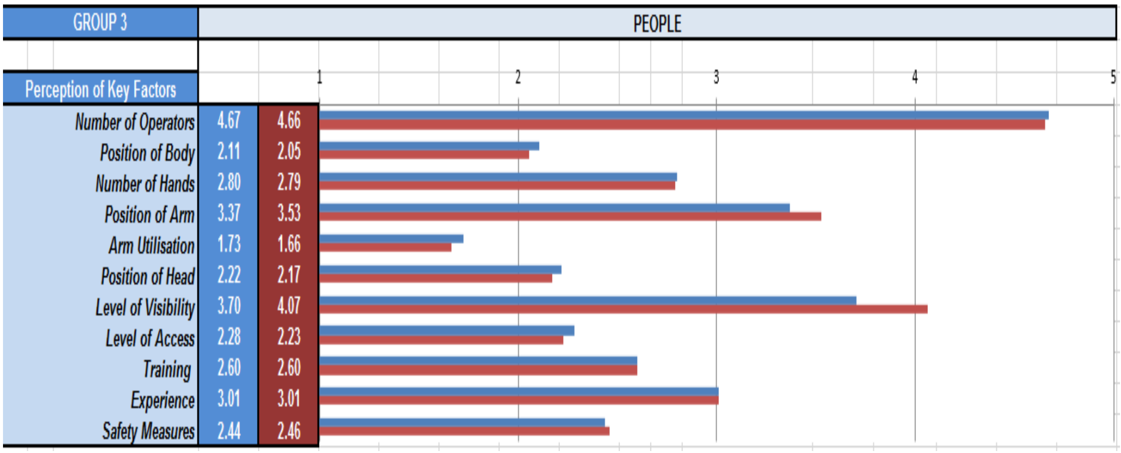


Figure 4-20: CS1 People PoW (TO-BE)

On this occasion, most KF would improve their PoW, especially *visibility* and *position of arm*, with PoW above 4. Nonetheless, KF which had previously obtained low PoW would maintain (or decrease slightly), except for *safety measures*, which increase slightly. In order to understand and interpret results, it is necessary to analyse each KF individually.

Finally, KFs in the **technology** group would display the most noticeable improvement (Figure 4-21).

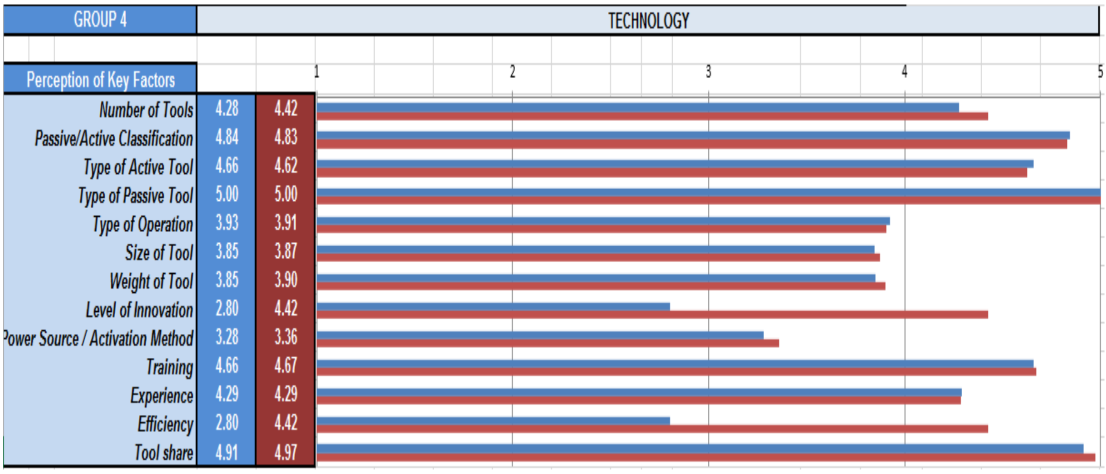


Figure 4-21: CS1 Technology PoW (TO-BE)

With very few exceptions, the perception for most KF would improve considerably, especially for *level of innovation* and *efficiency,* which have already been identified as areas of concern in the AS-IS report. KFs with high

PoW such as *technology share, training* and *number of tools* would keep increasing. However, several KFs with high PoW would slightly decrease their score with the incorporation of the selected IO. In order to understand what is going on with these KFs, a more detailed interpretation must be made.

4.1.2 Case-study 2: Flap Beam Installation

The second case-study to implement and test the methodology was the installation of flap beams. In the product under analysis in this project, there are three flap beams located under each wing. Components of the flap beam are installed once the main structure of the wing is finalised. Wing manufacture being a manual process, achieving the correct flap beam position is challenging due to the nature of the wing assembly process and the technology utilised. The requirement to shim the flap beam when installing it involves uncertainty surrounding the duration of the operation as well as the measurement accuracy.

The participant sample included **10 shop-floor employees** involved in the flap beam installation process of varying experience, skill or age.

4.1.2.1 Preparation for Methodology

The case-study's **boundaries** have been defined by the author and stakeholders from both the sponsoring company and Cranfield University. All agreed that the flap beam installation should be a case-study due to the continuous efforts from all sides to improve the process.

The sponsoring company's internal documentation included 128 operations as part of this case-study, and it also defined the scope of the project, the area of application, and the initial and final operations. Out of **128 operations**, only 85 referred to systems (6 electrical system; 79 movables).

The **building sequence** has also been extracted from the sponsoring company's internal documentation. However, the author observed that the flap beam shimming activity's repetition times was not specified in the documents.

It is important to understand that the flap beam shimming is an activity that requires high level experience to install it using only few operations. Therefore, the shop-floor operators experience and intuition will determine the duration of this operation.

In order to understand the effect of these challenges, the methodology identifies areas where the building sequence could be further optimised, and propose re-sequencing improvements to comply with the lean manufacturing philosophy.

4.1.2.2 Stage 1: Knowledge Gathering

4.1.2.2.1 Explicit Knowledge

As in CS1, explicit knowledge gathering has been carried out as described in Section 3.5.2. Due to the limited access of the author to some of the sponsoring company's internal documents, it has been challenging to get reports where the required information was described *(shape of component, area of work, repetition, value addition, weight and dimensions of component, size and weight of tools*…). Therefore, the missing information had to be obtained directly from the production line.

In addition, the questionnaire had to be slightly modified to suit the specific case-study of flap beam installation. Questions A01.11, A02.09 and A03.02, for example, required modifications.

- Question A01.11 – *Type of Connection*: the types of connectors in each case-study vary, and therefore the answers had to be modified to reflect the most common connection types in the flap beam installation. The question now includes *nuts, studs, washer, conical washer, sealant, bolts,* and *split pin* as answer options.
- Question A02.09 – *Area of Work*: the area of work varies depending on the system being installed, therefore, answer options had to be modified to cover all areas within the sub-assembly where operations take place. The question now includes *away of the wing* and *on top of the wing,* and several different *in front of wing* options to choose from.
- Question A03.02 – Position of Body: answers for this question, as well as for any other ergonomic aspect-related questions, had to be modified to cover all ergonomic positions that take place within the installation process. The question now includes *standing up, kneeling down* and several different *sitting down* positions.

The template questionnaire can be located in Appendix C and there is an entire list of questions that are likely to require modification in C.3,

4.1.2.2.2 Tacit Knowledge

Tacit knowledge gathering has been carried out as described in 3.5.3 interviewing participants following Part B of the questionnaire. In this specific case-study, it was easier to interview participants in their natural working environment. The author has also faced other challenges.

It was a challenge for the participants to complete one questionnaire for every operation without breaking their concentration and attention to both work and the field study. It is important to note that flap beam installation involves many operations and the questionnaire has many questions for each operation. If each participant had to answer to all the questions for each of the operations, it would probably take days to obtain the necessary information from each participant. This issue was solved by interviewing participants for a short period of time (maximum 15 minutes) to allow them keep up with their work and to avoid frustration with the questionnaire. Therefore, participants were asked only one section of the questionnaire each time and then, the author switched to another participant, allowing the first one to work. After obtaining the answers to the first section from all participants, the author went back to the first participant and asked questions on the second section, and so on.

As mentioned before, the process involves so many long operations that it was a challenge to obtain a completely homogeneous set of data from all participants within the time-scale. To overcome this issue, the author obtained a homogeneous set of data from participants by selecting a similar amount of answers for each KF.

Nonetheless, Part B of the questionnaire did not involve any modification for this specific case-study.

4.1.2.2.3 AS-IS Report: Interpretation of Results

This section is an overview of the AS-IS report for the Flap Beam Installation case-study, which highlights the main areas of concern as well as providing a discussion on the results obtained.

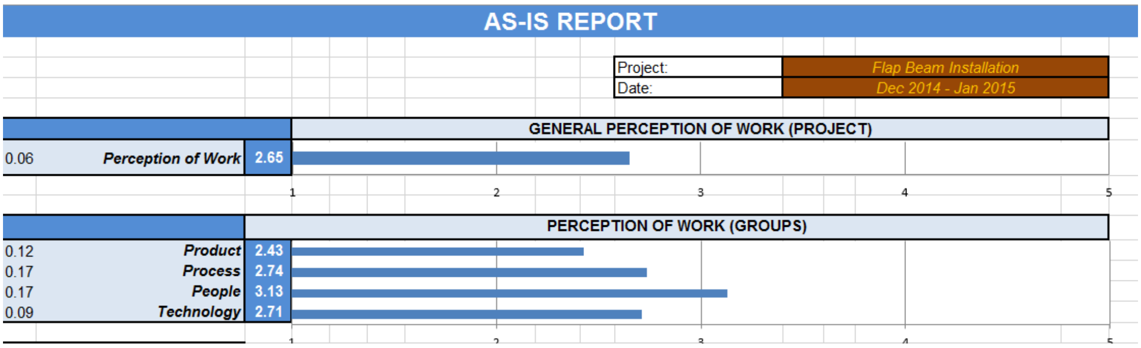


Figure 4-22: CS2 Overall PoW (AS-IS)

The AS-IS report shows a PoW of 2.65 for whole project, which means that the product *has not been designed to specifically ease the SIP, but instead slightly challenges it*. A similar conclusion can be extracted from the product, process and technology groups with the exception of the people group, where a PoW of 3.13 has been obtained, showing that designers are aware of the importance of some KFs, yet they are not utilised to ease the SIP.

4.1.2.2.3.1 Product Analysis

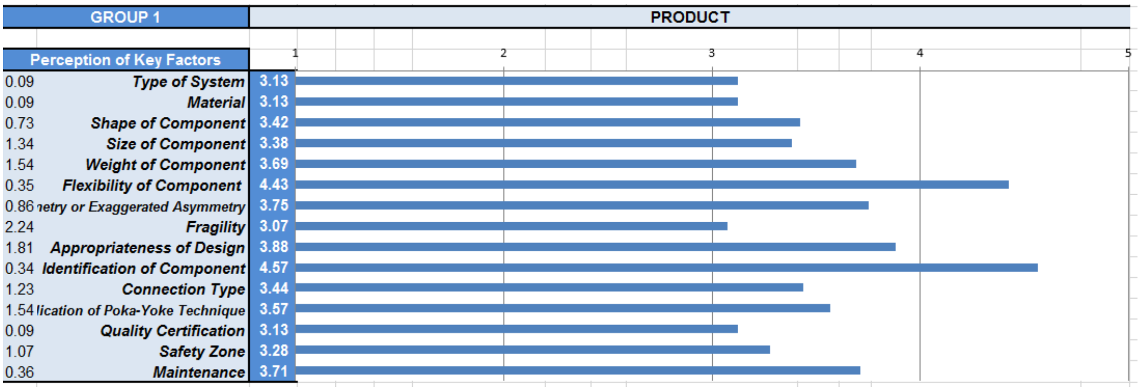
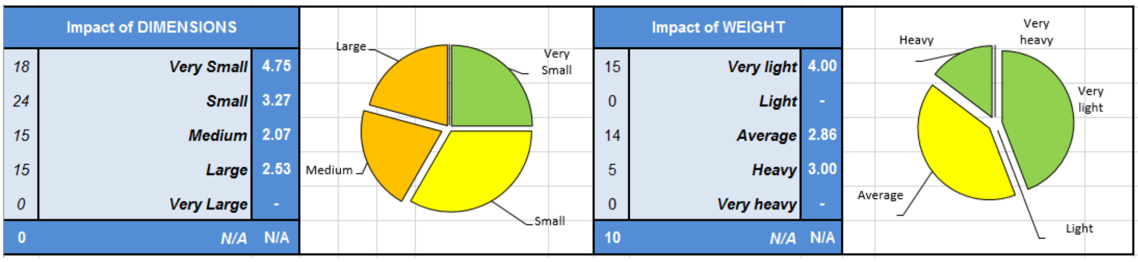


Figure 4-23: CS2 Product PoW (AS-IS)

Figure 4-23 highlights the areas of concern as well as some positive utilisation of certain factors. On the positive side, designers utilise *flexibility* and *identification* in an appropriate way, and as a result, the PoW is over 4 in both cases. The factors of concern are *type of system*, *material*, *asymmetry* and *poka-yoke application*, all of them scoring slightly above 3. The remaining KFs scored between 3 and 4, showing a consideration by designers to ease the SIP throughout the use of these factors, yet any improvement would benefit the flap beam installation process considerably.

A more **detailed analysis** within the product group provides further information on the areas of concern as well as highlighting IOs.

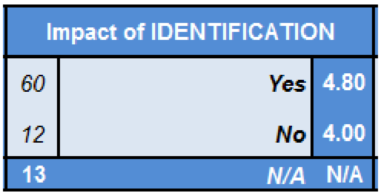
The methodology identifies that some shapes of components such as *cube/cuboid* shapes are more challenging to install than other shapes (Figure 4-24). The PoW is however above 3 in all cases, and the most common shape of component obtained the highest results of all. Interesting results have been obtained regarding the *size* and *weight* of components. As common sense might suggest, larger components obtained lower PoW whereas *average* weight components did not obtained a high PoW if compared to *heavy* components. Apparently, shop-floor employees perceived components classified as *heavy* or *average* weight to have a similar level of challenge when installing.



Impact of DIMENSIONS		
18	Very Small	4.75
24	Small	3.27
15	Medium	2.07
15	Large	2.53
0	Very Large	-
0	N/A	N/A

Impact of WEIGHT		
15	Very light	4.00
0	Light	-
14	Average	2.86
5	Heavy	3.00
0	Very heavy	-
10	N/A	N/A

Figure 4-24: CS2 Weight and Size of Component (AS-IS)



Impact of IDENTIFICATION		
60	Yes	4.80
12	No	4.00
13	N/A	N/A

Figure 4-25: CS2 Identification (AS-IS)

The participants did perceive that formally identified components are easier to install compared to components which have not been identified, although they obtained a significantly higher PoW. Nonetheless, this result ensures that identification of components enhances the SIP (Figure 4-25).

4.1.2.2.3.2 Process Analysis

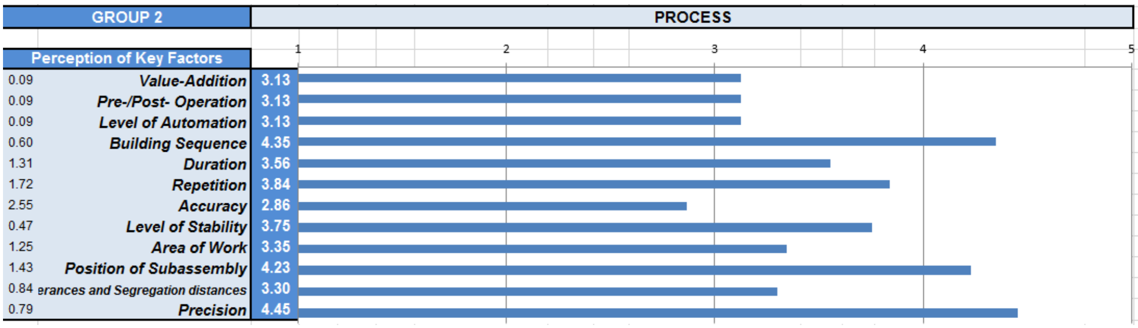


Figure 4-26: Process PoW of CS2 (AS-IS)

Figure 4-26 shows the positive perception of the *building sequence*, *position of sub-assembly* and *precision* in the process analysis. They all scored above 4, showing a perception improvement towards that these factors enhance the SIP. However, other aspects such as *value-addition* (3.13), *area of work* (3.35), and especially *accuracy* of the operation (2.86), have been identified as factors that significantly challenge the SIP.

A more detailed analysis of KFs suggests that the *value-addition* of an operation does not necessarily improve system installation. Results from this classification are average (slightly above 3), showing a high amount of *non-value-adding* activities (55 altogether). This aspect clearly needs some improvement, either to delete (or at least considerably reduce) the *non-value-adding* activities (see Figure 4-27).

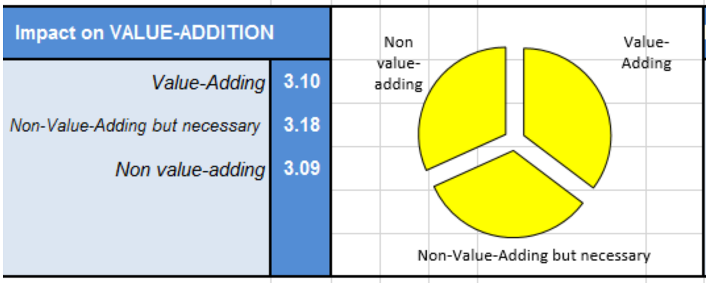
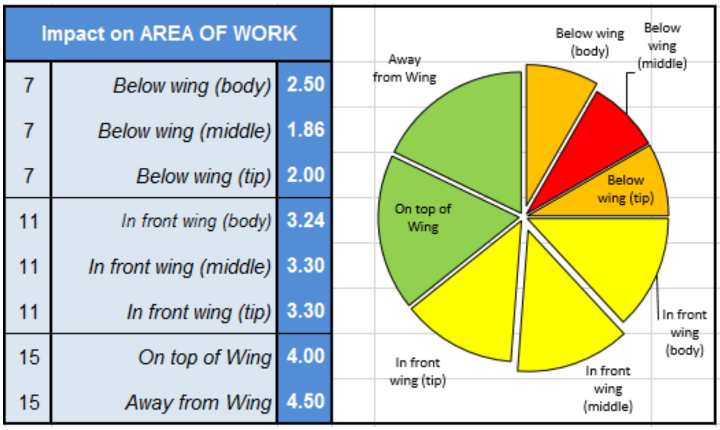


Figure 4-27: CS2 Value Addition (AS-IS)

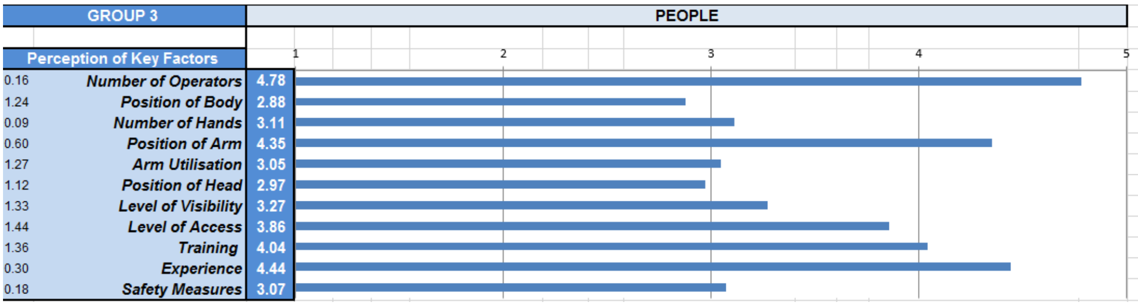
Regarding *the area of work*, there are certain areas within the wing which are perceived as more challenging than others. For instance, there is greater concern when participants work in the middle area *under the wing*, compared to the other two under-the-wing areas. For some reason, it is also more challenging to work in front of the wing when closer to the body (or fuselage) than in other places. These areas need further attention in order to determine the root-causes of these challenges in order to be able to solve them. The areas where most of the operations take place (*on top of* and *away from* the wing) obtained decent PoW, and have been discarded as areas of concern.



Impact on AREA OF WORK		
7	*Below wing (body)*	2.50
7	*Below wing (middle)*	1.86
7	*Below wing (tip)*	2.00
11	*In front wing (body)*	3.24
11	*In front wing (middle)*	3.30
11	*In front wing (tip)*	3.30
15	*On top of Wing*	4.00
15	*Away from Wing*	4.50

Figure 4-28: CS2 Area of Work (AS-IS)

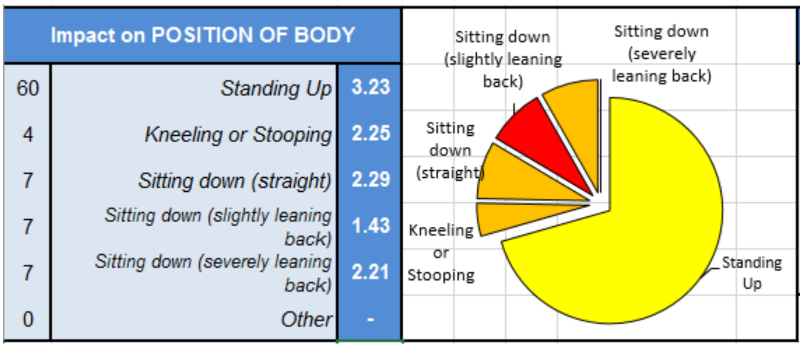
4.1.2.2.3.3 People Analysis



GROUP 3		
	Perception of Key Factors	
0.16	*Number of Operators*	4.78
1.24	*Position of Body*	2.88
0.09	*Number of Hands*	3.11
0.60	*Position of Arm*	4.35
1.27	*Arm Utilisation*	3.05
1.12	*Position of Head*	2.97
1.33	*Level of Visibility*	3.27
1.44	*Level of Access*	3.86
1.36	*Training*	4.04
0.30	*Experience*	4.44
0.18	*Safety Measures*	3.07

Figure 4-29: CS2 People PoW (AS-IS)

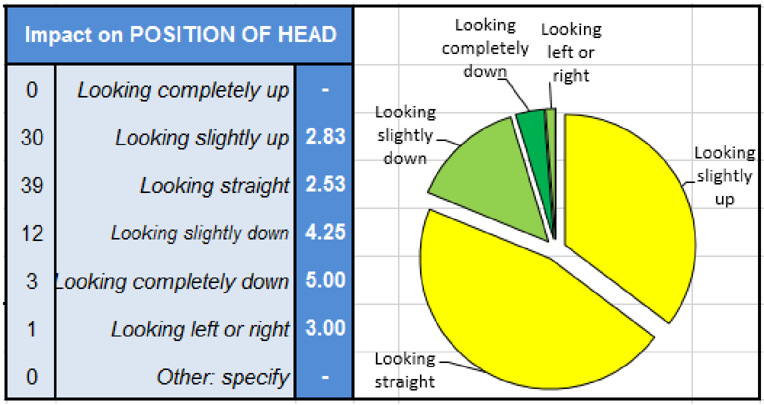
Figure 4-29 reveals the positive perception of the *number of operators*, *position of arms* and *experience* of operators, all scoring above 4. In addition, other factors such as *training* and *access* also obtained PoW above 3.5, meaning designers are aware of the benefits these factors represent to the SIP. However, some factors of concern can be identified in the diagram. *Position of body* (2.88) represents one of the main concerns together with the *position of* *head* (2.97). Scoring slightly above 3, *arm utilisation*, *safety measures* and *number of hands utilised* in the operations will require special attention for future improvements.



	Impact on POSITION OF BODY	
60	*Standing Up*	3.23
4	*Kneeling or Stooping*	2.25
7	*Sitting down (straight)*	2.29
7	*Sitting down (slightly leaning back)*	1.43
7	*Sitting down (severely leaning back)*	2.21
0	*Other*	-

Figure 4-30: CS2 Position of Body (AS-IS)

A more detailed analysis offers very interesting conclusions. Regarding the position of the body, *standing up* is the most populated position, and obtained an acceptable 3.23 PoW (Figure 4-30). However, the *sitting down* position is an area of concern, and interestingly enough, the operator *slightly leaning back* is perceived as worse (1.43) than *severly leaning back* (2.21). In general, the ergonomic position of the operators is an area of concern and further improvements are required in this regard. However, the root-cause must also be identified in order to understand why operators perceive the *slightly leaning back* position to be more challenging than the *severely leaning back* position.

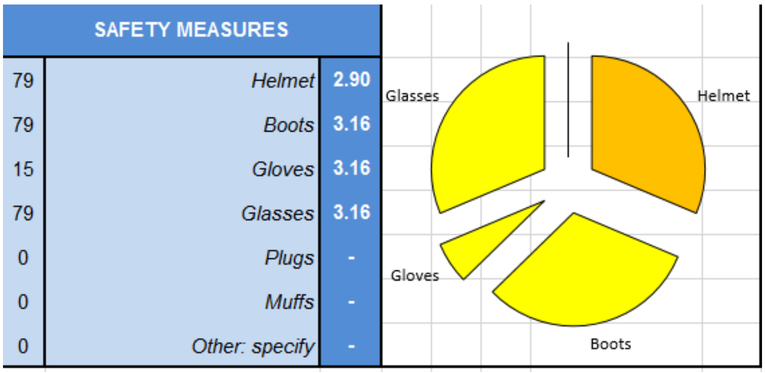


	Impact on POSITION OF HEAD	
0	*Looking completely up*	-
30	*Looking slightly up*	2.83
39	*Looking straight*	2.53
12	*Looking slightly down*	4.25
3	*Looking completely down*	5.00
1	*Looking left or right*	3.00
0	*Other: specify*	-

Figure 4-31: CS2 Position of Head (AS-IS)

Another concern from the ergonomic perspective comes with the *position of the head* when performing operations. It is interesting to see that the worst PoW was obtained when operators were *looking straight* (Figure 4-31). Common sense might suggest that when *looking straight*, the ergonomic position is the ideal. However, participants did not have the same perception, and further investigation must be carried out to identify the reason for these results. It might simply be because it is the most populated answer (39 operations). Participants, on the other hand, perceived that *looking completely down* was the most comfortable position, which obtained maximum PoW, whereas the *slightly looking down* position also challenges the installation process.

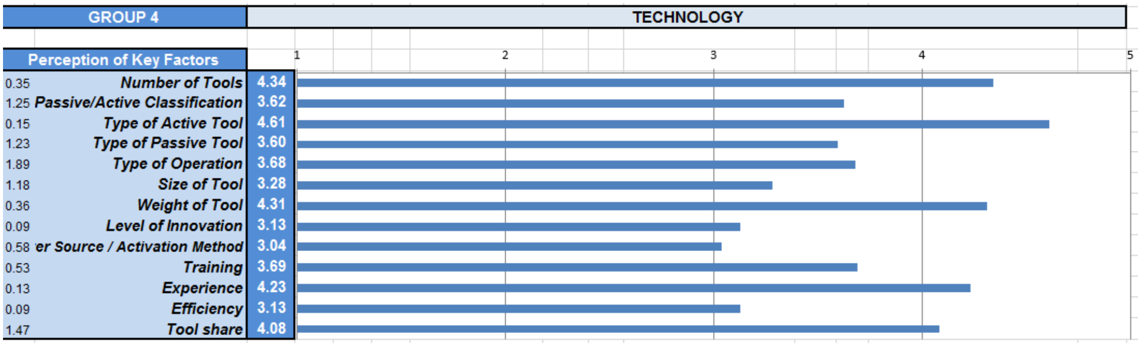
Regarding the mandatory *safety measures*, the report highlights some issues when using the helmet. Very closely related to the ergonomic positions, when working under the wing sitting down and slighlty or severely leaning back, operators identified an area of concern (Figure 4-32). Further investigation on the root-cause of a slightly low PoW is needed for the helmet's case.



SAFETY MEASURES		
79	*Helmet*	2.90
79	*Boots*	3.16
15	*Gloves*	3.16
79	*Glasses*	3.16
0	*Plugs*	-
0	*Muffs*	-
0	*Other: specify*	-

Figure 4-32: CS2 Safety Measures (AS-IS)

4.1.2.2.3.4 Technology Analysis

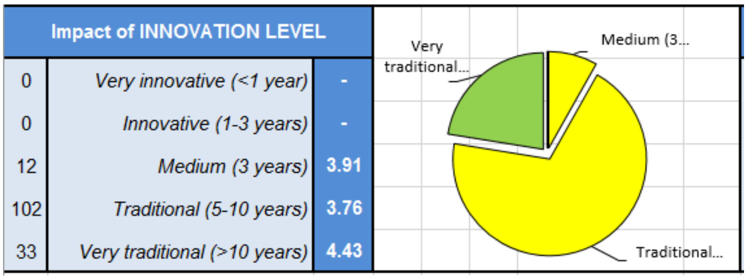


GROUP 4		
Perception of Key Factors		
0.35	*Number of Tools*	4.34
1.25	*Passive/Active Classification*	3.62
0.15	*Type of Active Tool*	4.61
1.23	*Type of Passive Tool*	3.60
1.89	*Type of Operation*	3.68
1.18	*Size of Tool*	3.28
0.36	*Weight of Tool*	4.31
0.09	*Level of Innovation*	3.13
0.58	*er Source / Activation Method*	3.04
0.53	*Training*	3.69
0.13	*Experience*	4.23
0.09	*Efficiency*	3.13
1.47	*Tool share*	4.08

Figure 4-33: CS2 Technology PoW (AS-IS)

Figure 4-33 presents some interesting results: even though the technology utilised results within a high amount of repetition and uncertainty in the installation process, the general perception of it is positive. All KFs score above 3, and more than 75% scored above 3.5. Only the *size of tool*, *innovation level*, *power source* and *efficiency* are highlighted as significant areas of concern. The explanation for this result is reflected in a more detailed analysis described below.

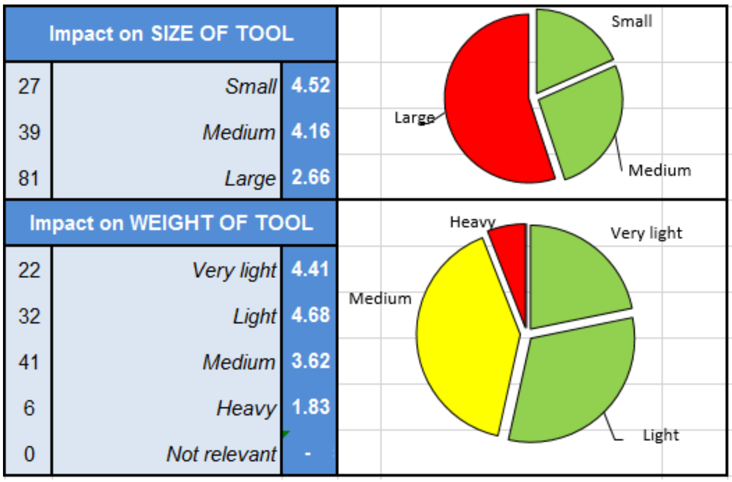
One of the most evident conclusions from the AS-IS report is that the innovation level of the tools utilised in this case-study is very low. Most of the tools are *very traditional* but have been utilised for years. Thus, the PoW is high. This does not necessarily mean that the accuracy of these tools is high, but probably the opposite (Figure 4-31).



Impact of INNOVATION LEVEL		
0	*Very innovative (<1 year)*	-
0	*Innovative (1-3 years)*	-
12	*Medium (3 years)*	3.91
102	*Traditional (5-10 years)*	3.76
33	*Very traditional (>10 years)*	4.43

Figure 4-34: CS2 Level of Innovation (AS-IS)

Another concern from the technology perspective is the *size* and *weight* of the tools utilised in this case-study. As common sense might suggest, there is a low perception of *large* and *heavy* technology (Figure 4-35). At the same time, *large* tools as well as *medium-heavy* tools are utilised more often than other tools. Therefore, improving the tooling must be an objective to improve the SIP.

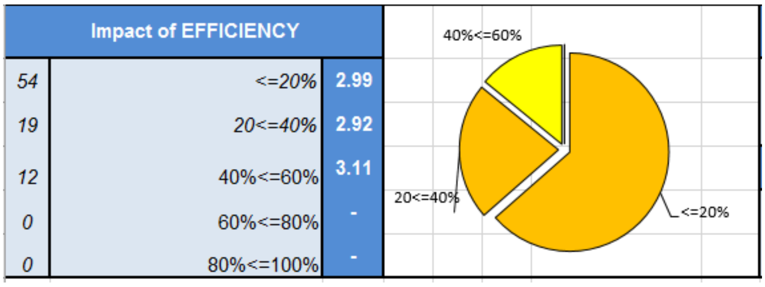


Impact on SIZE OF TOOL		
27	*Small*	4.52
39	*Medium*	4.16
81	*Large*	2.66

Impact on WEIGHT OF TOOL		
22	*Very light*	4.41
32	*Light*	4.68
41	*Medium*	3.62
6	*Heavy*	1.83
0	*Not relevant*	-

Figure 4-35: CS2 Weight and Size of Tools (AS-IS)

Finally, *efficiency* of the tools utilised is also highlighted in the AS-IS report (Figure 4-36). The fact that none of the tools has a higher efficiency than 60% is concerning, as well as the low PoW of tools which are utilised less often. IOs should be focused on improving efficiency as well as investigating how to improve the PoW of tools.



Impact of EFFICIENCY		
54	<=20%	2.99
19	20<=40%	2.92
12	40%<=60%	3.11
0	60%<=80%	-
0	80%<=100%	-

Figure 4-36: CS2 Efficiency (AS-IS)

4.1.2.3 Stage 2: Capture Improvement Opportunities

A total of 51 IOs have been extracted from participants for this second case-study, most of them aiming at improving the PoW of the technology (31), but also the process (10) and the product (8). Very few suggestions were captured from the people perspective (3), leaving aside again about the benefits of improving the ergonomic aspect. It was also identified that the majority focused on modifying the current situation (37) but this time, the IO dedicated to deleting a solution was higher than in the previous CS (8), and adding an innovation was also mentioned (7).

Captured IOs and the impact have been stored in a predefined table (refer to Appendix E). In addition, in cases where the IO did not directly involve a re-design to improve the perception, participants were asked to modify the IO so that it could provide a useful feedback for the design as done in CS1.

Due to company confidentiality, captured improvement opportunities could not be listed in this thesis.

4.1.2.4 Stage 3: Estimation of the TO-BE Situation

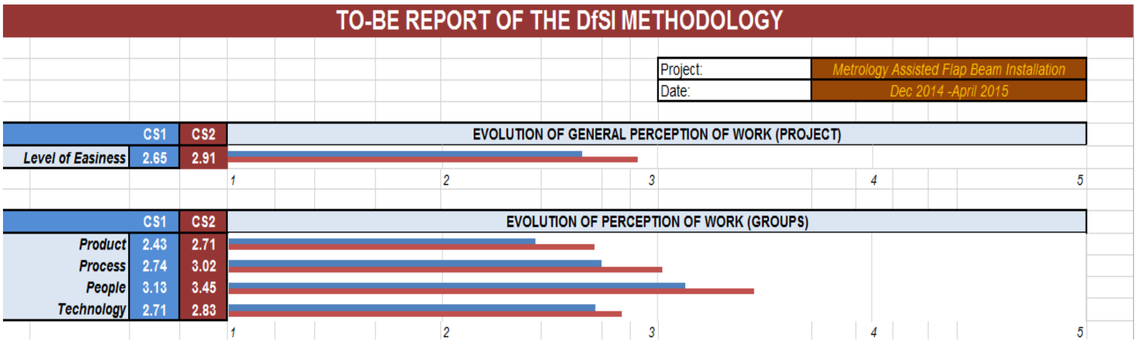
For each IO, participants have determined to what extent it benefits the PoW of the SIP and has also estimated the negative impact following the procedure described in Section 3.5.5. Then, the TO-BE Report was interpreted.

4.1.2.4.1 *Selecting IO and Estimating Impact*

Among all IO identified, participants have selected 1 IO (described in case-study 3) to visualise and measure the effect of the selected technology incorporation in the current project by iterating the methodology around the cycle in order to justify the spiral model.

4.1.2.4.2 *TO-BE Report: AS-IS Flap Beam Installation vs. AS-IS Metrology Assisted Flap Beam Installation*

The TO-BE report compares the AS-IS situation of the current flap beam installation process with the AS-IS situation of the metrology assisted flap beam installation. Figure 4-37 shows a high-level comparison of the PoW obtained in both case-studies:



TO-BE REPORT OF THE DfSI METHODOLOGY

Project:	Metrology Assisted Flap Beam Installation
Date:	Dec 2014 -April 2015

EVOLUTION OF GENERAL PERCEPTION OF WORK (PROJECT)

	CS1	CS2
Level of Easiness	2.65	2.91

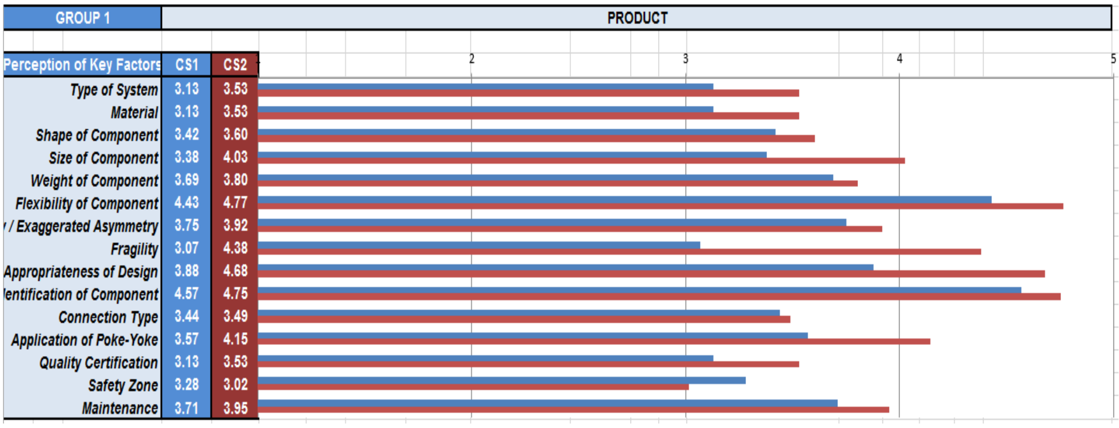
EVOLUTION OF PERCEPTION OF WORK (GROUPS)

	CS1	CS2
Product	2.43	2.71
Process	2.74	3.02
People	3.13	3.45
Technology	2.71	2.83

Figure 4-37: CS2/3 Overall PoW (TO-BE)

The benefits of incorporating a metrology assisted solution are noticeable in the figure above. As well as improving the overall PoW from 2.65 to 2.91, the incorporation of a metrology assisted solution would also improve the product (11%); process (10%); people (10%), and technology (5%). It is interesting to see that the incorporation of a new technology would not increase the technology aspect as much as other aspects, and the possible causes of a more moderate increase are mentioned below.

4.1.2.5 Product Analysis

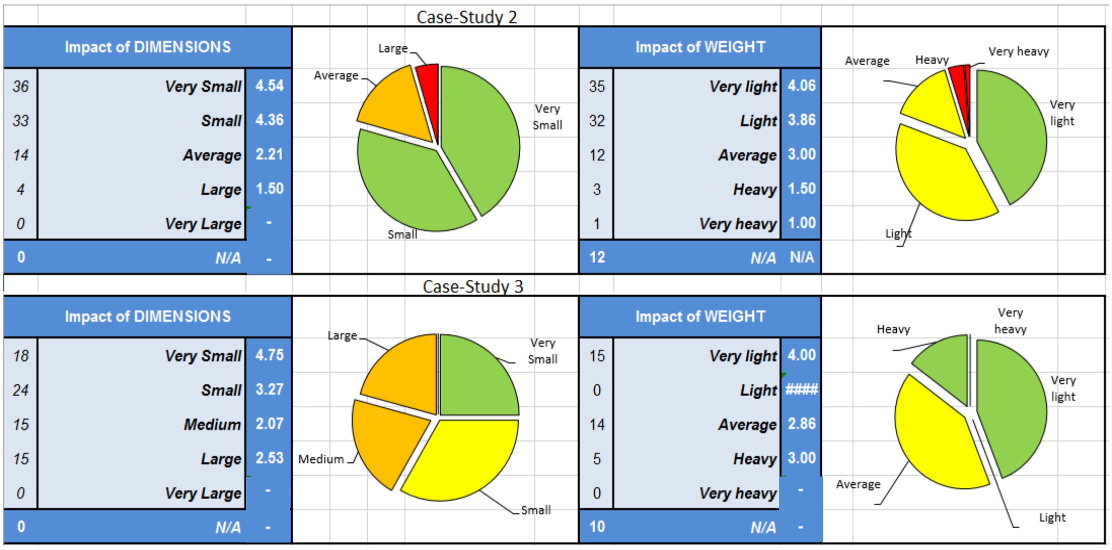


Perception of Key Factors	CS1	CS2
Type of System	3.13	3.53
Material	3.13	3.53
Shape of Component	3.42	3.60
Size of Component	3.38	4.03
Weight of Component	3.69	3.80
Flexibility of Component	4.43	4.77
/ Exaggerated Asymmetry	3.75	3.92
Fragility	3.07	4.38
Appropriateness of Design	3.88	4.68
entification of Component	4.57	4.75
Connection Type	3.44	3.49
Application of Poke-Yoke	3.57	4.15
Quality Certification	3.13	3.53
Safety Zone	3.28	3.02
Maintenance	3.71	3.95

Figure 4-38: CS2/3 Product PoW (TO-BE)

A deeper analysis of the first group of KFs shows a clear improvement of most aspects under analysis (Figure 4-38). 3.53 being the minimum score KFs would get, the positive impact KFs would have on the flap beam installation process it is palpable. KFs such as the *application of poka-yoke technique*, *fragility* and *size of component* deserve a special mention for their significantly noticeable improvement.

The new technological addition would involve the installation of more temporary components than before. However, these components would mostly be *small* in size and *very light*, and the installation of them is well perceived by participants (Figure 4-39). The rest of the components, which have been categorised as *large* or *heavy,* are estimated to decrease in number, although the PoW they would obtain is low and still needs further improvement.



Case-Study 2

Impact of DIMENSIONS		
36	Very Small	4.54
33	Small	4.36
14	Average	2.21
4	Large	1.50
0	Very Large	-
0	N/A	-

Impact of WEIGHT		
35	Very light	4.06
32	Light	3.86
12	Average	3.00
3	Heavy	1.50
1	Very heavy	1.00
12	N/A	N/A

Case-Study 3

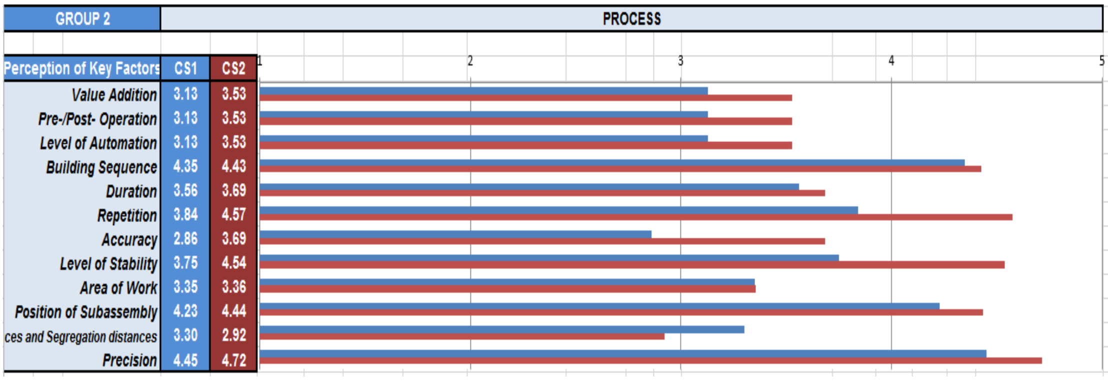
Impact of DIMENSIONS		
18	Very Small	4.75
24	Small	3.27
15	Medium	2.07
15	Large	2.53
0	Very Large	-
0	N/A	-

Impact of WEIGHT		
15	Very light	4.00
0	Light	####
14	Average	2.86
5	Heavy	3.00
0	Very heavy	-
10	N/A	-

Figure 4-39: CS2/3 Size and Weight (TO-BE)

There would also be a noticeable improvement on the *maintenance* of many components, which would be reduced, improving the overall PoW.

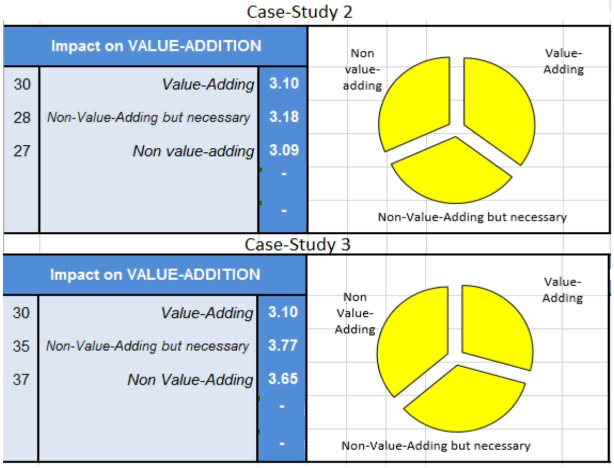
4.1.2.6 Process Analysis



GROUP 2		
Perception of Key Factors	CS1	CS2
Value Addition	3.13	3.53
Pre-/Post- Operation	3.13	3.53
Level of Automation	3.13	3.53
Building Sequence	4.35	4.43
Duration	3.56	3.69
Repetition	3.84	4.57
Accuracy	2.86	3.69
Level of Stability	3.75	4.54
Area of Work	3.35	3.36
Position of Subassembly	4.23	4.44
ces and Segregation distances	3.30	2.92
Precision	4.45	4.72

Figure 4-40: CS2/3 Process PoW (TO-BE)

The benefits that incorporating a metrology based solution bring to the **process** KFs are significantly noticeable in Figure 4-40. Except for *tolerances and segregation distances*, the remaining KFs are estimated to increase the PoW if compared to the current flap beam installation process. According to estimations, the PoW of the number of times an operation is performed would improve significantly, completely deleting operations whose repetition is *impossible to estimate* by converting them into once-performed operations.



Case-Study 2

Impact on VALUE-ADDITION		
30	Value-Adding	3.10
28	Non-Value-Adding but necessary	3.18
27	Non value-adding	3.09
		-
		-

Case-Study 3

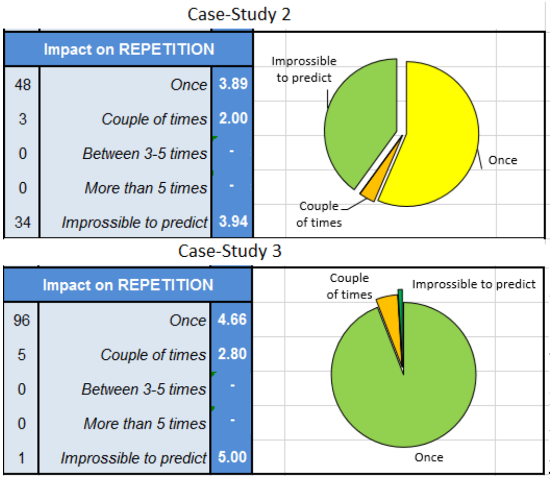
Impact on VALUE-ADDITION		
30	Value-Adding	3.10
35	Non-Value-Adding but necessary	3.77
37	Non Value-Adding	3.65
		-
		-

Figure 4-41: CS2/3 Value-Addition (TO-BE)

Other KFs such as *accuracy* and *stability* of the process show a positive trend, and aspects such as *duration* and *building sequence* would be perceived with better regard.

The TO-BE report shows an increase in the number of *non-value adding* operations if the suggested metrology assisted solution is implemented (Figure 4-41). The explanation is very simple: in order for the metrology assisted solution to identify coordinates, it requires components called *targets*. The installation of these targets is temporary and, therefore, they are considered *non-value-adding* operations. However, the incorporation of these additional non-value-adding operations would increase accuracy of the operation and decrease the uncertainty of repetitions in certain operations (read further down), identified as area of concern in CS2. Also, the PoW for non-value-adding operations for the future solution would be higher (3.65) than the PoW for the current solution (3.09).

There would also be some noticeable improvements regarding the *area of work* within the sub-assembly. For instance, areas such as *below the wing*, which obtained a PoW of 1.86 on CS2, would improve the PoW 12%.



Case-Study 2

	Impact on REPETITION	
48	*Once*	3.89
3	*Couple of times*	2.00
0	*Between 3-5 times*	-
0	*More than 5 times*	-
34	*Impossible to predict*	3.94

Case-Study 3

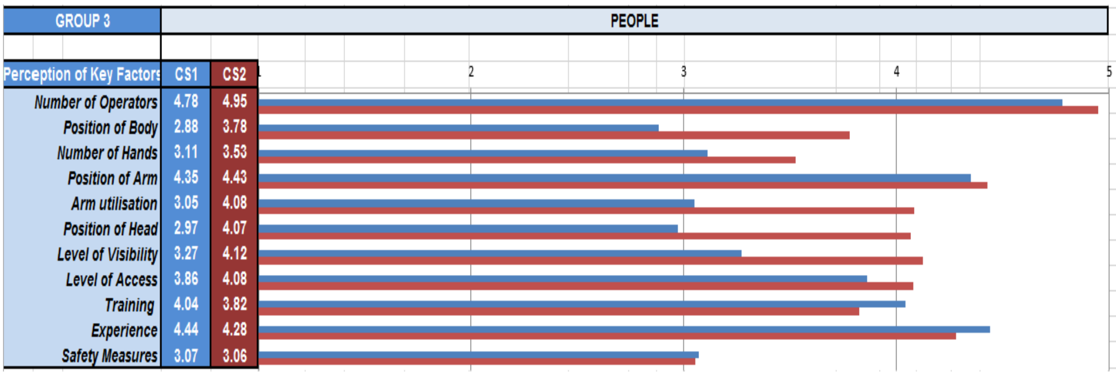
	Impact on REPETITION	
96	*Once*	4.66
5	*Couple of times*	2.80
0	*Between 3-5 times*	-
0	*More than 5 times*	-
1	*Impossible to predict*	5.00

Figure 4-42: CS2/3 Repetition (TO-BE)

As mentioned earlier, the number of repetition times is probably the most noticeable improvement of all. It is a significant concern for the current installation process, and it is exactly what the proposed solution focuses on.

The report shows that the amount of operations where the repetition is *impossible to predict* would be reduced from 34 operations to just 1, improving its PoW also. If the suggested change was incorporated, the majority of operations would only need to be performed once, considerably reducing the uncertainty of the overall duration of the installation process (Figure 4-42).

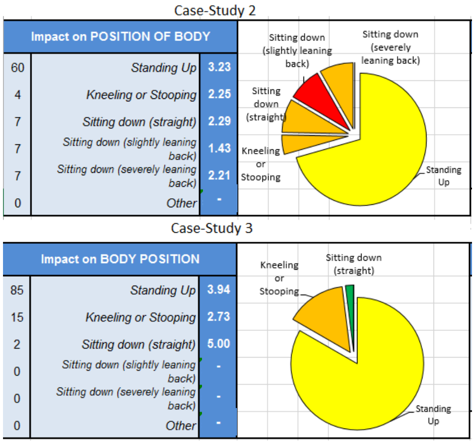
4.1.2.7 People Analysis



Perception of Key Factors	CS1	CS2
Number of Operators	4.78	4.95
Position of Body	2.88	3.78
Number of Hands	3.11	3.53
Position of Arm	4.35	4.43
Arm utilisation	3.05	4.08
Position of Head	2.97	4.07
Level of Visibility	3.27	4.12
Level of Access	3.86	4.08
Training	4.04	3.82
Experience	4.44	4.28
Safety Measures	3.07	3.06

Figure 4-43: CS2/3 People PoW (TO-BE)

Even though the people perspective has not been especially considered by participants when suggesting IOs, the metrology assisted solution would indirectly improve some factors. The *number of operations* involved in the operations would be perceived very close to perfection (4.95), and also operators' ergonomic position also shows significant improvements. For instance, the PoW for the *position of the body* would increase by 30% (Figure 4-44) whereas it would be 37% for the *position of the head*. Besides this, the *visibility* and *access* to the assembly point would increase by 25% and 5% respectively.



	Impact on POSITION OF BODY	
60	Standing Up	3.23
4	Kneeling or Stooping	2.25
7	Sitting down (straight)	2.29
7	Sitting down (slightly leaning back)	1.43
7	Sitting down (severely leaning back)	2.21
0	Other	-

	Impact on BODY POSITION	
85	Standing Up	3.94
15	Kneeling or Stooping	2.73
2	Sitting down (straight)	5.00
0	Sitting down (slightly leaning back)	-
0	Sitting down (severely leaning back)	-
0	Other	-

Figure 4-44: CS2/3 Position of Body

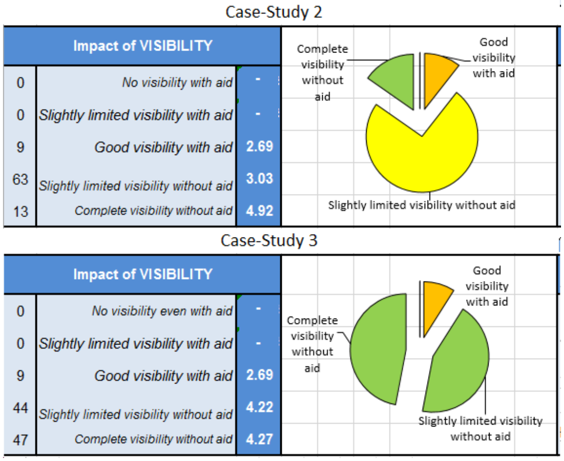
The report identifies that special *training* (3.82) and *experience* (4.28) are necessary if the sponsoring company decides to incorporate the metrology assisted solution, technology with which employees are currently unfamiliar.

It is noticeable in the TO-BE report that the ergonomic aspect would improve if the suggested change is incorporated (Figure 4-37). For instance, positions that are currently categorised as very uncomfortable body-positions, such as *sitting* *down, slightly leaning back* (1.43) and *sitting down, severely leaning back* (2.21), would be removed. Instead, there would be an increase in *standing up, kneeling* and *sitting down* positions, which scored considerably higher PoW (3.94; 2.73; 5.00).

Regarding the position of the arm and head, the PoW would generally improve. The report identifies that the *0-90 degrees between body and arm* position would increase the most (2.00 to 4.41), and the *slightly looking up* position would also improve (2.83 to 4.00), involving a more generally comfortable position for the operators.

Regarding *visibility* of the assembly point, the implementation of a metrology based solution would see noticeable improvement (Figure 4-45): the amount of operations with *complete visibility without aid* would increase from 13 to 47, highlighting the significant impact of the lighting improvement solution inside the wing suggested by participants. Besides this, operations with *limited visibility without aid* have increased PoW from 3.04 to 4.22.

The *access* to the assembly point has also improved: the report estimates that operations with *slightly limited access without aid* would be eliminated. Additionally, operations with *complete access* would increase the PoW from 4.01 to 4.54. On the negative side, the only operation existing with *good access with aid* would decrease its PoW, and the same would occur to operations with *slightly limited access without aid.* Therefore, although access would improve with the proposed solution, it would require additional attention.



Case-Study 2

Impact of VISIBILITY		
0	*No visibility with aid*	-
0	*Slightly limited visibility with aid*	-
9	*Good visibility with aid*	2.69
63	*Slightly limited visibility without aid*	3.03
13	*Complete visibility without aid*	4.92

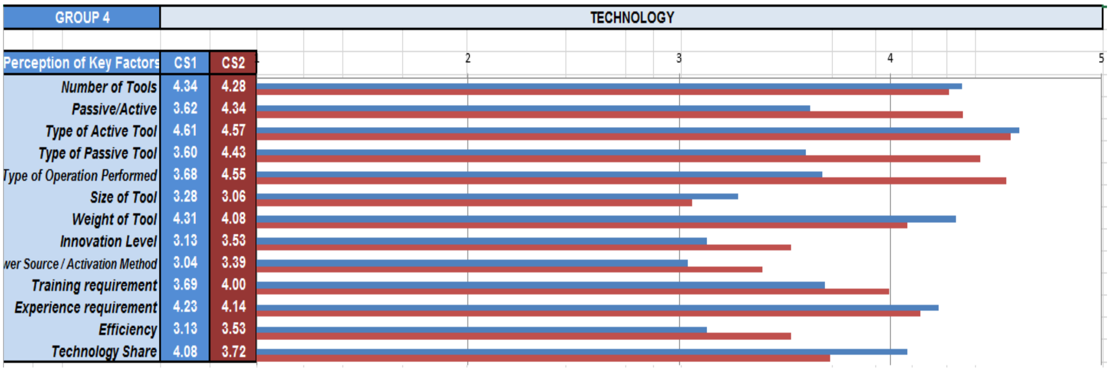
Case-Study 3

Impact of VISIBILITY		
0	*No visibility even with aid*	-
0	*Slightly limited visibility with aid*	-
9	*Good visibility with aid*	2.69
44	*Slightly limited visibility without aid*	4.22
47	*Complete visibility without aid*	4.27

Figure 4-45: CS2/3 Visibility (TO-BE)

As mentioned above, training and experience operators would become into areas of concern. A new technological solution would be incorporated and operators would require more specific training to effectively use the tool and familiarise themselves with the new process. This is why the number of operations that require *specific training* would increase, and so would their PoW (4%), highlighting that the operators feel confident that the solution would involve an easier SIP.

4.1.2.8 Technology Analysis



Perception of Key Factors	CS1	CS2
Number of Tools	4.34	4.28
Passive/Active	3.62	4.34
Type of Active Tool	4.61	4.57
Type of Passive Tool	3.60	4.43
Type of Operation Performed	3.68	4.55
Size of Tool	3.28	3.06
Weight of Tool	4.31	4.08
Innovation Level	3.13	3.53
wer Source / Activation Method	3.04	3.39
Training requirement	3.69	4.00
Experience requirement	4.23	4.14
Efficiency	3.13	3.53
Technology Share	4.08	3.72

Figure 4-46: CS2/3 Technology PoW (TO-BE)

The report shows a very interesting outcome from the **technology** analysis. The incorporation of a metrology assisted solution would substitute old measurement devices. Nonetheless, the new technology, due to its high reliability in measurement, would only be used once, reducing its efficiency considerably. It is important to understand that due to the repetition of several operations, the old measurement device was inefficiently used in several operations. That is probably the reason why in this case-study, the perception is that the technology would give a small overall increase with some decrease in certain tools.

KFs such as *number of tools, active tools, weight of tool* and *technology share* would suffer a slight decrease in perception, whereas other factors would benefit, such as *type of operation, passive tools, training requirement* and *efficiency.*

In this case-study, the interpretation of results is crucial. Even though the benefit might not be as easy-to-see in the results, the incorporation of the new measurement technology impacts very positively on the general perception of the SIP.

4.2 Case-study on Research Projects

In this section the implementation of a third case-study has been described on a project that it is still under research: the metrology assisted flap beam installation process.

4.2.1 Case-study 3: Metrology Assisted Flap Beam Installation

The third case-study to test and validate the methodology is the installation process of flap beams incorporating metrology assisted solution. This project has been under research and development for several years, and it was picked up by many participants in the CS2 as an IO that would significantly benefit the current process and design.

The metrology assisted flap beam installation removes the non-value adding and repetitive activities conventionally performed to determine the correct size of shim which locates the flap beam in its precise position. This activity being an experienced-based and also a very time-consuming activity, the metrology assisted installation brings accuracy and time savings by incorporating an accurate laser-based measurement prior to the installation of the flap beams which automatically determines which shim to utilise.

This case-study has two purposes: it highlights the benefits of incorporating this new technology when compared to the current solution, and validates the statement in Section 3.3 which suggests that the methodology is a "*spiral model based on continuous refinement of the case-study"* by applying the methodology to a future project.

The participant sample included 2 researchers involved in the research and development of the metrology assisted flap beam installation project in addition to the 10 shop-floor employees who have previously participated in CS2.

4.2.1.1 Preparation for Methodology

The case-study's **boundaries** have been defined with difficulty. The case-study involves the addition of a new technology to the process, yet this technology is still under development, and the solution is not completely defined. It has been agreed by the author and an expert in the topic from Cranfield University that this case-study would have the same boundaries as the case-study it was aiming to improve: flap beam installation. However, the author encountered several unclear areas when implementing the case-study, which are described in the following sections.

The documentation on this project vaguely stated the exact process of installation as the project was still under development. The author, together with experts in the field, managed to estimate the building sequence for the CS3 by slightly modifying the flap beam installation building sequence as the experts in the field described. However, it should be noted that this building sequence is based on assumptions and estimations gathered from conversations with an expert in the field.

The new flap beam installation process comprises 127 operations with the incorporation of the new technology. Some operations which have remained unchanged (for instance, *final installation of brackets,* or *final installation of flap beams*), although some others have been terminated *(*for instance, *install old measuring devices*) to make room for new operations (for example, *scan using laser tracker*). In total, there are 59 unchanged, and 68 are new. From all 127 operations, it was identified that only 101 referred to systems (6 refer to electrical system; 95 movables).

If compared with the flap beam installation building sequence in CS2, this case-study might seem to be composed of a greater number of operations. However, these operations are more precise and accurate. Hopefully, the metrology assisted solution will decrease the perception significantly, and the whole process will become more accurate from the measurement point of view, and will reduce uncertainty of repetition times (check 4.1.2.6 for further information).

4.2.1.2 Stage 1: Knowledge Gathering

4.2.1.2.1 Explicit Knowledge

Explicit knowledge capture has been carried out as described in 3.5.2 with small but necessary modification when implementing in future projects.

It is important to bear in mind that the metrology assisted flap beam installation requires a new technology addition that modifies both product and process. However, some operations would remain the same as in CS2. For these exact same operations, information obtained at CS2 has been kept, only capturing explicit knowledge for those new operations and components that have been incorporated.

The explicit knowledge for the metrology assisted solution was obtained from informal documents, internal videos and expert knowledge. During the early stages of the solution as well as the many possible alternatives, it was necessary to agree on one specific solution, and build the explicit analysis on that agreed solution. Participant’s involvement in this stage has been also necessary, but most of the information gathered from them is based on assumptions and estimations.

Additionally, the questionnaire had to be modified to suit future projects as described in 3.5.4, as the other two CSs.

4.2.1.2.2 Tacit Knowledge

Tacit knowledge gathering was carried out as described in 3.5.3 interviewing participants following Part B of the questionnaire. As in explicit knowledge capture, knowledge obtained at CS2 was kept when operations were similar, only capturing tacit knowledge for those new operations and components that have been incorporated into the process. However, the author faced other challenges in this case.

There were only a few participants knowledgeable of the metrology assisted solution as well as its future implementation in the production line, and therefore obtaining a two-way perspective was challenging. The two selected participants were experts in the metrology assisted flap beam installation involved in the research with enough shop-floor implementation experience to identify challenges they faced themselves when prototyping the solution.

As mentioned before, the project is in a very early stage of definition. Therefore, even though tacit knowledge in other case-studies was also based on assumptions and personal opinion, the uncertainty was even greater for this case-study, and this had to be taken into account when interpreting results.

Additionally, Part B of the questionnaire involved minimum modifications which are described in Section 3.5.4.

4.2.1.2.3 Interpretation of AS-IS Report

Refer to 4.1.1.2.3 for the interpretation of the AS-IS report on this case-study.

Note that the AS-IS report of this case-study is actually the TO-BE report of CS2, as it has been developed as a future solution for the current flap beam installation process.

4.2.1.3 Stage 2: Capture Improvement Opportunities

This stage is not applicable in this case-study. The main purpose of CS3 has been to highlights the benefits of incorporating this new technology when compared to the current solution, and to validate the spiral nature of the methodology. Therefore, this stage has not been performed, limiting the results to obtaining the AS-IS report.

4.2.1.4 Stage 3: Estimation of TO-BE Situation

Not applicable. Refer to 4.2.1.3.

4.3 Insights of the Methodology Implementation Phase

In the 3 case-studies presented in this section, the methodology has been able to extract experience-based knowledge from shop-floor employees to provide improvement opportunities and highlight current challenges. Nonetheless, it had been a time-consuming process.

Case-studies involved many activities and there were many shop-floor operators to gather information from. Therefore, the methodology required extensive collaboration and time from shop-floor employees which was often difficult due to their time pressures. The future work should therefore focus on compacting the questionnaire to decrease the necessary effort and time from shop-floor employees. Refer to section 6 for further discussion on challenges.

All in all, the methodology has been fit for this purpose as it provides a structured way to analyse all critical aspects of the aircraft system installation process in one single tool instead of using different tools for identifying inter-related aspects (VSM, FMEA…).

5 VALIDATION OF METHODOLOGY

In order to confirm by examination and to provide objective evidence of the suitability of the developed methodology, an initial validation has been carried out on several stages of the methodology development.

It is important to mention that this methodology is difficult to validate in short term because it is aimed to improve the processes in long term. However, two types of validations have been performer for initial evaluation of the methodology.

First, the **initial industrial validation** has been carried out with the sponsoring company during the development of the methodology with different departments as well as during the case-studies and at the end of the implementation phase. This validation involved industrial stakeholders from production to research & development.

Industrial stakeholders, who were senior production managers and research technologists from the sponsoring company, were presented the methodology, explained steps to implement it, provided the questionnaire during its development well as during the case-studies and at the end of the implementation phase with the results from 3 case-studies.

In this discussion, stakeholders were asked to analyse several aspects presented in the Validation Puzzle in Figure 5-1.

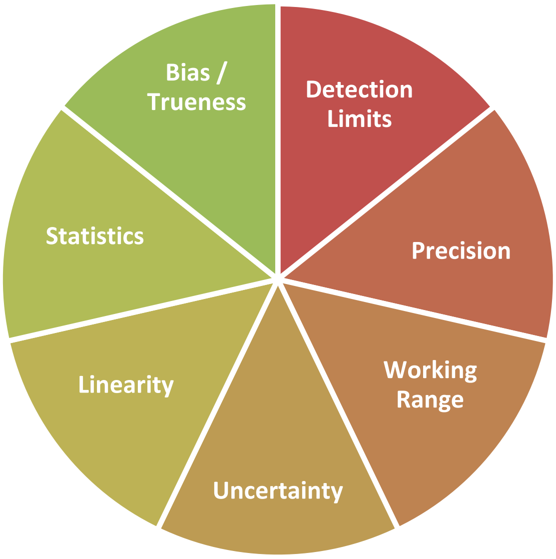


Figure 5-1: Validation Puzzle

Stakeholders highlighted the uniqueness of the methodology and the fitness for purpose to implement it in order to improve the system installation process (*working range, selectivity*). They were quite impressed with the results obtained (*statistics, bias/trueness*) and they especially liked the fact that shop-floor employees were directly asked to identify challenges and concerns in the SIP (*precision*).

The fact that the methodology highlights areas to improve but also provides raw information to improve future wings was very positively welcomed (*working range*). However, industrial experts stressed that this raw information ought to be provided to the design department for further investigation.

They also appreciated the improvement opportunities identified in the shop floor (*statistics, bias/trueness*), especially some hidden improvement opportunities they did not know of. Stakeholders admitted that shop-floor employees are an important source of identification of potential improvement opportunities rather than being only a resource for production. Nonetheless, they highlighted the fact that employees with less experience in production might not provide as good feedback as more experienced ones. In addition to that, the terminology used in the methodology questionnaire was considered too academic for some shop-floor operators to understand (*uncertainty*).

Also, stakeholders understood that this methodology could be very time-consuming to be able to perform in an industrial environment in a daily basis (*linearity, ruggedness*). Difficulties to extract technical and people related information were highlighted and a simplification of the questionnaire was suggested.

At the end of the work, a **real industrial validation** was carried out in order to evaluate how well the methodology estimated or predicted the challenges and improvement opportunities regarding the incorporation of a new technology into the production line (CS3).

Since November 2016, the metrology assisted flap beam installation process (CS3 explained in section 4.2.1) has been incrementally incorporated into production and therefore, shop-floor operators could now certify that the challenges and improvement opportunities predicted by the methodology are accurate or not.

In order to do so, the author has listed these estimations (

Table 5-1) and gathered whether current shop-floor perception agrees or disagrees with them. To the question, "*Would you say, from the shop-floor operator perspective, that the incorporation of the metrology assisted technology to the flap beam installation process….",* these are the answers received:

Table 5-1: Validation Q&A

List of improvements estimated by the methodology in 2015:		Estimated Change	Evaluation in 2017
ESTIMATED BENEFITS	*1) … has improved the process compared to the traditional flap beam installation?*	2.65 – 2.91	5
	2) … has considerably benefited the people aspect of the process (ergonomic aspect)?	3.13 – 3.45	5
	3) … has decreased the challenges related to accuracy of operations?	3.07 – 4.38	5
	4) … has decreased the challenges thanks to the application of poka-yoke techniques?	3.57 – 4.15	3
	5) … has increased the value adding activities which have, at the same time, ease the process?	3.13 – 3.53	4
	6) … has decreased the repetition of certain activities that were challenging the process before?	3.84 – 4.57	5
	7) … has stabilised the process?	3.75 – 4.54	5
	8) … has increased the precision of the process?	4.45 – 4.72	5
	9) … has improved the ergonomics of operators (specifically position of body)?	2.88 – 3.78	5
	10) … has increased visibility which also positively influenced the process?	3.27 – 4.12	3
	11) … has increased the access to the assembly point which also positively influenced the process?	3.86 – 4.06	3
	12) … has improved the process due to the fact of using more passive tools (laser tracker, for example)?	3.60 – 4.43	3
ESTIMATED CHALLENGES	*13) … has slightly challenged the process due to the lack of training?*	4.04 – 3.82	4
	14) … has challenged the process due to the lack of experience with it?	4.44 – 4.28	5
	15) … has challenged the process due to the fact that the incorporated technology had to be shared with other operators?	4.08 – 3.72	1

Answers (Evaluation 2017): ① Strongly disagree ② Slightly disagree ③ Neither agree nor disagree ④ Slightly agree ⑤ Strongly agree

The responses for the validation Q&A form were agreed by 3 individuals (2 manufacturing engineers from the company and 1 researcher heavily involved in this project). According to the answers received, the methodology has correctly anticipated 8 potential improvements and 2 potential challenges (scoring 4 or over) due to the implementation of a new technology. Only 4 estimated improvements received a neutral feedback (scored 3). Operators only disagreed with one challenge estimation meaning that the estimated challenge is not actually a challenge even though it was anticipated as such.

It is important to mention that the implemented technology is relatively new and operators are initially experiencing challenges due to the lack of experience and training. However, this fact was not reflected in the answers which means that shop-floor employees have adapted to the use of this technology very well and the training has been appropriate to avoid further challenges.

Whilst these two validations are supportive of the effectiveness of the methodology, there is clearly scope for further validation in the future as improved technologies are identified and implemented.

6 DISCUSSION AND CONCLUSIONS

The aim of this research was to present a solution to the existing gap in system installation process improvement methodologies.

The author addressed this gap by developing a new methodology which measures all critical aspects of the Aircraft System Installation Process. The methodology also identifies areas of concern for aircraft system architectures, and provides feedback and recommendations to ease the assembly process by keeping the shop-floor perspective in consideration.

The author implemented the 3-stage methodology in 3 industrial applications: two detailed design projects and research project. The author been able to apply the methodology in a circular approach - Case-Study (CS) 2 and 3, meaning CS3 is in fact one of the potential application of one Improvement Opportunity Ideas (IOI) from CS2. However, the author also admits that some modifications are necessary to implement the methodology efficiently and effectively in processes not yet in the production line.

The methodology has been able to measure a subjective aspect such as the Perception of Work (PoW) with all the case-studies as well as identify several improvement areas that would improve the PoW of shop-floor employees.

By applying some simple IOI suggestions in the first case-study, the methodology has estimated a reduction in the number of operations needed to install systems, reduced the duration of operations by 17%, and improved the PoW from 2.47 to 2.75, an improvement for the simplicity of the re-design suggestions. Additionally, other PoW have also improved such as $\text{PoW}_{\text{product}}$ 2.28 → 2.41; $\text{PoW}_{\text{process}}$ 2.41→2.62; $\text{PoW}_{\text{technology}}$ 3.04→3.20 (Refer to Figure 4-17).

By implementing a solution agreed by many participants in the second case-study, the methodology has shown a noticeable improvement in the technology and general PoW. For instance, the general PoW has improved from 2.65→2.91 and so did other groupal PoW: $\text{PoW}_{\text{product}}$ 2.43→2.71; $\text{PoW}_{\text{process}}$

2.74→3.02; PoWpeople 3.13→3.45; PoW$_{technology}$ 2.71→2.83 (Refer to Figure 4-37).

However, the uncertainty in this second iteration was bigger, as the author was dealing with a project that was not yet in production and had to predict the PoW. However, the methodology deals with perceptions and subjective data gathered from participant, and converts subjective data into objective in the best way possible.

Nonetheless, the author has faced several challenges when applying the methodology to validate it with the case-studies. Below is an explanation of the most relevant challenges faced:

In some case-studies more than others, **project boundaries** and specifications have been more challenging to determine. In the case where products are already in production (CS1, CS2), there is a general, unified understanding of the project as it is visible and measurable. Besides, the company's internal documentation helped significantly. Nonetheless, the third case-study, still at the early stages of development, required more assumptions and estimations to define the details of the project and determine the boundaries.

Identifying the **building sequence** was straight forward in most of the case-studies. In the case-studies where the product was already in production, the sponsoring company provided internal documents which clearly describe the assembly sequence as well as the operations involved. It was slightly more challenging to obtain the building sequence of the metrology assisted case-study, which is currently a research project. In this case-study, the building sequence was obtained from informal documentation as well as face-to-face meetings with the researchers involved in the project. This indicates some limitations when using estimations. Therefore, this methodology should be reviewed to be more suitable for new designs and processes.

Once the building sequence had been agreed upon, the identification of **operations related to systems** was carried out smoothly for all case-studies

At first glance, it might appear straight-forward to distinguish operations that **add value** from those which do not. However, clearly differentiating *non-value-adding* operations from *non-value-adding but necessary* operations proved to be very challenging. Even though both concepts have been described in Section A.5, classifying operations in a real case-study has led to some disagreements. This challenge has been overcome by following the literal definition, and only classified operations as *non-value-adding but necessary* when they kept the value-added operation going.

The process of capturing **explicit knowledge** presented many challenges for several different reasons. In business of the size of the sponsoring company and having the author access limitations to certain sensitive documentation, it has not been possible to locate some documents that contain the information required to complete the explicit knowledge questionnaire within the time available. Alternative solutions which involved physical measurement of components' weight or dimensions, for instance, were necessary. In these cases, the preciseness of results has been considerably reduced. For future reference, the author suggests obtaining all documents before implementing Stage 1 of the methodology, and perhaps also involving other participants from the shop-floor who are more knowledgeable.

Likewise, the process of capturing **tacit knowledge** might also need to be reviewed when implementing the methodology in long installation processes. The questionnaire required one-hour of the participants' time per operation. If this time is multiplied by the number of participants and operations, the tacit knowledge gathering process becomes very time consuming, especially for long processes such as the second case-study. Additionally, when operations required high level of accuracy and concentration, it was challenging to interview the participants following the technique described in 3.5.3 (interview while working). Therefore, the author had to come up with alternative solutions in order to collect a homogeneous set of data within the time-scale available for implementation with the minimum obstruction to the installation process.

Consequently, it might be a good idea to incorporate other knowledge capture techniques such as group workshops or team building activities.

Additionally, the length of applying methodology is considered too much and it is recommended to shortening. It is very time consuming for both researcher and participants to answer to the questionnaire. Questionnaire should be reviewed and compacted the questionnaire in order to involve participants more efficiently. It could be interesting to provide a pre-screening short questionnaire using a subset of the questions.

The **questionnaire** has also been a cause for controversy. The participants tended to misunderstand some of the questions or, at least, they demanded some clarification of certain questions (i.e. meaning of *poka yoke* or *fatigating)*. It has been difficult to conduct an interview efficiently to somebody who is completely unfamiliar of the terminologies and concepts mentioned in the questionnaire. For instance, participants tended to confuse the term *poka-yoke* with incorporating symmetry or asymmetry in a component. Thus, the questionnaire should be adapted to avoid confusion and to be equally comprehensible by someone familiar or unfamiliar with the concepts.

Part A of the questionnaire, intentionally designed to capture explicit knowledge, demands some modification as well. Even though the explicit knowledge should be objective, some of the questions are formulated in such a way that the answer requires some subjectivity. Future work is recommended to adapt these questions to give them a more objective perspective.

The physical shape of the participants has also created some disagreements when selecting answers to ergonomic-related questions. Contradictory answers arose and the root-cause of the perception had to be identified. It was not enough to say that the position of the head challenged the system installation, for example. The participant had to provide a deeper explanation for why a particular answer was selected (*I am too tall, I am too short…).*

Regarding Part B of the questionnaire, significantly better feedback has been obtained from experienced participants than from participants with little experience, as anticipated by Argote and Ingram (2000). However, these kinds of subjective questionnaires depend on emotional factors, and therefore results are more an indicator than an exact science. Nonetheless, participants were willing to share their concerns and provide useful feedback. The challenges described in Knowledge Management section (A.4) were avoided by successfully following the right techniques.

In fact, referring to the literature, Sehdev et al. (1995) surveyed 25 aerospace companies across Europe and the USA, looking at the involvement of suppliers and sub-contractors in the design phase in the implementation of a Design-for-Manufacturing (DfM) methodology, and concluded that a complex supply chain involving suppliers and sub-contractors in the detail design phase significantly challenges the process. In addition, other challenges such as misconception of DfM and product design/manufacturing deficiencies being discovered too late were also identified in that study. Aliende-Urrutia (2012) conducted an assessment on Design-for-Manufacturing-and-Assembly (DfMA) practices within the sponsoring company, and concluded that even though there has been a recent cultural change to loosely incorporate DfMA techniques, a full implementation of a systematic and formalised methodology is an essential step. Yet, what are the challenges a company faces when implementing the methodology? Kuo et al. (2001) said that the greatest challenge does not lay in the simple implementation of a new technique but overcoming organisational barriers and resistance to changing the way things are done. In fact, implementing the methodology is not only time consuming, it also needs a philosophical transformation and full collaboration from both shop-floor and management areas.

In order to overcome these challenges, firstly managers taking early decision making might need to incorporate PoW into the traditional cost, time and weight variables when choosing one or another alternative for future aircraft configurations. The shop-floor perspective, which is assessed using this methodology, could be considered as input information to avoid system installation challenges in future aircrafts by simply taking into account shop-floor perception. However, shop-floor employees must also trust the methodology and understand the relevance of their sincere collaboration.

It has been also challenging to **capture Improvement opportunity ideas** (IOI) from shop-floor participants. Their everyday activities do not require creativity and improvement identification and the author found them unfamiliarised when providing IOIs. The IOIs should be approached differently, in a creative workshop environment and probably in groups to encourage new ideas from each other and inspiring participants to identify more and better improvement opportunities. However, it is important to obtain the IOIs from shop-floor participants to meet the objective of this methodology.

As a future work, the author suggests implementing the recommended changes to avoid these challenges as well as applying the methodology ideally to every system within the aircraft wing, or at least to systems that are physically interacting with each other. This will provide a better understanding of the challenges of, not only one individual system, but also the interactions between them.

Additionally, it has been claimed that the developed methodology could also be deployed in similar complex assembly processes such as automotive industry, engine dressing or ship industry. It would be worthwhile extending the application of this methodology in the future to other sectors to validate its suitability.

Also, it would be interesting to analyse the **co-dependencies** of key factors as it has been identified during the case-studies that more information could be obtained if these co-dependencies were identified and studied.

Overall, the author has been able to effectively meet the objectives listed in Section 1.2 with the developed solution.

1. It measures and quantifies the perception of work from the shop-floor employee's perspective in complex assembly processes.
2. It provides a systematic approach to formulating and understanding problems, and identify possible continuous improvement solutions for the systems installation process.
3. It avoids recurrent system installation problems by facilitating the capture of knowledge and lessons learnt.
4. It identifies and understands which factors facilitate or challenge the system installation process from the product, process, people and technology perspective.
5. It gathers raw information to be able to inform the design department about the challenges in the shop-floor environment due to the current designs.
6. It validates the above by implementing the developed methodology in three case-studies for a specific wing configuration within Airbus.

Thus, this solution fills the objectives presented in previous sections by analysing previously unconsidered yet critical aspects. It has also been verified with real case studies that the methodology can be applied along the product design phases, and with the right knowledge management techniques, shop-floor employee's perspectives could be fed into the design as raw information for a potential Design-for-System-Installation methodology.

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APPENDICES

Appendix A : Background Reading

A.1 Current Research on Aircraft Systems

This subsection provides a summary of the published research on different aircraft systems and their installation process. It is important to highlight that some systems undergo more extensive research than others, which might be a flag on the evolution of future aircrafts. Additionally, it is also evident that there is little published research that looks at improving the actual SIP.

A.2 Aircraft Systems

This PhD aims at enhancing the aircraft SIP, but, in order to understand the challenges in the installation process, it is essential to learn what aircraft systems imply and what the current research on aircraft systems focuses on.

In general terms, aircraft systems are the equipment that ensures continued airworthiness of the aircraft. They are normally broken down into simpler sub-systems that carry out homogeneous functions, such as the electrical, hydraulic, pneumatic, fuel system and movables. Literature suggests extensive research on some of the aircraft systems, which might reflect the tendency of companies to design systems for future aircrafts. Nonetheless, the fact that some systems undergo more extensive research than others might not reflect reality with rigorous accuracy either, as companies are biased towards keeping innovative researchers under lock and key to maintain competitive advantage in the market.

One of the most complete explanation of aircraft systems in general was done by Wilkinson (1996), who published a book titled ‘Aircraft Structures and Systems’. This book provides a general description of each system and their functions, and mentions key features and components within each system. Some years later, Moir and Seabridge published two books on the topic: ‘Aircraft Systems’ (Moir and Seabridge, 2001), an in-depth study on the general systems of an aircraft, and ‘Military Avionics Systems’ (Moir et al., 2006), describing avionic systems in military aircraft. However, these published works provide a very high level description on aircraft systems, the intention being more explanatory than a research work.

Several pieces of research have been identified on individual systems, some more in depth than others, which are described in the following subsections.

A.2.1 Fuel System

The fuel system is probably the most researched system of all, together with the electrical system explained in subsection A.2.2. The fuel system makes sure that fuel gets to the engine in the proper quantity and at the correct pressure. The fuel system should provide positive and reliable fuel flow in all conditions.

Moir and Seabridge (2001), who described aircraft fuel systems in more depth than other systems. There has been a constant pursuit to develop a more efficient engine, as well as to solve current issues in the fuel system such as water concentration in tanks. This research led to various pieces of work published in important journal papers described below.

On the one hand, there is an issue with water concentration in tanks. Wilkinson (1996) explained in his book that a very large aircraft in flight uses as much as 50.000 litres per hour. The fuel is mostly stored in the wing, although it is sometimes located in the fuselage or in the tail as well. Tanks are part of the actual structure of the aircraft, and a system of pumps is used to move the fuel between the tanks. Therefore, it is not physically possible to remove them to clean or remove water in such a way.

Water management within fuel tanks is a critical safety issue. Lawson and Lim (2008) published an analysis of how to prevent the precipitation of water in fuel as well as water condensation in fuel tanks in current and future practices. They also mention fuel additives and alternative fuel as solutions for water management in the fuel system.

Fuel cells are also a well-researched topic. Jenal et al (2012) studied the performance of a fuel cell powered propulsion system for vehicles, and they state the need to develop a fuel cell powered aircraft. Keim et al. (2013) proposed a multifunctional approach to fuel cell systems. Peters and Samsun (2013) published a paper applying fuel cell technologies to avionic applications for cleaner and higher efficiency energy converters. A multistep process analysis methodology is implemented here to select the most appropriate fuel cell system configuration. After introducing specifications for avionic fuel cell systems, theoretical aspects are discussed. Previously, Seidel et al. (2011), and later Pratt et al. (2013), published work related to fuel cell application in commercial aircraft and analysed some scenarios. Finally, Wu and Li (2014) presented an analysis of some fuel cell applications on electrical aircrafts to achieve a more efficient and environmentally friendly alternative, whereas Lucken et al. (2014) proposed optimising the fuel cell system using bypass converters.

Additionally, researchers also focused on improving fuel pipes. Currently, these are rigid metallic tubes, although in more recent projects slightly flexible pipes have also been introduced in certain situations. The most rigid pipes are made of aluminium alloys, whilst flexible hoses are generally made of synthetic rubber. Moir and Seabridge's (2001) work is the most specific published information, and stated real examples in Airbus' fuel systems. As said by the authors, Airbus A320 has "*linear DC probes located in the two wing tanks*" and three fuselage tanks compared to the extra one the A340 has in the rear fuselage or tail-plane. However, the research on a full introduction of flexible pipes into the aircraft fuel system is yet to be undertaken.

In this topic, Miao and Wang (2014) investigated the wet resistance force in aircraft fuel pipes, whilst Wang et al. (2011) simulated the health management or aircraft fuel systems pipe network.

A.2.2 Electrical System

The electrical system is the core control system of the aircraft. Most modern aircraft have a large number of electrical systems, and also need electrical power to control hydraulic and pneumatic systems. Microair (2006) published a very detailed document describing typical electrical systems in aircraft, although it was referring to smaller aircrafts than those under analysis in this project. Zhao et al. (2014) reviewed the aircraft electric systems and architectures, whilst Nya et al. (2012) presented the benefits to aircraft electrical systems when applying higher voltage levels. Montgomery and Galloway (2014) suggested a new design approach for aircraft electrical power systems, and Terorde et al. (2013) proposed weight saving in an aircraft electrical system using an innovative concept.

The Concept of "More Electric Aircraft"

The concept of "More Electric Aircraft" (MEA) has been discussed for a long time. Back in 1999, Jones (1999) wished to see a MEA enter service. Now, 16 years later, there are International and European conferences entirely dedicated to this topic.

Wheeler et al. (2012) overviewed the MEA concept and determined the benefits as well as challenges of creating a more electric aircraft, whilst Naayagi (2013) reviewed some of the most notable MEA initiatives undertaken by the aerospace industry. In fact, the pioneering F-35 Fighter's (Lockheed Martin) "power-by-wire" followed by Boeing's 787 Dreamliner and Airbus' double-decker A380 are clear examples of the tendency in the aerospace industry to replace hydraulic and pneumatic systems with their electric equivalents.

Other Research

According to Wilkinson (1996), "*only a relatively small amount of energy can usually be stored in batteries*" and therefore, many authors have researched aiming at increasing the capacity of these batteries. However, this research is mostly applied to private aircraft and not for commercial ones.

There is also research focusing on the study of the impedance (Xie et al., 2014) and super-conduction (Malkin and Pagonis, 2014) characteristics in electrical cables. Flight control actuators are also a topic of research, the aim being to successfully implement electrically powered actuators, also called electro-mechanical actuators (EMA). However, as mentioned by Wheeler et al. (2012), "*it is very difficult to guarantee that the ball-screw will never jam'*, an issue which is currently not entirely solved. Lawson and Pointon (2008) proposed a thermal management of EMA, suggesting a distributed approach to controlling the temperature for more efficient control of the movement. More recently, Ogoltsov et al. (2014) managed to develop electrically powered electro-hydraulic and EMA for a MEA. In addition, Deng et al. (2014) published a conference paper describing a regenerative electrical power system for the actuation systems (ailerons, rudder, flaps, spoilers and others).

A.2.3 Hydraulic System

The hydraulic system in current aircraft provides the force required to activate movables in order to control the movement of the aircraft. Wilkinson (1996) stated "*the system could be much lighter than an electrical or mechanical system because of the high pressures used which produce small units of high power*". Although, in the pursuit of a MEA, the hydraulic system is probably nearing the end of its days. According to the author, hydraulic fluid presents an important damage risk, which is even greater when in high pressure.

For this reason, Peters and Samsun (2013) stated that nearly all forecasts for commercial airplanes predict an increase in electrical requirements to the detriment of hydraulic systems. For this exact trend, little research has been identified on new tendencies for aircraft hydraulic systems, thus the case-studies in this project did not focus on hydraulic systems.

A.2.4 Pneumatic System

The pneumatic system works in a very similar way to hydraulics, but uses high pressure air instead of hydraulic fluid. Using air as a medium for transmitting motion means exhausted air is vented directly to the atmosphere and a non-returning valve is needed. As Bremmer (2006) mentioned in his article, a pneumatic system is important for pilots who fly at night or in extreme meteorological conditions as there is no risk of fire, and air can be pumped in unlimitedly. The major disadvantage is the inefficiency of the system as energy is lost in the process of compressing air. Wilkinson (1996) mentioned the above as a reason that some aircraft are not equipped with a pneumatic system.

In order to overcome the mentioned challenge, there is some general research focusing on simulating bleed air behaviour during flight (Shi et al., 2013), or modelling a pressure regulation valve to control nonlinear aircraft pneumatic systems (Turcio et al., 2013). In addition to those, Wei et al. (2014) proposed a combination of pneumatic and digital model for cabin pressure control, whereas Woods et al. (2014) described an artificial pneumatic muscle system to activate aircraft trailing edge flaps.

There is also a general concern with the pneumatic system's function under high-temperatures. Shi et al. (2014a) proposed improvements in the design of the insulation structure of pneumatic ducts to overcome high temperatures, while in another research based on loads analysis (Shi et al., 2014b), researchers proposed a safety design method to compensate for high temperatures. Pan et al. (2014) published a paper on an experimental analysis of overheat detection for high-temperatures.

It is evident that research in pneumatic systems is at the peak of its popularity. This is probably due to inefficiency issues in pneumatic systems.

A.2.5 Movables

Except for the previously mentioned electrical methods of activating the actuators (Woods et al., 2014; Deng et al., 2014; Ogoltsov et al., 2014), there is very little research available on aircraft movables. Zhao et al. (2013) studied the method of the fatigue test for certain aircraft movables, and Ye et al. (2013) proposed a new method for improving aircraft landing performance with a numerical simulation. However, the author could not identify any published work on the rest of aircraft movables (flaps, slats, ailerons, etc.).

A.3 Complex Assembly Processes

During the statement of the problem, it has been said that the current methodology could be applicable for other complex assembly processes with similar characteristics. The definition of terminologies such as *complex assembly process* and *complex product* have continuously been used in the literature in assorted contexts. This section provides a research on the use of these terminologies to understand whether the SIP is a complex assembly process or not, and what similarities it has with other similar complex assembly processes.

The extensive research on published works has enabled identification of the characteristics involving complex assembly processes for each researcher. Nevertheless, these views often contradict each other. Therefore, this section provides an explanation of the complex assembly processes, identifies characteristics, and lists those that better define the SIP, or similar complex processes targeted.

Deshmukh et al. (1995, p.645) stated that it is unrealistic to "*express complexity by a single measure*", and define "complex product" as "*static structure alone is complex, whose complexity makes prediction of system behaviours difficult without substantial analysis, or one in which decision-making structures make effects of choice to evaluate*". However, some characteristics have been overlooked by the authors that other researchers have identified.

De Fazio et al. (1999) defined "complex assemblies" for the first time as assemblies with very high level part-counts, limited redesign options, and final assembly as an "assembly of subassemblies", similarly to the aerospace case.

In a more specific context, Kerdprasop and Kerdprasop (2013) affirmed that wafer fabrication in the semiconductor industry is "*one of the most complex processes*" because it involves technically complicated operations, and the process is composed of "*hundreds of steps*". However, it is unrealistic to define one specific process as being *the most complex* per se.

Referring to the automotive industry, Liu and Hsiao (2006) considered having multiple operations, stages and stations enough for a process to be referred to as a complex assembly process, and Ding et al. (2002) acknowledged a complex assembly process when a high amount of multi-stations are involved (i.e. automotive or aerospace structural framework build). Additionally, Dong et al. (2009) added the ship-building industry to the list.

Apparently, the complexity in the assembly comes from "*unapparent dependencies within the manufacturing process*" as well as the need for a final measurement to check the entire integrity of the product (Pfingsten et al., 2007, p.1). A *"great amount of steps involving many different machines*" is the most commonly mentioned characteristic to define complex assembly processes.

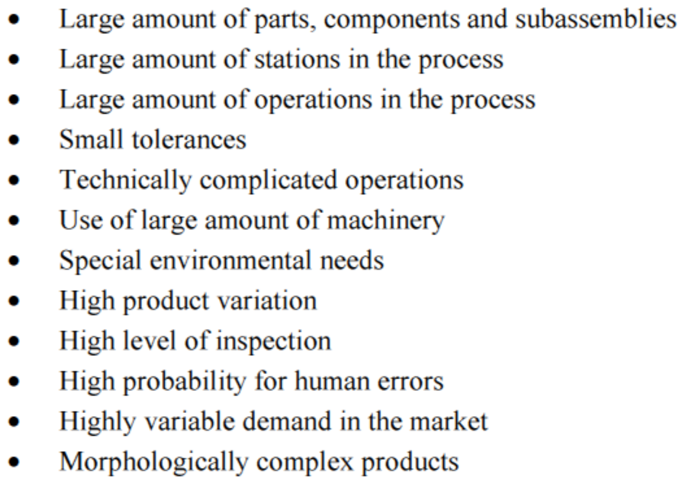
Hu et al. (2008, p.45) added supply chain modular assembly by saying that high product variability complicates the manufacturing system, and causes human errors that impact on the performance. Authors mentioned the automotive industry (more specifically BMW) as an example.

Umeda (2008, p3) mentioned the 'High-complex assembly factory' in the semiconductor equipment manufacturing industry. For the author, a highly variable demand of product is a characteristic of a process considered "complex". Fejer (2009) on the other hand, focused only on the morphology of the products to determine if a process is complex or not.

Other lower veracity publications described below have also investigated the concept of complex assembly process, but their relevance should be carefully considered.

Bosch Rexroth Corp (2005) defined the complexity of products according to the assembly steps, time to market, product variation, and life-cycle contracts. The company relates the complexity of a product with the product mix. Nanochip Lab Solutions (2012) published an issue regarding complex manufacturing environments. The company agrees with Kerdprasop and Kerdprasop (2013, p.344) by saying that the semiconductor industry has always been the "*world's most complex manufacturing process*", but does not investigate in detail the complexity of the process. Finally, Siemen's (Gironimo et al., 2006) SIMATIC is a software implementable for "complex" manufacturing and assembly processes, understanding complexity as a process where high level of adaptability and rapid response to events are required (Siemens, 2009).

To sum up, the literature compilation reveals that a complex assembly process should involve one or more of the following characteristics:



- Large amount of parts, components and subassemblies
- Large amount of stations in the process
- Large amount of operations in the process
- Small tolerances
- Technically complicated operations
- Use of large amount of machinery
- Special environmental needs
- High product variation
- High level of inspection
- High probability for human errors
- Highly variable demand in the market
- Morphologically complex products

Most of these characteristics could be appropriate for the aircraft SIP, yet its assembly process challenges and specific regulations have not been reflected in the characteristics listed above.

Aircraft system installation is considered to be a complex assembly process due to the large amount of components being assembled at many (and mostly manual) operations where employee’s expertise and training are essential. Unlike the rest of the assembly processes, the SIP is embedded into the structural building process of the whole aircraft. Components belonging to the fuel, hydraulic, electric and pneumatic systems are incorporated into the aircraft at the same time as the main structure is built. Most of the time, the space available for both installation and access is very limited with many safety constraints. The installation of systems must be highly accurate in order to meet strict aerospace restrictions, such as segregation rules, and any proposed redesign must follow internal design rules and guidelines.

The combination of all these characteristics provides a full definition of the SIP as a complex assembly process.

A.4 Background on Knowledge Management

This subsection provides a background on successful knowledge management techniques, and identifies the most suitable techniques for this project.

A.4.1 Importance of Knowledge

‘*Scientia potential est’* claims the Latin aphorism commonly attributed to Sir Francis Bacon. Nowadays, many companies have completely interiorised that knowledge is one of the most important organisational resources (Drucker, 1993; Nonaka and Takeuchi, 1995; Erden et al., 2008; Davenport et al, 1998; Alavi and Leidner, 2001) This competitive advantage, unlike other resources that tend to depreciate with use, is an intangible resource which appreciates with use (Davenport et al., 1998), and should be held in high regard.

Knowledge transfer is becoming an increasingly valuable process within organisations (Argote et al., 2000; McBriar et al., 2001), although how to successfully manage it has become an important issue over the past few decades (Liao, 2003). According to Wang and Noe (2010), many organisations still fail to exploit knowledge effectively, yet those who do are more likely to survive (Argote et al., 2000).

In simple terms, the field of knowledge management explores methods to identify, codify, store, and automate knowledge (Alavi and Leidner, 1999; Gregory, 2000). Nonetheless, the entire body of knowledge is not easy to identify in the first place. As Goldblatt’s metaphor illustrates, *‘80% of the knowledge iceberg lies under water and it is largely ignored’* (Goldblatt, 2000), in reference to tacit knowledge, explained in the next section.

A.4.2 Explicit Knowledge versus Tacit Knowledge

Polanyi (1966) first mentioned the differences between two dimensions of knowledge: explicit and tacit knowledge.

Explicit knowledge is objective, can be articulated in words, figures, and numbers, and is relatively easy to share by means of verbal communication and written documents (Nelson and Winter, 1982). **Tacit knowledge**, which is a “*subtle level of understanding often difficult to put into words*” (Fleck, 1996), is grounded in personal experience (Sternberg and Horvath, 1999; Khuzaimah and Hassan, 2012), and possesses a particular challenge in that its notion is often “not measurable” (Erden et al., 2008), even though in Section A.4.3 the author of the thesis explains why she disagrees with this statement. It can be described as a '*comprehensive justification of beliefs that are embedded in the human body and mind leading to such characteristics as 'gut feelings' and intuition'* (Varela et al., 1991). This form of knowledge could be either embodied in the individual (Johannessen et al., 2001), or developed through social interaction (Von Krogh et al., 2000; Erden et al., 2008; Ryan and O'Connor, 2013).

Generally, effort has concentrated on capturing explicit knowledge which is easier to grasp, even though most researchers in the industry and academia agree that the lack of focus on tacit knowledge capture is a missed opportunity (Anand et al., 2010). If captured, it could significantly improve organisational performance according to several researchers (Prahalad and Hamel, 1990; Nonaka and Takeuchi, 1995; Ahammad et al., 2014).

This PhD project goes beyond capturing independently only explicit or tacit data. It provides a structured way to capture, measure, compare and convert the knowledge into a more understandable output.

A.4.3 Understanding Tacit Knowledge: Is It Really Convertible?

Since Polanyi's theory, there is a slight disagreement on the literature as to whether it is possible to capture tacit knowledge or not. Many scholars believe that tacit knowledge cannot be articulated and, therefore, captured in any form (Polanyi, 1966; Tsoukas, 2003; Johannsson et al., 2012). Even though others agree on the challenge and difficulty involved in capturing some of the tacit knowledge, they support that the rest could be codified (Nonaka and Takeuchi, 1995; Kabir and Carayannis, 2013).

In 1995, Nonaka published the *Theory of Knowledge Creation* (Nonaka and Takeuchi, 1995), where the author presented a framework of knowledge conversion of the view that any kind of knowledge can be converted to another. In Nonaka's opinion (Nonaka and Takeuchi, 1995), explicit knowledge can be captured either by sharing such knowledge through **combination** practices (explicit to explicit), or by making it tacit through **internalisation** practices (explicit to tacit). Tacit knowledge can be converted with **socialisation** practices (tacit to tacit), or by making it explicit through **externalisation** practices (tacit to explicit). This last form, converting tacit knowledge into explicit in the form of a written description, objective numbers, or pictures and diagrams, facilitates discussion and analysis (Bohn, 1994; Hansen et al., 1999) and could be used to improve a process (Raelin, 1997) within a company.

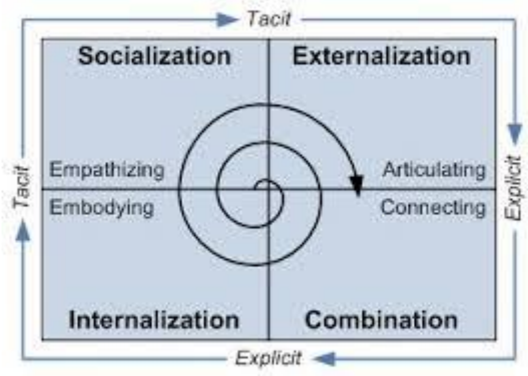


Figure A6-1: Theory of Knowledge Creation (Nonaka and Takeuchi, 1995)

Although the figure’s title is “knowledge creation”, the diagram refers the conversion of the knowledge from one type to another. Traditionally, most efforts have focused on capturing and converting explicit knowledge due to it being easier to handle than tacit knowledge (Ahmed et al., 2001). Some companies left tacit knowledge capture to one side because of its non-structured features and difficulty to transfer or share (Zhao et al., 2012), finding it too laborious and not worth the effort (Khuzaimah and Hassan, 2012). However, other scholars have stressed the importance of capturing and converting tacit knowledge into explicit (Beesley and Cooper, 2008; Schenkel and Teigland, 2008), which makes successful companies protect tacit knowledge more than explicit knowledge (Lubit, 2001) and avoid being copied by competitors (Do Rosario et al., 2015). Besides, companies that transfer knowledge effectively are more productive and likely to survive than those that are less adept at knowledge transfer (Argote et al., 2000).

The author of this PhD thesis believes that tacit knowledge is convertible, and is aiming to convert both tacit and explicit knowledge into structured and systematic explicit knowledge which can be compared.

Regarding techniques for knowledge capture, Lubit (2001) suggests tacit knowledge can be captured by writing and studying learning stories, commonly known as “Lessons Learnt”, and are especially helpful as they “*deal with mistakes which have been made and the logic and assumptions which underlay decisions*” (Lubit, 2001). Koskinen et al. (2003) consider face-to-face interactions to be the most efficient medium of capturing tacit knowledge as it allows perception of other cues such as body language, facial expression and tone of voice. Argote and Ingram (2000), however, defend the performance-based measurement approaches as being more efficient at capturing tacit knowledge than others that attempt to measure it directly.

A.4.4 How to get an Effective Knowledge Share

Achieving an effective knowledge transfer is not an easy task. According to Park et al. (2015), companies face many challenges when attempting to extract tacit knowledge. It is known that ‘*we know more than we can tell’* (Polanyi, 1966), yet it is difficult to express clearly what ‘*we know, how we make our own decisions, and how welcome to conclusions*’ (Koskinen et al., 2003). Szulanksi (1996) identified that individuals might not find any benefit in communicating their knowledge with others and are reluctant to share it, and Stasser and Tituss (1987) found that organisational members may not share information they possess with other members. Strong social identities and in-group favouritism may also impede knowledge sharing across a company (Brewer, 1979; Ashforth and Mael, 1989; Messic and Mackie, 1989). Many differences may exist between organizations including spatial, technological, cultural, institutional, linguistics and others (Javidan et al., 2005; Perez-Nordtvedt et al., 2008) which would challenge the process.

In order to enhance knowledge transfer, firms must trust, communicate and coordinate with each other. This requires commitment of resources, managerial time, attention and effort, and cooperative competency (Chen et al., 2014), a philosophy that should also be used when applying this continuous improvement methodology.

Several factors that might influence efficacy and consequently, knowledge transfer, are the lack of consideration of organisational and individual characteristics (Wang and Noe, 2010) such as absorptive capacity, characteristics of the knowledge transferred, dissemination capacity, knowledge transfer, organisational context, investment mode, and social factors such as relationship capital, exchange climate, relationship development capability, and interpersonal similarity. However, the major challenge in knowledge management involves motivating people to share (Hung et al., 2011).

The literature highlights aspects that challenge the knowledge sharing environment. Neither employees nor enterprises are unaware of the benefits that a tacit knowledge sharing culture could bring them (Zhao et al., 2012). It might be that individuals are afraid of sharing what they know (Stasser and Titus, 1987), do not know how to communicate their knowledge (Polanyi, 1966; Fernie et al., 2003), or are hesitant to use the knowledge of others (Lubit, 2001). There could also be strong social identities and favouritism that may challenge knowledge sharing across individuals or groups (Ashforth and Mael, 1989).

Some researchers (Sanidas, 2004; Si et al., 2005) debate whether an incentive mechanism is an effective method of enhancing tacit knowledge transfer and sharing. However, there is agreement on the necessity to motivate employees and managers to create a change in the culture and work practices (Holthouse, 1998) of companies to systematically share new knowledge (Nonaka and Takeuchi, 1995). It is at the same time one of the major challenges (Holthouse, 1998).

When a certain employee is convinced of the benefits of knowledge sharing, they will be intrinsically moved to share knowledge in a natural manner, while other people need extrinsic motivation to engage in that action (Deci and Ryan, 2000). Research shows that these two types of motivation can lead to different performance and behaviour (Hung et al., 2011). A successful business will not need extrinsic motivation techniques to create a knowledge sharing environment, and employees will share their knowledge either because they understand the power of knowledge sharing, because they are altruists, or because they believe in reciprocity and would like to help those who have helped them (Hung et al., 2011). Less successful or beginner companies will need to use techniques such as economic reward or reputation feedback to convince employees of the importance of sharing tacit knowledge (Hung et al., 2011).

All in all, most companies in the industry continue to struggle to find the best way to motivate their employees and managers to value intellectual assets enough to create a natural knowledge sharing environment to ensure long term growth and success (Rezgui, 2001).

In this project, the author utilises face-to-face interactions for more effective tacit knowledge sharing as well as referring to mistakes from the past (Lessons Learnt). Once tacit knowledge is captured the methodology is able to identify the most relevant challenges, and to obtain a more detailed explanation than a measurement. It is important to motivate participants to collaborate, no matter their experience or training, and to explain the personal benefits they will experience if the tacit knowledge they are sharing is honest.

A.5 List of 51 Key Factors with Explanation

In this section, there is an explanation of each of the KFs included in the methodology as well as justification for its incorporation. They are codified for easier identification: the first two numbers determine the group they belong to (01 product; 02 process; 03 people; 04 technology) and the last two numbers determine the KF within that group (01.01 type of system; 01.02 material…).

These KFs have been identified as critical by comparing the literature review with the challenges identified in the initial assessment of the SIP (refer to section 3.2). The aim is to identify if these KF have a positive or negative impact on the SIP and why.

A.5.1 Product

The methodology analyses a total of 15 KFs belonging to the product group. Below is a definition of each KF and an explanation for why it has been incorporated into the methodology (codified in no particular order):

01.01: *Type of System*

Determining the type of system is an important piece of information. The methodology only analyses operations which are related to systems, and therefore, identifying whether an operation belongs to the system installation or not is key.

This KF classifies operations into groups according to the system they are related to (electric, hydraulic, fuel, etc.) and discards from the analysis operations that do not refer to systems. According to the answers received, operations are analysed separately and the perception of work (PoW) is calculated for each type of system from the ratings of shop-floor participants. For instance, fuel system operations could obtain an average PoW of 3.5/5 whereas electrical system operations obtain a PoW of 4.5/5 (further information on PoW on section 3.6.2). The excel tool presents results in a report using user-friendly diagram to extract conclusions. By interpreting these results, the user of the methodology will be able to identify the reasons why some systems face more challenges than others, and to suggest improvements (refer to questions A01.01 and B01.01 in Appendix CAppendix C).

01.02: *Material*

Boothroyd (1994), one of the most important researchers in DfX topic, listed a set of principles for effective DfA methodologies. According to this researcher, if the materials used are different, converting two components into one is more challenging. Nevertheless, Boothroyd is not the only researcher focusing on the material. Other researchers take into account the material selection and availability (Sanchez and Priest, 1991), component material type, and other more specific aspects such as particles embedded inside the material and whether the material is susceptible to corrosion and oxidation (Das et al, 2010). Hence, the author decided to incorporate this KF into the methodology, on the one hand to check if what Boothroyd stated was also applicable to systems, and on the other hand, to determine if it would in fact ease or challenge the SIP.

The initial assessment of the SIP showed that there is no clear conclusion regarding to the material of the components being assembled. In fact, it was necessary to understand why sometimes having the same time of material eased the SIP and other times challenged it. Hence, the importance of introducing this KF into the analysis.

Therefore, the methodology categorises operations depending on the material of both assembling parts, calculates the average PoW for both cases, and presents results in a report using a user-friendly diagram. By interpreting these results, the user of the methodology will be able to identify whether, as Boothroyd stated, different materials complicate the SIP, or the complete opposite happens. Additionally, the user will also be able to propose improvements based on facts extracted from the results (refer to questions A01.02 and B01.02 in Appendix C)

01.03: *Shape of Component*

Many researchers analyse the shape of the component as part of a DfX methodology (Boothroyd, 1994; Adachi et al., 1985; Sanchez and Priest, 1991; Edwards, 2002; Das et al, 2010). However, their focus on what this methodology is aiming to achieve differs. General Electric (Maczak, 1984) analysed the *producibility* of individual parts by simple shapes. Adachi et al. (1985) and Edwards (2002) tries to simplify the structure of the components, and some other researchers (Sanchez and Priest, 1991; Edwards, 2002; Miles, 1989; Koch et al., 2004) aim to find a commonality or standardization of components to ease the assembly and manufacture of the component. Das et al. (2010) find similarity in other parts of the whole assembly and classifies them according to their geometry, while Edwards (2002) encourages the interchangeability of components.

The necessity of including this KF within the methodology is due to the importance of knowing if there is a specific shape of component that especially challenges the SIP (refer to questions A01.03 and B01.03 in Appendix C).

01.04: *Size of Component*

Miles and Swift (1992) specifically consider size of the component as a factor for their DfX methodology. However, there was not a methodology identified which suggests the importance of this KF. The initial assessment of the SIP within the sponsoring company (described in Section 3.2) suggested the size of components impacts on the ease of system installation. Literature suggests that the bigger the component, the more challenging the operations that will result.

However, the initial assessment of the SIP showed that there is no clear conclusion regarding to the size of the components being assembled. In order to certify that, the size of the components being assembled has been introduced into the methodology to assess its real effect on the SIP (refer to questions A01.04 and B01.04 in Appendix C).

01.05: *Weight of Component*

As in the previous KF, Miles and Swift (1992) considered weight of the component as a factor for their DfX methodology. Connected with the previous concept, Das et al. (2010) also mention gravitational force as a factor to consider. The initial assessment of the SIP suggested that weight of the components is in fact another factor that challenges the SIP. Literature suggests that the heavier the component, the more challenging the operations that will result. However, according to the initial assessment, this rule might vary depending on other factors. Hence, the author has decided to incorporate it into the methodology to understand the reasoning behind (refer to questions A01.05 and B01.05 in Appendix C).

01.06: *Flexibility of Component*

Only one reference has been identified which mentions flexibility of parts as a factor to analyse in a DfX methodology (Das et al., 2010), according to them, the more flexible the component, the better for the process. However, the initial assessment of the SIP showed that there is no clear conclusion regarding to the flexibility of components. In some cases, flexible components ease the SIP whereas in other cases, it challenges it. In order to understand the reasoning behind, the author has incorporated this as a Key Factor to analyse (refer to questions A01.06 and B01.06 in Appendix C).

01.07: *Symmetry or Exaggerated Asymmetry*

The symmetry of parts is a feature that has been analysed by some DfX methodology developers (Edwards, 2002; Miles, 1989; Das et al., 2010). It has been assumed that the use of symmetry eases the X characteristic (Edwards, 2002), and the literature recommends designing symmetrical components if possible (Miles, 1989). When symmetry is not possible, exaggerated asymmetry is recommended (Miles, 1989).

Other researchers (Das et al., 2010) investigate further, and suggest analysing the direction of the mating surface to the axis of symmetry. However, the initial assessment did not show a consistent conclusion on this topic; for certain components, it has been identified that symmetry is not the best, and in other cases, the complete opposite occurs. In order to extract the logic behind for the system installation case, the author has decided to incorporate this KF into the methodology (refer to questions A01.07 and B01.07 in Appendix C).

01.08: *Fragility*

The literature suggests that fragility of the components has been considered a factor that impacts on the X characteristic, however, none of them use the concept of “fragility” as such.

Das et al. (2010) analyse how susceptible the part is to corrosion, oxidation, and damage on transit or inventory. Although a bit out of scope, Edwards (2002) on the other hand, suggests avoiding components that can tangle or nest and obstruct the process. The initial assessment highlighted the importance of taking special care when installing certain system components which are susceptible to damage. Hence, the importance of incorporating this KF into the methodology (refer to questions A01.08 and B01.08 in Appendix C).

01.09: *Fit for Purpose*

The *fit for purpose* KF has been mentioned by many researchers (Das et al., 2010; Edwards, 2002; Fabricius, 1994; Miles, 1989; Gironimo, 2006) although none of them refer to it as “appropriateness of design”. Das et al. (2010) analyse purely the design of the product to see if it is suitable for the X characteristic they are aiming to improve, as well as examining the criticality of the part regarding the functionality of the product. The aim was to reduce the number of components to reduce assembly costs (DfA). Miles (1989) agreed with the previously mentioned researchers and checked whether every component in the assembly is essential, ensuring each component is fully and correctly specified. Edwards (2002) was more specific and evaluated the design to find the component which is most suitable for the production process. Fabricius (1994) on the other hand focused on the quality of the product to comply with the desired function, very similar to what Gironimo (2006) proposed by analysing the suitability of the product through analysis of the functionality of components by the customers themselves. Nonetheless, the focus of these researchers is quite different to what the author of this thesis wants to achieve.

The initial assessment highlighted that in some cases, due to the lack of fit for purpose, shop-floor employees are forced to perform extra-operations to be able to install certain wrongly-designed components. These extra-activities, which would not need to be performed if the component’s design was appropriate, challenge the SIP and, hence, the author decided to incorporate this into the methodology and clearly identify the issue (refer to questions A01.09 and B01.09 in Appendix C).

01.10: *Identification of Components*

Existing DfX methodologies do not consider identification of a part a factor in improving the X characteristic. However, during the initial assessment of the SIP, the author has identified that a lack of correct identification of certain parts challenges the SIP, hence, it has been incorporated into the methodology as a KF to analyse.

The methodology classifies components according to the presence or lack of identification, calculates average PoW for each of the options, and presents results in a report using a user-friendly diagram. By interpreting these results, the user will be able to identify whether the identification does in fact challenge the SIP, or not, and to propose improvements based on facts extracted from the results (refer to questions A01.10 and B01.10 in Appendix C).

01.11: *Connection Taxonomy*

Several researchers have analysed the way components are connected aiming at improving the X characteristic (Das et al., 2010; Edwards, 2002). Das et al. (2010) provide a deeper analysis than Edwards (2002) by identifying and analysing the direction of fastener separation force, the spacing between them, both functional and positional relationships of mating components, the number of mating surfaces that are in each component, as well as the number of components per fastener. Edwards (2002) on the other hand, suggests eliminating fasteners, and in cases where this is not possible, standardising them. However, the type of connector used in each case has not been selected as a factor to analyse by any of the other researchers. Hence, it has been incorporated into the methodology (refer to questions A01.11 and B01.11 in Appendix C).

01.12: *Application of Poka-Yoke Technique*

The poka-yoke is a widely-known Japanese technique used to avoid mistakes when assembling a component. The purpose is to eliminate product defects by preventing and correcting human errors before they occur. The literature review on Continuous Improvement (section 2.2) also suggested this technique should be incorporated into the methodology. Simultaneously, the initial assessment highlighted the importance of employee experience and training and, therefore, a technique that would avoid inexperienced employee mistakes seemed to be a beneficial KF to incorporate into the methodology (refer to questions A01.12 and B01.12 in Appendix C).

01.13: *Quality Certification*

Quality certification is another factor that has been overlooked by existing DfX methodologies, and the initial assessment highlighted the importance of quality certification in the aerospace business. In order to understand whether a component being certified has an influence in the SIP, this as a KF into the methodology.

The methodology ensures that all components have a quality certification, calculates average PoW, and presents results in a report using a user-friendly diagram (refer to questions A01.13 and B01.13 in Appendix C).

01.14: *Safety Zone*

The literature has disregarded the concept of "safety zone", a specific and critical concept in the aerospace industry. The initial assessment identified that safety zones are very important areas within the aircraft. In case of engine failure, the equipment in these areas might fail but the aircraft should be able to function to ensure a safe landing. Therefore, special attention must be paid to components installed in these locations. Hence, the importance of incorporating this factor into the methodology (refer to questions A01.14 and B01.14 in Appendix C).

01.15: *Maintenance*

Boothroyd (1994) keeps in mind the importance of disassembly in his DfX methodology, and Sanchez and Priest (1991) suggest quality and inspection as a factor to consider, yet no researchers take into account maintenance operations to improve the SIP. The initial assessment of the SIP has suggested that maintenance operations challenge the system installation design as components with high maintenance operations must be located in specific locations. In order to understand whether a high maintenance components specifically challenges the SIP or not, maintenance has been incorporated into the methodology as part of the assessment (refer to questions A01.15 and B01.15 in Appendix C).

A.5.2 Process

The methodology analyses a total of 12 KFs belonging to the process group. Below is a definition for each KF and an explanation for why it has been incorporated into the methodology (codified in no particular order):

02.01: *Value-Addition*

The addition of value and the elimination of *waste* in each of the operations is a well-established concept created by Taiichi Ohno (1988), which evolved into the Lean Manufacturing principals. There are some methodologies specifically aiming at reducing “waste” (refer to section 2.2) and the author decided to incorporate it to identify priorities to remove or reduce these operations.

Within the DfX research topic, as far as functionality is concerned, Warnecke and Bassler (1988) and Das et al. (2010) assessed the parts functionality to measure how critical the part is and how difficult it is to assemble. Regarding value-addition, Edwards (2002) was the only researcher who measures three KFs related to it: eliminating excessive operations and orientations activities, and reducing inventory waste by reconsidering stock. The initial assessment of the SIP identified that certain operations were not adding value to the final product, and therefore, should be eliminated. Hence, the author decided to incorporate value-addition as a KF in the methodology (refer to questions A02.01 and B02.01 in Appendix C).

02.02: *Pre-/Post- Operations*

Closely linked to the value-addition, and never mentioned in the literature on continuous improvement, this KF aims at identifying whether non-value-adding operations occur before or after the value-adding operation. During the initial assessment, many preparation operations were identified, and the author decided to incorporate this KF into the methodology to extract how shop-floor employees perceived these operations. This KF has been incorporated to the methodology to understand the effect pre-operations or post-operations have on the shop-floor perception of work. In other words, if the fact that they are pre- or post-operations specifically have an effect on the SIP (refer to questions A02.02 and B02.02 in Appendix C).

02.03: *Level of Automation*

There is a general disagreement among researchers considering the level of automation in a DfX methodology. Whilst Miyakawa and Ohashi (1986) did not differentiate the analysis for manual, robot or automatic assemblies, other researchers did (Boothroyd and Dewhurst, 1983; Swift and Brown, 2003; Das et al., 2010; Edwards, 2002; Ohashi et al., 2002). For example, Boothroyd and Dewhurst (1983) suggested designing for automatic feeding, automatic insertion and robot assembly, and so did Swift and Brown (1981). Edwards (2002) on the other hand, specifically suggested introduction of automation when possible by reducing manual processes to minimum, and Ohasi et al. (2002) aimed to measure the ease of automatic attach and feed operations with their methodology. The initial assessment highlighted that automation would have a great deal of impact on the SIP, in some cases positive but negative in others. There were several operations that have high potential to be automated, and therefore bypass the challenges shop-floor employees face. Hence, the author has decided to incorporate this KF into the methodology to understand what kind of impact it produces in the shop-floor perception of work (refer to questions A02.03 and B02.03 in Appendix C).

02.04: *Building Sequence*

Choi et al. (2002) considered the order of assembly operations within their DfX methodology, and Boothroyd and Dewhurst (1983) suggested analysing them in turn in the same order they are inserted into the product. Miles (1989) used a precedence diagram to check the sequence of assembly, and Das et al. (2010) suggested a more detailed analysis of the building sequence.

From the initial assessment, it has been identified that the building sequence plays an important role in the ease of the SIP. If one particular operation is performed earlier or later than recommended, it would significantly impact on the process. As it is also an essential KF, the author has decided to incorporate it into the methodology to understand until which degree a change in the building sequence would improve the perception of work from the shop-floor operators. This is where a light version of a VSM will be produced (refer to questions A02.04 and B02.04 in Appendix C).

02.05: *Duration*

The duration of the operation is a KF which has only been considered by Edwards (2002). He suggested reducing not the duration of the operation in general, but specifically that of machined operations, and avoiding long fastening operations.

During the initial assessment, it has been identified that the duration of the operation critically impacts on the SIP, hence, the importance of incorporating it into the methodology. It is important to understand whether the fact of being a long or short operation impacts on the SIP and what the nature of this impact is (refer to questions A02.05 and B02.05 in Appendix C).

02.06: *Repetition*

Repetition is another KFs that has not been mentioned in the literature. During the initial assessment, it has been identified that repetitive operations have a great impact on the process, affecting the performance as well as the human factors. It has been identified during this initial assessment that there is no direct link between repetition and perception from shop-floor. Therefore, the author has decided to incorporate it into the methodology to investigate in-depth the impact of repetition has on the shop-floor employees' perception of work (refer to questions A02.06 and B02.06 in Appendix C).

02.07: *Accuracy*

Accuracy of operation has not been specifically mentioned in existing DfX methodologies. The initial assessment identified that certain operations require a high level of accuracy. Without the appropriate training and experience, these operations might become challenging and involve extra-operations which, according to the Lean principles, are wasteful (refer to question A02.07 in Appendix C).

02.07: *Level of Stability*

In order to enhance automation, it is essential to understand the level of stability of the process. The process is stable when operations are performed the same way every time. This KF, which has not been mentioned in existing DfX methodologies, determines whether or not the process is stable, to incentivise automation.

The methodology categorises operations according to the level of stability, calculates average PoW for each case, and presents results in a report using a user-friendly diagram. By interpreting these results, the user will be able to identify where the lack of stability challenges the SIP, determine possible trends, and to propose improvements based on facts extracted from the results (refer to questions A02.07 and B02.07 in Appendix C).

02.08: *Area of Work*

The initial assessment identified that the area of work within the sub-assembly considerably impacts the installation process. Due to the dimensions of the final product, this is a critical factor for the SIP. Some operators mentioned that it was particularly challenging to work inside the wing whilst others have similar opinion when working under the wing. However, no existing methodology mention this as a factor of analysis. Hence it has been incorporated into the methodology to understand which working areas impacted the most on the shop-floor employees perception of work, and to identify areas for improvement (refer to questions A02.08 and B02.08 in Appendix C).

02.10: *Position of Sub-Assembly*

During the initial assessment, it has been identified that the position in which the sub-assembly is located when the operations are performed can substantially complicate or simplify the process. Due to the dimensions of the final product, it is a critical factor for the SIP. There has not been identified any continuous improvement methodology that mentions position of sub-assembly as a factor of analysis. Hence, it has been incorporated into the methodology to understand which position of the final product relative to the natural position of the product provides more benefits within the system installation process and why (refer to questions A02.10 and B02.10 in Appendix C).

02.11: *Tolerances and Segregation Distances*

Researchers who do mention tolerances in their DfX methodology refer to types of finish in mating surfaces (Das et al., 2010) or aim at minimising tolerances and surface demands (Edwards (2002). Nonetheless, this definitions are far from being applicable to SIP.

There are certain distances that systems need to maintain in relation to other systems and structure in order to meet aerospace regulations and design rules. The initial assessment identified that, in some cases, the space available to install system components is very limited, and it can therefore be very challenging to install a component within the space available. Some operations become even more challenging with limited visibility (03.07) and access (03.08). Hence, the author has decided to incorporate this KF into the methodology (refer to questions A02.11 and B02.11 in Appendix C).

02.12: *Precision*

Significantly linked to the previous KF, the precision with which the systems are installed has been identified as a critical factor by the initial assessment. This aspect has not been analysed by existing DfX methodologies and the author has decided to incorporate it to understand whether readjustment operations positively or negatively impact the system installation process and why.

The methodology identifies which operations and components are installed without requiring any adjustment operations, and which ones do require these operations, as well as calculating average PoW for both cases. Additionally, results will be visualised in a very user-friendly diagram, and the user of the methodology can find the root-cause and identify IOs (refer to questions A02.12 and B02.12 in Appendix C).

A.5.3 People

The people aspect has generally been disregarded by the existing DfX methodologies, with little importance given to the human interaction within the process. Only Fabricius (1994) makes reference to the labour costs. The author has incorporated 11 KFs that analyse the ergonomic related aspects, visibility and access of the operator to the assembly point as well as the experience and training required for the operator to perform the operation successfully.

Below is definition of each KF and an explanation for why it has been incorporated into the methodology (codified in no particular order):

03.01: *Number of Operators*

There is no methodology which specifically analyses the number of operator needed, yet the initial assessment highlighted the importance of achieving the ideal number of operators. In some cases, having only one employee could challenge the process, whilst at other times, issues emerge due to there being more than one. It has been identified during the initial assessment that the number of people dedicated in some operations could challenge the SIP for no specific reason. Hence, the importance of incorporating this KF into the methodology to understand the reasoning behind (refer to questions A03.01 and B03.01 in Appendix C).

03.02: *Position of Body*

Due to the relevance of human factors within the SIP, the position of the body is an essential ergonomic aspect to incorporate into the methodology. There are several ergonomic studies classifying body positions mostly focused on office work (Chaffin, 1975, Grandjean and Hunting, 1977; Genaidy et al., 1993; Juul-Kristensen et al., 1997) and traditional seating production lines (Lueder et al., 1994; Stinson et al., 2003) and recently also on surgeons (Nguyen et al., 2001; Berquer et al., 2002). However, most of the traditionally challenging position has been identified in the initial assessment as less influential in the system installation process.

In order to understand the reasoning behind this perceptions, different position of the body (*sitting on a chair; sitting on the floor; standing up, etc.*) had been investigated. By interpreting the results from shop-floor operators, the user of the methodology will be able to identify which operations are more challenging from the shop-floor perspective, and propose improvements to avoid uncomfortable positions (refer to questions A03.02 and B03.02 in Appendix C).

03.03: *Number of Hands*

Due to the relevance of human factors within the SIP, the number of hands utilised is an essential ergonomic aspect to incorporate into this methodology. There is no existing DfX methodology that analyses the ergonomic aspect.

Similarly to the *position of body* key factor, this has also been incorporated into the methodology to understand how the utilisation of one or two hands impacts on the system installation process (refer to questions A03.03 and B03.03 in Appendix C).

03.04: *Position of Arm*

Due to the relevance of human factors in the SIP, the position of the arm is an essential ergonomic aspect to incorporate into this methodology. There is no existing DfX methodology that analyses the ergonomic aspect.

Similarly to the *position of body,* different position of the arm had been investigated. By interpreting the results from shop-floor operators, the user of the methodology will be able to identify which operations are more challenging from the shop-floor perspective, and propose improvements to avoid uncomfortable positions (refer to questions A03.04 and B03.04 in Appendix C).

03.05: *Utilisation of Arm*

Due to the relevance of human factors within the SIP, the utilisation of the arm is an essential ergonomic aspect to incorporate into this methodology.

Currently, there is not any existing DfX methodology that analyses the ergonomic aspect into the analysis.

Similarly to the *position of body,* the methodology classifies operations according to the part of the arm the shop-floor employee utilises when performing each operation (*finger tips; fingers and thumb; all fingers and wrist, etc)* in order to understand how these different options impact on the system installation process and why (refer to questions A03.05 and B03.05 in Appendix C).

03.06: *Position of Head*

Due to the relevance of human factors within the SIP, the position of the head is an essential ergonomic aspect to incorporate into this methodology. There is no existing DfX methodology that analyses the ergonomic aspect.

Similarly to the *position of body,* the methodology classifies operations according to the head position the shop-floor employee when performing each operation (*looking straight, looking slightly down, looking left/right, etc.*) in order to understand how these different options impact on the system installation process and why (refer to questions A03.06 and B03.06 in Appendix C).

03.07: *Level of Visibility*

Visibility of the assembly area is a critical factor in the SIP. There is no DfX methodology which specifically analyses the visibility that the shop-floor employee has of the assembly point, yet the initial assessment highlighted that limited visibility challenges the SIP considerably.

The methodology classifies operations according to level of visibility (*no visibility; slightly limited visibility; good visibility, etc)* in order to understand how these different options impact on the system installation process and why (refer to questions A03.07 and B03.07 in Appendix C).

03.08: *Level of Access*

Access to the assembly area is a critical factor in the SIP. There is no DfX methodology which specifically analyses the access that the shop-floor employee has to the assembly point except for Das et al. (2010), who mentioned the access to the fastener. Yet, the initial assessment highlighted that having a limited access challenges the SIP significantly.

The methodology classifies operations according to level of access (*no need to go inside the wing; hand/arm inside the wing; head inside the wing…*), in order to understand how these different options impact on the system installation process and why (refer to questions A03.08 and B03.08 in Appendix C).

03.09: *Training*

Das et al (2010) are the only researchers to consider lack of skills and training in an existing DfX methodology. Other researchers seem to not to be taking into account the level of training required to successfully perform each operation. Due to the relevance of the human aspect in the SIP, the author also incorporated the training as a KF into the methodology.

The methodology classifies operations according to level of training needed to successfully perform each operations (*highly specific; specific; general training; no training…)* in order to understand how these different options impact on the system installation process and why (refer to questions A03.09 and B03.09 in Appendix C).

03.10: *Experience*

As mentioned in the previous subsection, Das et al (2010) are the only researchers to consider lack of skills in a DfX methodology. Other researchers appear not to consider the level of experience required to successfully perform each operation. Due to the relevance of the human aspect within SIP, the author also incorporated the experience as a KF into the methodology.

The methodology classifies operations according to level of experience recommended to successfully perform each operations (*very high level; medium level; low level; no experience required…)* in order to understand how these different options impact on the system installation process and why (refer to questions A03.10 and B03.10 in Appendix C).

03.11: *Safety Measures*

There is no methodology which specifically analyses safety measures shop-floor employees need to take, yet the initial assessment highlighted some challenges shop-floor employees face specifically for this reason. Hence, the importance of incorporating it into the methodology.

The methodology classifies operations according to safety equipment shop-floor employee's need to wear (*helmet, glasses, boots…*), in order to understand how these different safety measures impact on the system installation process and why (refer to questions A03.11 and B03.11 in Appendix C).

A.5.4 Technology

Although Edwards (2002) considered factors connected to the technology, this researcher's only suggestion is to use the cheapest manufacturing method as well as reducing manual processes to the minimum. The author has identified encouraging automation and, therefore, the implementation of new technology as an important aspect to incorporate within the methodology.

This section describes each KF included in the technology group within the methodology and sets out the reasons for their incorporation.

04.01: *Number of Tools*

The literature on existing DfX methodologies does not focus extensively on analysing the number of tools needed to install each component. Only Edwards (2002) recommended reducing the number of machining operations, and therefore, also machine tools, as well as avoiding special machinery for close tolerances. Ohashi et al. (2002) on the other hand, focused on the requirement of special tools, and Das et al. (2010) on the number of auxiliary stress devices for each operation. The initial assessment highlighted the impact that using too many tools has on the process. Hence, this factor has been incorporated into the methodology (refer to questions A04.01 and B04.01 in Appendix C).

04.02: *Passive/Active Tools*

The classification of tools into two groups aims to identify the level of automation of the process under analysis. Passive tools are tools that humans still have some kind of manual interaction with (for example, a hammer or a screwdriver). Active tools, on the other hand, are those that do the job for the shop-floor employee with very little human interaction (for example, a laser tracker or an electrical test device). The author has not been able to identify any research referring to the use of passive or active tools in existing DfX methodologies, yet the initial assessment highlighted that the more passive tools are used, the more challenging the system installation becomes. Hence, it has been incorporated as a factor in the methodology to investigate this fact (refer to questions A04.02 and B04.02 in Appendix C).

04.03: *Type of Active Tool*

In order to provide further information about the active tools used in the process, the methodology gives a set of choices to identify the type of active tool being used at each operation (*driller; vacuum cleaner, etc.* – check questionnaire). There could be as many options as necessary. Then, the methodology captures shop-floor perception from each type of tool to understand how these tools impact on the system installation process (refer to questions A04.03 and B04.03 in Appendix C).

04.04: *Type of Passive Tool*

In order to provide further information about the passive tools used in the process, the methodology gives a set of choices to identify the type of active tool being used at each operation (*holding fixture, guideline, lighting device, etc.*). There could be as many options as necessary. Then, the methodology captures shop-floor perception from each type of tool to understand how these tools impact on the system installation process (refer to questions A04.04 and B04.04 in Appendix C).

04.05: *Type of Operation*

Even though the type of operation that tools perform is not a factor that existing DfX methodologies have focused on, the author has decided to incorporate it into the methodology in order to understand how it is perceived at shop-floor. It would incorporate extra information which would likely also create new knowledge by identifying unknown facts. The methodology classifies tools according to the type of operation they perform (*measurement, assembly, etc*.). There could be as many options as necessary. Then, the methodology captures shop-floor perception from each type of tool to understand how these tools impact on the system installation process (refer to questions A04.05 and B04.05 in Appendix C).

04.06: *Size of Tool*

Although the size of components has been discussed in the literature (refer to KF 01.04), none of the existing DfX methodologies mention the size of the tool as a factor to improve the X characteristic. The initial assessment concluded that the size of the tool does in fact impact on the process and hence, it is incorporated as a factor to analyse in the methodology and understand the impact of the size of tools in the perception of work of shop-floor operators (refer to questions A04.06 and B04.06 in Appendix C).

04.07: *Weight of Tool*

Although the weight of components has been discussed in the literature (refer to KF 01.05), none of the existing DfX methodologies mention weight of the tool as a factor to improving the X characteristic. The initial assessment of SIP concluded that the weight of the tool very much impacts on the process and, hence, it is incorporated as a factor to analyse in the methodology and understand the impact of the weight of tools in the perception of work of shop-floor operators (refer to questions A04.07 and B04.07 in Appendix C).

04.08: *Level of Innovation*

The level of innovation is another KF that has not been considered by existing DfX methodologies. Even though Edwards (2002) encourages the introduction of automation, the level of innovation of the automation is not specifically mentioned in any existing DfX methodology. However, the initial assessment has identified that a tool's innovation level affects the SIP and, hence, has been incorporated into the methodology.

The methodology classifies tools according to their innovation level (*very innovative; innovative; traditional; very traditional, etc)* and provides information to understand the impact of innovation level of the tool in the perception of work of shop-floor operators (refer to questions A04.08 and B04.08 in Appendix C).

04.09: *Power source / Activation Method*

The power source is another KF that has not been considered by existing DfX methodologies. The initial assessment identified that depending on the power source (for active tools) or activation method (for passive tools), the SIP challenges or eases. Hence, it has been incorporated into the methodology.

The methodology classifies tools according to their power source or activation method (*electrical, hydraulic, battery, manual, etc.*), and provides information to understand the impact of activation method of the tool in the perception of work of shop-floor operators (refer to questions A04.09 and B04.09 in Appendix C).

04.10: *Training Requirement*

Although training has been discussed in the literature (refer to KF 03.09), none of the existing DfX methodologies mention tool's training requirements as a factor to improve the X characteristic. The initial assessment has concluded that the training to correctly use the tools very much impacts on the process and, hence, it is incorporated as a factor to analyse in the methodology (refer to questions A04.10 and B04.10 in Appendix C).

04.11: *Experience Requirement*

Although experience has been discussed in the literature (refer to KF 03.10), none of the existing DfX methodologies mention tool's experience requirements as a factor to improving the X characteristic. The initial assessment has concluded that possessing experience required to correctly use tools very much impacts on the process and, hence, it is incorporated as a factor to analyse in the methodology (refer to questions A04.11 and B04.11 in Appendix C).

04.12: *Efficiency*

Even though Fabricius (1994) mentions investment efficiency in his research, the author of this thesis could not find any reference to efficiency of tools in existing DfX methodologies. The author has identified efficiency as a useful factor to consider in methodology because the initial assessment identified that the low or high efficiency of utilisation of certain tools challenged the installation process for different reasons and, therefore, it was decided to incorporate this aspect in this methodology.

The methodology categorises tools according to the efficiency with which they are used along the system installation process and provides enough information to understand whether the mostly utilised tools are less challenging for the system installation process or the contrary (refer to questions A04.12 and B04.12 in Appendix C).

04.13: *Tool Share*

Even though the need to share tools is not a factor that existing methodologies have focused on, the author has decided to incorporate it into the methodology in order to understand how it is perceived at shop-floor. The initial assessment has shown that shared tools have a different effect on the SIP than tools which are not shared. Hence, it has been incorporated into the methodology to understand whether shared tools or nor shared tools provide benefit to the system installation process (refer to questions A04.13 and B04.13 in Appendix C).

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Appendix B Weighting System

B.1 Weighting System – Groups (Results from participants)

GROUP	Participant 1	Participant 2	FINAL
01 Product	50%	40%	**45%**
02 Process	20%	20%	**20%**
03 People	10%	20%	**15%**
04 Technology	20%	20%	**20%**

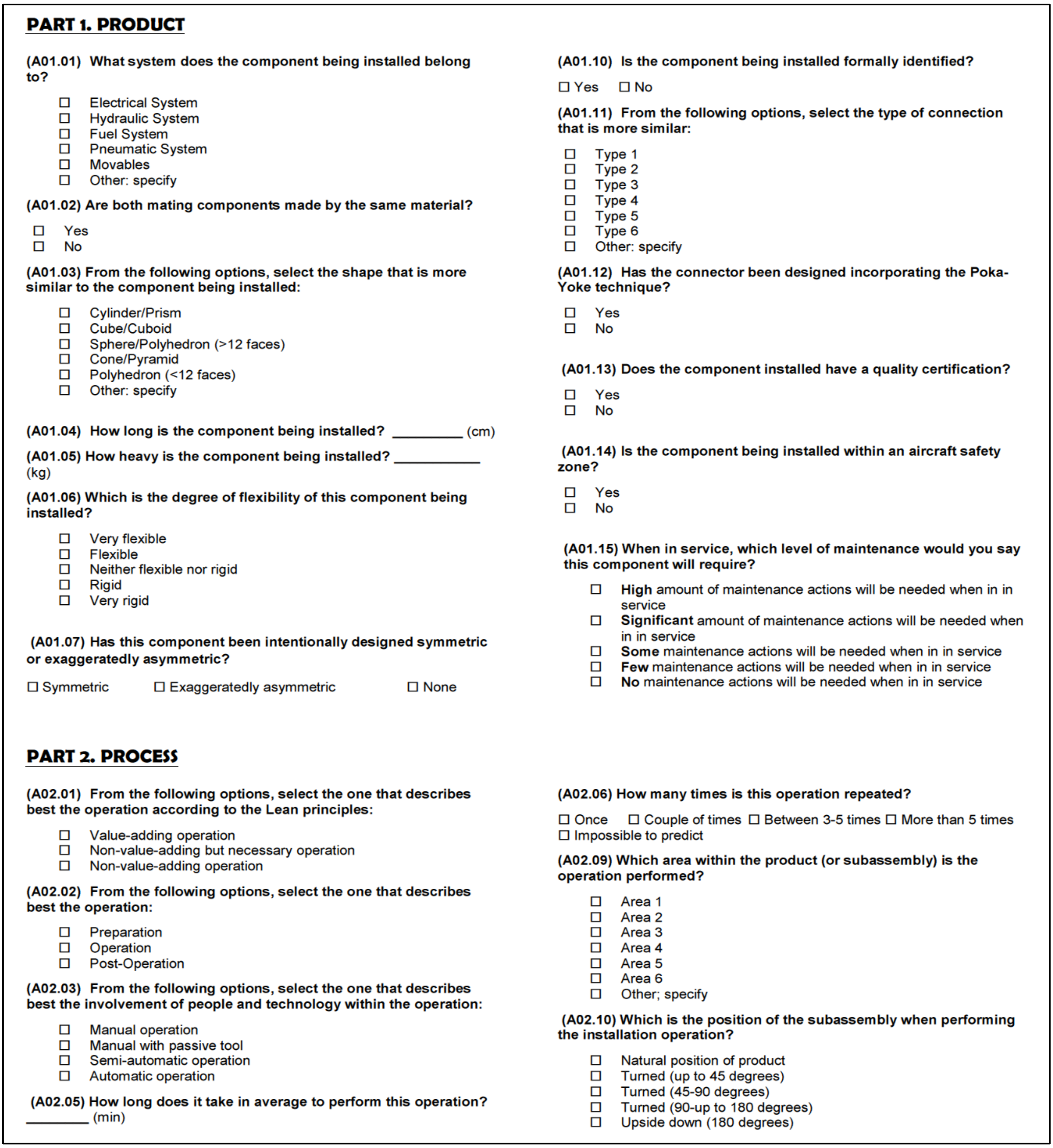
B.2 Weighting System – Key Factors: results from participants (2 pages)

KEY FACTOR	Participant 1	Participant 2	**FINAL**	**KEY FACTOR**	Participant 1	Participant 2	**FINAL**
01 PRODUCT				**03 PEOPLE**			
01-01 Type of System	4	2	**3**	*03-01 Number of Operators*	4	10	**7**
01-02 Material	4	2	**3**	*03-02 Position of Body*	10	8	**9**
01-03 Shape	6	8	**7**	*03-03 Number of Hands*	4	4	**4**
01-04 Length	7	8	**7.5**	*03-04 Position of Hands*	10	10	**10**
01-05 Weight	7	8	**7.5**	*03-05 Utilisation of Arm*	10	10	**10**
01-06 Flexibility	8	8	**8**	*03-06 Position of Head*	8	10	**9**
01-07 Symmetry	6	8	**7**	*03-07 Visibility*	10	4	**7**
01-08 Fragility	4	8	**6**	*03-08 Accessibility*	10	10	**10**
01-09 Appropriateness of Design	8	8	**8**	*03-09 Training*	10	10	**10**
01-10 Identification	8	8	**8**	*03-10 Experience*	10	10	**10**
01-11 Connection Type	8	8	**8**	*03-11 Safety Measures*	10	6	**8**
01-12 Poka-Yoke	6	8	**7**				
01-13 Quality Certification	10	4	**7**				
01-14 Safety Zone	6	6	**6**				
01-15 Maintenance	8	6	**7**				

KEY FACTOR	Participant 1	Participant 2	**FINAL**	**KEY FACTOR**	Participant 1	Participant 2	**FINAL**
02 PROCESS				**04 TECHNOLOGY**			
02-01 Value Addition	10	6	**8**	*04-01 Number of Tools*	2	8	**5**
02-02 Pre/Operation/Post	2	2	**2**	*04-02 Passive/Active*	6	6	**6**
02-03 Manual/Semi/Auto	6	10	**8**	*04-03 Type of Active Tool*	9	9	**9**
02-04 Building Sequence	9	8	**8.5**	*04-04 Type of Passive Tool*	2	2	**2**
02-05 Duration	10	2	**6**	*04-05 Type of Operation*	6	10	**8**
02-06 Repetition	8	8	**8**	*04-06 Size of Tool*	8	8	**8**
02-07 Accuracy	8	8	**8**	*04-07 Weight of Tool*	10	6	**8**
02-08 Stability	8	10	**9**	*04-08 Innovation Level*	10	6	**8**
02-09 Area of Work	6	10	**8**	*04-09 Power Source*	8	4	**6**
02-10 Position of Subassembly	7	10	**8.5**	*04-10 Training Requirement*	10	10	**10**
02-11 Tolerances and Segregation Distances	9	8	**8.5**	*04-11 Experience Requirement*	10	10	**10**
02-12 Precision	8	10	**9**	*04-12 Efficiency*	10	8	**9**
				04-13 Technology Share	4	10	**7**

Appendix C Questionnaire Templates

C.1 Part A: Explicit Knowledge Gathering (3 pages)



PART 1. PRODUCT

(A01.01) What system does the component being installed belong to?

- ☐ Electrical System
- ☐ Hydraulic System
- ☐ Fuel System
- ☐ Pneumatic System
- ☐ Movables
- ☐ Other: specify

(A01.02) Are both mating components made by the same material?

- ☐ Yes
- ☐ No

(A01.03) From the following options, select the shape that is more similar to the component being installed:

- ☐ Cylinder/Prism
- ☐ Cube/Cuboid
- ☐ Sphere/Polyhedron (>12 faces)
- ☐ Cone/Pyramid
- ☐ Polyhedron (<12 faces)
- ☐ Other: specify

(A01.04) How long is the component being installed? __________ (cm)

(A01.05) How heavy is the component being installed? ____________ (kg)

(A01.06) Which is the degree of flexibility of this component being installed?

- ☐ Very flexible
- ☐ Flexible
- ☐ Neither flexible nor rigid
- ☐ Rigid
- ☐ Very rigid

(A01.07) Has this component been intentionally designed symmetric or exaggeratedly asymmetric?

☐ Symmetric ☐ Exaggeratedly asymmetric ☐ None

(A01.10) Is the component being installed formally identified?

☐ Yes ☐ No

(A01.11) From the following options, select the type of connection that is more similar:

- ☐ Type 1
- ☐ Type 2
- ☐ Type 3
- ☐ Type 4
- ☐ Type 5
- ☐ Type 6
- ☐ Other: specify

(A01.12) Has the connector been designed incorporating the Poka-Yoke technique?

- ☐ Yes
- ☐ No

(A01.13) Does the component installed have a quality certification?

- ☐ Yes
- ☐ No

(A01.14) Is the component being installed within an aircraft safety zone?

- ☐ Yes
- ☐ No

(A01.15) When in service, which level of maintenance would you say this component will require?

- ☐ **High** amount of maintenance actions will be needed when in in service
- ☐ **Significant** amount of maintenance actions will be needed when in in service
- ☐ **Some** maintenance actions will be needed when in in service
- ☐ **Few** maintenance actions will be needed when in in service
- ☐ **No** maintenance actions will be needed when in in service

PART 2. PROCESS

(A02.01) From the following options, select the one that describes best the operation according to the Lean principles:

- ☐ Value-adding operation
- ☐ Non-value-adding but necessary operation
- ☐ Non-value-adding operation

(A02.02) From the following options, select the one that describes best the operation:

- ☐ Preparation
- ☐ Operation
- ☐ Post-Operation

(A02.03) From the following options, select the one that describes best the involvement of people and technology within the operation:

- ☐ Manual operation
- ☐ Manual with passive tool
- ☐ Semi-automatic operation
- ☐ Automatic operation

(A02.05) How long does it take in average to perform this operation? __________ (min)

(A02.06) How many times is this operation repeated?

☐ Once ☐ Couple of times ☐ Between 3-5 times ☐ More than 5 times ☐ Impossible to predict

(A02.09) Which area within the product (or subassembly) is the operation performed?

- ☐ Area 1
- ☐ Area 2
- ☐ Area 3
- ☐ Area 4
- ☐ Area 5
- ☐ Area 6
- ☐ Other; specify

(A02.10) Which is the position of the subassembly when performing the installation operation?

- ☐ Natural position of product
- ☐ Turned (up to 45 degrees)
- ☐ Turned (45-90 degrees)
- ☐ Turned (90-up to 180 degrees)
- ☐ Upside down (180 degrees)

PART 3. PEOPLE

(A03.01) How many operators are needed to perform this operation successfully? ______________ (number of people)

(A03.02) When performing this operation, which is the position of operator's body?

☐ Position of body 1
☐ Position of body 2
☐ Position of body 3
☐ Position of body 4
☐ Position of body 5
☐ Other; specify

(A03.03) How many hands are needed to perform this operation?

☐ One hand
☐ Both hands

(A03.04) When performing this operation, which is the position of the arm?

☐ Arms in 0 degrees with body (down)
☐ Arms between 0-90 degrees with body
☐ Arms in 90 degrees with body
☐ Arms between 90-180 degrees with body
☐ Arms in 180 degrees with body (up)
☐ Other

(A03.05) When performing this operation, which part of the hand/arm do you use?

☐ Finger tips
☐ Thumb and fingers
☐ Fingers and wrist
☐ Fingers, wrist and forearm
☐ Fingers, wrist, forearm and upper arm

(A03.06) When performing this operation, which is the position of the head?

☐ Looking completely up
☐ Slightly looking up
☐ Looking straight
☐ Looking slightly down
☐ Looking down
☐ Looking left or right
☐ Other: specify

(A03.07) When performing this operation, which is the visibility of the assembly area you have?

☐ No visibility even with aid
☐ Slightly limited visibility with aid
☐ Good visibility with aid
☐ Slightly limited visibility without aid
☐ Complete visibility without aid

(A03.08) When performing this operation, which is the accessibility you have to the assembly area?

☐ No access even with aid
☐ Slightly limited access with aid
☐ Good access with aid
☐ Slightly limited access without aid
☐ Complete access without aid

(A03.09) Which is the level of training needed to know how to perform this operation successfully?

☐ Highly specific training needed
☐ Specific training needed
☐ General training needed
☐ Very general training needed
☐ No training needed

(A03.10) What is the level of experience required to perform this operation successfully?

☐ Very high level
☐ High level
☐ Medium level
☐ Low level
☐ No experience needed

(A03.11) Select which of the following safety measures you are supposed to wear when performing this operation:

☐ Helmet
☐ Boots
☐ Gloves
☐ Glasses
☐ Plugs
☐ Muffs
☐ Other: specify

PART 4. TECHNOLOGY

(A04.01) How many tools do you need in total to carry out this operation? __________ (number of tools)

Tool ID: __________

(A04-02) Is it a passive or an active tool?
☐ Passive
☐ Active
(A04-03) If active, what kind of active tool is it?
☐ Active tool type 1
☐ Active tool type 2
☐ Active tool type 3
☐ Active tool type 4
☐ Active tool type 5
☐ Other; specify
(A04-04) If passive, what kind of passive tool is it?
☐ Passive tool type 1
☐ Passive tool type 2
☐ Passive tool type 3
☐ Passive tool type 4
☐ Passive tool type 5
☐ Other: specify
(A04-05) What type of operation does it perform?
☐ Operation type 1
☐ Operation type 2
☐ Operation type 3
☐ Operation type 4
☐ Operation type 5
☐ Operation type 6
☐ Operation type 7
☐ Other: specify
(A04-06) What is the size of the tool?
☐ Small
☐ Medium
☐ Large
(A04-07) What is the weight of the tool?
☐ Light
☐ Medium
☐ Heavy
☐ Very heavy
☐ Not Relevant
(A04-08) How innovative is to use this tool in this specific context?
☐ Very innovative (<1 year)
☐ Innovative (1-3 years)
☐ Medium (3 years)
☐ Traditional (5-10 years)
☐ Very traditional (>10 years)
(A04-09) What kind of power source/activation method does it need?
☐ Electrical Power
☐ Hydraulic Power
☐ Battery
☐ Manual
☐ Other: specify
(A04-10) What is the level of training needed to know how to use this tool correctly?
☐ Highly specific training
☐ Specific training
☐ General training
☐ Very general training
☐ No training
(A04-11) What is the level of experience required to use this tool properly?
☐ Very high level
☐ High level
☐ Medium level
☐ Low level
☐ No experience needed
(A04-12) Which is the efficiency of the tool?
______ (percentage)
(A04-13) Do you have to share the tool with other people in other stations?
☐ Yes
☐ No

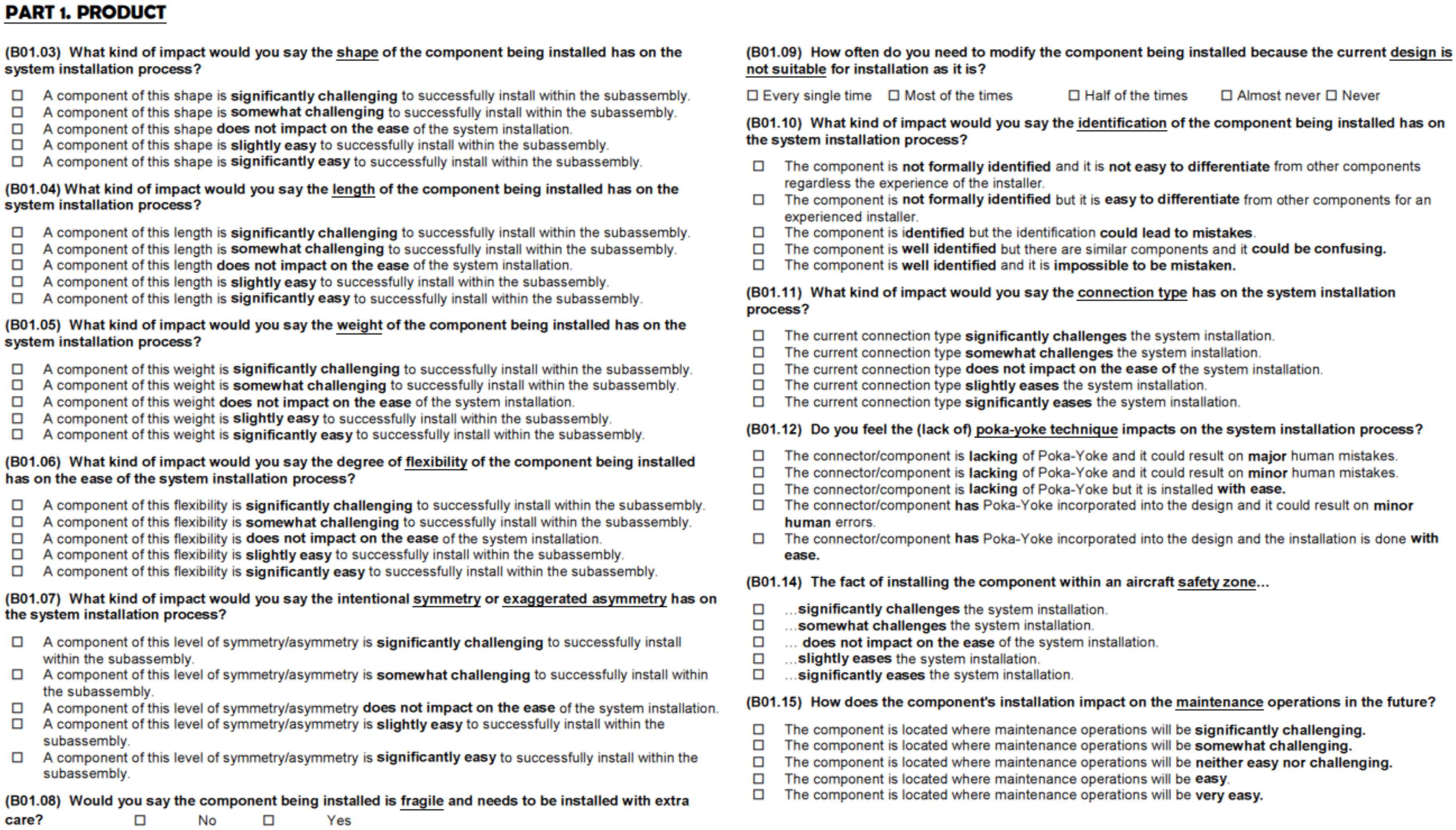
Tool ID: __________

(A04-02) Is it a passive or an active tool?
☐ Passive
☐ Active
(A04-03) If active, what kind of active tool is it?
☐ Active tool type 1
☐ Active tool type 2
☐ Active tool type 3
☐ Active tool type 4
☐ Active tool type 5
☐ Other; specify
(A04-04) If passive, what kind of passive tool is it?
☐ Passive tool type 1
☐ Passive tool type 2
☐ Passive tool type 3
☐ Passive tool type 4
☐ Passive tool type 5
☐ Other: specify
(A04-05) What type of operation does it perform?
☐ Operation type 1
☐ Operation type 2
☐ Operation type 3
☐ Operation type 4
☐ Operation type 5
☐ Operation type 6
☐ Operation type 7
☐ Other: specify
(A04-06) What is the size of the tool?
☐ Small
☐ Medium
☐ Large
(A04-07) What is the weight of the tool?
☐ Light
☐ Medium
☐ Heavy
☐ Very heavy
☐ Not Relevant
(A04-08) How innovative is to use this tool in this specific context?
☐ Very innovative (<1 year)
☐ Innovative (1-3 years)
☐ Medium (3 years)
☐ Traditional (5-10 years)
☐ Very traditional (>10 years)
(A04-09) What kind of power source/activation method does it need?
☐ Electrical Power
☐ Hydraulic Power
☐ Battery
☐ Manual
☐ Other: specify
(A04-10) What is the level of training needed to know how to use this tool correctly?
☐ Highly specific training
☐ Specific training
☐ General training
☐ Very general training
☐ No training
(A04-11) What is the level of experience required to use this tool properly?
☐ Very high level
☐ High level
☐ Medium level
☐ Low level
☐ No experience needed
(A04-12) Which is the efficiency of the tool?
______ (percentage)
(A04-13) Do you have to share the tool with other people in other stations?
☐ Yes
☐ No

Tool ID: __________

(A04-02) Is it a passive or an active tool?
☐ Passive
☐ Active
(A04-03) If active, what kind of active tool is it?
☐ Active tool type 1
☐ Active tool type 2
☐ Active tool type 3
☐ Active tool type 4
☐ Active tool type 5
☐ Other; specify
(A04-04) If passive, what kind of passive tool is it?
☐ Passive tool type 1
☐ Passive tool type 2
☐ Passive tool type 3
☐ Passive tool type 4
☐ Passive tool type 5
☐ Other: specify
(A04-05) What type of operation does it perform?
☐ Operation type 1
☐ Operation type 2
☐ Operation type 3
☐ Operation type 4
☐ Operation type 5
☐ Operation type 6
☐ Operation type 7
☐ Other: specify
(A04-06) What is the size of the tool?
☐ Small
☐ Medium
☐ Large
(A04-07) What is the weight of the tool?
☐ Light
☐ Medium
☐ Heavy
☐ Very heavy
☐ Not Relevant
(A04-08) How innovative is to use this tool in this specific context?
☐ Very innovative (<1 year)
☐ Innovative (1-3 years)
☐ Medium (3 years)
☐ Traditional (5-10 years)
☐ Very traditional (>10 years)
(A04-09) What kind of power source/activation method does it need?
☐ Electrical Power
☐ Hydraulic Power
☐ Battery
☐ Manual
☐ Other: specify
(A04-10) What is the level of training needed to know how to use this tool correctly?
☐ Highly specific training
☐ Specific training
☐ General training
☐ Very general training
☐ No training
(A04-11) What is the level of experience required to use this tool properly?
☐ Very high level
☐ High level
☐ Medium level
☐ Low level
☐ No experience needed
(A04-12) Which is the efficiency of the tool?
______ (percentage)
(A04-13) Do you have to share the tool with other people in other stations?
☐ Yes
☐ No

C.2 Part B: Tacit Knowledge Gathering (4 pages)



PART 1. PRODUCT

(B01.03) What kind of impact would you say the shape of the component being installed has on the system installation process?

- ☐ A component of this shape is **significantly challenging** to successfully install within the subassembly.
- ☐ A component of this shape is **somewhat challenging** to successfully install within the subassembly.
- ☐ A component of this shape **does not impact on the ease** of the system installation.
- ☐ A component of this shape is **slightly easy** to successfully install within the subassembly.
- ☐ A component of this shape is **significantly easy** to successfully install within the subassembly.

(B01.04) What kind of impact would you say the length of the component being installed has on the system installation process?

- ☐ A component of this length is **significantly challenging** to successfully install within the subassembly.
- ☐ A component of this length is **somewhat challenging** to successfully install within the subassembly.
- ☐ A component of this length **does not impact on the ease** of the system installation.
- ☐ A component of this length is **slightly easy** to successfully install within the subassembly.
- ☐ A component of this length is **significantly easy** to successfully install within the subassembly.

(B01.05) What kind of impact would you say the weight of the component being installed has on the system installation process?

- ☐ A component of this weight is **significantly challenging** to successfully install within the subassembly.
- ☐ A component of this weight is **somewhat challenging** to successfully install within the subassembly.
- ☐ A component of this weight **does not impact on the ease** of the system installation.
- ☐ A component of this weight is **slightly easy** to successfully install within the subassembly.
- ☐ A component of this weight is **significantly easy** to successfully install within the subassembly.

(B01.06) What kind of impact would you say the degree of flexibility of the component being installed has on the ease of the system installation process?

- ☐ A component of this flexibility is **significantly challenging** to successfully install within the subassembly.
- ☐ A component of this flexibility is **somewhat challenging** to successfully install within the subassembly.
- ☐ A component of this flexibility is **does not impact on the ease** of the system installation.
- ☐ A component of this flexibility is **slightly easy** to successfully install within the subassembly.
- ☐ A component of this flexibility is **significantly easy** to successfully install within the subassembly.

(B01.07) What kind of impact would you say the intentional symmetry or exaggerated asymmetry has on the system installation process?

- ☐ A component of this level of symmetry/asymmetry is **significantly challenging** to successfully install within the subassembly.
- ☐ A component of this level of symmetry/asymmetry is **somewhat challenging** to successfully install within the subassembly.
- ☐ A component of this level of symmetry/asymmetry **does not impact on the ease** of the system installation.
- ☐ A component of this level of symmetry/asymmetry is **slightly easy** to successfully install within the subassembly.
- ☐ A component of this level of symmetry/asymmetry is **significantly easy** to successfully install within the subassembly.

(B01.08) Would you say the component being installed is fragile and needs to be installed with extra care? ☐ No ☐ Yes

(B01.09) How often do you need to modify the component being installed because the current design is not suitable for installation as it is?

☐ Every single time ☐ Most of the times ☐ Half of the times ☐ Almost never ☐ Never

(B01.10) What kind of impact would you say the identification of the component being installed has on the system installation process?

- ☐ The component is **not formally identified** and it is **not easy to differentiate** from other components regardless the experience of the installer.
- ☐ The component is **not formally identified** but it is **easy to differentiate** from other components for an experienced installer.
- ☐ The component is **identified** but the identification **could lead to mistakes**.
- ☐ The component is **well identified** but there are similar components and it **could be confusing.**
- ☐ The component is **well identified** and it is **impossible to be mistaken.**

(B01.11) What kind of impact would you say the connection type has on the system installation process?

- ☐ The current connection type **significantly challenges** the system installation.
- ☐ The current connection type **somewhat challenges** the system installation.
- ☐ The current connection type **does not impact on the ease of** the system installation.
- ☐ The current connection type **slightly eases** the system installation.
- ☐ The current connection type **significantly eases** the system installation.

(B01.12) Do you feel the (lack of) poka-yoke technique impacts on the system installation process?

- ☐ The connector/component is **lacking** of Poka-Yoke and it could result on **major** human mistakes.
- ☐ The connector/component is **lacking** of Poka-Yoke and it could result on **minor** human mistakes.
- ☐ The connector/component is **lacking** of Poka-Yoke but it is installed **with ease.**
- ☐ The connector/component **has** Poka-Yoke incorporated into the design and it could result on **minor human** errors.
- ☐ The connector/component **has** Poka-Yoke incorporated into the design and the installation is done **with ease.**

(B01.14) The fact of installing the component within an aircraft safety zone…

- ☐ …**significantly challenges** the system installation.
- ☐ …**somewhat challenges** the system installation.
- ☐ … **does not impact on the ease** of the system installation.
- ☐ …**slightly eases** the system installation.
- ☐ …**significantly eases** the system installation.

(B01.15) How does the component's installation impact on the maintenance operations in the future?

- ☐ The component is located where maintenance operations will be **significantly challenging.**
- ☐ The component is located where maintenance operations will be **somewhat challenging.**
- ☐ The component is located where maintenance operations will be **neither easy nor challenging.**
- ☐ The component is located where maintenance operations will be **easy**.
- ☐ The component is located where maintenance operations will be **very easy.**

PART 2. PROCESS

(B02.04) How do you feel about the building sequence and the moment to carry out this specific operation?

- ☐ The operation takes place in such moment within the building sequence that **significantly challenges** the system installation.
- ☐ The operation takes place in such moment within the building sequence that **somewhat challenges** the system installation.
- ☐ The operation takes place in such moment within the building sequence that **neither eases nor challenges** the system installation.
- ☐ The operation takes place in such moment within the building sequence that **slightly eases** the system installation.
- ☐ The operation takes place in such moment within the building sequence that **significantly eases** the system installation.

(B02.05) What kind of impact would you say the duration of the operation has on the system installation process?

- ☐ The duration of the operation is **very long** and it **significantly challenges** the system installation.
- ☐ The duration of the operation is **long** and it **somewhat challenges** the system installation.
- ☐ The duration of the operation is **about right** and it **neither eases nor challenges** the system installation.
- ☐ The duration of the operation is **short** but it **does not ease** the system installation **very much.**
- ☐ The duration of the operation is **very short** and it **eases** the system installation.

(B02.06) What kind of impact would you say the repetition of the operation has on the system installation process?

- ☐ The operation is repeated the amount of times that it **significantly challenges** the system installation.
- ☐ The operation is repeated the amount of times that it **somewhat challenges** the system installation.
- ☐ The operation is repeated the amount of times that it **neither eases nor challenges** the system installation.
- ☐ The operation is repeated the amount of times that it **slightly eases** the system installation.
- ☐ The operation is repeated the amount of times that it **significantly eases** the system installation.

(B02.07) What kind of impact would you say the accuracy of the operation has on the system installation process?

- ☐ The installation of the component requires a **high** level of accuracy and it gets **significantly challenging** to install it.
- ☐ The installation of the component requires a **medium** level of accuracy and therefore, it gets **significantly challenging** to install it.
- ☐ The installation of the component requires a **medium** level of accuracy and therefore, it gets **somewhat challenging** to install it.
- ☐ The installation of the component requires a **low** level of accuracy but for some other reason, it is **not easy** to install it.
- ☐ The installation of the component requires a **low** level of accuracy and therefore, it is **significantly easy** to install.

(B02.08) Would you say the operations are performed the same way (stability) every time?

- ☐ No, the process is **variable.**
- ☐ Yes, the process is **stable.**

(B02.09) How you feel the area of work impacts on the system installation process?

- ☐ The area of work where this operation takes place **significantly challenges** the system installation.
- ☐ The area of work where this operation takes place **somewhat challenges** the system installation.
- ☐ The area of work where this operation takes place **neither eases nor challenges** the system installation.
- ☐ The area of work where this operation takes place **slightly eases** the system installation.
- ☐ The area of work where this operation takes place **significantly eases** the system installation.

(B02.10) What kind of impact would you say the position of subassembly where you need to install the systems has on the system installation process?

- ☐ The position of the subassembly where I need to install the systems **significantly challenges** the system installation.
- ☐ The position of the subassembly where I need to install the systems **somewhat challenges** the system installation.
- ☐ The position of the subassembly where I need to install the systems **neither eases nor challenges** the system installation.
- ☐ The position of the subassembly where I need to install the systems **slightly eases** the system installation.
- ☐ The position of the subassembly where I need to install the systems **significantly eases** the system installation.

(B02.11) Could you describe how the space available (segregation distances) where you have to install the component impacts on the system installation process itself?

- ☐ The space available is **significantly smaller** than the space needed and the installation of the system is challenging.
- ☐ The space available is **somewhat smaller** than the space needed and the system is not installed with ease.
- ☐ The space available is just **as big as** the space needed but the system is installed about right.
- ☐ The space available is **slightly bigger** than the space needed and the system is installed well enough.
- ☐ The space available is **significantly bigger** than the space needed and the system installation is easy.

(B02.12) Would you say that the component is usually assembled with precision the first time without needing extra operations?

- ☐ The component **usually** needs **several** adjustment activities before it is located in the right position.
- ☐ The component is **sometimes** assembled in an incorrect position and it normally needs a **couple of** adjustment operations later on.
- ☐ The component assembled is sometimes assembled in the incorrect position and it normally needs **one extra** adjustment operation.
- ☐ **Most of the times**, the component is assembled in the correct position.
- ☐ The component is **always** assembled correctly the first time it is installed.

PART 3. PEOPLE

(B03.01) What kind of impact would you say the number of operators currently working on this operation has on the system installation process?

☐ There are **too many** operators and the system installation is **significantly challenging.**
☐ There are **many more** operators than the ideal and the system installation is **somewhat challenging.**
☐ There are **some more** operators than the ideal and the system installation **could get challenging.**
☐ There are **few more** operators than the ideal but the system installation is **easy.**
☐ The amount of operators performing this operation is **the ideal** and this fact **significantly eases** the system installation.

(B03.02) What kind of impact would you say the position of your body has on the system installation process?

☐ The position of my body **significantly challenges** the system installation.
☐ The position of my body **somewhat challenges** the system installation.
☐ The position of my body **neither eases nor challenges** the system installation.
☐ The position of my body is **suitable enough** to install the system with ease.
☐ The position of my body is **the most suitable** to install this system with ease.

(B03.04) What kind of impact would you say the position of your hand(s) has on the system installation process?

☐ The position of my hand(s) **significantly challenges** the system installation.
☐ The position of my hand(s) **somewhat challenges** the system installation.
☐ The position of my hand(s) **neither eases nor challenges** the system installation.
☐ The position of my hand(s) is **suitable enough** to install the system with ease.
☐ The position of my hand(s) is **the most suitable** to install this system with ease.

(B03.05) What kind of impact would you say the utilisation of your arm(s) has on the system installation process?

☐ The utilisation of my arms(s) **significantly challenges** the system installation.
☐ The utilisation of my arms(s) **somewhat challenges** the system installation.
☐ The utilisation of my hand(s) **neither eases nor challenges** the system installation.
☐ The utilisation of my hand(s) is **suitable enough** to install the system with ease.
☐ The utilisation of my hand(s) is **the most suitable** to install this system with ease.

(B03.06) What kind of impact would you say the position of your head has on the system installation process?

☐ The position of my head **significantly challenges** the system installation.
☐ The position of my head **somewhat challenges** the system installation.
☐ The position of my head **neither eases nor challenges** the system installation.
☐ The position of my head is **suitable enough** to install the system with ease.
☐ The position of my head is **the most suitable to** install this system with ease.

(B03.07) What kind of impact would you say the visibility has on the system installation process?

☐ The visibility I have from my usual working position **significantly challenges** the system installation.
☐ The visibility I have from my usual working position **somewhat challenges** the system installation.
☐ The visibility I have from my usual working position **neither eases nor challenges** the system installation.
☐ The visibility I have from my usual working position **eases** the system installation.
☐ The visibility I have from my usual working position **significantly eases** the system installation.

(B03.08) What kind of impact would you say the accessibility has on the system installation process?

☐ The accessibility I have from my usual working position makes for a **significantly challenging** system installation.
☐ The accessibility I have from my usual working position makes for a **somewhat challenging** system installation.
☐ The accessibility I have from my usual working position **neither eases nor challenges** the system installation.
☐ The accessibility I have from my usual working position **eases** the system installation.
☐ The accessibility I have from my usual working position **significantly eases** the system installation.

(B03.09) What kind of impact would you say the level of training has on the system installation process?

☐ We currently **lack** of any kind of training to install systems successfully.
☐ The level of training we currently receive is **not sufficient** to install systems successfully.
☐ The level of training we currently receive is **not quite sufficient** to install systems successfully.
☐ The level of training we currently receive is **sufficient** to install systems successfully.
☐ The level of training we currently receive is **more than sufficient** to install systems successfully.

(B03.10) What kind of impact would you say the level of experience has on the system installation process?

☐ We currently **lack** of the experience required to install systems successfully.
☐ The level of experience we currently have is **not sufficient** to install systems successfully.
☐ The level of experience we currently have is **not quite sufficient** to install systems successfully.
☐ The level of experience we currently have is **sufficient** to install systems successfully.
☐ The level of experience we currently have is **more than sufficient** to install systems successfully.

(B03.11) What kind of impact would you say the SAFETY MEASURES (hat, boots, glasses…) have on the system installation process? *- Anwer as many times as safety measures -*

☐ The safety measures I need to wear **significantly challenge** the system installation very much.
☐ The safety measures I need to wear **somewhat challenge** the system installation.
☐ The safety measures I need to wear **do not impact** on the system installation at all.
☐ The safety measures I need to wear **slightly ease** the system installation.
☐ The safety measures I need to wear **significantly ease** the system installation.

GENERAL PERCEPTION: How … do you find the operation? (1 minimum: 5 maximum)

	1	2	3	4	5
1. CHALLENGING	☐	☐	☐	☐	☐
2. BORING	☐	☐	☐	☐	☐
3. EASY	☐	☐	☐	☐	☐
4. COMPLEX	☐	☐	☐	☐	☐
5. SATISFACTORY	☐	☐	☐	☐	☐

	1	2	3	4	5
6. FATIGATING	☐	☐	☐	☐	☐
7. MONOTONOUS	☐	☐	☐	☐	☐
8. ANNOYING	☐	☐	☐	☐	☐
9. COMFORTABLE	☐	☐	☐	☐	☐
10. MOTIVATING	☐	☐	☐	☐	☐

PART 4. TECHNOLOGY

(B04.01) If you need tools to perform the assembly operation for you, what kind of impact would you say the number of tools needed has on the system installation process?

- ☐ The system installation would be **less challenging** with **fewer amounts** of tools.
- ☐ The system installation would be **less challenging** with **less variety** of tools.
- ☐ I don't believe the amount of tools **neither eases nor challenges** the system installation.
- ☐ The system installation is **not challenging** due to the **variety** of tools.
- ☐ The system installation **is not challenging** due to the **amount** of tools.

(B04.02) What kind of impact would you say the fact of being a passive or active tool has on the system installation process?

- ☐ The fact that the tool is passive (or active) **significantly challenges** the system installation.
- ☐ The fact that the tool is passive (or active) **somewhat challenges** the system installation.
- ☐ The fact that the tool is passive (or active) **neither eases nor challenges** the system installation.
- ☐ The fact that the tool is passive (or active) **eases** the system installation.
- ☐ The fact that the tool is passive (or active) **significantly eases** the system installation.

(B04.03) What kind of impact would you say the active tool you use has on the system installation process?

- ☐ The active tool I use **significantly challenges** the system installation.
- ☐ The active tool I use **somewhat challenges** the system installation.
- ☐ The active tool I use **neither eases nor challenges** the system installation.
- ☐ The active tool I use **slightly eases** the system installation.
- ☐ The active tool I use **significantly eases** the system installation.

(B04.03) What kind of impact would you say the passive tool you use has on the system installation process?

- ☐ The passive tool I use **significantly challenges** the system installation.
- ☐ The passive tool I use **somewhat challenges** the system installation.
- ☐ The passive tool I use **neither eases nor challenges** the system installation.
- ☐ The passive tool I use **slightly eases** the system installation.
- ☐ The passive I use **significantly eases** the system installation.

(B04.05) If you need any tool to perform the assembly operation, what kind of impact would you say the type of operation the tool performs has on the system installation process?

- ☐ It makes the operations **significantly challenging.**
- ☐ It makes the operation **somewhat challenging.**
- ☐ It **does not impact on the ease** of the operation.
- ☐ It makes the operation **slightly easy.**
- ☐ It makes the operation **significantly easy.**

(B04.06) If you need any tool to perform the assembly operation, what kind of impact would you say the size of the tool has on the system installation process?

- ☐ The size of the instrument I am using makes the system installation **significantly challenging.**
- ☐ The size of the instrument I am using makes the system installation **somewhat challenging.**
- ☐ The size of the instrument I am using makes **neither eases nor challenges** the system installation.
- ☐ The size of the instrument I am using makes the system installation **slightly easy.**
- ☐ The size of the instrument I am using makes the system installation **significantly easy.**

(B04.08) If the tool needs power to be able to work, what kind of impact would you say the power source has on the system installation process?

- ☐ This type of power source **significantly challenges** the system installation.
- ☐ This type of power source **somewhat challenges** the system installation.
- ☐ This type of power source **neither eases nor challenges** the system installation.
- ☐ This type of power source **slightly eases** the system installation.
- ☐ This type of power source **significantly eases** the system installation.

(B04.09) What kind of impact would you say the level of training required use the tool has on the system installation process?

- ☐ We currently **lack** of any kind of training to use the tool successfully.
- ☐ The level of training we currently receive to use the tool is **not sufficient** install systems successfully.
- ☐ The level of training we currently receive to use the tool is **not quite sufficient** to install systems successfully.
- ☐ The level of training we currently receive to use the tool is **sufficient** to install systems successfully.
- ☐ The level of training we currently receive to use the tool is **more than sufficient** to install systems successfully.

(B04.10) What kind of impact would you say the level of experience required to use the tool has on the system installation process?

- ☐ We currently **lack** of the experience required to use the tool successfully.
- ☐ The level of experience we currently have on the tool is **not sufficient** to install systems successfully.
- ☐ The level of experience we currently have on the tool is **not quite sufficient** to install systems successfully.
- ☐ The level of experience we currently have on the tool is **sufficient** to install systems successfully.
- ☐ The level of experience we currently have on the tool is **more than sufficient** to install systems successfully.

(B04.12) If you need to SHARE the tool, what kind of impact would you say this fact has on the system installation process?

- ☐ It **significantly challenges** the system installation.
- ☐ It **somewhat challenges** the system installation.
- ☐ It **neither eases nor challenges** the system installation.
- ☐ It **slightly eases** the system installation.
- ☐ It **significantly eases** the system installation.

C.3 Modifications of Questionnaire (2 Tables)

Table 6-1: Questionnaire modifications to suit a case-study

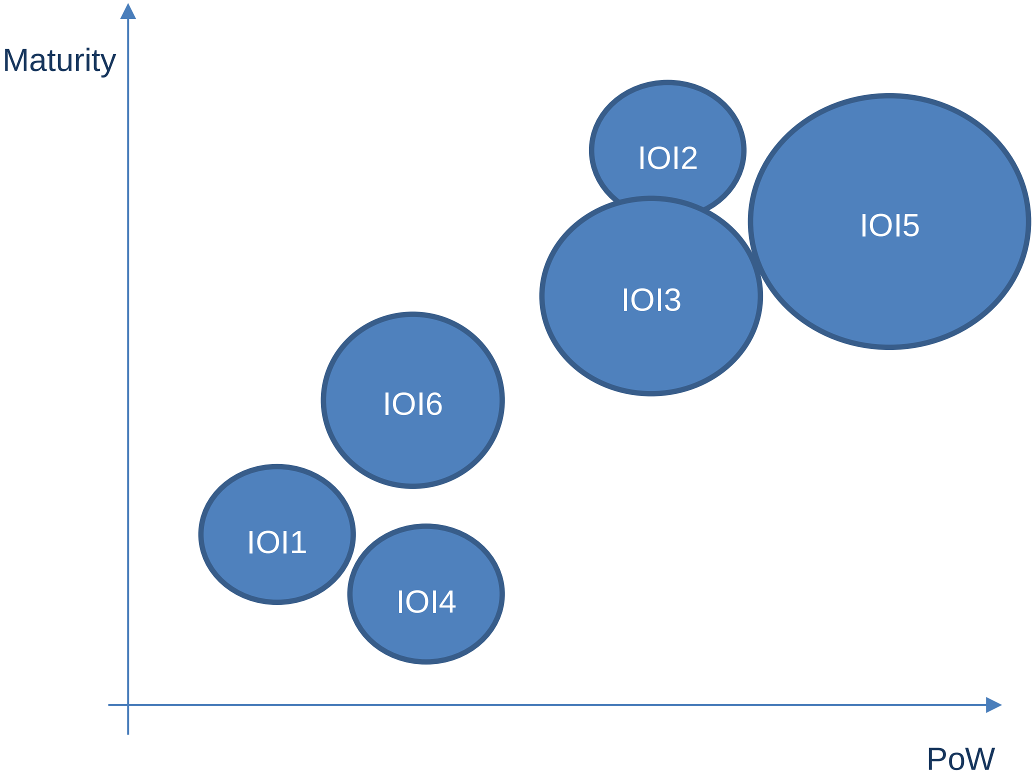
	Template	CS1	CS2	CS3
(A01.11) From the following options, select the type of connection that is more similar:	☐ Type 1 ☐ Type 2 ☐ Type 3 ☐ Type 4 ☐ Type 5 ☐ Type 6 ☐ Other: specify	☐ Nuts ☐ Studs ☐ Washer ☐ Conical washer ☐ Sealant ☐ Bolts ☐ Split Pin ☐ Other: specify	☐ Connector ☐ Adaptor ☐ Clamps ☐ Brackets ☐ Mounting block ☐ Deflector plate ☐ Other: specify	
(A02.09) Which area within the product (or subassembly) is the operation performed?	☐ Area 1 ☐ Area 2 ☐ Area 3 ☐ Area 4 ☐ Area 5 ☐ Area 6 ☐ Other; specify	☐ Below the wing on track 2 ☐ Below the wing on track 3 ☐ Below the wing on track 4 ☐ In front of the wing on track 2 ☐ In front of the wing on track 3 ☐ In front of the wing on track 4 ☐ On top of the wing ☐ Away from the wing	☐ Away from the wing ☐ Inside the wing (between R7-9) ☐ Inside the wing (between R9-11) ☐ Inside the wing (between R11-17) ☐ Below the wing (between R7-11) ☐ Below the wing (between R11-17) ☐ Other: specify	☐ Below the wing on track 2 ☐ Below the wing on track 3 ☐ Below the wing on track 4 ☐ In front of the wing on track 2 ☐ In front of the wing on track 3 ☐ In front of the wing on track 4 ☐ On top of the wing ☐ Away from the wing
(A03.02) When performing this operation, which is the position of operator's body?	☐ Position of body 1 ☐ Position of body 2 ☐ Position of body 3 ☐ Position of body 4 ☐ Position of body 5 ☐ Other; specify	☐ Standing up ☐ Kneeling or Stooping ☐ Sitting down (straight) ☐ Sitting down (slightly leaning back) ☐ Sitting down (severely leaning back) ☐ Other	☐ Sitting on a chair ☐ Sitting on the floor or pallet ☐ Standing up, legs and body straight ☐ Standing up, legs slightly flexed, body straight ☐ Standing up, legs slightly flexed, body bended forward ☐ Standing up, legs severely flexed ☐ Other: specify	☐ Standing up ☐ Kneeling or Stooping ☐ Sitting down (straight) ☐ Sitting down (slightly leaning back) ☐ Sitting down (severely leaning back) ☐ Other
(A04-03) If active, what kind of active tool is it?	☐ Active tool type 1 ☐ Active tool type 2 ☐ Active tool type 3 ☐ Active tool type 4 ☐ Active tool type 5 ☐ Other; specify	☐ Driller ☐ Vacuum cleaner ☐ Paint / Sealant ☐ Working tool ☐ Transport ☐ Other; specify	☐ Driller ☐ Vacuum cleaner ☐ Paint/Sealant ☐ Working tool ☐ Transport ☐ Treatment remover ☐ Other: specify	☐ Driller ☐ Vacuum cleaner ☐ Paint/Sealant ☐ Working tool ☐ Transport ☐ Other; specify
(A04-04) If passive, what kind of passive tool is it?	☐ Passive tool type 1 ☐ Passive tool type 2 ☐ Passive tool type 3 ☐ Passive tool type 4 ☐ Passive tool type 5 ☐ Other: specify	☐ Holding fixtures ☐ Measurement tool ☐ Precision Fit ☐ Guideline ☐ Lighting device ☐ Other:	☐ Holding fixtures ☐ Measurement tool ☐ Precision Fit ☐ Guideline ☐ Lighting device ☐ Other:	☐ Holding fixtures ☐ Measurement tool ☐ Precision Fit ☐ Guideline ☐ Lighting device ☐ Other:
(A04-05) What type of operation does it perform?	☐ Operation type 1 ☐ Operation type 2 ☐ Operation type 3 ☐ Operation type 4 ☐ Operation type 5 ☐ Operation type 6 ☐ Operation type 7 ☐ Other: specify	☐ Transport ☐ Hold ☐ Measure / Test ☐ Paint / Seal ☐ Drill ☐ Fasten / Bolt / Torque / Fit / Wirelock / Split pin ☐ Remove particles ☐ Improve visibility	☐ Remove particles ☐ Improve visibility ☐ Torque / Fasten ☐ Paint ☐ Hold ☐ Measure / Test ☐ Other: specify	☐ Transport ☐ Hold ☐ Measure / Test ☐ Paint ☐ Drill ☐ Fasten / Bolt / Torque / Fit / Wirelock / Split pin ☐ Remove particles ☐ Improve visibility

Table 6-2: Questionnaire modifications to suit the information available

	Original Option	Alternative Option
(A01.04) What are the dimensions component being installed?	_________ (cm)	☐ Very small ☐ Small ☐ Medium ☐ Large ☐ Very large
(A01.05) How heavy is the component being installed?	_________ (kg)	☐ Very light ☐ Light ☐ Average ☐ Heavy ☐ Very heavy
(A02.06) How many times is this operation repeated?	☐ Once ☐ Couple of times ☐ Between 3-5 times ☐ More than 5 times ☐ Impossible to predict	______ (number of times)
(A03.09) Which is the level of training needed to know how to perform this operation successfully?	☐ Highly specific training needed ☐ Specific training needed ☐ General training needed ☐ Very general training needed ☐ No training needed	_______ (days/months)
(A03.10) What is the level of experience required to perform this operation successfully?	☐ Very high level ☐ High level ☐ Medium level ☐ Low level ☐ No experience needed	______ (years)
(A03.11) Select which of the following safety measures you are supposed to wear when performing this operation:	☐ Helmet ☐ Boots ☐ Gloves ☐ Glasses ☐ Plugs ☐ Muffs ☐ Other: specify	*Add any if needed*
(A04-08) How innovative is to use this tool in this specific context?	☐ Very innovative (<1 year) ☐ Innovative (1-3 years) ☐ Medium (3 years) ☐ Traditional (5-10 years) ☐ Very traditional (>10 years)	_______ (years)
(A04-09) What kind of power source/activation method does it need?	☐ Electrical Power ☐ Hydraulic Power ☐ Battery ☐ Manual ☐ Other: specify	*Add any if needed*

Appendix D : Improvement Opportunity Idea (IOI) Down-Selection Technique

The aim of this technique is to put the traditional improvement selection aside (cost and weight driven) and consider PoW, maturity for implementation and popularity of the IOI as drivers. Ideas are incorporated into the diagram with collaboration of industrial experts who determine each of these drivers.



The bubble diagram on the left shows an example of 6 Improvement Opportunity Ideas (IOI) identified from shop-floor operators. They have been located according to the Perception of Work (PoW) estimated by the operators and the implementation maturity assessed by industrial experts. The size of the bubble determines the popularity of the idea among the shop-floor operators.

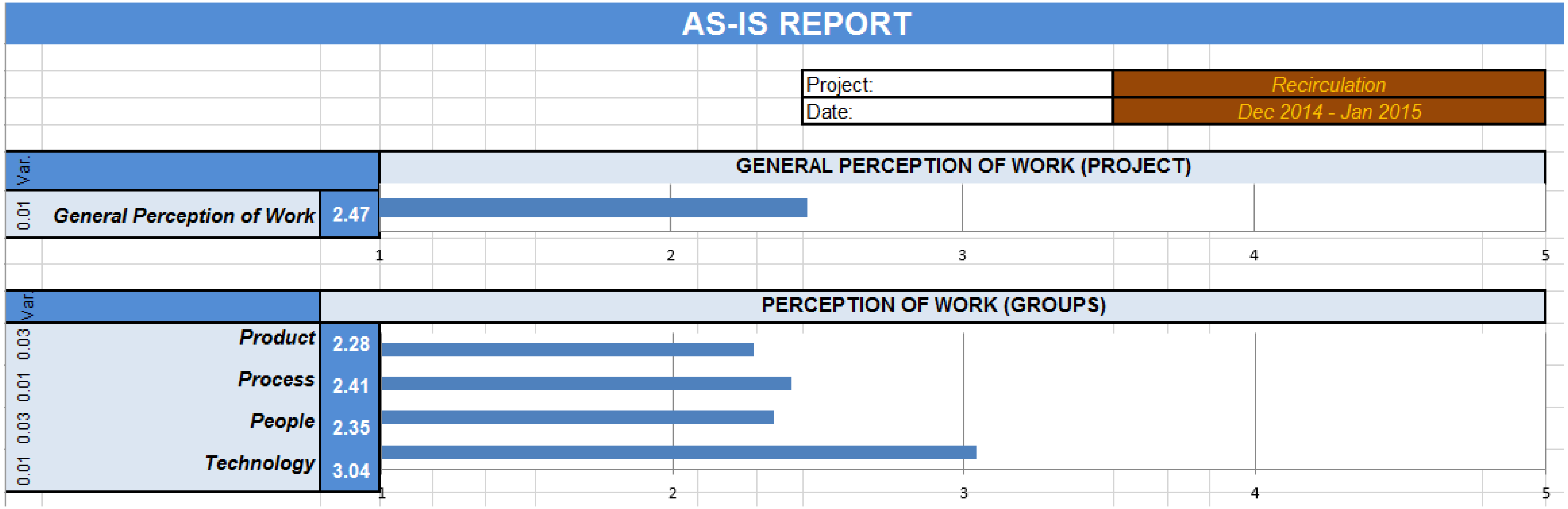
In general terms, the ideas to select would be at the top right corner and would have greater diameter.

Appendix E Improvement Opportunity Capture Template with Example

I, …, would like to suggest an improvement opportunity (IO):		***This IO will require …-ing***			***The … aspect of the system installation***				***And more specifically the key factor number***	***More information and description***	***On the one hand, this IO will BENEFIT the following aspects***	***On the other hand, this IO might affect NEGATIVELY the following aspects***
IDXXX	*AUTXXX*	*ADD*	*MODIFY*	*DELETE*	*PRODUCT*	*PROCESS*	*PEOPLE*	*TECHNOL*	*KF CODE*	-	*Add information on KF, influence, operation, AS-IS, TO-BE….*	*Add information on KF, influence, operation, AS-IS, TO-BE….*
ID001	AUT001		1		1				KF01.11	Author identifies component X as challenging due to the current design (it has a predrilled hole). Author suggest adding 2 predrilled holes in perpendicular to raise the probability to line up holes with nuts.	50% reduction in operation time and repetition PoW improved to 4 Appropriateness of design improved to 3.5 Accuracy of operation reduced.	Efficiency of component reduced. Different connection type

Appendix F : Enlarged Figures

Figure 3-2 (Page 47)



AS-IS REPORT

Project: Recirculation

Date: Dec 2014 - Jan 2015

Figure 3-3 (Page 47)

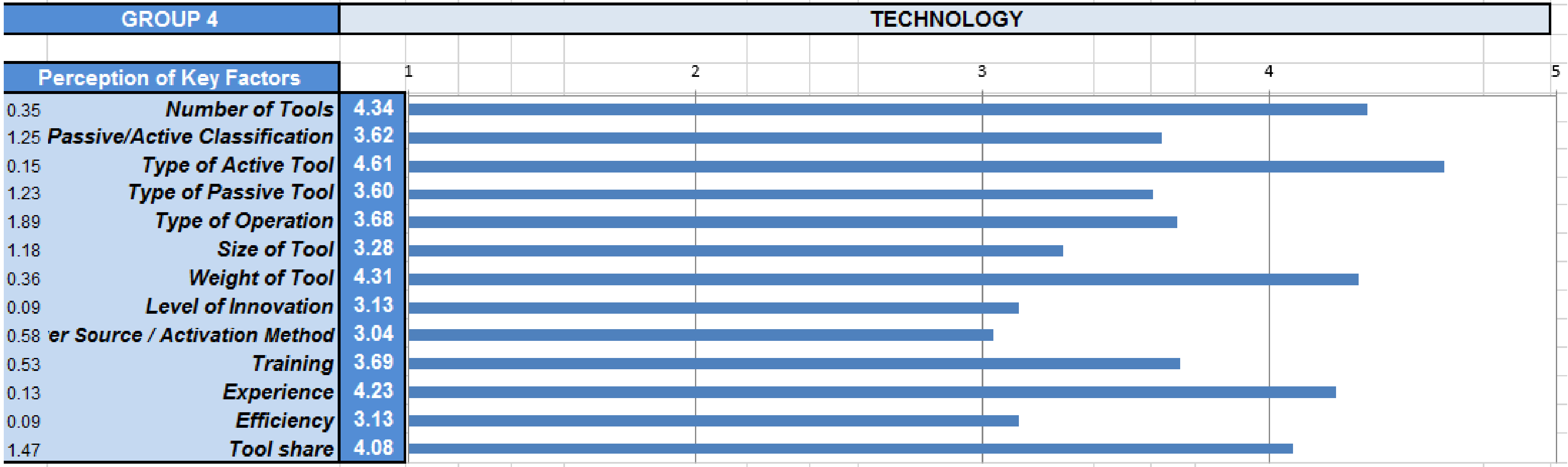


Figure 3-6 (Page 50)

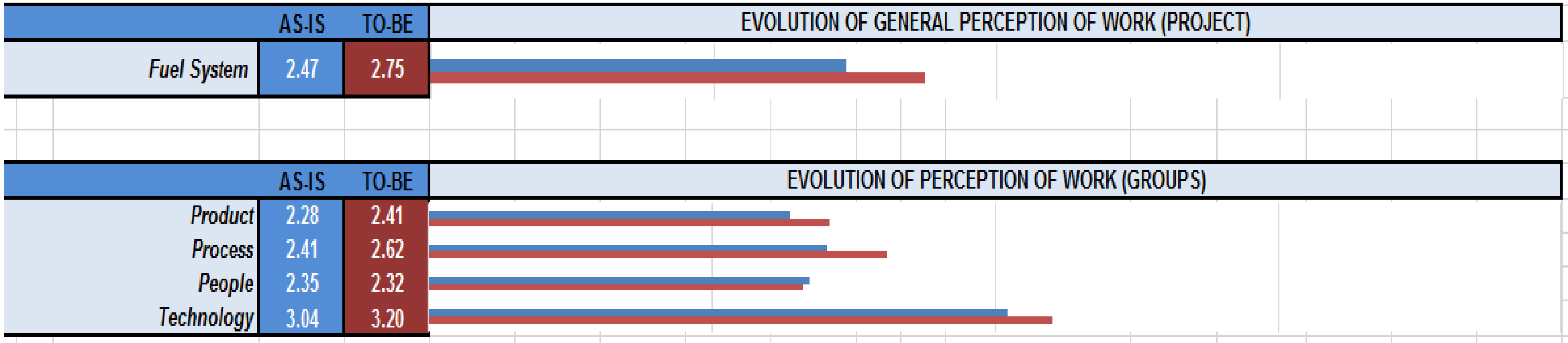


Figure 3-7 (Page 51)

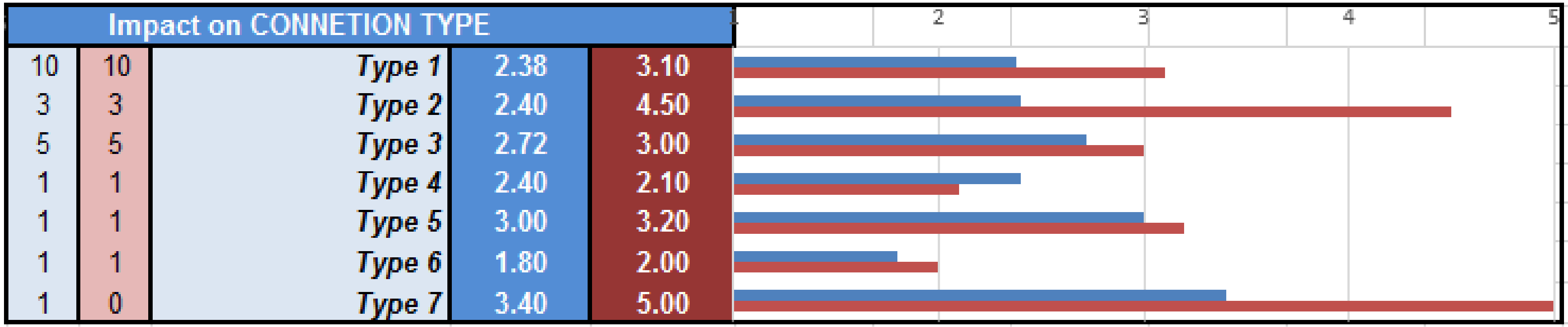
EVOLUTION OF PERCEPTION OF WORK (Key Factors)

GROUP 1

PRODUCT

Perception of Key Factors		
Type of System	2.80	2.79
Material	2.80	3.00
Shape	3.50	3.68
Length/Dimensions	3.70	4.50
Weight	3.66	3.00
Flexibility	3.81	3.90
Symmetry	3.90	4.25
Fragility	3.44	3.45
Appropriateness of Design	4.81	4.98
Identification	4.12	4.48
Connection Type	2.51	2.46
Poka-Yoke	2.89	2.87
Quality Certification	2.80	2.79
Safety Zone	3.00	2.98
Maintenance	3.54	3.52

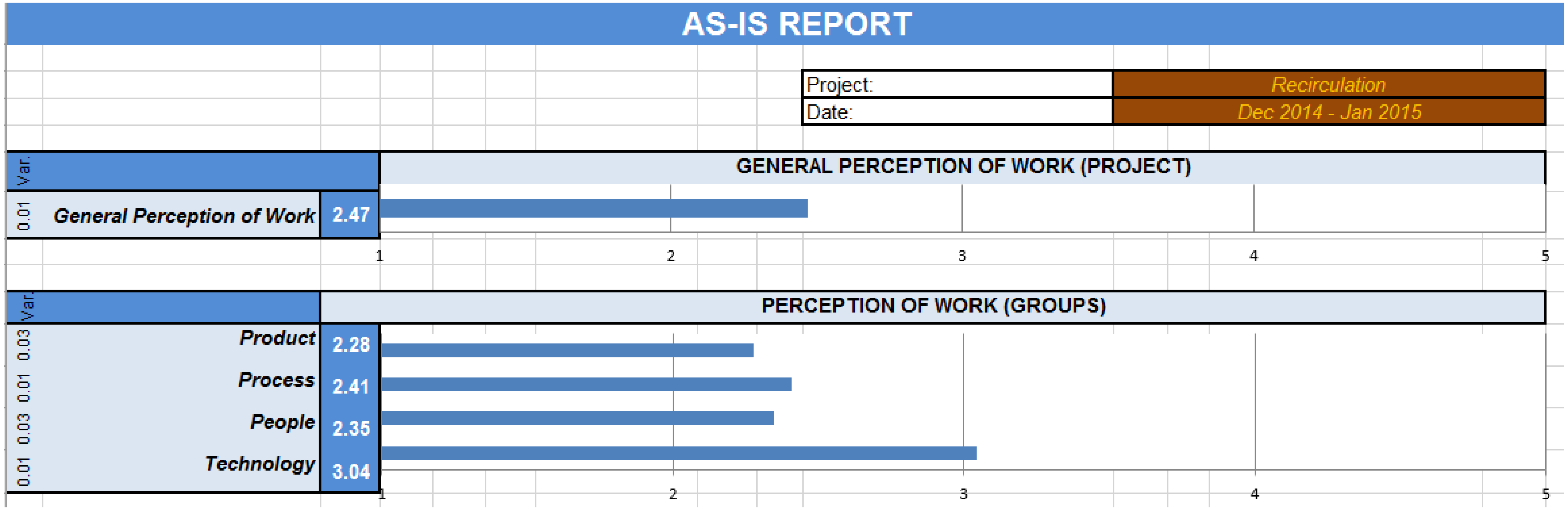
Figure 3-8 (Page 51)



Impact on CONNETION TYPE

10	10	*Type 1*	2.38	3.10
3	3	*Type 2*	2.40	4.50
5	5	*Type 3*	2.72	3.00
1	1	*Type 4*	2.40	2.10
1	1	*Type 5*	3.00	3.20
1	1	*Type 6*	1.80	2.00
1	0	*Type 7*	3.40	5.00

Figure 4-1



AS-IS REPORT

Project:	*Recirculation*
Date:	*Dec 2014 - Jan 2015*

GENERAL PERCEPTION OF WORK (PROJECT)

Var.		
0.01	***General Perception of Work***	2.47

PERCEPTION OF WORK (GROUPS)

Var.		
0.03	***Product***	2.28
0.01	***Process***	2.41
0.03	***People***	2.35
0.01	***Technology***	3.04

Figure 4-2 (Page 57)

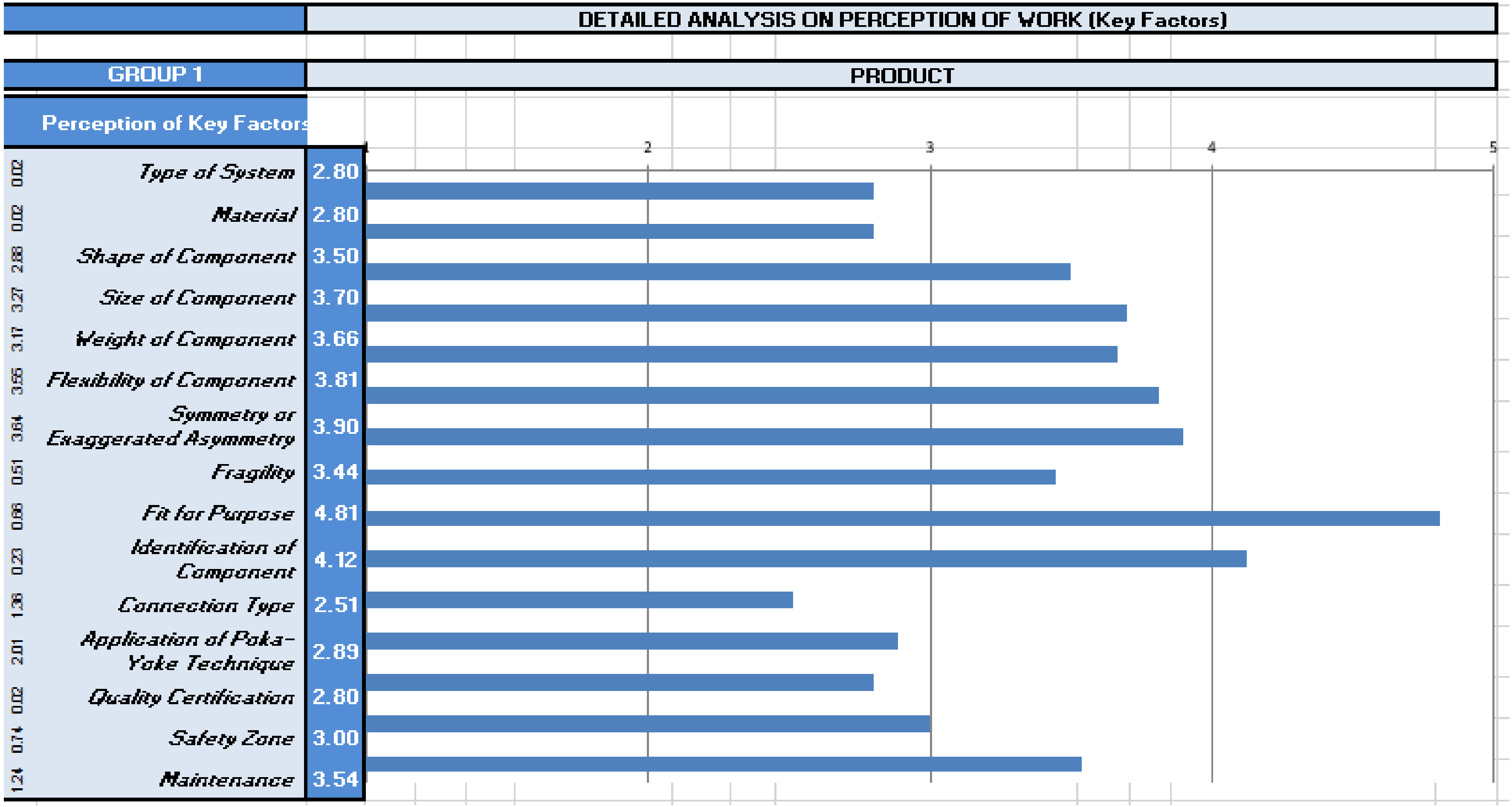


Figure 4-6 (Page 59)

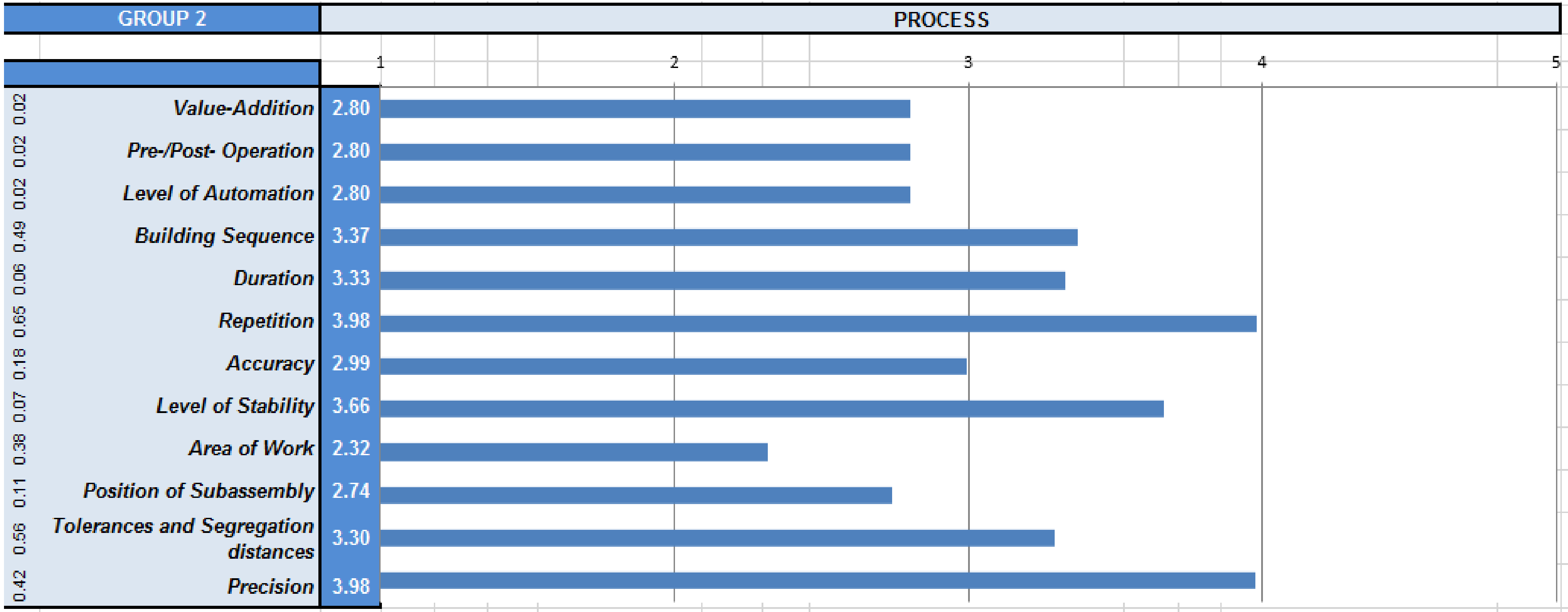


Figure 4-11 (Page 62)

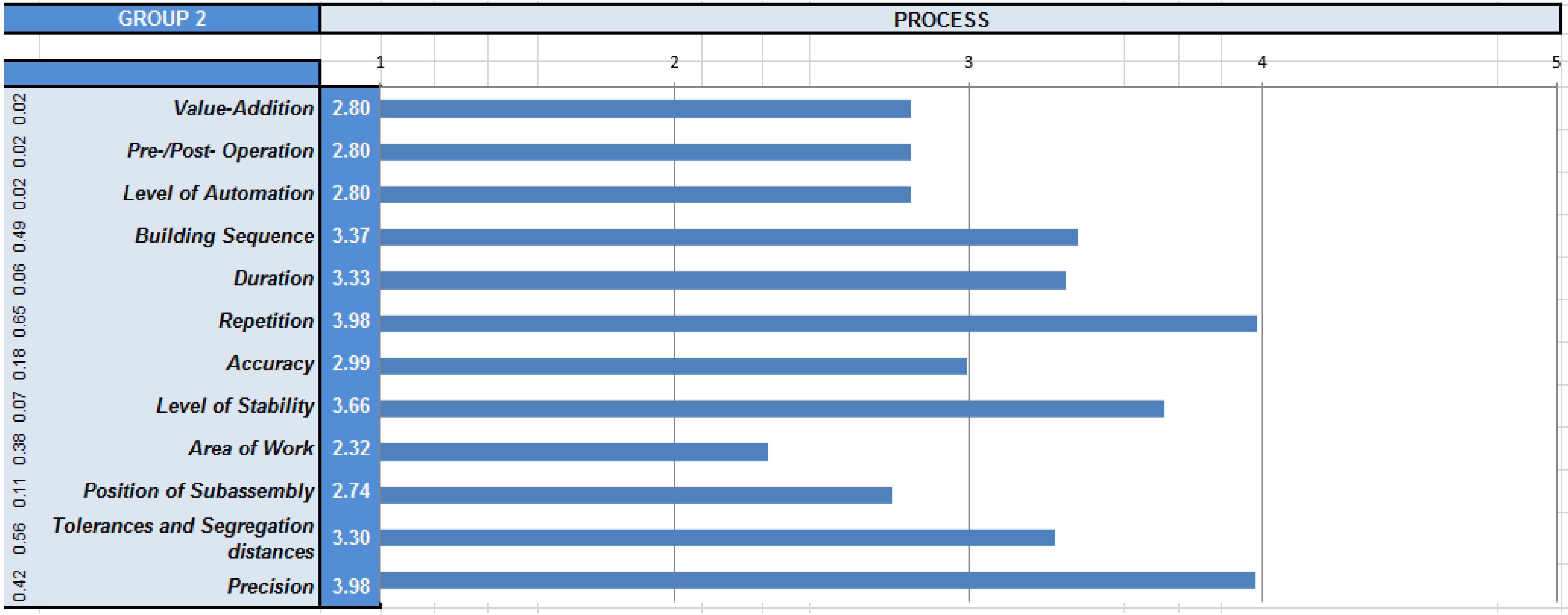


Figure 4-14 (Page 64)

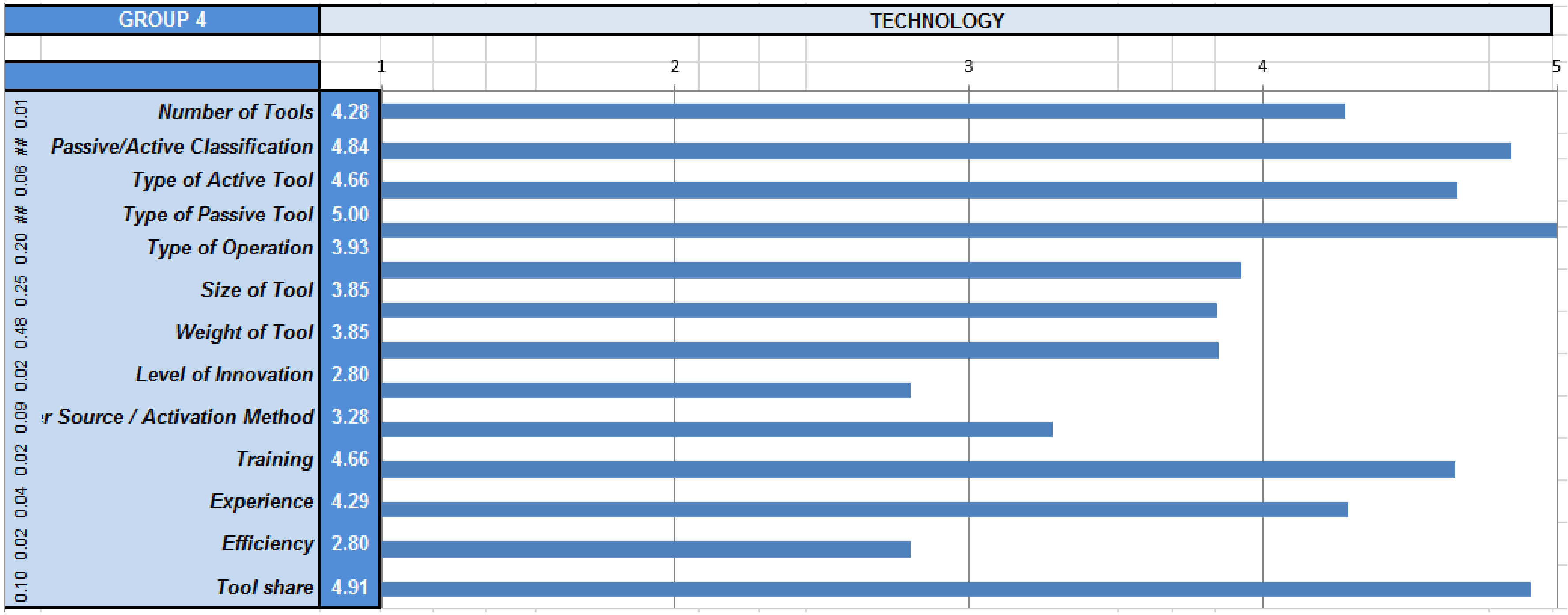
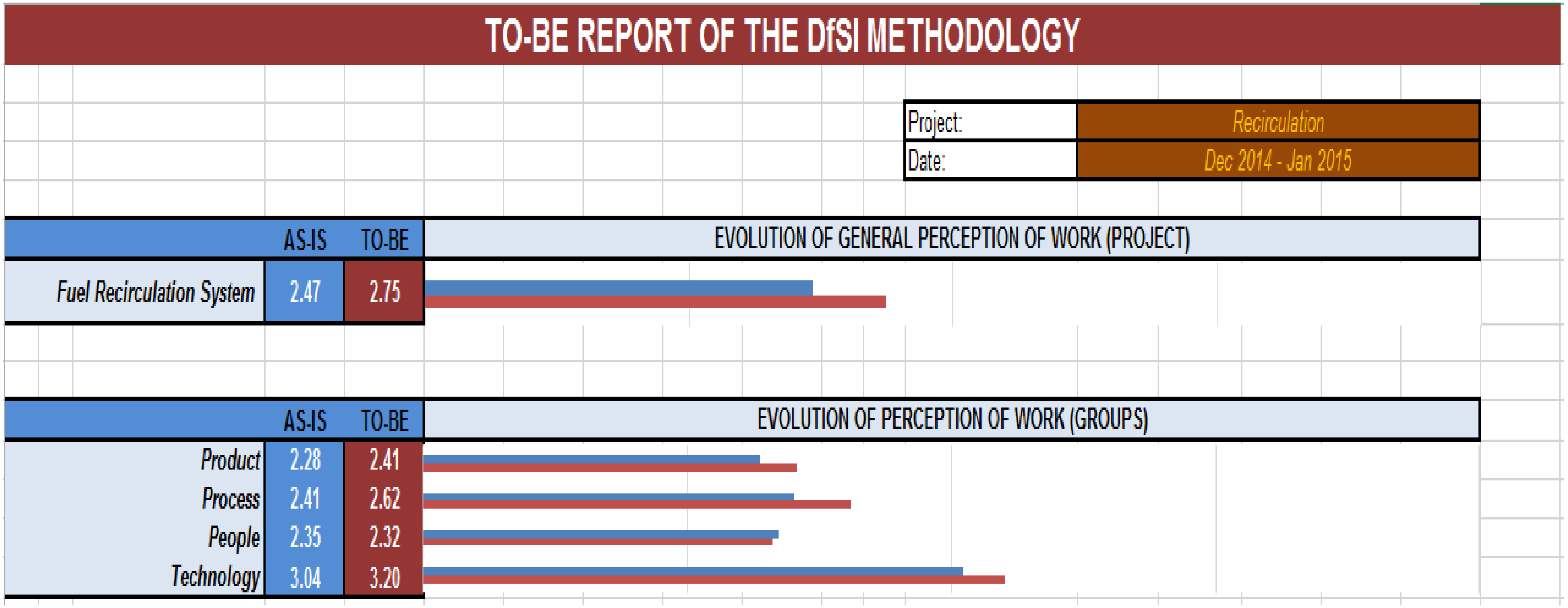


FIGURE 4-17



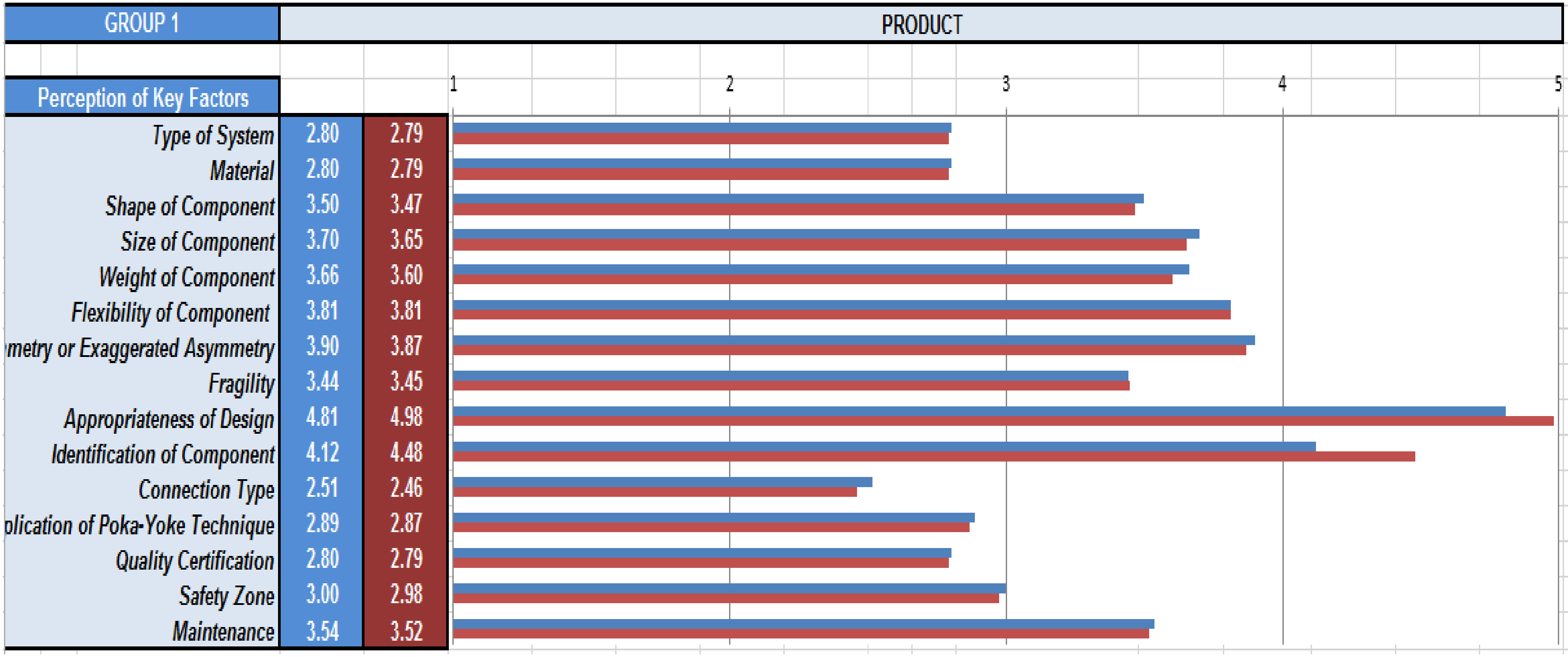
TO-BE REPORT OF THE DfSI METHODOLOGY

Project:	*Recirculation*
Date:	*Dec 2014 - Jan 2015*

	AS-IS	TO-BE	EVOLUTION OF GENERAL PERCEPTION OF WORK (PROJECT)
Fuel Recirculation System	2.47	2.75	

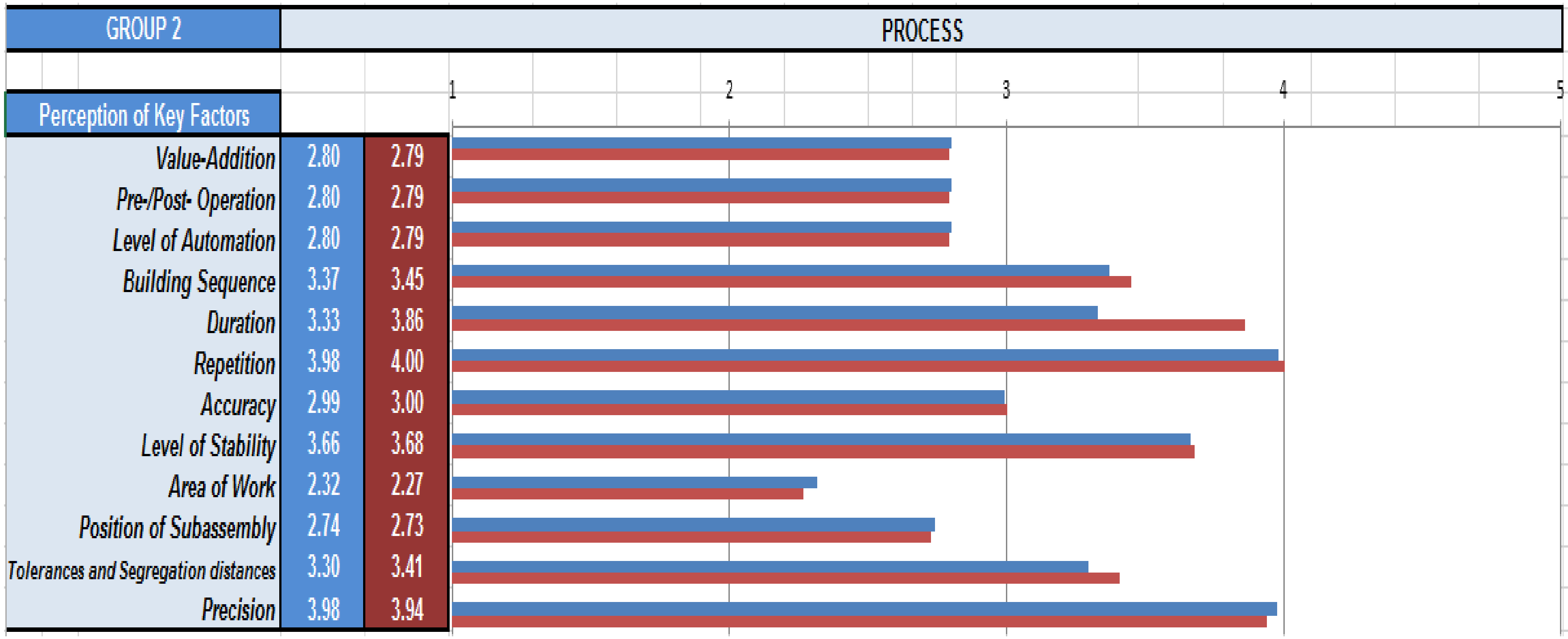
	AS-IS	TO-BE	EVOLUTION OF PERCEPTION OF WORK (GROUPS)
Product	2.28	2.41	
Process	2.41	2.62	
People	2.35	2.32	
Technology	3.04	3.20	

Figure 4-18 (Page 69)



Perception of Key Factors		
Type of System	2.80	2.79
Material	2.80	2.79
Shape of Component	3.50	3.47
Size of Component	3.70	3.65
Weight of Component	3.66	3.60
Flexibility of Component	3.81	3.81
metry or Exaggerated Asymmetry	3.90	3.87
Fragility	3.44	3.45
Appropriateness of Design	4.81	4.98
Identification of Component	4.12	4.48
Connection Type	2.51	2.46
plication of Poka-Yoke Technique	2.89	2.87
Quality Certification	2.80	2.79
Safety Zone	3.00	2.98
Maintenance	3.54	3.52

Figure 4-19 (Page 70)



Perception of Key Factors		
Value-Addition	2.80	2.79
Pre-/Post- Operation	2.80	2.79
Level of Automation	2.80	2.79
Building Sequence	3.37	3.45
Duration	3.33	3.86
Repetition	3.98	4.00
Accuracy	2.99	3.00
Level of Stability	3.66	3.68
Area of Work	2.32	2.27
Position of Subassembly	2.74	2.73
Tolerances and Segregation distances	3.30	3.41
Precision	3.98	3.94

Figure 4-20 (Page 71)

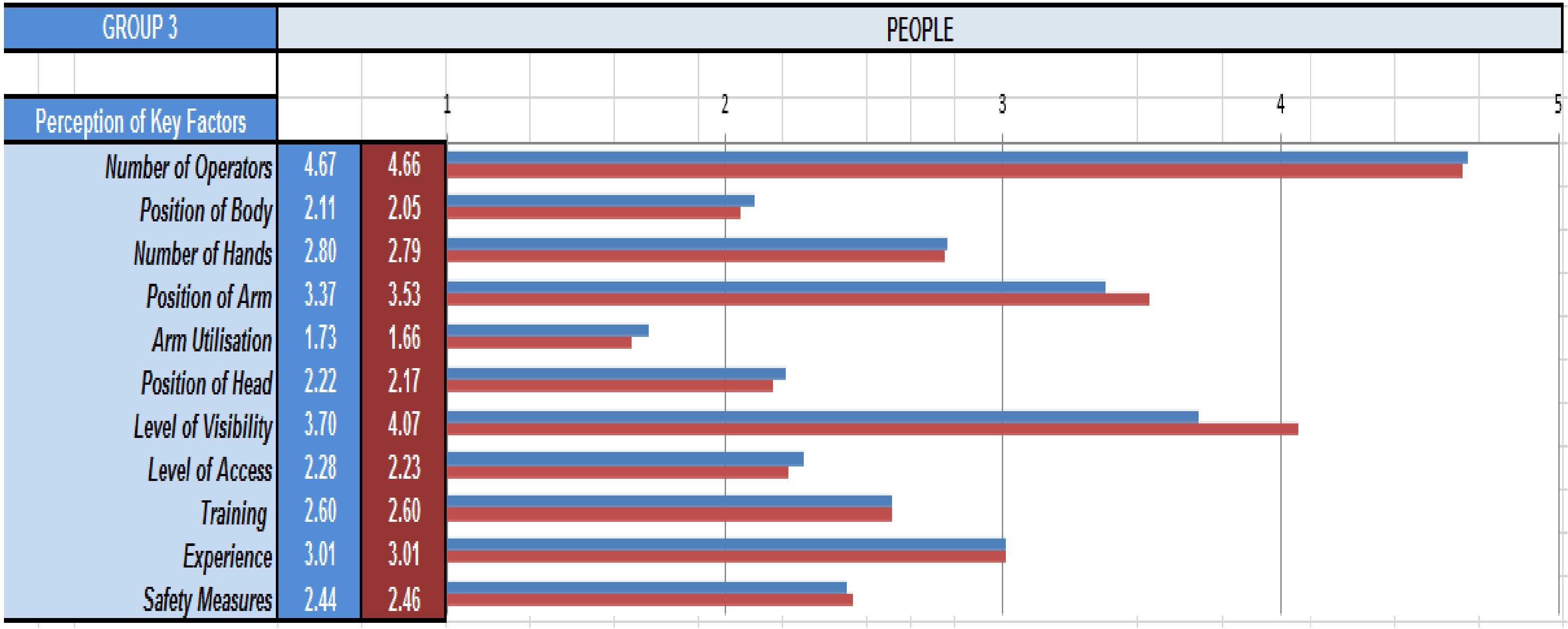
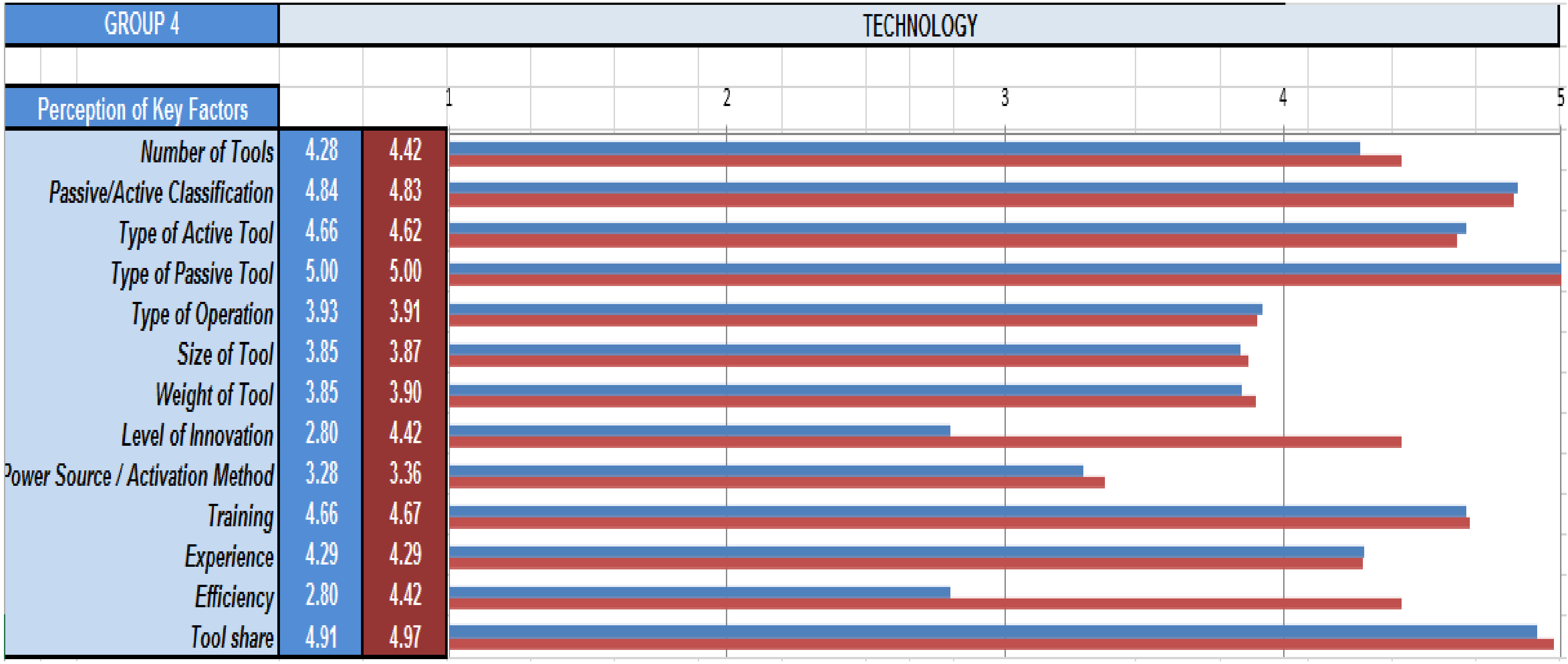
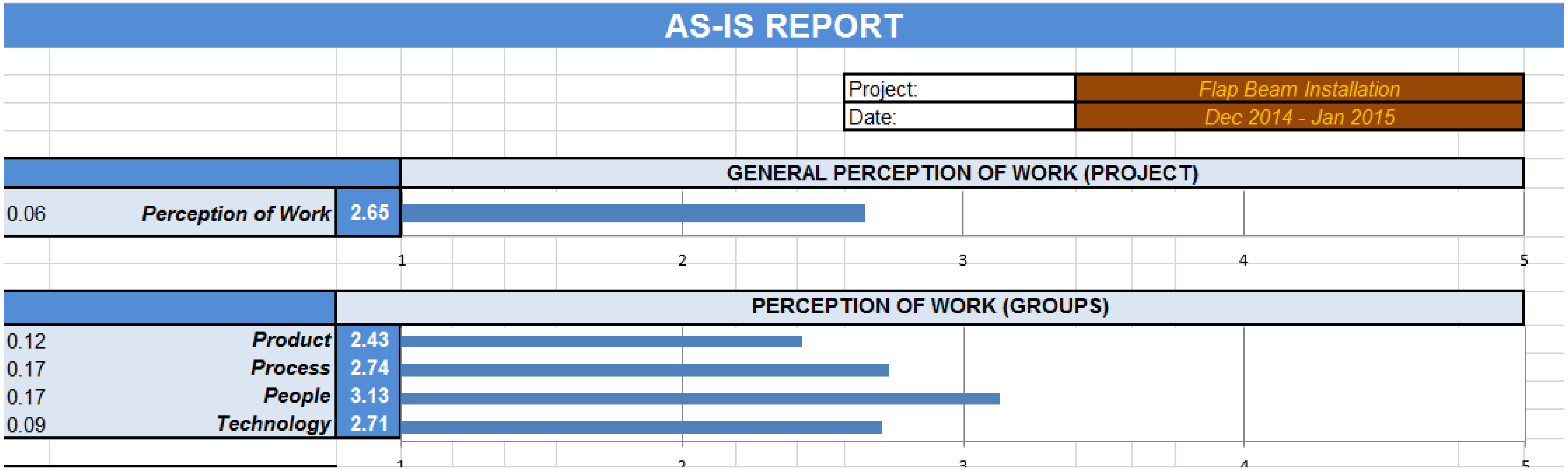


Figure 4-21 (Page 71)



Perception of Key Factors		
Number of Tools	4.28	4.42
Passive/Active Classification	4.84	4.83
Type of Active Tool	4.66	4.62
Type of Passive Tool	5.00	5.00
Type of Operation	3.93	3.91
Size of Tool	3.85	3.87
Weight of Tool	3.85	3.90
Level of Innovation	2.80	4.42
Power Source / Activation Method	3.28	3.36
Training	4.66	4.67
Experience	4.29	4.29
Efficiency	2.80	4.42
Tool share	4.91	4.97

Figure 4-22 (Page 76)



AS-IS REPORT

Project:	*Flap Beam Installation*
Date:	*Dec 2014 - Jan 2015*

GENERAL PERCEPTION OF WORK (PROJECT)

0.06	***Perception of Work***	**2.65**

PERCEPTION OF WORK (GROUPS)

0.12	***Product***	**2.43**
0.17	***Process***	**2.74**
0.17	***People***	**3.13**
0.09	***Technology***	**2.71**

Figure 4-23 (Page 76)

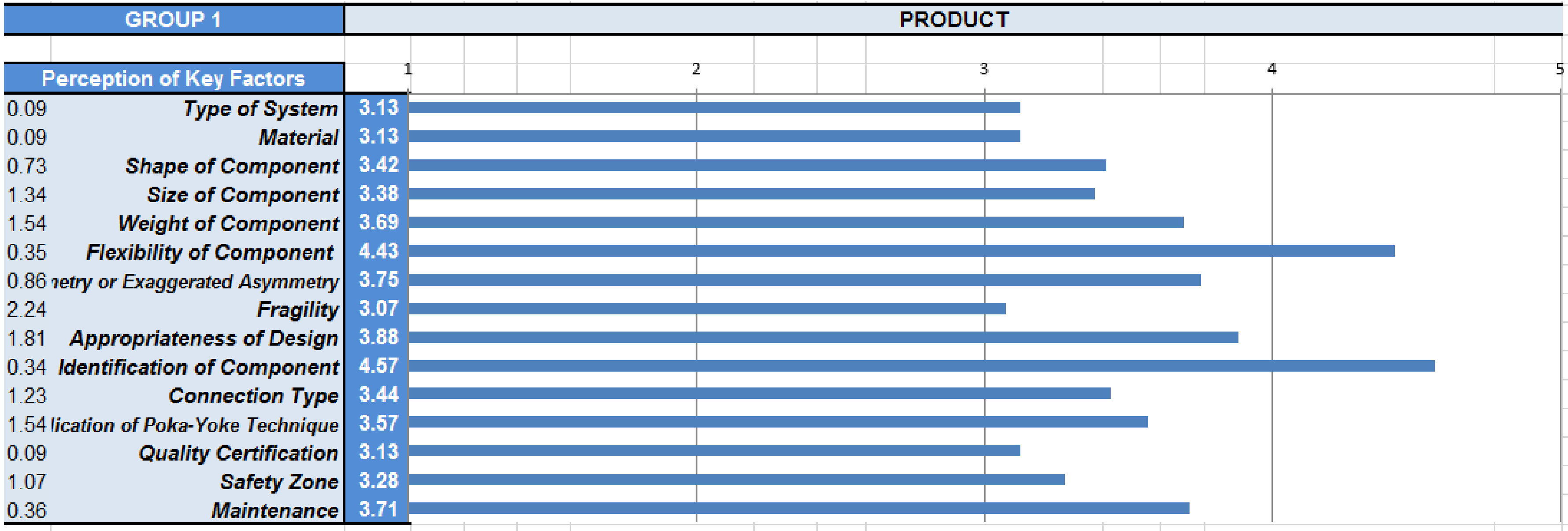


Figure 4-26 (Page 78)

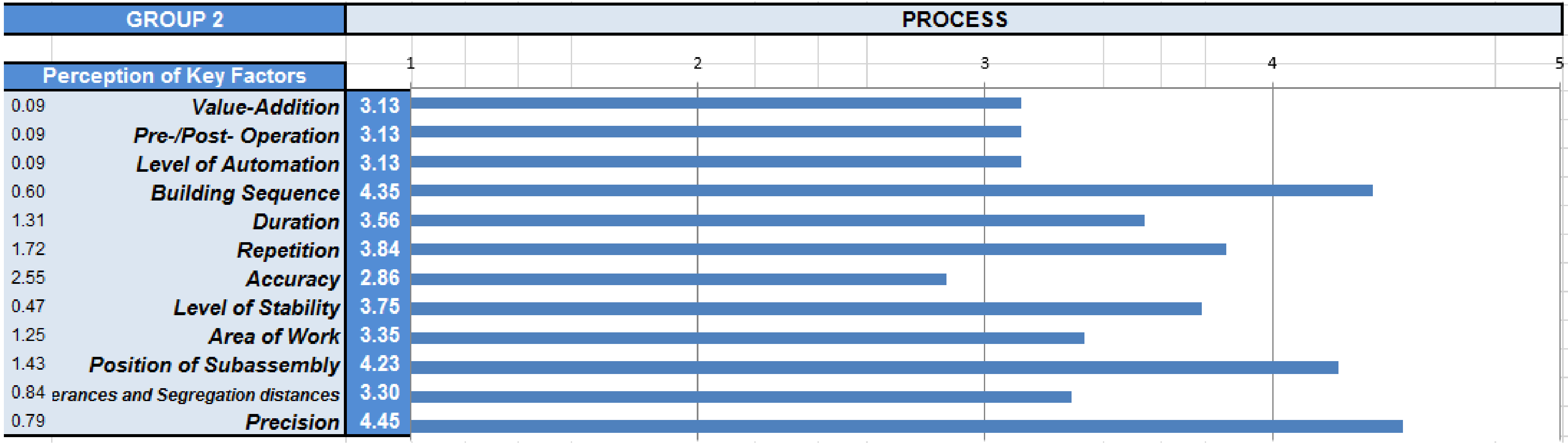


Figure 4-29 (Page 79)

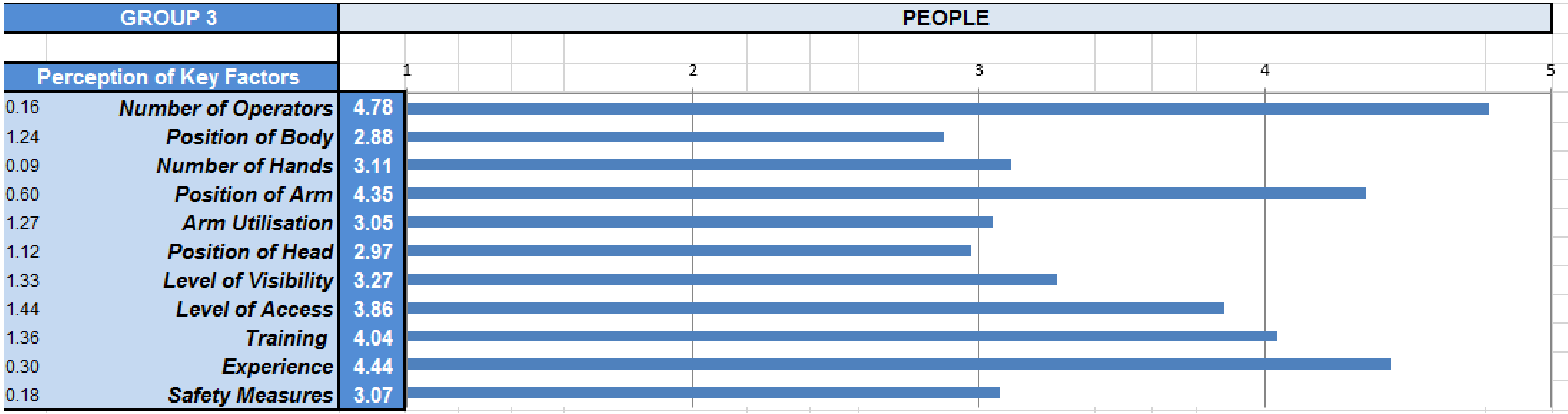


Figure 4-33 (Page 81)

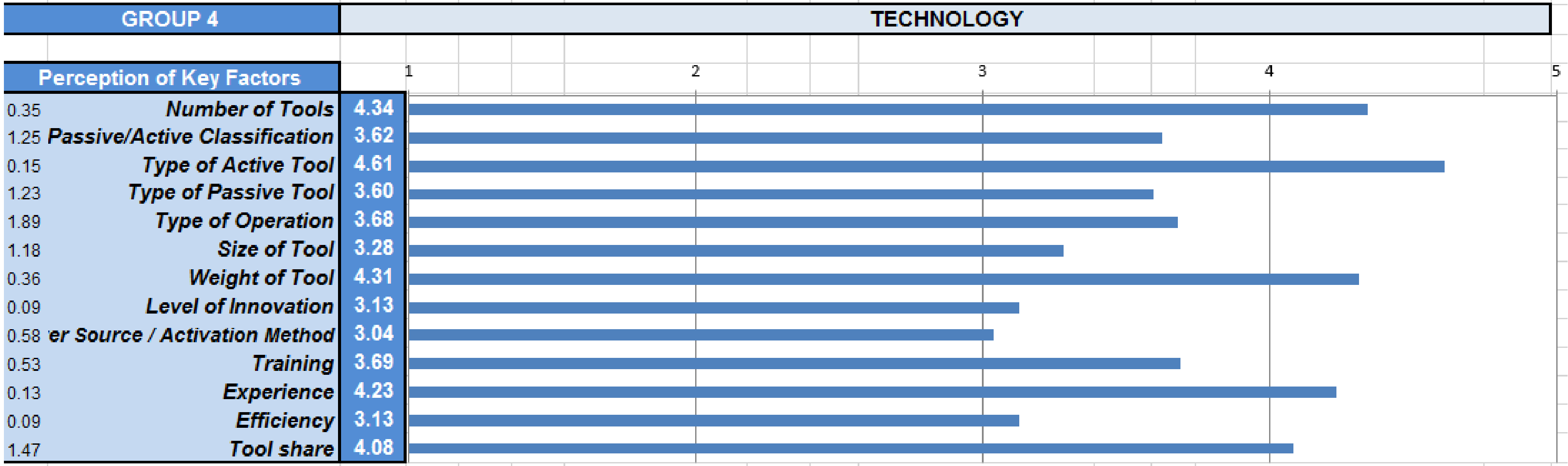
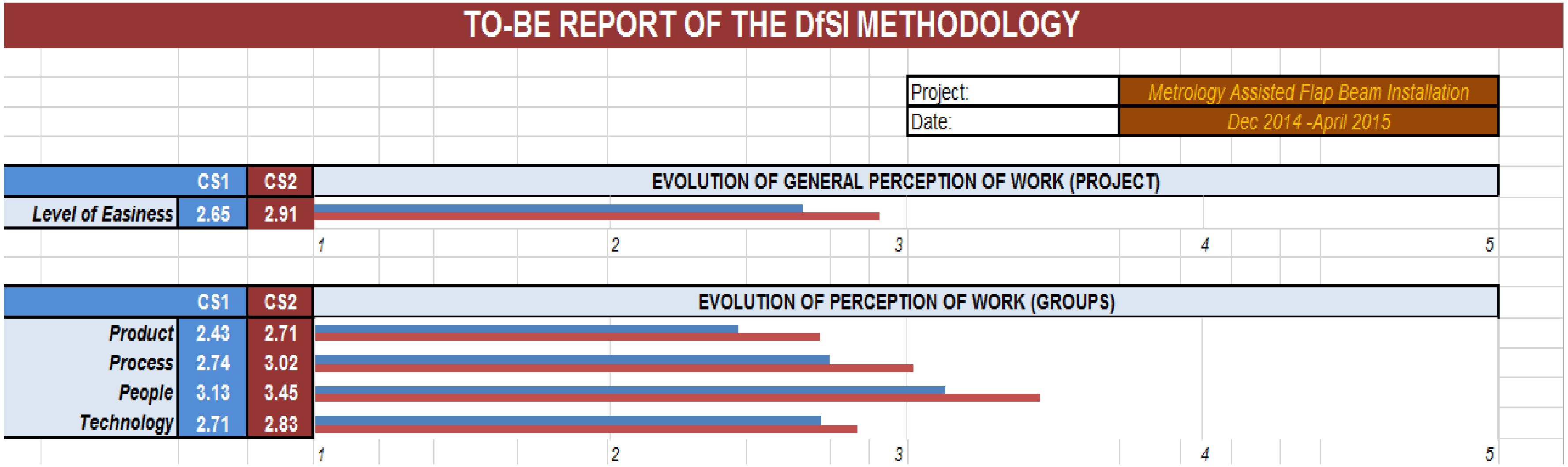


FIGURE 4-37



TO-BE REPORT OF THE DfSI METHODOLOGY

Project:	*Metrology Assisted Flap Beam Installation*
Date:	*Dec 2014 -April 2015*

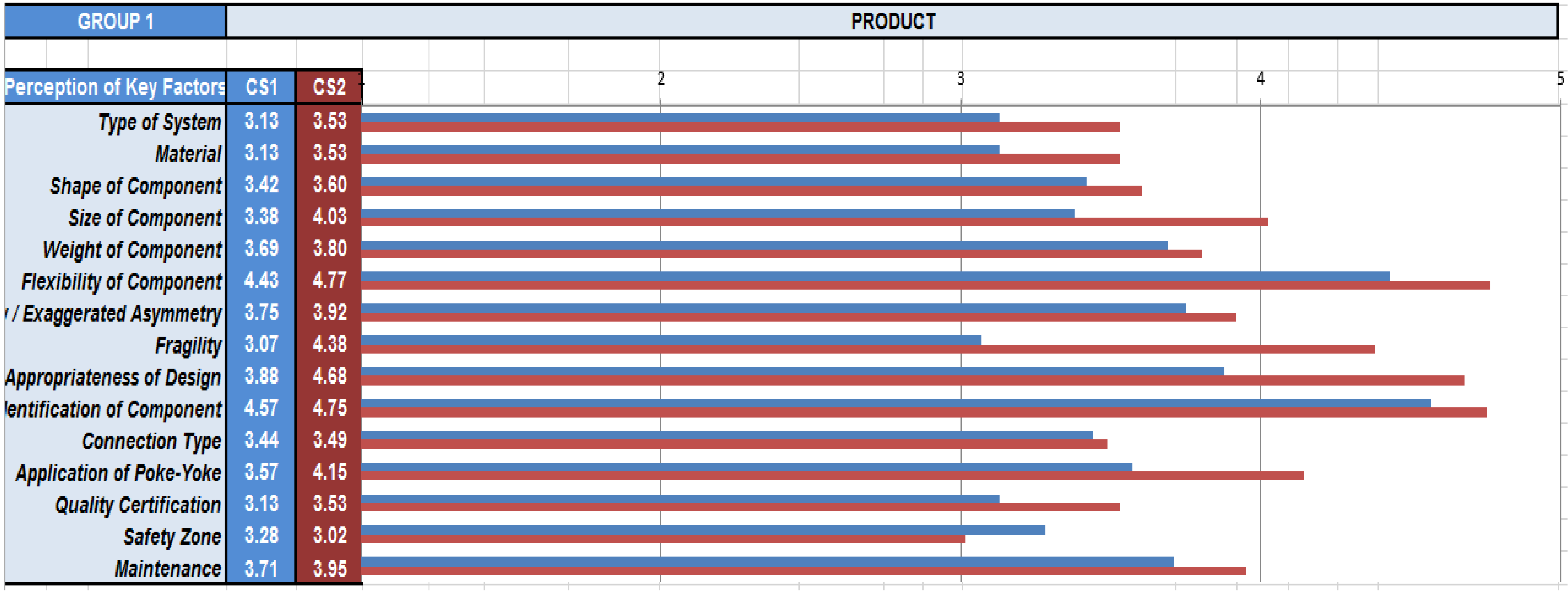
EVOLUTION OF GENERAL PERCEPTION OF WORK (PROJECT)

	CS1	CS2
Level of Easiness	2.65	2.91

EVOLUTION OF PERCEPTION OF WORK (GROUPS)

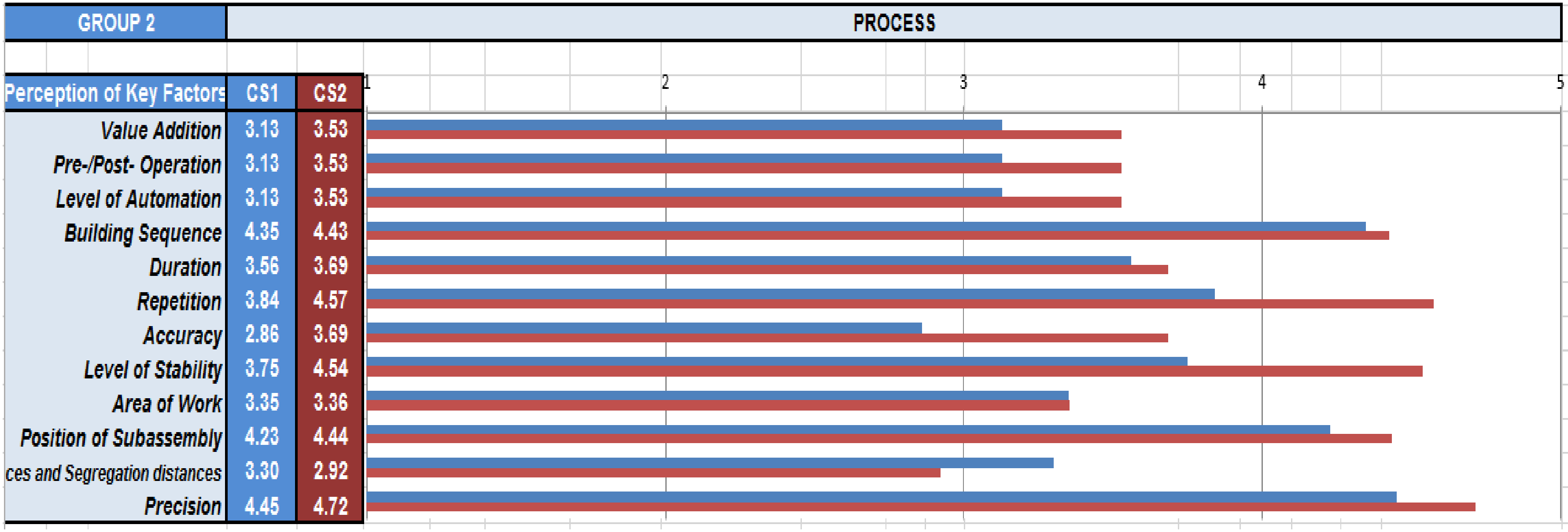
	CS1	CS2
Product	2.43	2.71
Process	2.74	3.02
People	3.13	3.45
Technology	2.71	2.83

Figure 4-38 (Page 85)



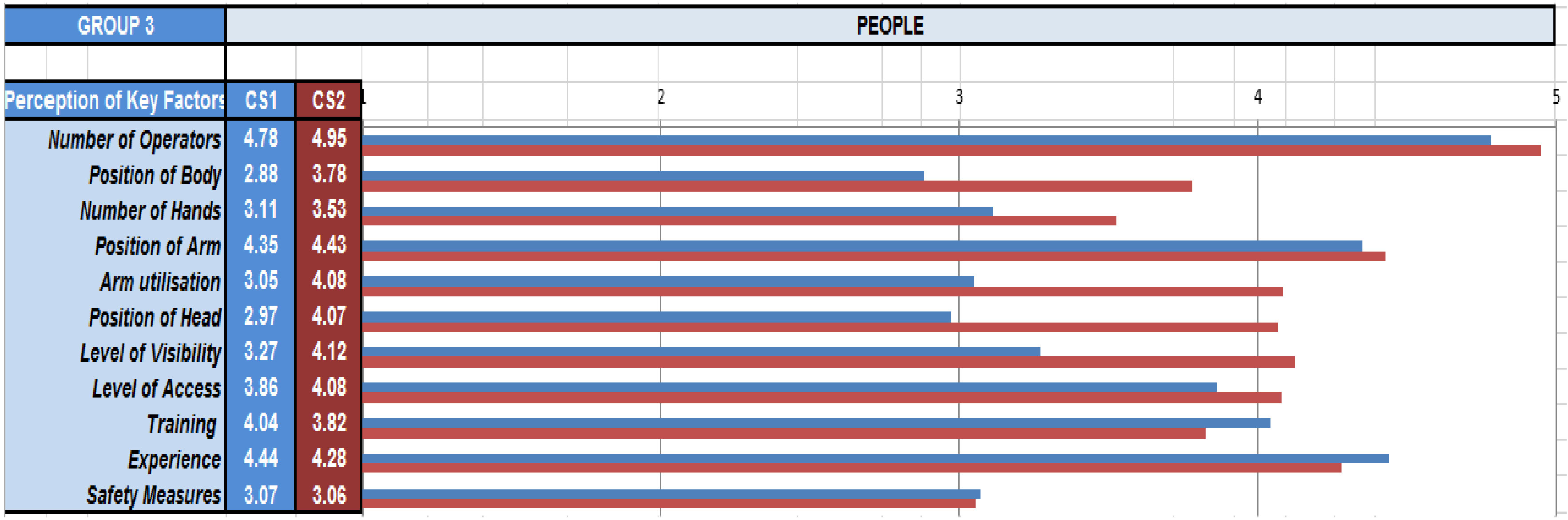
GROUP 1	PRODUCT	
Perception of Key Factors	CS1	CS2
Type of System	3.13	3.53
Material	3.13	3.53
Shape of Component	3.42	3.60
Size of Component	3.38	4.03
Weight of Component	3.69	3.80
Flexibility of Component	4.43	4.77
/ Exaggerated Asymmetry	3.75	3.92
Fragility	3.07	4.38
Appropriateness of Design	3.88	4.68
entification of Component	4.57	4.75
Connection Type	3.44	3.49
Application of Poke-Yoke	3.57	4.15
Quality Certification	3.13	3.53
Safety Zone	3.28	3.02
Maintenance	3.71	3.95

Figure 4-40 (Page 87)



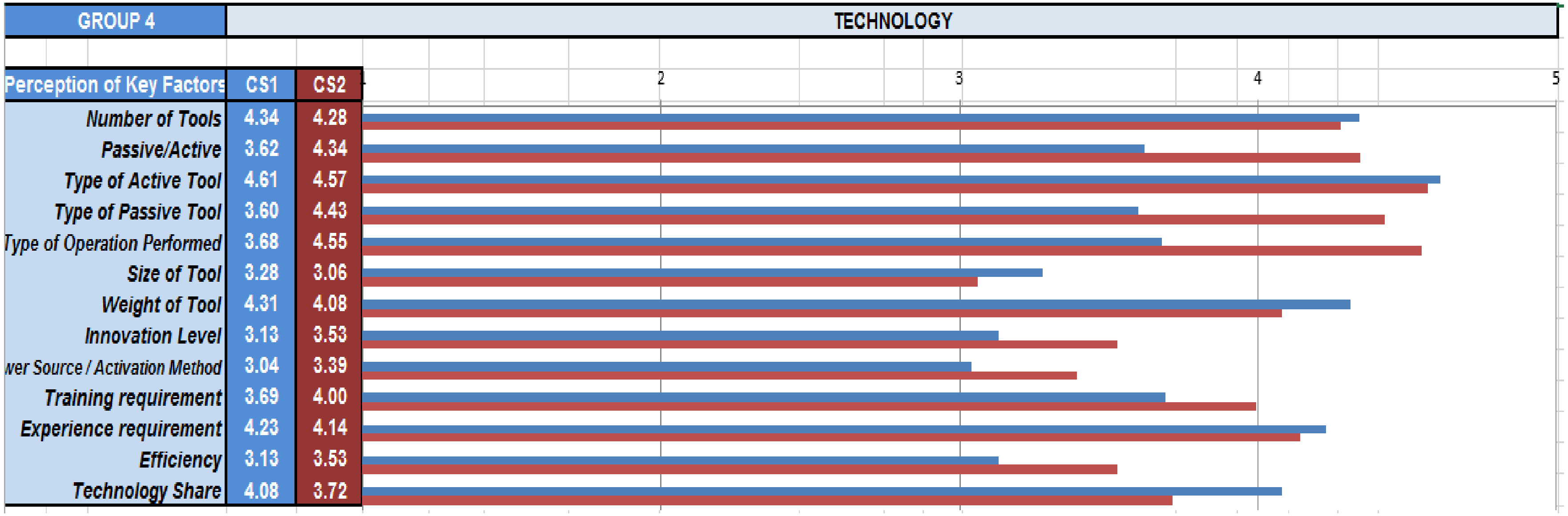
Perception of Key Factors	CS1	CS2
Value Addition	3.13	3.53
Pre-/Post- Operation	3.13	3.53
Level of Automation	3.13	3.53
Building Sequence	4.35	4.43
Duration	3.56	3.69
Repetition	3.84	4.57
Accuracy	2.86	3.69
Level of Stability	3.75	4.54
Area of Work	3.35	3.36
Position of Subassembly	4.23	4.44
ces and Segregation distances	3.30	2.92
Precision	4.45	4.72

Figure 4-43 (Page 89)



Perception of Key Factors	CS1	CS2
Number of Operators	4.78	4.95
Position of Body	2.88	3.78
Number of Hands	3.11	3.53
Position of Arm	4.35	4.43
Arm utilisation	3.05	4.08
Position of Head	2.97	4.07
Level of Visibility	3.27	4.12
Level of Access	3.86	4.08
Training	4.04	3.82
Experience	4.44	4.28
Safety Measures	3.07	3.06

Figure 4-46 (Page 91)



GROUP 4	TECHNOLOGY	
Perception of Key Factors	CS1	CS2
Number of Tools	4.34	4.28
Passive/Active	3.62	4.34
Type of Active Tool	4.61	4.57
Type of Passive Tool	3.60	4.43
Type of Operation Performed	3.68	4.55
Size of Tool	3.28	3.06
Weight of Tool	4.31	4.08
Innovation Level	3.13	3.53
wer Source / Activation Method	3.04	3.39
Training requirement	3.69	4.00
Experience requirement	4.23	4.14
Efficiency	3.13	3.53
Technology Share	4.08	3.72