CRANFIELD UNIVERSITY

RAHMAN ALAM

# DEVELOPMENT OF A LEAN DESIGN FRAMEWORK FOR ENHANCING THE APPLICATION OF PRODUCT DESIGN

SCHOOL OF AEROSPACE, TRANSPORT AND MANUFACTURING

PhD THESIS
Academic Years: 2009 - 2015

Supervisors: Dr. Ahmed Al-Ashaab and Dr. Essam Shehab
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# ABSTRACT

Substantial benefits can be achieved through the adoption of lean type thinking earlier at the design stage to create more viable products. A complex design cannot be easily leaned out in production; therefore, the production of affordable and sustainable products requires effective lean design considerations at the conceptual level. The research presented in this thesis investigates and demonstrates the application of lean design for product enhancement.

The aim of the research was to develop a novel lean design framework that would support the generation of product design with attributes such as maximise value, manufacturable, and operable with minimum waste and resources ensuring avoidable harm is eliminated. The framework consists of a systemised process which is organised in to phases and activities that provides a unique practical manner to lean out a design.

The construction of the framework initiated with an extensive literature review and proceeded with an industrial field study which consisted of 34 interviews with 11 manufacturing companies in Europe. The findings were amalgamated to generate a lean design definition and principles which would form the foundations of the framework. A real-life industrial case study of an offshore oil/water separator was used to validate the framework.

In conclusion, the lean design framework provides the necessary means by which a lean design can be achieved. As a result a functionally viable and enhanced design that is cheaper to manufacture through controlling waste and eliminating avoidable harm occurrence can be realised with minimal effort.

The research makes the following contributions: (1) identification of essential elements in lean design, (2) generation of a lean design definition and principles, (3) Lean Design Framework development and (4) illustrative guidelines based on the framework to be used by designers in realising a lean product design.

Keywords: Product Design; Lean Thinking, Design Methods and Theories, Design for Manufacture and Assembly, Poka-Yoke, Harm elimination, Off-shore units

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In the name of ALLAH, the Most Gracious, the Most Merciful

Endless salutations and benevolent prayers upon Prophet Muhammad, all the pure relatives of this exalted Prophet, to all his companions and all the pious until the day of resurrection.

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Most importantly, to my mother and father, thank you for your unconditional love, support and motivation. Finally, I express my gratitude to my family and friends for their persistent provision of hope and reinforcement.


*The Angel is free because of his knowledge, the beast because of his ignorance. Between the two remains the son of man to struggle –* ***Rumi***

# LIST OF PUBLICATIONS

1) Alam, R., Wasim, A., Al-Ashaab, A., Shehab, E., and Martin, C. (2011), “Value translation and presentation for lean design”, *Proceedings of the 9$^{th}$ International Conference on Manufacturing Research (ICMR 2011),* Glasgow Caledonian University, Scotland, pp. 1-5.

2) Al-Ashaab A, Shehab E, Alam R, Sopelanad A, Sorli M, Flores M, Taisch M, Stokic D and James-Moore M, (2010), “The Conceptual LeanPPD Model”, *New world situation: new directions in current engineering: proceedings of the 17th ISPE International Conference on Concurrent Engineering*, Krakow.

3) Wasim, A., Shehab, E., Abdalla, H., Al-Ashaab, A., Sulowski, R., and Alam, R, (2012) “An innovative cost modelling system to support lean product and process development”, *International Journal of Advanced Manufacturing Technology,* vol. 65, no.1-4, pp. 165-181.

4) Wasim, A., Shehab, E., Abdalla, H., Al-Ashaab, A., Alam, R., And Sulowski, R., (2011), “Towards a cost modelling system for lean product and process development”, *Proceedings of the 9th International Conference on Manufacturing Research (ICMR 2011), Glasgow Caledonian University, Scotland*, pp. 151-156.

5) Alam, R., Wasim, A., Al-Ashaab, A., Shehab, E., and Beg, N (2015), “Enhancing Product design through the application of lean design” (to be submitted in the *Journal of Engineering Design*)

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| | |
|---|---|
| CU | Cranfield University |
| DMT | Design Method and Theory |
| LDG | Lean Design Guidelines |
| LeanPPD | Lean Product and Process Development |
| NPD | New Product Development |
| QCO | Quick Change Over |
| SMED | Single Minute Exchange of Dies |
| TPS | Toyota Production System |
| ISTD | Institute for Safety Through Design |
| PD | Product Development |

# Chapter 1

# INTRODUCTION

## 1.1 Research Background

Constant elevations in global competitiveness and socio-technical advancements have pressurised companies in populating the required capabilities to address the needs of the changing market in order to sustain their business. Long term organisational survival rests upon New Product Development (NPD) and its importance connoted through decreased product lifecycles and increased global demands (Zhang and Sharifi 2000). Monetary aspects of design are essential to the success of business (Ulrich 2011), as a primary generator of ideas; it is known to create viable business platforms (Luchas and Swan 2011). In essence 10-15% of the total product development cost is incurred when a design of a product is complete (Shehab and Abdalla 2001).

At the start of the 1990s, the concept of lean manufacturing was introduced to the Western manufacturing world through the work of Womack et al. (1990). Two major lean thinking projects were undertaken, the Lean Aerospace initiative conducted by MIT in USA and the UK Lean Aerospace Initiative, which were specifically oriented for the aerospace sector. The second major project was International Motor Vehicle Program (IMVP) which initiated with understanding the Toyota Production System (TPS) through publishing the book “The Machine that Changed the World.” Efforts were applied in understanding lean application on the shop floor, developing both practical models and the lean techniques to help the implementation. This effort evolved to the lean transformation of the enterprise. Lean enterprise covers the adoption of lean thinking to the management of the enterprise as well as its supply chain.

European manufacturing companies are in need to develop capabilities that stretch beyond the concept of lean manufacturing and encompass all of the lean principles into the New Product Introduction process. This is a respond to the market demand of value creation, incorporating sustainability and customisation as well as ensuring business growth through the development of high quality products in a cost effective manner at the shortest intervals.

The objective of lean is the elimination of waste. The possibilities of rendering this is possible within a manufacturing company, however this alone is not sufficient. What is needed is a new paradigm that will extrapolate lean manufacturing and lean thinking concepts from waste elimination into value creation. In order to make a significant change in enterprise performance and saving ultimate system costs, there is a need for the entire enterprise to undergo a lean transformation. Furthermore, lean design plays a significant role in this transition, as design is a dictator of the proceeding activities in the product life cycle process. Complex geometry and over styling places an overload during production and simplification i.e. rework at this stage causes many complications, therefore lean type thinking must originate at the component level and must be followed through the subsequent activities.

## 1.2 Research Motivation

Maintaining a high level of quality, sustaining competitiveness, shorter time and reducing cost to market is essential for survival in a challenging global environment. Manufacturing firms are seeking ways to attain substantial improvements through innovations, such as the adoption of design strategies and novel product development methods (Friedman 2003).

As explained by Kim and Chhajed (2000) the design phase accounts for only 6% of the total product development cost, however 70% of the production cost is determined at this stage. The encompassment of design deals with the product lifecycle related issues such as strategy, customer involvement, manufacturability, marketability and recyclability. Poor design leads to changed rework, cost over runs and delay, decreased market response. Therefore a well-designed product is the key to allowing companies to gain competitive advantage, which increases the chances of obtaining larger market share. Through attentive and careful design decisions companies are able to maximise profits as well as decrease production costs (Tarasewich and Nair 2001).

Typically, designers employ the use of Design Methods and Theories (DMT) as a means of achieving desired design targets and developing better products. The current domain of DMT contains a rich collection of techniques that has been developed throughout the course of history, of which some highly influenced by industrial demands whilst others have been developed through academic research. A list of some DMT is presented with details of their particular benefits:

- Axiomatic Design is an ideal design method to systematically analyse the transformation of customer needs into functional requirements
- Design for Manufacture and Assembly is a set of guidelines developed to ensure the Manufacturability and Assemblability with minimum effort, time and cost
- Design for X is a wide collection of design guidelines to meet specific design issues that are caused by the product characteristics
- Adaptable design focuses to effectively and efficiently enhance the functionality of the product through adaptability. Adaptable design is ideal for increasing functionality through product upgrades

The contributions made by the application and acceptance of the design methods and theories is well acknowledged, however Stokes (2011) explains the Design Methods and Theories need to evolve further in response to social, cultural and economic problems i.e. climate change, safety, organisational welfare etc. The creation of better designs requires an integrated approach which ensures functionality, manufacturability, less waste and resources are used in its production and all avoidable harm is eliminated in a cost effective manner, this can be explained as lean design. Furthermore this approach should focus on the design of geometry as opposed to improving the design process which receives very little discussion in Traditional Design Methods and Theories.

## 1.3 Overview of LeanPPD FP-7 Project

Lean Product and Process Development (LeanPPD) is a European project, funded under FP7 Theme 4 (NMP-2007-214090). The project is addressing the need of European manufacturing companies for a new model that goes beyond lean manufacturing to ensure the transformation of the enterprise into lean environment. The aim of LeanPPD is to develop a new model based on lean thinking that will consider entire product life cycle, providing a knowledge based environment to support value creation to the customers through innovation and customization, and delivering high quality, more sustainable and affordable products (LeanPPD Website).

A main output of the LeanPPD programme is to develop a framework designed to help industry in their journey towards maximizing lean design realisation, which focuses on the adoption of lean thinking to the design of the product at the component level. Building towards a novel approach, namely lean design, would primarily seek to transpose lean thinking earlier at the conceptual design phase which would ensure the successful control of waste and aim to create and maximise value at the source while the concepts are abstract.

## 1.4 Research Aim and Objectives

The aim is to develop a lean design framework that will support the generation of product design with attributes such as maximise value, manufacturable and operable with minimum waste and resources ensuring avoidable harm is eliminated.

The main objectives of the research are to:

1. To establish the evolution and trends in design research and investigate the status of lean thinking in product design through an extensive literature review
2. To construct the lean design principles in a scientific manner based on the amalgamated information from the review of scientific literature and industrial field study

3. To develop lean design framework which encompasses guidelines and its associated processes that will support the generation of conceptual lean designs
4. Validate the lean design framework through an industrial case study and experts opinion

## 1.5 Thesis Structure and Summary

This section presents the structure of the thesis. An outline of the activities conducted in realising the research aim has been illustrated in Figure 1-1.

Chapter 1 introduces the research and discusses the background, motivation, aim and objectives.

In Chapter 2, an extensive scientific literature review is presented. The two areas covered in the literature review are (1) evolution in design research and extending beyond traditional Design Methods and Theories, (2) the status of lean design in academic literature. The objective is to capture the state-of-the-art in these areas and identify research gaps.

Chapter 3 presents the research methodology adopted during the course of the research. A detailed analysis of the research approaches and strategies is explained, followed by a justification for the selected methodology.

Chapter 4 presents the current industrial practices and perspectives of European industrial sectors on design. It describes in detail the multiple activities conducted during the field study. In addition, it provides an industrial understanding about the working lean design definition proposed by the author.

Chapter 5 sets the foundations and principles of lean design. This is achieved by establishing a theory construction approach to formalise the research. A description of the context and considerations for each principle is presented.

Chapter 6 describes the Lean Design Framework that consists of a four phase process and supported tools (illustrated through the Lean Design Guidelines) that allows the realisation of a lean design.

The purpose of Chapter 7 is to describe the validation of the elements of the Lean Design Framework with an industrial case study. The details demonstrate the development of a leaner oil/water separator through the application of the Lean Design Guidelines.

Finally, Chapter 8 synthesises the work of the research and its outcomes discussed. The contributions made to knowledge, the limitations and possible future research directions are also discussed. To end, the conclusions are drawn, with details of how the research aim and objectives were achieved.

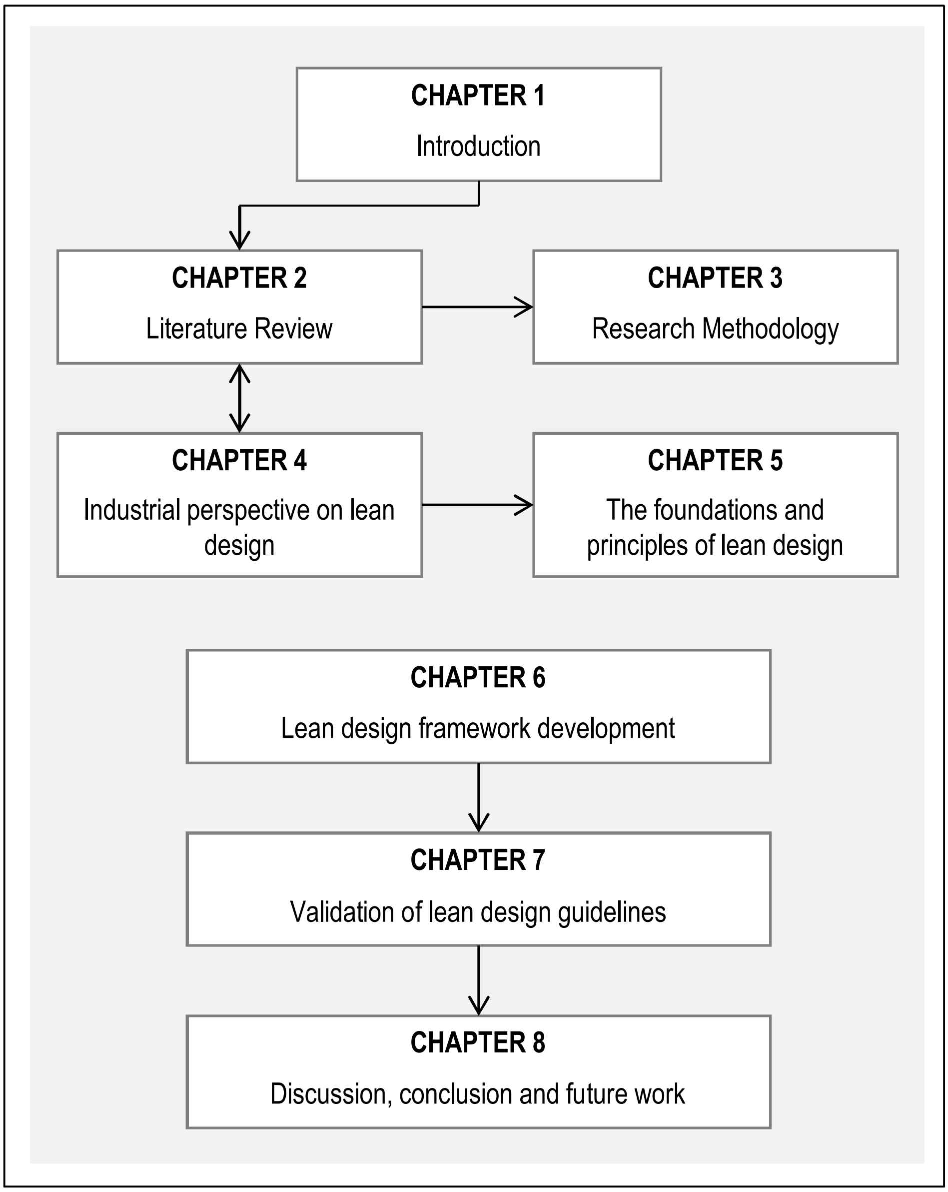



Figure 1-1: Thesis Structure

# Chapter 2

# LITERATURE REVIEW

## 2.1 Introduction

One of the outcomes of the research reported in this thesis is to establish the evolution and trends in design research and investigate the status of lean thinking in product design through an extensive literature review which is presented in this chapter. The key topics for investigation in literature are depicted in Figure 2-1.

Section 2.1 introduces the chapter; in section 2.2 the author initiates the literature review by exemplifying the role and importance of design within New Product Development (NPD). The evolution in design practice and research is presented in the sub section with an emphasis on extending beyond traditional Design Methods and Theories (DMT) to address the current global changes. Section 2.3 introduces the lean thinking philosophy and a state of the art is performed through a systematic search to identify literature on lean design. Following a review of the available literature on lean design, the possibility of adopting lean manufacturing tools/techniques earlier in design is explored. In section 2.4 the review seeks to synthesise the meaning of value and the methods for value translation and representation. Additionally a sub section is dedicated to waste minimisation techniques for value enhancement. Finally, section 2.6 the research gap from the current pool of knowledge is assimilated. The chapter then closes with a summary.

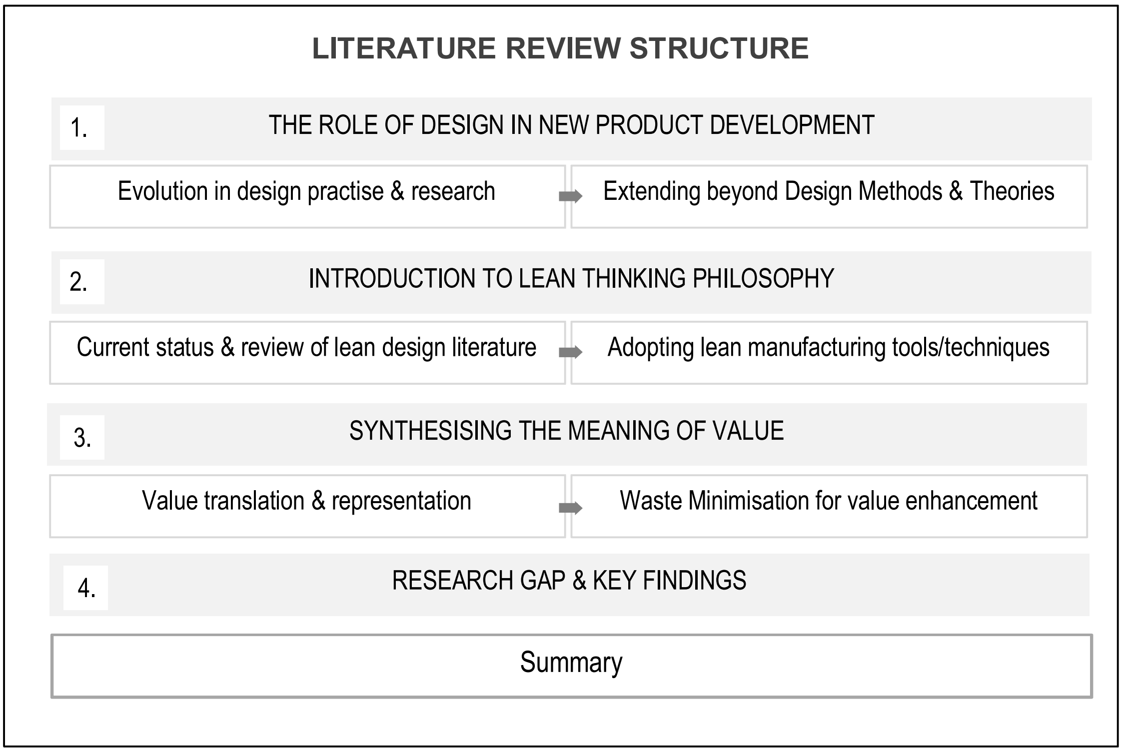



Figure 2-1: Topics discussed in the literature review

## 2.2 Importance of design in New Product Development

New Product Developments (NPD) is a vital part in developing and maintaining a strong stance in a competitive business environment. Decreased product lifecycle and increased global competition has given a high level of importance to NPD. Long-term organisational performance is dependent on NPD, continuous changes in customer needs, new scientific and technological discoveries, shortened lifecycles, international and local competitions has forced organisations to either modify existing products or introduce new ones. Failure to address these changes results in organisations losing a vital proportion of competitive advantage (Vayvay and Cobanoglu 2006).

As suggested by Cooper (1985) the introduction of product development results from the careful selection of a 'design strategy' and is represented through different NPD. Studies have attempted to classify new product types, for example, Cross (2006) identify six types of new products: new to the world products, new product lines, adding to existing product lines, improvements and revisions to existing products, repositioning and cost reduction. Objectively, Ulrich and Eppinger (2011) decompose NPD into four classes: new product platforms, derivatives of existing product platforms, incremental improvements to existing products, and fundamentally new products.

It can be inferred that maintaining a high level of quality, sustaining competitiveness, shorter time and reducing cost to market are considered fundamental objectives for survival in a challenging global environment. As a response to this, manufacturing firms are seeking ways to attain substantial improvements through innovation, such as the adoption of design strategies and new product development methods (Friedman 2003).

Having acknowledged the importance of design strategy selection and its role in NPD, the impact of design is explained by Shehab and Abdalla (2001) and Hundal (1993), stating that 70% of the committed manufacturing cost is determined in the design phase. As the project advances, the possibility of reducing the final cost is less likely due to the high costs of modifications (Duverlie and Castelain 1999). A well-designed product is the key to allowing businesses to gain competitive advantage, hence increasing the chances of obtaining larger market share. Through careful design, companies are able to maximise profits as well as decrease production costs (Tarasewich and Nair 2001). The proceeding subsections presents the evolution in design practise and research to identify the current focus; its emerging themes and trends and the opportunity to extend beyond traditional Design Methods and Theories.

### 2.2.1 Evolution in design practise and research

The practise of product design is in constant evolution, like any other discipline where centralised focus shifts from unclear ground to a reasoned investigation to address the needs of the time. Product design and development practices are evolving by ways of applying new design practices to create better and more viable products, much quicker than previously done. The number of scientific journals is increasing; the shift in focus and expansion of target audience, as highlighted in Table 2-1. This interesting fact highlights the growing interest of design from both a research and practical point of view.

Design research as a discipline is primarily based on the grounds that design has its own elements of interests and its own ways of knowing them (Stokes, 2011). Cross (2006) explains that research in to design 'came of age' in the 1980s, specialised schools with particular design interests also started to emerge but also this was the period of the emergence of the first design research journals (Durling, 2006). Since the launch of Design Studies in 1979, eleven other recognised design journals have emerged to surface which includes the Journal of Design Research, Design Management Review, Design Research Quarterly etc. as shown in Table 2-1.

Since the initial publications, design research has evolved in the following areas, which demonstrates its rapid growth:

- Contextualisation: where the primary focus is on philosophy, history, culture positions of design (Chen 2007)
- Strategisation: which deals with the management of design; the benefits obtained from alternative design methodologies in different contexts (Cross 2006)
- Conceptualisation: the fundamental aspect of design, where imagination and inventiveness is considered to address social needs through the production of new artefacts, systems and products (Durling and Shakelton 2002)
- Implementation: focusing on detailed design development, testing, manufacturing, where the reflected output is in a physical form, virtual or conceptual. The interaction between socialists, technologists and anthropologists with designers to resolve technical problems is also being witnessed (Stokes 2011)

- Customisation: emphasises on post-implementation tactics to expand brand image, the relationship between consumers and the product firm and the experiences created from the interaction with the product (Lucas and Swan 2011)

Table 2-1: Design journal publication by launch (adopted from Stokes 2011)

| JOURNAL | FOCUS | AUDIENCE | LAUNCHED |
|---|---|---|---|
| *Design Studies* | All aspects of design activity and experience | Researchers, educators and professionals | 1979 |
| *Design Issues* | Cultural and intellectual issues including design history, theory and criticism | Practitioners and scholars | 1984 |
| *Journal of Design History* | Design history, including the history of crafts and applied arts, as well as visual and material culture | Researchers and scholars | 1988 |
| *Research in Engineering Design* | Design theory and methodology in mechanical, civil, chemical, electrical, architectural, and manufacturing engineering | Practitioners and academia | 1989 |
| *Design Management Reviews* | Design strategy, methods and leadership | Researchers, educators and scholars | 1989 |
| *The Design Journal* | Design in cultural and commercial contexts | Researchers, educators, managers and scholars | 1998 |
| *The Journal of Design Research* | Design theories, models and products, including engineering, architecture, industrial design and planning | Practitioners and academics | 2001 |
| *Codesign* | Collaborative, co-operative, concurrent, human-centred, participatory, socio-technical and community design | Researchers and practitioners | 2005 |
| *Artifact* | Design theory, interaction design, aesthetic theory, design knowledge | Scholars, researchers and practitioners | 2006 (now ceased) |
| *Design Research Quarterly* | News on design research, research skills, research teaching and training and interdisciplinary research | Scholars, researchers and practitioners | 2006 |
| *International Journal of Design* | All fields of design, including industrial, visual communication, interface, animation and game, architectural and urban design | Researchers and practitioners | 2006 |

'Design seems to be moving into a new era, the disciplines that have framed our work are reshaping themselves, new kinds of designs are emerging and we have not yet been able to define these new and hybrid professions, some created by peoples not previously thought of as designers (Durling and Stokes 2002)' . This statement confesses the characterisation of design that has come to surface through the involvement and participation on the basis of interest, there is an evident shift from orthodox towards contemporary design. Eppinger

(2011) a respected scholar endorses this statement and sees this evolution as an on-going process, and believes that academics and practitioners are in position to contribute and influence this for the betterment and progression of design application and research.

The emergences of new themes in design research indicate new directions being undertaken, for example:

- Designs role is extending as the artificial world increasingly affects the natural world (Eppinger 2011)
- Design of the user experiences goes beyond any single disciplinary boundary and research topics reflect multidisciplinary teams (Luchs and Swan 2011)
- Design theories and methodologies are evolving in response to social, cultural and economic problems, such as climate change, safety and organisational welfare (Luchs and Swan 2011)

The proceeding section focuses on the last statement mentioned above and provides insight into current traditional Design Methods and Theories and seeks to identify the limitations and ways to extend beyond them.

### 2.2.2 Extending beyond traditional Design Methods and Theories

The Design Methods and Theories (DMT) domain contains a rich collection of techniques which have been developed throughout the course of history dating back to 1860s (Stokes 2011), some through industrial design applications whilst others in academic institutions. Design theory can be defined as the understanding of design, and design methodologies deals with how to design or how design should be (Tomiyama et al., 2009). The author was able to populate a list of commonly used DMT by reviewing the following: Cross (2008), Pahl et al. (2006), Charles and Kumar (2012), Hanington and Martin (2012), Wu (2012) and Pugh (1990). The initial list of DMT was lengthy and for discussion purposes it has been filtered in terms of relevance. A brief synopsis of the DMT is provided before drawing conclusions and listing areas further development.

*1) Adaptable Design*

Adaptable design theory refers to the process of creating designs and products that allow ease of adaption as the requirements change (Gu et al., 2004). Designers are able to re-use existing designs as the customer changes requirements, in affect shortening the product development lead time and focusing more on addressing quality issues. The economic and environmental benefits of using adaptable design as posed to other traditional methods i.e. modular, reconfigurable and mass customisation design is much more noticeable. Adaptable design relies on designer's individual skill and experience, however as suggested by Sivaloganathan and Shahin (1999) knowledge-based design and design repositories could be used as aids for inexperienced designers. A typical example would be a well branded mobile phone which has undergone minute geometrical improvements and is released as an upgrade with its own individual identity.

*2) Axiomatic Design*

Axiomatic Design is a design methodology using design matrix methods to logically transform customer needs in to functional requirements, numerical design parameters etc. in an attentive framework (Suh, 1998; Cebi and Kahrman, 2000). Based on four design domains; customer, functional, physical and process domain, for each adjacent domain the left seeks to represent 'what we want to achieve' while the right provides a solution as to 'how we propose to achieve it.' Successful utilisation in industrial applications has been cited which include product, system and software (Lee and Suh, 2005; Gu et al., 2001). Unfortunately due to the intellectual challenges associated with it, Axiomatic Design is less favourable option for product designers (Suh and Do, 2000; Meijer, 2006).

*3) Design Structure Matrix (DSM)*

Design Structure Matrix (DSM) is a method by which designers are able to manage problems related with information flow which are domain related

(Browning, 2001). Pimmler and Eppinger (1994) have suggested that DSM is a commodity for designers; as it provides a systematic method for structuring product components. The DSM represents the product via matrix, denoting single components; clustering algorithms are used to identify interactions between the constituents. The analysis provides an understanding of how the product can be managed and the effects of component modularisation on the dependencies. The popularity of adopting DSM has increased over the years, and its applications are now being used in aerospace, automotive, construction and telecommunications sector (Tomiyama et al., 2009)

*4) Design for Manufacture and Assembly*

Design for Manufacture and Assembly is a combination of Design for Manufacture and Design for Assembly, Pioneered by Professor Gregory Boothroyd and Pete Dewhurst. DFMA is a set of design guidelines that ensure that the product can be manufactured and assembled with minimum effort, time and cost (Boothroyd & Dewhurst 1983). Generally products designed using DFMA have a higher level of quality and reliability as opposed to products designed using traditional methods, which ensure a smooth transition from design to production (Groover, 2007). The benefits of considering DFMA include: lower assembly cost, shorter assembly time, increased reliability, shorter total time-to-market.

Practically, considering DFMA in the design process is a lean activity and many benefits can be borne from its successful utilisation. The concept of reducing parts and ‘proactively’ considering manufacturing and assembly through the modification of the physical geometry enhances the product through simplification. Based on three simple rules, one is able to reduce parts and enhance the manufacturability and assembly of a product.

The rules are as follows (Boothroyd, 2005):

1. During the operation of the product: does the part move with respect to all other parts already assembled?

2. For fundamental reasons: does the part have to be of a different material from all the other parts already assembled?

3. Does the part have to be separate from the parts already assembled because otherwise the necessary assembly or disassembly of a separate part could be carried out?

Successful case studies in aerospace, manufacturing equipment, computing peripherals, telecommunications and medical equipment and transportation have been widely discussed. An example of a defence related case study is presented to provide the reader with a graphical representation of the effects of DFMA on the geometry and product architecture, in terms of reduction and simplification.

*5) Feature Based Design*

Numerous definitions of 'feature' have been cited in literature; Başak & Gülesin (2004) for instance defines it as dimensional (numerical) region of a part. It could also be an operational construction that is identified on an adjacent face (Joshi and Chang, 1990). Shah & Mantyla (1995) in their book 'Parametric And Feature Based CAD' clarify that the featured based design is most commonly associated with product modelling. The integration between CAD and CAM systems is made possible through the adoption of feature-based modelling (Figure 2-2). Common CAD primitives i.e. circles, splines etc. do not retain manufacturing information, however feature based design include both design and manufacturing information and suffices both activities (Mantyla et al., 1996). Feature based design, unlike other method provides the designer with a library of predefined features which could be selected during conceptualisation, hence speeding the design process.

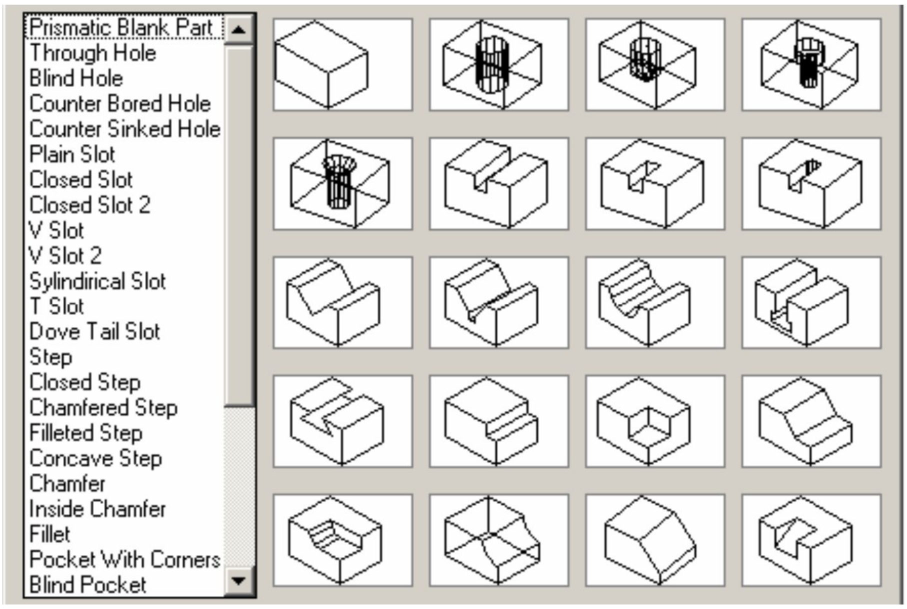



Figure 2-2: Example of feature based CAD models (Başak & Gülesin 2004)

*6) Pahl & Beiz Method*

One of the most familiar DMT in industry and academia is that of Pahl & Beitz. This method captures the complete product life cycle. Pahl et al (2007) acknowledge design as an interactive and iterative process and therefore place it at the centre – as a critical activity. Design process is segmented in to four sequential phases: (1) Planning and clarification, (2) Conceptual design, (3) Embodiment design and (4) Detail Design. Many institutions have standardised this model and teach it as part of the curricular, however Tomiyama et al (2009) believe only experienced designers will be able to utilise this method correctly. The reason for this drawback is as follows: the textbooks outline the activities in a simple manner; during transition, students underestimate the rigour, difficulty and the associated pitfalls of using this method incorrectly.

*7) Total Design of Pugh*

The Total Design method was constructed with industrial design practices in mind (Pugh, 1991). The unique ‘Concept selection’ in the methodology uses a matrix (Pugh Matrix) which iteratively allows the designer to select and converge the best concept, this can be utilised not just in the conceptualisation stage but also at any stage of design development. The generic applicability and overall simplicity of the model has allowed many companies to adopt this methodology, for example General Motors has used it in the Saturn Project (Tomiyama et al., 2009).

### 2.2.3 Concluding remarks on traditional Design Methods & Theories

The contributions made by the application and acceptance of the DMT i.e. Pugh's Total Design (Pugh, 1991), Pahl and Beitz Method (Pahl et al. 2007), Adaptable Design (Gu et al. 2004) and Grabowski's Universal Design Theory (Grabowski et al. 1999) are widely acknowledged, however there are elements which are still missing and which need to be addressed, for example:

1. Majority of the methods and theories are associated with the design process and place minimal focus on the geometry of the product. Kroes (2002) believes the current focus of design improvement research is primarily based on the design process and suggests product design and process design are intimately related; an understanding of process design requires insight in to the product itself. Therefore a balanced approach must be taken in addressing product design and process design.

2. The methods which focus on geometry i.e. Design for Manufacturing (Dixon and Poli, 1995), Design for X (Hauang, 1996) Design for Manufacture and Assembly (Boothroyd, 2005), Feature Based Design (Dong et al.1991) will ensure a certain element of design improvement however they will not ensure waste and resource minimisation during manufacture as a consequence of geometrical improvement.

3. Product harm crises management is a growing area of research, as technology is becoming more vulnerable, manufacturing firms are pressuring design engineers to improve the level of safety in their designs (Klein and Dawar 2004; Rsuli and Shariff, 2010; Fadier et al., 2003). Recognising the importance of *'reducing hazards through better designs'* an Institute for Safety Through Design (ISTD) was established in 1995. Since then a number of articles have appeared in scientific journals, (Aaker et al. 2004; Dawar and Pillutla, 2000; Moe et al., 2011; Siomkos and Malliaris, 2011; Vassilikopoulou et

al., 2011) Approaches to safety mentioned in these articles include safety checklists, safety analyses and CE mark (common level of safety for goods to move through EU countries), Preliminary Hazrad Analysis, Faliure Mode and Effects Analysis, Fault tree analysis etc. In conclusion, product harm management (inherently safe design) is an extremely important consideration however the traditional DMT fail to address it as an essential component of design during geometrical generation.

The aforementioned analysis conducted by the author, through an in-depth understanding of the individual DMT lead us to the conclusion that there is an opportunity to go beyond the traditional approaches by considering the adoption of lean thinking in product design. By considering lean thinking during design would ensure learner designs are generated, a complex design cannot be leaned out in production once the design has been fixed. Therefore the production of affordable and sustainable products would require effective lean design and engineering that allows the maximum representation of customer value with minimal waste and resources, which can be manufactured and delivered with no harm, without compromising the quality of the product. The proceeding section provides an introductory background to lean thinking, followed by a detailed investigation in to the available literature on lean design.

## 2.3 Introduction to Lean Thinking

Krafcik (1988) a quality engineer for Toyota was the first to introduce the term lean as opposed to ‘buffered’ in a magazine article to describe the Toyota Production System (TPD) as compared to the ‘Fordist’ mass production system. In *The Machine that Changed the World* at the beginning of 1990s Womack, Jones and Ross introduced the concept of lean manufacturing to the western world based on TPS. According to Womack et al. (1990) lean was described as a management method that was not strictly assigned to the manufacture of automobiles but could be applied to other industries. Even though *The Machine that Changed the World* was not an academic publication, rather represented a personal view, in spite of this it is listed as an important publication in the research on lean.

Womack, Jones and Ross holistically define lean as “tools and methods through which waste is minimised while end user value is maximised and continuous improvement can be achieved.” Furthermore Womack and Jones (2005) introduced five principles, the first stage being *specify value*. Without knowing what a customer values it is considered impossible to deliver a product that truly satisfies a market. Compounded with this jump to eliminate waste without first understanding value, is the perception that the lean thinking principles do not translate to the product development process (Browning 2003). The remaining principles include: identify and map the value stream, create flow by eliminating waste, respond to customer pull and pursue perfection.

Karlsson and Ahlstrom (1996) also carried out research based on observing several industries to come up with recommendations about the path to Lean Product Development. The research did not define the meaning of lean and the general recommendations were more related to Concurrent Engineering applications such as supplier involvement, cross-functional teams, simultaneous engineering and integration of activities.

There were two major lean thinking projects in USA and UK. The Lean Aerospace Initiative coordinated by MIT (USA-LAI 2010) and the UK Lean Aerospace Initiative (UK-LAI 2007). The project was specifically oriented to the aerospace industry in USA and UK and the information was withheld from the public domain. The second project was IMVP, the efforts started by understanding the TPS through publishing the book *The Machine that Changed the World*. Most of the efforts were put in understanding lean applications on the shop floor and developing both practical models and lean techniques to help implementation. This effort further evolved to the lean transformation of the enterprise. This is now called the Lean Enterprise that covers the adoption of lean thinking to the management of the enterprise as well as it supply chain (Khan et al. (2011).

Lean product and process development can be described as an incremental progression in the journey of lean thinking. Ward et al (1995) have attempted to describe the Toyota Product Development (PD) from a design perspectives;

Sobek at al. (1999) proposed the set-based concurrent engineering alongside its principles and tools, Morgan and Liker (2006) presented 13 principles of lean product development which have been categorised under three distinctive groups i.e. people, processes and technology. As highlighted in Figure 2-3 the application of lean thinking in PD is not firmly established as lean manufacturing and lean enterprise, it is considered a new idea; there are no tools, no value stream mapping, and no practical models. Whilst much work has been published concerning the implementation of the lean principles into product development, little evidence has been presented to validate its success (Alam et al. 2010).

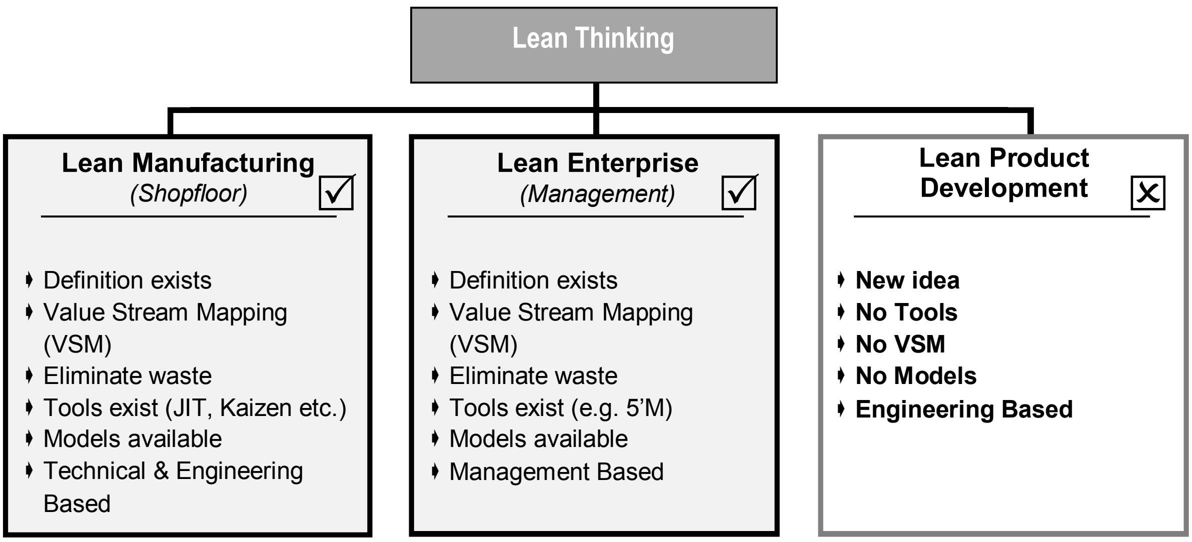



Figure 2-3: Application of lean thinking

### 2.3.1 Lean Product and Process Development (LeanPPD)

European manufacturing companies need to develop the capability to stretch beyond the concept of lean manufacturing and encompass all of the lean principles into the New Product Introduction process. The Lean Product and Process Development (LeanPPD) project addresses this requirement. Consisting of twelve European partners, the research forms part of the Seventh Framework programme (Project Number NMP-2008-214090).

This four year programme aimed to deliver tools and techniques for manufacturing companies to help them reduce waste and maximise value from their current product development processes. LeanPPD rests upon a number of enablers or building blocks (Khan et al., 2013, Al-Ashaab et al., 2013; Khan et al., 2011). One of the enablers, is the development of a framework which will enable the journey maximising lean design realisation, this particular research contributes to this area. As part of the development this framework, lean design principles form the basis which are illustrated in a logical process and listed in the Lean Design Guidelines.

Considering lean design is fairly new area of research; a systematic investigation and review of the current academic literature on lean design is presented in the proceeding section.

### 2.3.2 Strategy to identify literature on lean design

Baines et al. (2006) produced a state of the art report to establish the possibilities of adopting lean manufacturing principles in to other areas of the product lifecycles. Drawing upon the findings from that research, the author developed a search strategy as illustrated in Figure 2-4 to investigate the current status of lean design in literature.

The search strategy was developed by identifying a broad selection of databases covering journal, conference proceedings, books, trade journals and articles which included: Scopus, Emerald, IEEE, Science Direct, Engineering Village, Global Factivia, Knovel books and other traditional library cataloguing systems. A number of relevant keywords were selected, and to restrict the search to more recent publications, the time frame was set to 2005 to 2015. To further extend the research, the search criteria were extended to include publications prior to 2005.

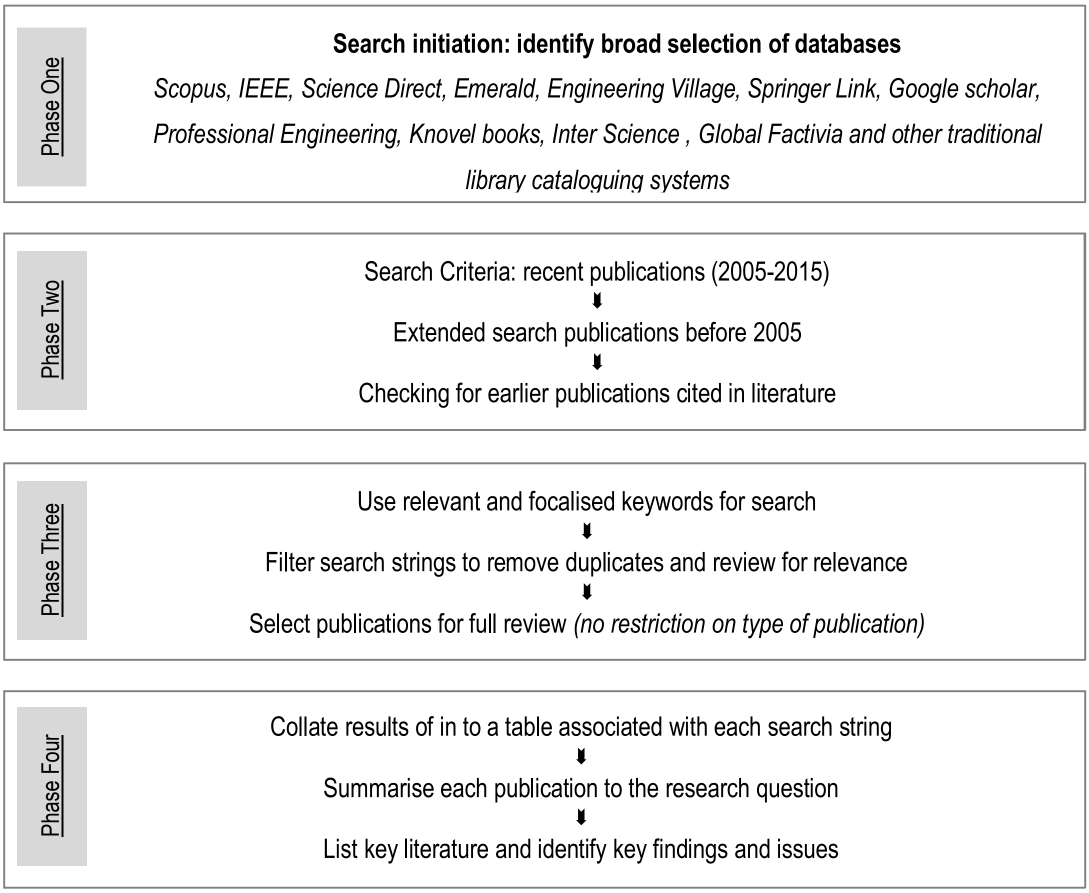



Figure 2-4: Search strategy for identifying literature on lean design

The search contained a total of 14 keywords; some directly associated with the research topic whilst others could be considered beneficial to cover the scope, typical examples included: lean, design, product etc. as shown in Table 2-2. Each hit was then edited to eliminate duplicate records and was conformed in to a spread sheet. Each article was reviewed by checking the title and then categorised in terms of its level of relevance. The abstract of articles 'very relevant' and 'somewhat relevant' were reviewed before and selections for full review were made. The search strategy did not place any restrictions on the types of publications hence book, trade journals etc. were also reviewed.

The outcome of the survey confirmed there are simply no relevant publications on the research topic and clearly identified the opportunity for research in this area, as conceived in Table 2-3.

Table 2-2: Literature keyword search results

| | Keywords searched | Total number of article hits | |
|---|---|---|---|
| S1 | Lean + Design<br>*Publications before 2005* | 147<br>128 | 275 |
| S2 | Lean + Product + Design<br>*Publications before 2005* | 18<br>23 | 41 |
| S3 | Lean + Product + Introduction<br>*Publications before 2005* | 3<br>11 | 14 |
| S4 | Lean + Design + Toyota<br>*Publications before 2005* | 2<br>1 | 3 |
| S5 | Lean + Design + MIT<br>*Publications before 2005* | 0<br>0 | 0 |
| S6 | Lean + Design + Case Study<br>*Publications before 2005* | 0<br>0 | 0 |
| S7 | Lean + NPD<br>*Publications before 2005* | 3<br>1 | 4 |
| S8 | Design + for + Lean + Manufacture<br>*Publications before 2005* | 3<br>5 | 8 |
| S9 | Design + Lean + Product + Development<br>*Publications before 2005* | 6<br>1 | 7 |
| S10 | Lean + Design + Strategy<br>*Publications before 2005* | 8<br>1 | 9 |
| S11 | Lean + Design + Technique<br>*Publications before 2005* | 5<br>0 | 5 |
| S12 | Lean + Design + Aerospace<br>*Publications before 2005* | 2<br>1 | 3 |
| S13 | Lean + Design + Automotive<br>*Publications before 2005* | 4<br>7 | 11 |
| S14 | Lean + Design + Domestic<br>*Publications before 2005* | 0<br>0 | 0 |

Table 2-3: Most relevant articles identified from the search

| | Keywords searched | Filtered Results |
|---|---|---|
| S1 | Lean + Design | 23 |
| S2 | Lean + Product + Design | 7 |
| S3 | Lean + Product + Introduction | 1 |
| S4 | Lean + Design + Toyota | 0 |
| S5 | Lean + Design + MIT | 0 |
| S6 | Lean + Design + Case Study | 0 |
| S7 | Lean + NPD | 0 |
| S8 | Design + for + Lean + Manufacture | 3 |
| S9 | Design + Lean + Product + Development | 3 |
| S10 | Lean + Design + Strategy | 0 |
| S11 | Lean + Design + Technique | 0 |
| S12 | Lean + Design + Aerospace | 0 |
| S13 | Lean + Design + Automotive | 1 |
| S14 | Lean + Design + Domestic | 0 |
| | **Total** | 38 |

The proceeding section presents a selection of the most relevant articles describing lean design, which were extracted from the investigation. The section seeks to establish the following: (1) what is meant by lean design? (2) Is there a framework/method based on academic research to achieve lean design? (3) Are there lean design principles available? (4) Has the success of lean design been demonstrated through an industrial case study?

### 2.3.3 Review of current literature on lean design

A detailed listing of articles discussing lean design has been presented in Table 2-4; the table highlights whether lean design has been explicitly defined followed a description of the contents of the article.

In relation to product design, lean design is considerably less discussed and investigated than production issues (Jørgensen and Emmitt 2007). Publications generally adopt the term lean design in relation to construction referring to approaches and methods for managing processes of design. For example, Holmes and Schwengerdt (2008) relate lean design in the improvement of a hospital layout through digital mock-up in for enhancement of room equipment. Similarly Freire and Alarcón (2002) consider lean design for process improvement, based on the lean principles of flow conversion and value generation for increasing productivity. The term lean design is explicitly synonymised with minimising waste during project initiation (Whelton 2004; Emmitt et al. 2005).

Based on their experiences as consultants, Huthwaite (2004) and Masciteli (2004), proposed approaches to achieve lean design through the integration of traditional design tools/techniques. Huthwaite's approach is set by objectifying the designer to 'optimise values and to prevent wasteful processes' this is to be achieved by 'Lean Design Mapping Kazien.' Additionally designers are encouraged to apply Boothroyd's Design for Manufacture and Assembly and traditional Design for Modularity in ensuring the design is 'leaned out.' Mascitellis approach is based on 18 tools (such as 'LeanQFD', Design for Six Sigma, DFMA etc.) that aim to reduce manufacturing cost.

Table 2-4: A selection of relevant articles covering lean design and a synopsis of the contents

| Literature | Explicit definition of Lean design | Comment |
|---|---|---|
| Miles (1998) | No | Conference paper of IGLC. It suggests lean production will influence construction industry from bottom up as opposed to a top down approach. |
| Freire and Alarcón (2002) | Yes | "Lean design is the application of lean production principles, which promote the elimination of waste and non-value activities in processes, to engineer and design. |
| Brookfield et al. (2004) | Yes | "The purpose of lean design is to improve the 'manufacturability' of a product through attention to information coordination and flows at the outset of projects…" |
| McNeel (2004) | Not clear | The article discusses the benefits of applying lean principles earlier at the design phase, a model, framework is not presented. |
| Huthwaite (2004) | Not clear | The book titled 'the Lean design Solution' provides a 'universal lean design equation' that encourages the optimisation of values and prevention of wasteful processes. |
| Emmitt el al. (2005) | Not clear | Lean design management is explained as a design management in construction that ensures the enhancement of stakeholder values whilst reducing waste in the project. |
| Tilley (2005) | Not clear | Conference paper suggesting the introduction of lean production principles to the process of design to ensure more efficient and better quality is achieved. |
| Pavnasker et al. (2006) | Not clear | The paper highlights the cost benefits of reduction through adoption of lean thinking at the design phase; the novel Design for lean manufacturing (DFLM) method provides guidelines in considering lean manufacturing operations during design. |
| Mascitelli (2007) | Not clear | 'The Lean Design Guidebook' provides a toolbox of tools that enable manufacturing cost to become the foundational part of product design and development. |
| Holmes and Schwengerdt (2008) | Not clear | The authors of the article relate lean design in the improvement the topology of a hospital via digital mock-up to allow staff to gain a better visual of the room and equipment. |
| Tonchia (2008) | Not clear | Lean design is described a global objective of design improvement by slimming down designs that are bulky in terms of unnecessary parts and resources invested in the single, uncoordinated projects. |
| Sprovieri (2011) | No | The article titled: 'Design First, Lean Second' argues that Design for Manufacture Assembly (DFMA) should be considered as a mandate to enable engineers to design products that are lean from the start. |
| Dewhurst (2011) | No | The article seeks to promote the benefits of adopting DFMA earlier in the design stage to yield more savings rather than applying lean manufacturing after the design if fixed and is set for production. |
| Reifi and Emmitt (2013) | No | The article provides a theoretical conclusion drawn from an industrial survey which sought to identify the understanding of current design management processes in UK. |
| Ko and Chung (2014) | No | The paper proposes a lean design process to enhance design reliability by creating a learning environment using design correctness ratio. |
| Reijula et al. (2014) | No | In this article the challenged of modern of modern health care facilities is discussed and the possibility of adopting lean thinking to improve the service is discussed. |
| Pease (2014) | No | The paper discusses the benefits of considering lean design for developing world markets |
| Ide et al. (2015) | No | The article describes a knowledge based heterogeneous model which aim to trace design rationale which provides least commitment convergence of space of design solutions. |

Jugulum and Samuels (2008) suggest that lean design is the maximisation of stakeholder values and the minimisation of cost and harm. No particular or technique is developed, however the use of Value Engineering, Modular Design and TRIZ (Theory of Inventive Problem Solving) is encouraged.

No significant contribution in to the research of lean design has been identified in recent publications; rather a repetition of concepts is witnessed, Masciteli (2007) synonymised lean design with DFMA, recent publications have reinstated this fact (Tonchia 2008; Sprovieri 2011; Dewhurst 2011). Furthermore, the only case study available to date is that of Dyer (2012) who claims to have developed a yacht through 'lean design' which he explains as: spending more effort at the beginning of the design cycle on the cost implications of material selection, component form, and especially manufacturing processes.

The review of available literature on lean design suggest: there is no commonly agreed definition of lean design, furthermore there is no formal framework/method based on academic research to achieve lean design. A case study has emerged on a physical product however the concepts considered can be explained as 'informal consideration of design for manufacture and assembly' concepts.

The discussion in this chapter up to this point has reviewed traditional DMT and identified areas of further enhancement, the opportunity to consider lean thinking earlier in design and the current literature on lean design. With this in mind the author believes there is an opportunity to select traditional Lean Manufacturing tools and techniques that could be adopted to design.

## 2.4 Adoption of Lean Manufacturing techniques to product design

The success of Lean Manufacturing (LM) rests upon the strict enforcement and utilisation of tools and techniques that coincide with the lean philosophy on the shop floor. This section aims to draw upon the well-established tools/techniques and seeks to establish if the underlining philosophies can be adopted earlier in design to instigate the sense of leanness earlier in the design.

### 2.4.1 Selection of Lean Manufacturing techniques

Unlike traditional production systems, the Toyota Product Development places emphasis on process engineering and process simplification. This is achieved not through the extensive use of control charts, rather inbuilt techniques such as Poka-Yoke, Single Minute Exchange of Dies (SMED), Quick Change Over, Andonds etc. (Bicheno and Mattias 2009) as shown in Figure 2-5. An inquiry was performed to assess the possibility of adopting the philosophies of the LM tools/techniques which are directly related to the geometry. Generic questions were posed as criteria which were a result of the authors understanding of the topic, as seen in Table 2-5 to make a selection of the lean manufacturing tools that could be adapted in to design.

| A SELECTION OF LEAN MANUFACTURING TOOLS AND TECHNIQUES | |
|---|---|
| Standardised work | Just in Time |
| Andon | 7 Wastes |
| 5S | Takt time |
| SMED | Kanban |
| Poka-Yoke | Value Stream Mapping |
| Visual Management | Autonomation |
| Standardised work | Kaizen |

Figure 2-5: A selection of Lean Manufacturing tools/techniques

Table 2-5: Lean manufacturing tool selection criteria

| Questions posed as criteria for selection of Lean manufacturing tools | Results |
|---|---|
| Is it possible to adopt the underlining philosophy in to product design? | 5S, Poka-yoke, SMED/QCO |
| Is the tool/technique directly associated with the geometry and can it provide direct benefit to the geometry? | Poka-yoke, SMED/QCO, Standardisation |
| Economic gains be achieved by employing the tools/techniques earlier in the design? | Lean performance indicators, Poka-yoke, SMED/QCO, standardisation |
| Does the tool/technique assist in minimising waste during production? | SMED/QCO |
| Does the tool/technique eliminate/minimise the occurrence of harm? | Poka-yoke |

Following the inquiry two notable techniques consistently appeared namely Poka-yoke and SMED/QCO. An in-depth discussion of the two techniques is provided in the proceeding sections to demonstrate the applicability, feasibility and the impact of these techniques on the physical design of the geometry and the possibility of adopting them earlier in to product design.

### 2.4.2 Poka-Yoke, a mistake proofing philosophy

The term Poka-Yoke was first introduced by Shigeo Shingo (1989), which can be translated as mistake-proofing. Mistakes occur as a result of any activity, either mental of physical that deviates from what was intended (Chase and Stewart, 1995). Mistakes are inevitable, though defects are not; Poka-Yoke is based on the axiom that most mistakes are caused due to human error, thus places much efforts on human factors. For example, by replacing repetitive tasks that requires concentration to be replaced by tools that allow the task to be performed in a particular way (Shingo, 1986). A typical example is that of the process of drilling a hole in a steel forge. Variables including, speed (of the drill), condition of the tool, the angle, speed etc. cause each forge to be different, whilst the customer expects all the forges to be identical. By reducing the variable and the choices, the risk of mistakes is reduced, options diminished but to do the task in no way but the right way.

According to Murphy's Law if anything can go wrong, it will (Yeo, 2009), this is pertinent for organisations, having accepted this phenomena, they constantly seek ways to (1) anticipate, (2) avoid and (3) defeat unforeseeable worst-case scenarios.

As a result, the concept of developing for error/mistake proofing tools and techniques is acquitted, with the objective of reducing repetitive and costly mistakes through permanent enforcement of peripherals and operational activities; hence the opportunity for errors is eliminated.

Chase and Stewart (1995) explain that mistake proofing is but a quality control approach, even though it does not aim to redesign or engineer process nor does it tackle problems using statistical methods. Quality control should include elements which allow for (1) prevention of defects caused as a result of mistakes, (2) avoid wasted products and (3) detect mistakes before they result in defects (Hinckley, 2000).

The adoption of Poka-Yoke in industrial applications is widely discussed, for example Al-Araidah et al. (2010) have developed system which uses fuzzy Poka-yoke to restrain gas poising through the control of air, and the control of the motor blades ensures correct extractor units are engaged. Gamberini et al. (2009) have also considered Poka-yoke to develop low cost operating tools for manufacturing lines; as a result much improvement is witnessed. Ford Motor Co has also benefited from the use of Poka-yoke to improve the productivity (Manivannan, 2007). In summary, the utilisation of Poka-Yoke philosophies is being discussed in literature with positive results.

#### 2.4.2.1 Benefits of Poka-Yoke for Manufacture

Some of the benefits discussed by Hinckley (2000) include a drastic reduction of scrap material from excessive production; this also includes machining, procurement and disposal of the scrap. Additional benefits include the elimination of traditional inspection, which speeds up the production steps. Other benefits are as follows:

- Reduction in re-design, rework and repair
- Achieving high levels of quality
- Lowered defect rates resulting in declined interruptions during production
- Reduction of defects in the factory also reduce the cost of warranty

The listed benefits are directly associated with the manufacturing, it is projected that through the incorporation of Poka-yoke inspired features many benefits can be achieved, however this is a novel idea and requires supportive evidence to ensure its validity. The methods of mistake proofing discussed in literature are presented in the next section, followed by examples of common Poka-yoke features in the commencing section.

#### 2.4.2.2 Poka-Yoke Methods in design

Individual Poka-Yoke tools have been developed with specific functions, and an extensive list has been provided in 'Zero Quality Control: Source Inspection and the System' (Shingo, 1986) however a systematic method for designing such tools is not mentioned. Characterised methods mistake-proofing have been discussed by Hinckley (2000), Beauregard et al. (1997) and Chase and Stewart (1995). Though based on similar concepts each process initiates with identification of problem and resolves with the implementation of the solution. These methods however do not provide discussion on the activities and decisions a designer must undertake during conceptualisation, in determining the required features/functions to select to prevent mistakes in the product.

***Method 1: Beauregard et al. (1997)***

Beauregard et al (1997) suggest that mistake proofing can be acquired by following the three phases:

- Defining the *purpose* of the mistake-proofing
- Outlining the desired *outcome*
- Adopting the best *method* for the mistake-proofing situation

**(a) Purpose**

Initially by defining the purpose it is possible to determine whether the purpose for the mistake proofing is to (a) prevent a mistake from occurring or (b) detecting when a mistake has come about. Prevention is a proactive approach whilst detection is reactive; once a mistake has occurred.

### (b) Outcome

Within the mistake proofing process four possible outcomes come about when a mistake is detected or is about to befall. These include (a) control, (b) shutdown, (c) warning and (d) sensory alert. Control can be termed as a self-correcting approach which aims to render immediate feed and self-correction to ensure the there is no commotion in the process. The example of a three pin plug, which fits in only one orientation, is a control outcome. Shutdown is more of an activation outcome which appears when a mistake occurs and as a result the process is halted to prevent further mistakes from taking place. An automatic shut-off feature in an iron which shuts off the iron if it is not used for a number of minutes is a familiar example of shutdown outcome. The third outcome is warning which signals the user before or after a mistake has occurred. It doesn't ensure 100% avoidance of the consequences that might be related to the mistake. A light signal and a buzzer will sound when a driver fails to put his seat belt on whilst driving. The final outcome discussed is sensory alert which requires user diligence to sense the mistake prior to making the alert. A familiar example is that of an egg crate which can hold up to 30 parts, if it is not filled (as required) the operator.

### (c) Method

Shigeo Shingo has provided three methods of classification (a) contact, (b) performance step, and (c) fixed-value. Building upon these Beauregard et al (1997) has added a fourth category 'making it easy to do it right.' A description of the four methods and examples are provided in Table 2-6.

Table 2-6: Mistake proofing method description and examples

| Method | Description and examples |
|---|---|
| Contact | This method requires physical 'contact' between two or more objects.<br><br>Example: A protruded guide pin on a mould of a plastic part will ensure the alignment of the two moulds is correct. |
| Performance-step | Performance-step requires constant monitoring of the activities involved in a process to ensure an activity is not skipped.<br><br>Example: If a part requires a number of operations, if a step is missed the outcome will be highlighted. |
| Fixed-value | After setting a fixed-value to the activity of the process, until the value is not met the user/operator will not be able to proceed.<br><br>Example: If an operator is required to pack 20 aerosol cans in a box, until 20 have been picked up and packaged the user will not be able to proceed – causing the conveyor to halt. |
| Making it easy to do it right | Investing in intelligent and automated electrical mistake-proofing devices might be costly for some organizations. Simple methods such as (a) colours and colour coding, (b) shapes, (c) symbols, (d) operator initiated tools and (e) other tools can be used to make it easy it to do it right.<br><br>Example: Colour/colour coding: computer ports; red and green for microphone and speakers.<br>Symbols: stop signs, give way signs and diversion signs.<br>Shapes: driving symbols; circular, rectangular etc.<br>Other: checklists, forms, simplified workflows. |

### *Method 2: Chase and Stewart (1995)*

Chase & Stewart (1995) provide a detailed explanation of a tytpical mistake-proofing process, in comparison to the aforementioned method. This paticular method gives insight in to specific tools and techniques that one can use during the process. Figure 2-6 representes the five stages of the method, which are logical and self explanatory.

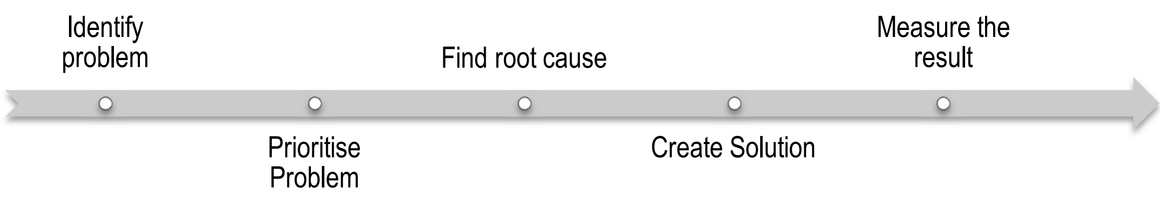



Figure 2-6: Mistake-proofing method (adopted from Chase & Stewart 1995)

This process is systematic and addresses all the important aspects; however some weaknesses are apparent. For example, more efforts should be allocated in finding a resolution for the mistake, additionally no logical technique or recommendations are provided in the generation of solutions, as shown in Table 2-7. Moreover, the current process is a reactive approach to mistake proofing; it can be implemented once a mistake has occurred.

Table 2-7: Mistake proofing method description and examples

| Steps | Tools/techniques |
|---|---|
| 1. Identify problem | Brainstorming, customer returns, scrap analysis, error reports, reliable data. |
| 2. Priorities problems | Priorities problems from; frequency of occurrence, wasted material, rework/detection time and overall cost. |
| 3. Find root cause | The five W's and one H; who, what, where, when, why and how. |
| 4. Create solutions | Make it impossible to do it wrong methods and cost-benefit analysis |
| 5. Measure the results | Analyse financial impact, analyse error elimination |

***Method 3: Hinkley (2000)***

Hinkley (2000) has developed a methodology (based on Deming's work; plan, do, check & act) through a combination of (a) efficient problem-solving procedure, (b) an outcome-based classification scheme, (c) examples sorted by classification, (d) mistake proofing principles and (e) techniques for selecting the best mistake proofing ideas. The six stages can be explained as:

**Identify and select problem:** the design team initiate with localising and selecting a design problem

**Analyse the problem:** assess the urgency of the problem. Evaluate and assign a numerical rating for the following three factors: problem frequency, production process impact and company impact. Identify the root cause of the observed or anticipated defects and if the problem is a mistake then classify it accordingly

**Generate potential solutions:** review examples of mistakes with the same classification. Review useful principles for that mistake from available literature.

Identify several principles that may be useful in solving the problem, and then generate alternative concepts for the mistake-proofing problem

**Compare, select and plan solutions:** compare potential effectiveness of the alternative solutions. Compare solutions based on additional decisions factors such as cost, difficulty of implementation and the potential speed of implementation. Select best alternative based on effectiveness and considerations. Refine the design of the device for usability. And finally, plan and schedule the deployment to minimise the impact on production

**Implement solutions:** procure the mistake-proofing device hardware. Evaluate functionality and utility offline before insertion in to the production process. Familarise and train operators regarding the operation of the device and then deploy on production line.

**Evaluate and standardise solution:** firstly determine if the problem has been solved, if the solution is ineffective or incomplete, identify other actions that need to be taken. Publish results in the organisation to communicate mistake-proofing opportunities and standardise solution where there is a broad application.

A Poka-Yoke example is provided for the reader in the section 2.4.2.3, to acknowledge the effects simple geometrical modifications on resolving mistakes. The section on Poka-Yoke will be summarized by drawing conclusion of the aforementioned three methods of mistake-proofing in section 2.4.2.4.

#### 2.4.2.3 Poka-Yoke examples

This section presents a graphical illustration of a typical Poka-yoke/ mistake proofing example, emphasising the effects of geometry through contact method (as described in section 2.4.2.2).

**Poka-Yoke example 1:** over tightening fuel cap after fuelling

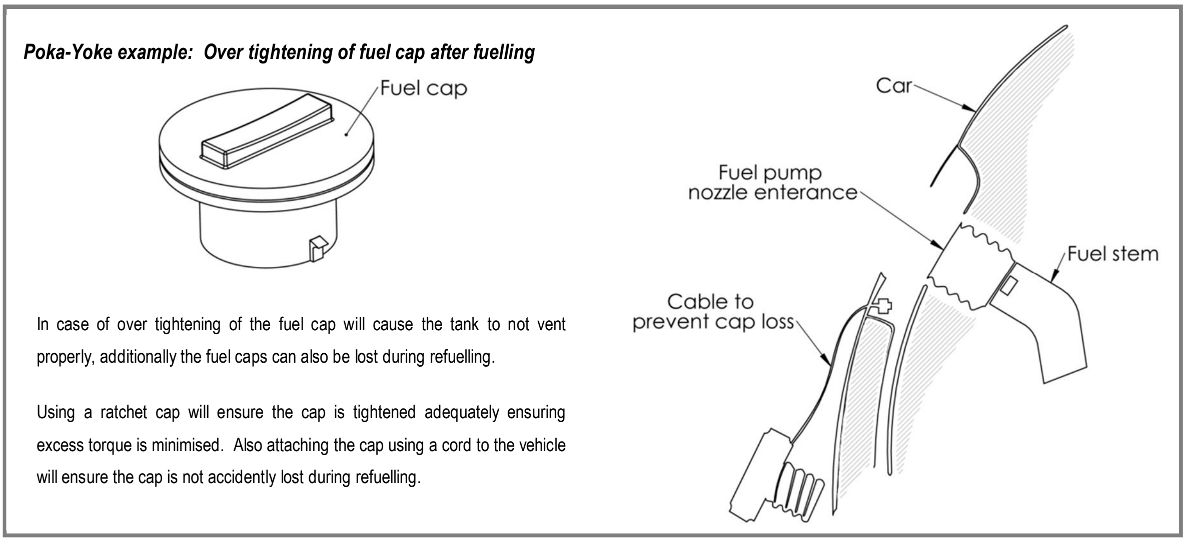



Figure 2-7: Poka-yoke example of fuel cap

This example solves two possible mistakes with simple geometrical modifications; by using a ratchet it will be ensured the cap is not over tightened, causing the internal thread to become damaged. Furthermore, attaching a chord to the cap with the chassis of the vehicle will ensure the cap is not lost during fuelling.

### 2.4.2.4 Concluding remarks on Poka-Yoke

The review on Poke-yoke literature has shown that philosophy in itself is accepted throughout the different business departments but still holds a firm ground in manufacturing. The benefits of incorporating Poka-Yoke during manufacturing has given birth to new research whereby designer and engineers are seeking to 'fool proof' their designs, as discussed in section 2.4.2. The methods discussed in scientific literature are still grey and primarily focus on the problem, the solution sought and the benefits achieved; details of the mistake-proofing process are less discussed. The founder of the mistake proofing philosophy himself reserved the generic process of mistake proofing in his discussion, but focused mainly on the physical solutions, which can be found in 'Zero Quality Control: Source Inspection and the System.' The three methods discussed in section 2.4.2.2 provide a logical explanation of how mistake-proofing can be achieved; moreover there are still limitations with the current methods. For example:

- The methods provide a holistic view of confronting mistake-proofing, however there is minimal guidance, rules or suggestions of tools to address mistake proofing earlier at the product conceptual design stage
- The current methods tackle mistake-proofing in a reactive manner as opposed to a proactive manner
- Hinckley (2000) has provided a more up to date and complex system however the designer are required to be well equipped and experienced in order to successfully follow this method.
- The methods focus directly on one aspect of the product lifecycle, mainly manufacturing solutions. However little is discussed on mistake proofing for the product life cycle i.e. the end user, service, maintenance, disassembly, which all can be considered as equally important where the opportunity of human error may occur.
- The impact of geometrical modifications is considerably effective as shown in the poke-yoke examples in section 1.4.2.3, more efforts should be placed on providing viable geometrical solutions as opposed to using statistical quality control methods

Having discussed Poka-Yoke, the proceeding section will provide insight in to Single Minute Exchange Die and how the philosophy can be adapted earlier in to product design.

### 2.4.3 Single Minute Exchange of Dies (SMED)

Rapid and high quality process changeover greatly assists in providing manufacturing flexibility and responsiveness (Reik et al., 2006). Unless changeover capability is not present, a great deal of production loss is likely (Urbani et al., 2003). Shiego Shingo developed a technique; Single Minute Exchange of Dies (SMED) to minimise waste during production. For example the set up time required to devise a part of the production system for a different product is a waste thus by minimising it to the lowest value reduces the waste output. McIntosh et al. (2000) explain SMED as a scientific approach to set-up time reduction that can be applied in any factory and to any machine. Esrock (1985) exclaims that the 10 minute or fewer changeovers can breed set up reduction to as much as 90% with moderate investment. In principle, the SMED approach consists of three conceptual stages which are divided between internal and external processes. Internal refer to the operations that can be performed once the machine is shut down for either attachment of removal of die. Eternal refer to the activities that can be performed during operation such as preparing for set-up.

The utilisation of SMED is starting to appear in academic and industrial literature, and receives minimal criticism due to its high rate of acceptance. Moxam and Greatbank's (2001) research provides a pre-requisite assessment to highlight the different levels of applicability before proceeding to SMED commitments in the textile industry. Cakmakci (2008) perceives SMED as a method not only for manufacturing but also for tool/die design development. By preliminary consideration of set up minimisation during design will allow for the development of better equipment. Reik et al. (2006) have considered the benefits of SMED by proposing a novel Design for Change over (DfC) rules which are used to develop change over equipment. In summary, the discussion on the current research on SMED has shown an interesting drift towards instances prior to production. Therefore authors believe the philosophies of SMED could be considered as an inspiration in lean design generation, for example Figure 2-8 shows that by modifying the design of the plate using pear shaped bolt holes fastening time is reduced.

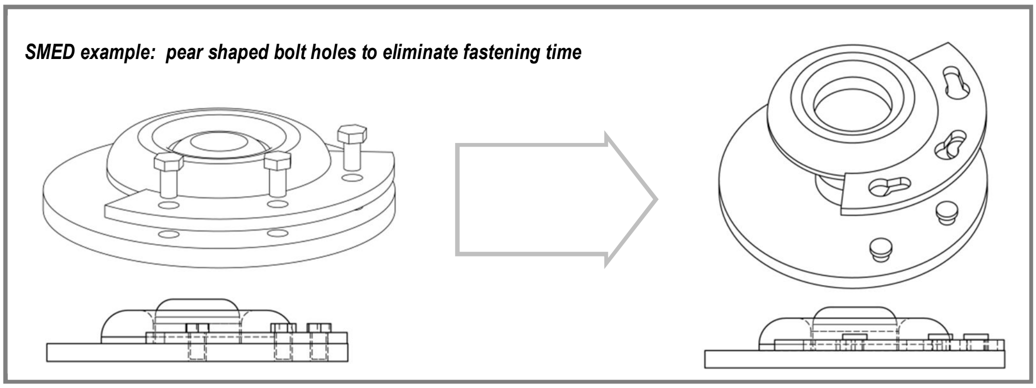



Figure 2-8: Replacing the cover with a pear bolt to reduce fastening time

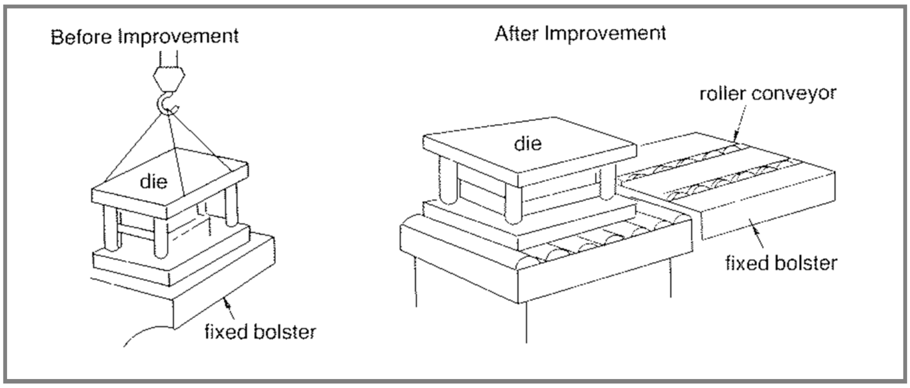



Figure 2-9: Improved settings of die on fixed bolster (Shingo, 1983)

Figure 2-9 shows that using a crane to hoist transport dies was replaced by a roller conveyor, so dies could be inserted and removed without machines. A significant reduction in time and resources was achieved, however the argument is such considerations should be made earlier in the design and not once the design has been frozen. Examples of fasteners have been presented In Figure 2-10 as an alternative to screw fixings. For example reducing the excess number of screws by considering the magnitude and direction of forces, using magnets and snap methods etc. these solutions aid in the simplification of manufacture and contribute towards the minimisation of waste and resources. In summary, the inquiry of adopting the philosophy of SMED earlier in to the design is not just viable but also monetarily constructive.

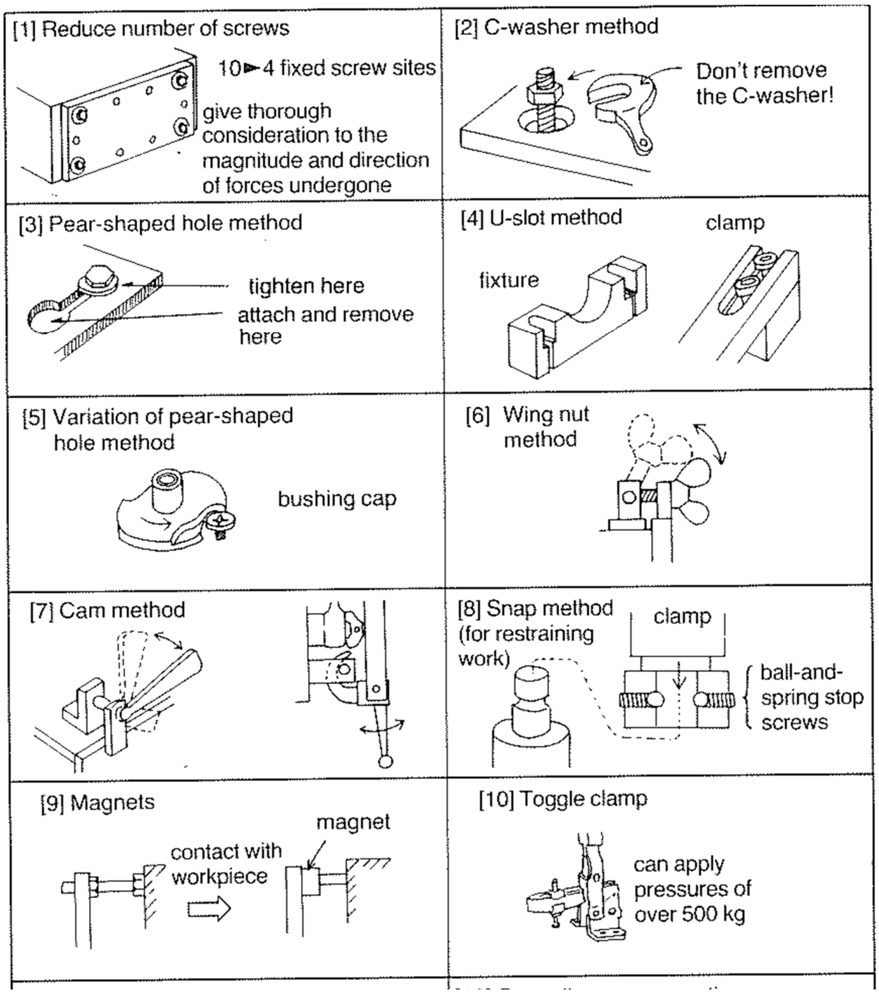



Figure 2-10: Improved settings of die on fixed bolster (Shingo, 1983)

## 2.5 Synthesising the meaning of value

This section of the review defines the academic outlook on value. The discussion seeks to address the latter part of the first research objective; which is to synthesise the meaning of value. A discussion on scientific methods employed for value translation and representation is also presented. The final parts of the section provide an insight in to waste minimisation as a means of value enhancement and the current design techniques that are used to achieve this.

### 2.5.1 The importance of value realisation

Organisational survival and long-term growth depends on the introduction of new products, companies often depend on products introduced within 5 years for more than 50% of their annual sales, between 33-60% of all new products fail to reach market to generate economic return (Schilling and Hill 1998) and as a result are withdrawn. Only a staggering 20% of new products regardless of product category or market make it to a grade to achieve the levels of sales predicted.

From the many factors cited in literature, the most common is the inability of firms identifying and adequately meeting the needs of the end user. To address this marketers adopt a value oriented approach which considers benefits and sacrifices of a new product and therefore convey a more stable sense of worth. Marketing failure occurs when the marketer fails to perceive the residing value in the market place therefore consistently delivering irresistible value to the customer is necessary.

Competitive advantage of an organisation is through the successful delivery of quality product/service that satisfy the customer's value in order to gain satisfaction and loyalty, which manifests to results in enhanced and increased profitability (Wang et al. 2004; Cronin et al. 2000). It is the organisational capabilities that enable the organisation to produce and deliver 'superior customer value' (Narver et al., 2004). However the control pole is still held by the customer, according to Rintamäki et al. (2007) customers always define what is valuable or not, firms can only produce value propositions that intend to suffice and support the customers.

### 2.5.2 Commonly used terms related to value realisation

The concept of value has been discussed and applied in a number of fields; for example, economics, accounting, information systems, marketing and product management (Ulaga & Chacour 2001), the interpretations vary contextually (Sweeney & Soutar 2001), as it has a large variation in connotation and determinants.

Zeithaml (1988) provides four opinions of value: "(1) Value is low price, (2) Value is whatever one wants in a product, (3) Value is the quality that the consumer receives for the price paid, and (4) Value is what the consumer gets for what they give. These definitions have been used as the foundation of defining the concept of value, which can be termed as the "trade-off" between overall benefits gained and sacrifices made by the customer (Woodall 2003; Lin et al., 2005 & Olaru et al., 2008). Benefits include quality of the product/service provided as well as the formation of relationship (Lindgreen and Wyndstra 2005). Sacrifices include monetary (acquisition/service costs) and non-monetary (time, effort, energy etc.) (Cannon & Homburg 2001). However these explanations are short of defining what value is.

Agreeing on 'what is customer value' is a complex process (Wang et al. 2004). This is compounded further within the product development process when an engineering team has to consider delivering product value and process value. There are many definitions of value on offer within published literature: ranging from the functionally simple to the emotionally complex, as illustrated between the two definitions shown:

Definition 1: Value is function divided by cost (Kaufman 1985)

Definition 2: Customer value is the emotional bond established between a customer and a producer after the customer has used a salient product or service produced by that supplier and found the product to provide an added value (Butz and Goodstein 1996)

From these definitions the concept of value is seen to be a balance between rational functionality and irrational emotive ties. However, what is clear from every definition of customer value is that the only person that can determine what is valuable is the customer; this is compounded further into realizing that what is important to one customer is irrelevant to another. Consideration must also be given to 'unknown values' i.e. those values that the customers are unaware currently exist and 'historic values' i.e. those values that were once delight factors but are now expected. This raises issues between capturing these customer values and realising values within a final product.

If the question of value is based on the first lean principle then consideration also has to be given to who is the customer. In an industry such as household goods, then the customer is the end user. In an industry such as public transport then the end customer is harder to define, i.e. within aerospace, is the end customer the paying passenger or the flight crew whose employee paid for the aircraft? The product development team must also be mindful of the other customers that they have e.g. operations, senior management, shareholders, etc.; all of these customers also have values that require fulfilment.

Within literature there is an expectation and need to be able to define value using a single sentence. The author believes that the definition of value changes during the design process, the production process into application and finally into disposal. To incorporate all of these changing processes into a single definition is considered too restrictive to achieving a lean design that meets all of its values.

### 2.5.3 Scientific techniques for value translation and representation

There are numerous methodologies currently available to industry to translate customer value into design requirements e.g. QFD, brainstorming, etc. There are elements of each tool that are useful but no single tool will complete the translation in its entireness (Alam et al. 2011). The other issue is that some of the tools are seen as too methodical and, thus, too restrictive to generating design flair. Van Kleef et al. (2003) have attempted to map possible value translation and representation techniques against the NPD process, as shown in Figure 2-11. Unfortunately the techniques enlisted will encourage communication amongst the different departments however it is down to designers to successfully represent the values which are fit for realisation. It can be concluded that there is not a single tool/technique to suffice the successful translation and representation of customer values earlier at the conceptual design stage (Alam et al. 2011) and this area of research calls for further investigation.

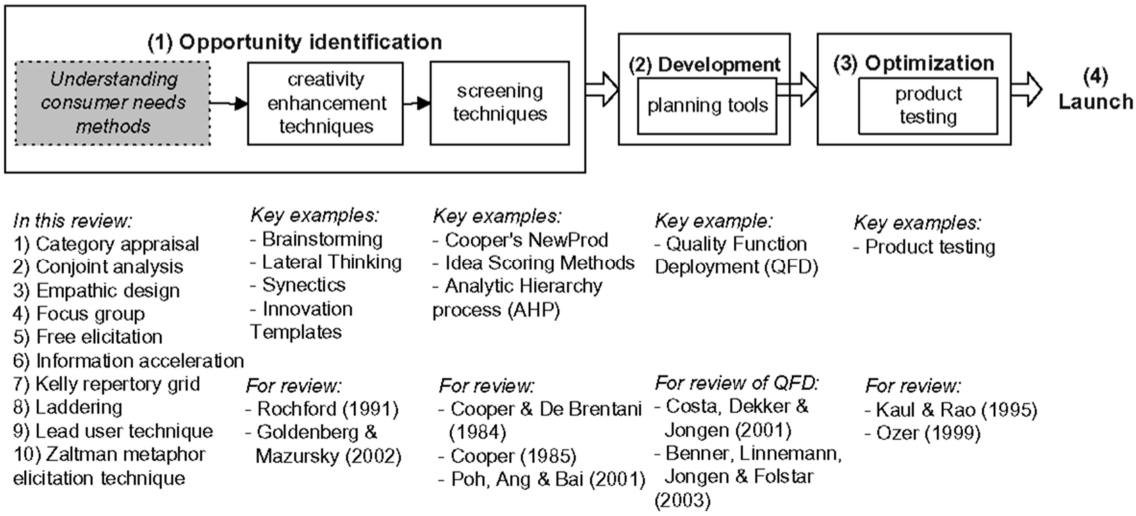



Figure 2-11: NPD process along customer value translation methods (van Kleef et al., 2003)

### 2.5.4 Waste elimination as a means for value enhancement

Waste elimination can be considered a by-product of the lean thinking philosophy. General categorisations of waste are listed in literature, for example Taiichi Ohno's seven wastes include: over production, inventory, processing, movement, waiting, transportation, defective products (Ohno 1988). Complexity, dangerous working practices, excess information are also explained as waste (Schonberger 2001). Waste can be explained as anything that does not create value for the customer; from a design perspective it could be interpreted as over styling or poor defining of features etc. hence a relative link between value and waste is established. Therefore in order to define waste, it is necessary to know what value first.

Designers seek ways to eliminate waste, because it barricades the creation of value at a price. Products are usually conceptualised to meet a particular specification, designer's knowledge of what is required during concept generation is vague as compared to engineers who know more or less what is required from the outset. Usually, during the process of creative design excessive styling and fine tuning is experienced which gives birth to the harnessing of non-value adding features.

Assuming design is an iterative and lengthy process which deals with the generation of many ideas, knowing what waste is a challenging task. From the design process point of view Koskela and Huovila (1997) suggest minimising unnecessary tasks for completion is value generation. Techniques for minimising non-value adding tasks include the use of team problem solving, cross functional teams, concurrent engineering, set-based vs. point-based design etc. (Ballard 2000). However from a product design point of view other types of wastes include design errors, over design, slimming down designs that are too bulky in terms of non-value adding parts and features.

Eppinger (2011), having recognised the need for consideration of waste minimisation in product design, calls on designers to generate designs that are environmentally safe. Green/life cycle design which includes Design for Long Life, Design for Disassembly and Design for Recycling are technique focussing on a singular aspect of design tweak and as a result aid in the minimisation of waste. Other examples include Design for Sustainability, Eco-design and 'good design practices' published by independent design consultants. However these particular techniques consist of generic and abstract guidelines that provide an overlook of design and give design suggestions. They fail to consider the preliminary impact of waste prior to geometrical generation. Additionally the emphasis of the techniques is primarily associated with the design process as opposed to the physical geometry of the product. The author holds a point that in order to challenge 'waste minimisation; the main emphasis should be placed on the geometry which should dictate the proceeding activities in design.

## 2.6 Research Gap

The extensive review of scientific literature has identified a number of key trends and the consequent research gaps, which are as follows:

1. The current literature on lean design is minimal and the following inferences can be drawn:-
    a. There is still obscurity regarding the definition of lean design and the required processes to generate a lean design.
    b. The current literature is primarily focused on the design process as opposed to the design of the physical product.

   c. There is an inclination towards the adoption of lean thinking in industry in to the design however no formal tool/technique has been developed through an academic study.

2. Lean Manufacturing techniques and tools are widely discussed in literature and the benefits one may obtain from implementing them are also justified however there is no discussion on ways of adopting these at the philosophies earlier in the conceptual stage to generate a leaner design
   a. Poka-yoke, a well-established mistake proofing philosophy is used during manufacture to minimise harm and error during operation, however there is no discussion on the formal use of it during design for the minimisation/elimination of errors that are prone to that product for the product life cycle.
   b. Single-Minute Exchange of Die/Quick Change Over is a Japanese philosophy used in assisting set-up reduction during manufacture, proactive consideration of during product concept design is not thought of. The author believes by taking in to consideration earlier in conceptual design, the future efforts and iterative designs will be reduced.
3. Currently there is no clear evidence of a formal tool or technique available to designers that will ensure the systematic elimination of harm and reduction of waste (at the component level) for production and in use, as well as assuring the lean manufacturability of the design at concept design stage.

## 2.7 Summary

This Chapter has provided a detailed review on scientific literature in the area of evolution in design research and practice, lean design and the meaning of value. Initially the role of design in New Product Development was discussed. The current evolution being witnessed in design practise and research was identified. The author was able to list ways of extending beyond the traditional Design Methods and Theories to address the current expectations of design.

The possibility of adopting lean thinking to the design was explored, and a systematic search strategy was conducted to identify state of the art literature on lean design.

The available literature on lean design is premature and many avenues are yet to be addressed. For example, there isn't a clear definition, framework or tool that is associated with the design of the product. As a response to this the possibility of adopting lean manufacturing techniques was explored by the author and Poka-yoke and SMED were identified as possible techniques that could be adopted during the generation of geometry.

A discussion was presented on the meaning of value and the tools/techniques to translate and realise values during design was presented. The findings suggested there are elements of each tool that are useful but no single tool will complete the translation in its entireness.

Finally, the author was able to list a number of research gaps in the area of design research and practice, lean design and the adoption of lean manufacturing techniques earlier in design. The proceeding Chapter presents the research methodology adopted by the author in the successful completion of the design objectives. Details of the research strategies and data collection methods have also been explained.

# Chapter 3

# RESEARCH METHODOLOGY

## 3.1 Introduction

The purpose of this chapter is to describe the methodology followed to ensure the aim and objectives of the research were achieved. The chapter has been organised in to four sections. Following the introduction, section 3.2 details the typical four levels of research i.e. research purpose, research design, and research strategy and data collection techniques, with a rationale for the selected methods. In section 3.3 the adopted research methodology with reference to the research objectives is described. The chapter then ceases with a summary in section 3.4.

## 3.2 Research methodology overview

Research has been defined as : 'studious inquiry or examination; especially: investigation of experimentation aimed at the discovery and interpretation of facts, revision of accepted theories or laws in the light of new facts, or practical application of such new or revised theories of law' according to Merriam-Webster Dictionary (2014). Bunge (1999) further expands the definition by reinstating that research is the 'methodical search for knowledge. Original research tackles new problems or checks previous findings. Rigorous research is the mark of science, technology and the living branches of the humanities'

Successful completion of research consists on the completion of the following five key components: research purpose, conceptual context, research question, methods (research strategy and data collection) and validity (Bickman and Rog, 1997). The discussion in the proceeding sub-sections describes these in detail.

### 3.2.1 Research purpose and application

Design of research initiates with establishing the purpose (Robson, 2002), which can be classified in to the following three categories:

- Exploratory; seeks to undertake investigations of the current situation in order to pursue new understandings and as a result generate a hypothesis from the investigation
- Explanatory; provides detailed descriptions of a situation or a problems and aims to identify and establish correlations between two aspects of a phenomena
- Descriptive; provides thorough and precise details of a person, event or situation

Taking in to account the aim and objectives of this research, both exploratory and explanatory is considered suitable approaches. During the earlier stages of the research, exploratory is more relevant, where the information on lean design is still premature. During the latter parts of the research explanatory becomes more pertinent where the relationship between lean thinking and design is clarified.

Research application falls in to two categories: pure research and applied research. The former is usually performed to expand current knowledge or to investigate the unknown. The latter addresses practical problem solving. In context, it can be inferred the research is applied.

### 3.2.2 Research Design

The two distinctive approaches to research design are qualitative or quantitative (Gummesson, 1991; Burns, 2000; Kumar, 2005). The former is also referred to as flexible and is known as positivistic or scientific, while the latter is described as fixed and is naturalistic interpretive (Robson, 2002; Walsh, 2001).

There is a clear distinction between qualitative research and quantitative research, as illustrated in Table 3-1. The information acquired from quantitative research is represented in a numerical expression, and usually obtained from a controlled environment (Robson, 2002). The research has control of the experimental conditions (which are referred as variables). To minimise the effects of influence of the research, the researcher is usually 'detached' (Robson, 2002). In qualitative research, the information attained is not numerical, however the emphasis is on experience, the contextual and lingual meanings expressed of the participant. Usually direct quotations of the participants are used as a base of argument. According to Creswell (1998) the researcher "builds a complex, holistic picture, analyses words, and reports detailed views of informants and conducts the study in a natural setting." As qualitative research progresses an evolution is experienced as the research problem and environment become clearer.

Table 3-1: Comparison of Qualitative and Quantitative approaches (adopted from Burns, 2002)

| Description | Qualitative | Quantitative |
|---|---|---|
| Assumptions | • Reality socially constructed<br>• Variables are complex and interlaced and can be difficult to measure<br>• Dynamic quality to life | • Facts and data have an objective reality<br>• Variables are identifiable and measurable<br>• Static reality to life |
| Purpose | • Clarification<br>• Contextualisation<br>• Understanding the viewpoint of others | • Prediction<br>• Generalisation<br>• Casual justification |
| Method | • Data collection via participant observation, unstructured interviews<br>• Completes with a hypothesis and grounded theory<br>• Inductive and naturalistic<br>• Data analysis by themes from informants description and usually written in language of informant<br>• Descriptive write up | • Testing and measuring<br>• Ceases with hypothesis and theory<br>• Deductive and experimental<br>• Static analysis<br>• Statistical reporting<br>• Abstract impersonal write-up |
| Role of researcher | • Researcher as instrument<br>• Directly involved<br>• Empathic | • Researcher applies formal apparatuses<br>• Detached<br>• Objective |
| Strengths | • Functionally interpretive<br>• Flexible<br>• Accommodates the development of new concepts<br>• Sensitive to environment | • Structured approach<br>• Fixed<br>• Illustrates casual effects<br>• Suitable for cross comparison |
| Weaknesses | • Lacks structured approach<br>• Time consuming in forming research<br>• Possibly bias<br>• Validity and reliability concerns | • Strictly measures objects<br>• Insensitive to personal environment<br>• Very rigid – lacks flexibility<br>• Completely dependant on data and valid theories |

Since, the research is focused on exploration and investigation of lean thinking in design, the research strategy must be flexible and must accommodate multiple points of views. Therefore a qualitative approach is more suitable for the core of the research i.e. where the research is seeking to establish the status of lean design in academic literature, the industrial opinions of lean design and developing the lean design framework. Quantitative approaches will be more suitable for latter parts of the study that deal with numerical analysis i.e. comparing the proposed lean design against the original design.

### 3.2.3 Research strategy

After defining the research, the next step was to select a suitable research strategy to fulfil the inquiry of the research. There is a wide collection of traditional research strategies mentioned in literature regarding a qualitative research investigation. Creswell (1998) has undertaken an extensive review of all these different perspectives and has summarised his findings in to five strategies and their relationships, which can be seen in Figure 3-1. Likewise, Robson (2002) settles on three qualitative research strategies i.e. Case Study, Ethnography study and Grounded Theory Study.

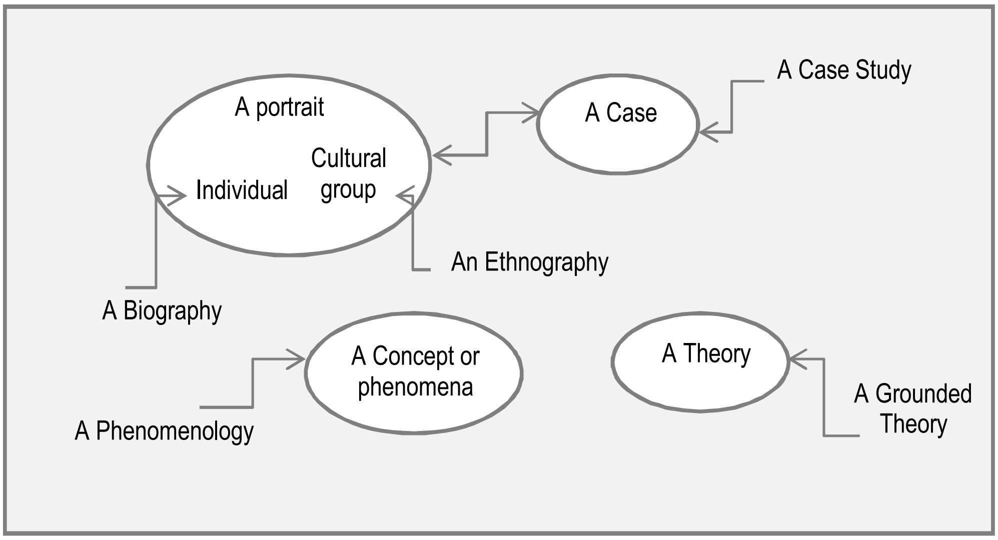



Figure 3-1: Relationship between research strategies (Creswell, 1998)

Prior to selection of a suitable research strategy a number of elements were considered, such as the context and focus of the research, the resources available to the researcher for data collection. A comparison of Creswell's' five strategies is presented followed by a rationale of the strategy selected for this research.

Table 3-2: Comparison of research traditions in qualitative research's (Creswell, 1998)

| Description | Grounded theory | Case study | Biography | Phenomenology | Ethnography |
|---|---|---|---|---|---|
| Focus | Developing a theory grounded in data from the field | Developing an in-depth analysis of a single or multiple cases | Exploring the life of an individual | Understand the essence of about a phenomenon | Describing and interpreting a cultural and social group |
| Discipline origin | Sociology | Political sciences, sociology, urban studies and other social sciences | Anthropology, literature, history, sociology, psychology | Philosophy, sociology, psychology | Cultural anthropology, sociology |
| Data Collection | Interview with 20-30 individuals to saturate categories and detail a theory | Multiple sources, documents, interviews, observations, physical artefacts | Primarily interviews and documents | Long interviews with up to 10 people | Primarily observations and interviews with additional artefacts during extended time in the field |
| Data analysis | Open coding, axial coding, selective coding, conditional matrix | Description, themes, assertions | Stories, epiphanies, historical content | Statements, meaning, meaning themes | Description, Analysis, interpretations |
| Narrative form | Theory or theoretical model | In-depth study of a case or cases | Detailed picture of an individuals life | Description of the essence of the experience | Description of the cultural group behaviour |

Case study was selected as the most suitable research strategy from the above comparison table. A number of considerations were taken in to account i.e. the focus and scope of the research, the resources available and the involvement of industrial partners prior to the selection. Taking in to account the research topic is relatively new phenomenon with minimal theoretical background; the case study strategy would be most suited for this type of research. Additionally the topic is directly associated with product design and interactions with physical artefacts (products) would be an essential parts of the research. The case study strategy would accommodate the application of the lean design guidelines to a product.

Interpreting evidence from a case study can pose many dangers to the research, for example drawing general conclusion from a single atypical scenario. Another predicament with case study is the prolonged involvement of the researcher which could pose potential risks of introducing biasness to the study. On the contrary, value can be obtained from case study – as it suggests hypotheses which can then re-tested with controlled circumstances for a broader selection of cases.

To minimise the aforementioned risks to the validity of the research, the researcher sought ways to establish trustworthiness which will ensure pro-active steps are performed to minimise the risks. The proceeding section details the necessary steps taken in order to ensure trustworthiness.

### 3.2.4 Establishing trustworthiness

The two main areas that need to be addressed in conforming trustworthiness to a qualitative research study include: validity and generalisability. As explained by Robson (2002) validity is concerned with identifying the accuracy and correctness of research. The common threats associated with validity research are:

- Reactivity - the interference of the researchers presence in an environment, which influences the behaviour of the involved participants
- Respondent bias - causing obstructiveness by withholding information from the researcher, usually where a threat is seen or it could just be company policy
- Researcher bias - "what the researcher brings to the situation" such as their persona, the selection of individual for interview and types of questions asked (Robson, 2002)

The strategies that could be employed to deal with the above-mentioned risks include:

- Prolonged involvement - time spent in a particular environment must be kept in moderation to ensure casual relationships are not formed which could influence the mind-set and as a result increase the researcher bias

- Triangulation – enhance the rigor of the research through the use of a variety of sources, theories and settings
- Peer debriefing and support – debriefing following prolonged sessions can revitalise the research environment atmosphere
- Audit trail – collating transcripts, notes, scientific articles and a set of activities all activities performed and a regular review brings clarity to surface
- Negative case analysis – regularly applying the theory/hypothesis to a negative case, or gaining constructive criticism; which will lead to the refinement of the theory (Creswell, 1998; Robson, 2002)

Generalisability is concerned with the applicability of the research study in other contexts, times, environments or to those that are not involved (Maxwell, 2002). The two types of generalisability are: internal and external – where the former regulates outside the boundaries of those involved outside the study i.e. institutions, community, persons etc. (Maxwell, 2002). The latter is broader in its reach and provides generalisation to other institutions and conditions. Given the scope of the research external generalisation will be difficult to achieve in this study, therefore the focus will remain on internal generalisability.

### 3.2.5 Data collection methods

In a research intensive inquiry multiple data collection methods are employed. The selection of these methods is closely linked with the type of information been sought, its recipient and under what circumstances it is been required (Robson, 2002). The main methods employed as data collection are literature review, interviews, observation and document (artefact). A description of these methods is presented, details of the advantages and disadvantages are also listed where necessary.

- **Literature review**

According to Blaxter et al., (2001), the literature review is a systematic, concise and reproducible method for the identification, interpretation and evaluation of archived works by academic professionals. As explained by Burns (2000) a literature review should be treated as a stimulus for discerning rather than an opportunity to present a summary of preceding research in the research domain. Neuman (2003) has listed the different types of literature review, for example it can be treated as a self-study to increase the reader's awareness, a historical review to witness the extrapolation of a topic through time or as a theoretical review to compare intellectual arguments on different theories.

- **Interviews**

Interviews are a useful technique of data collection whereby questions are asked and the results of the respondent are analysed. Based on the degree of structure, interviews vary considerably. The three types of interviews based on their degree of structure are: fully-structured, semi-structured and unstructured (Robson, 2002).

*Fully structured interviews:* have predetermined questions in a prefixed order using fixed language (Fontana and Frey, 1998; Robson, 2002). This type of approach is mainly used during surveys and opinion polls (Robson, 2002).

*Semi-structured interviews:* too have predetermined questions but the interviewer has the flexibility and freedom to select the wording and order of the questions. In turn allowing the interviewer to build an understanding with the respondent and facilitate the communication on mutual grounds (Burns, 2000). In consequence, the analysis would be deemed more challenging and time consuming, whilst amalgamating the diverse responses.

*Unstructured interviews:* are usually informal with open ended questions; whilst maintaining focus on the topic the interviewer allows the respondent to openly express themselves (Bernard, 2002) this allows the interviewer to clear any misunderstandings and gain a good bond with the respondent (Robson, 2002).

In general interviews are a good technique of data collection; other advantages include an easy means to recover historical and personal experience of the respondent. Disadvantages include time limitations and the difficulties in establishing reliability.

- **Surveys**

Surveys are used to collect data by means of a structured questionnaire, the three methods of administration include: self-completion, where the respondents complete the questionnaire independently; face to face interview, where the interview asks the respondent questions and records the responses in the presence of the respondent. And third is telephone interview, where the respondent is contacted via phone and a recording is made of the interview (Robson, 2002). The advantages of surveys include: easy way to retrieve responses that represent a wider audience, anonymity encourages openness on sensitive issues and an efficient way to gather large amount of data at minimal expense. The downsides of surveys are that the data must be persistent to maintain linkage, the data provides a brief synopsis instead of details of specific points and the surveys rely on quantity rather than quality.

- **Observation**

There are numerous types of observational studies and the output of data can vary – from been qualitative or quantitative. The intended purpose of performing observations is to accumulate 'inside knowledge' of the field of inquiry (Achanga, 2007). Observational studies can be direct or indirect; the former implicates physical involvement (the use of five senses) i.e. watching the respondents, recording their actions etc. Indirect observations include listening to recordings, examining maps and other material and reading. According to Blaxter et al., (2001) observations can be informal or formally structured. During structured observations the observer performs a constructed activity and categorically analyses each event. With regards to trustworthiness of the results obtained from observations, the stance is bio-polar and requires critical and analytical examination. For example observations can be either re-active or non-reactive, where the former is aware that they are being observed and could conceal a trait. A vast pool of knowledge can be extracted from observations; however they are time and resource consuming.

- **Documents**

Documents refer to the data collection method that gather, collate and analyse documents such as written artefacts: letters, pamphlets, magazines, technical reports etc. or non-written documents such as maps, photographs, virtual reality and other types of interactive media. As mentioned in the previous data collection method, that documents can be considered a non-reactive type of observation in which the source origin remains intact. The advantages of documents are that they can be collated without the interference of people; primary data can be gathered through direct observation. However the major disadvantage is that documents are time and resource consuming.

## 3.3 Research methodology adopted

This section provides a detailed account of the research methodology adopted. A summary of the research methodology design has been presented in Figure 3-2 highlighting the research approach, data collection/idea generation and data analysis/validation stages of the research. The research objectives have been organised in Table 3-3 consisting of four phases and the tasks undertaken to achieve the deliverable of each phase. A description of each task is provided with a discussion of the tools/techniques employed by the author to achieve the required phase deliverable.

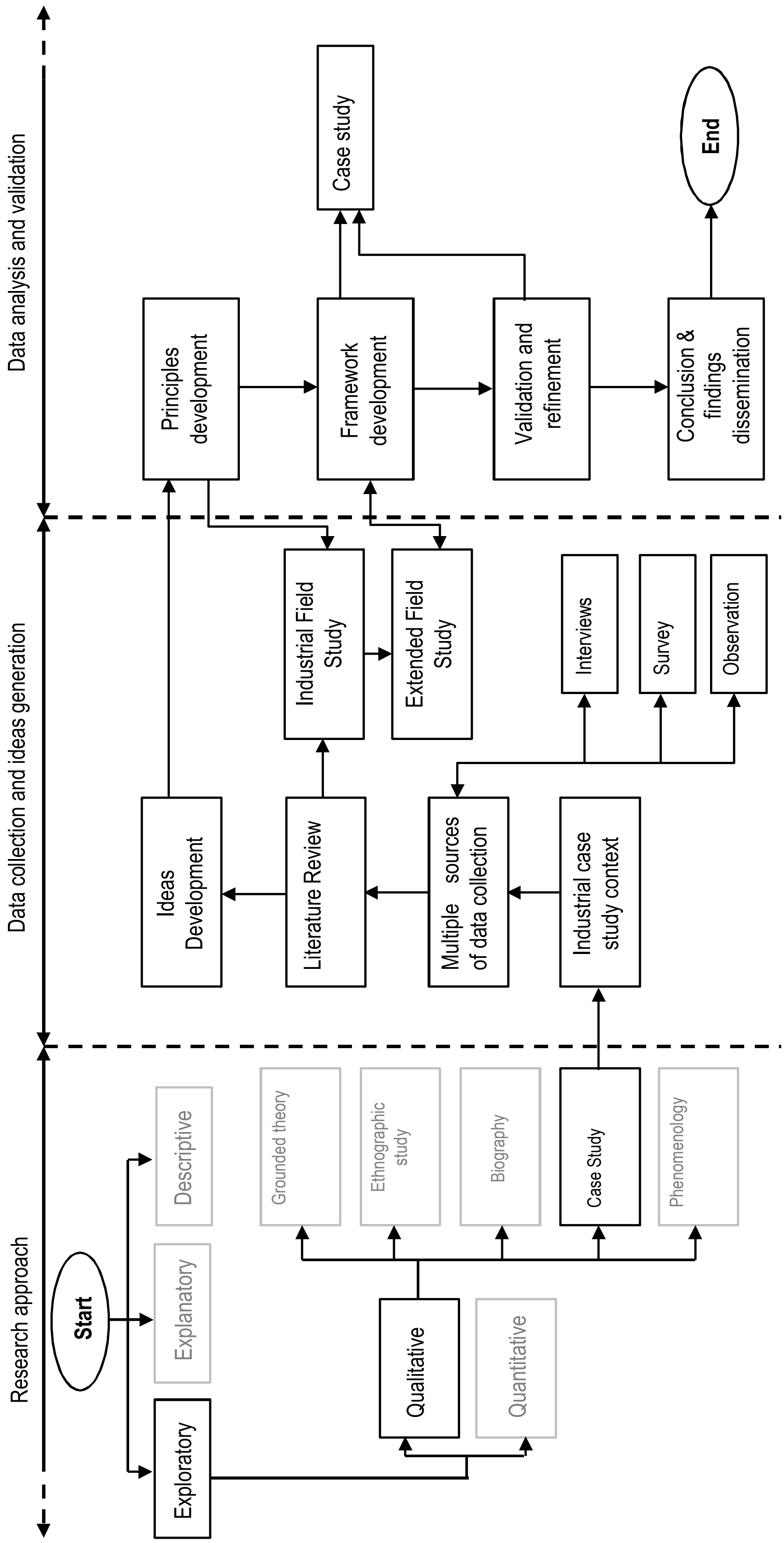



Figure 3-2: Research methodology design

Table 3-3: Research methodology

| Phase | Tasks | Deliverable |
|---|---|---|
| 1. Background Theory | **1.1** Establish the evolution and trends in design research<br>**1.2** Investigate the status of lean design in scientific literature<br>**1.3** Design a semi-structured questionnaire based on the analysis of literature to identify current design practices and validate the working definition | Foundation for a working definition of lean design |
| 2. Definition of lean design principles | **2.1** Perform an industrial field study with European Manufacturing companies<br>**2.2** Set the foundations for lean design principles from the research findings<br>**2.3** Formulate and validate the lean design principles with industry | Lean Design Principles |
| 3. Lean Design Framework Development | **3.1** Develop the lean design framework including its process and activities<br>**3.2** Generate the lean design guidelines and its supported tools | Lean Design Framework |
| 4. Validation | **4.1** Validate through industrial business case<br>**4.2** Industrial expert judgement | Validate Lean Design Framework |

### 3.3.1 Phase 1: Background Theory

The first phase of the research methodology has been described as background theory which aimed to provide contextual grounds of the research. Merriam-Webster (2014) defines theory as: the analysis of a set of facts in their relation to one another. As highlighted in Table 3-3 key tasks were performed of which the first two directly linked to the first research objective. The nature of the research objectives required an extensive literature review to be performed; this was conducted initially at the beginning of the research but was updated throughout the course of the study.

A plan was constructed which provided the literature review structure and the topics that needed to be explored. Initial reading was conducted by the researcher to gain familiarisation with the primal concepts, the key terms, topics in the area of research. As an outcome of this phase the researcher was able to populate a working definition of lean design and design a semi-structured questionnaire which was used in the industrial field study.

- Task 1.1 and 1.2: *Establish the evolution and trends in design research and investigate the status of lean design in scientific literature*

An extensive literature review was performed (Chapter 2) to establish the evolution and trends in design research. The purpose of this task was to identify the areas of growth and opportunities for improvement. A review of traditional design methods and theories suggested the current approach is not sufficient and a more wholesome, integrated approach to design is required which would focus more on product geometry as well as consider multiple elements such as: ensure functionality, manufacturability, ensure waste minimisation and all avoidable harm elimination.

Task 2.2 was performed in conjunction with the previous task, with the intent of identifying the current status of lean design within scientific literature. A systematic method to identify the literature was employed, which has been detailed in Section 2.3.2. Based on the results of the search the author extended the study by taking in to consideration the feasibility of adopting lean manufacturing tools and techniques earlier in to design. As an outcome of these two tasks a research gap was identified and the author was able to populate a working definition of lean design based on the understanding of the research (Section 2.6).

The research is exploratory in nature and its application can be explained as applied research, therefore the method chosen for data collection is literature review. The relevance and benefits of adopting this method have been discussed in Section 3.2.5.

- Task 1:3 *Design a semi-structured questionnaire based on the analysis of literature to identify current design practices and validate the working definition*

The findings from the Task 1.1 and 1.2 provided a sufficient base, however to expand on the research an industrial field study would be required. The intent of the Task 1.3 was to identify the current industrial design practises and validate the working lean design definition. In order to complete this task a semi-structure questionnaire was developed. The author populated questions based on the understanding and analysis of the literature. As explained in Section 3.2.5, a number of techniques can be employed during interviews to capture the interviewee's opinion. With this in mind a semi-structured questionnaire was developed with both closed end questions. However additional open ended questions were generated that were used to incite discussions.

### 3.3.2 Phase 2: Definition of Lean Design Principles

This phase was practical in the sense that it involved direct communication with industry. An industrial field study was conducted, which consisted of 34 face-to-face interviews and group workshops. The current industrial design practices were captured and the working lean design definition was validated. An extended field study was performed with updated questions; the overall findings provided the researcher with essential resource to populate the lean design principles and further enhance the lean design definition.

- Task 2:1 *Perform an industrial field study to capture industrial design practises and validate the working lean design definition*

An industrial field study was performed to capture the opinions of the industry on lean design, a number of activities were performed which consisted of face-to-face and group interviews with experts using a semi structure questionnaire which was developed in Task 1:3. Other activities included Site visits – including shop floor, observations and performing technical workshops. The findings from the research were amalgamated in Microsoft Excel and results generated. The general findings from the field study were shared amongst the participating companies; a more in-depth analysis was reserved for the formation of ideas of the research. Using mind mapping and data analysis techniques the results were analysed for quality and reliability.

- Task 2:2 *Set the foundations for lean design principles by collating the results from literature review and industrial field study*

To establish the foundation of lean design using scientific methods, literature on 'Theory Construction' was implemented, which is detailed in Section 5.2. The technique used in this instance was based on the seven generic components of construction for a design theory (Table 5-1). The understanding from literature and the findings from industrial opinion allowed the researcher to successfully generate a concrete definition of lean design and the essential lean design principles. Each principle was defined and (the necessary considerations required to achieve it were detailed (as listed in Section 5.3.3)

- Task 2:3 *Formulate and validate lean design principles with industry*

Constant interaction with industry throughout the research provided the opportunity to validate the findings of the research as it progressed and matured. The author was able to validate the Lean Design Principles on a number of occasions, for example during the extended field study and the two annual Industrial LeanPPD workshops. The author was able to present the principles by giving a presentation to leading European industrial representatives and demonstrated the theoretical foregrounds of the lean design principles. The industry readily accepted the principles and provided a positive response.

### 3.3.3 Phase 3: Lean Design Framework Development

This phase of the research was directly concerned with the development of the Lean Design Framework, its process, activities and the guidelines. The three tasks were performed by carrying out additional research on the available design tools and techniques, analysing the design processes documentation of the industry and performing technical workshops with the consortium. The construction was an iterative process that required regular adjustments and corrections. Theoretical knowledge and industrial advice provided the necessary constituents in the development process.

- Task 3:1 *Develop the lean design framework including its process and activities*

To realise the complete benefits of the lean design principles, a lean design framework was developed and organised in to four phases. The author was inspired by the simple Design for Six Sigma process due to its simple nature and decided to follow a similar pathway. The author incorporated existing tools and techniques and embedded them within the framework i.e. DFMA, Poka-yoke method etc. However additional processes were created to ensure the essence of lean design is preserved. The framework, its process and tools were regularly assessed by the consortium by performing workshops, until a final agreed framework was achieved.

- Task 3:2 *Generate the lean design guidelines*

The Lean Design Guidebook is a tangible outcome of the research conducted from Chapters 2-5. It is a graphical representation of the lean design framework, its processes and tools. The knowledge generated from Task 3.1 was organised in to the four phases (as described in Chapter 6.2) and then collated in to a book format. Adobe Illustrator was used to generate the template and graphics of the guidebook, high quality images and fonts were used to a good level of user friendliness. The Lean Design Guidebook was assembled in Microsoft Word to ensure it can be readily accessed on a common word processing package.

### 3.3.4 Phase 4: Validation

The final phase of the research methodology focussed on the implementation and validation of the Lean design framework to a real case scenario. The validation consisted of two elements, firstly validating the lean design framework with an industrial business case and secondly with industrial expert judgement.

- Task 4:1 *Validate through industrial business case*

A single case study at a design company that develops and supplies off-shore solutions was used. The case company can be categorised as a specialist design firm offering innovative solutions. The study initiated with interviews and collation of general and specific data about oil/water separator application. The researcher was able to work with the employees on a more in-depth understanding. The oil/water separator unit was studied by reviewing the geometrical design, 2D drawings etc. The lean design framework was validated by providing an alternative leaner design.

- Task 4:2 *Industrial expert judgement*

To validate the lean design guidelines an attempt was made to gather expert judgement regarding the lean design manual that was produced. The foundations of lean and the principles were explained to the experts. The experts were requested to review the manual and provide ratings for the key questions provided in the questionnaire. The feedback was organised and suggestions for improving the lean design guidelines (manual) was taken in to account.

## 3.4 Summary

A description of the research methodology that has been followed during the course of the research in achieving the research aim and objectives has been presented in this Chapter. The discussion initiated with details of the typical four levels of research which included research purpose, research design, research strategy and data collection techniques. Considering the nature of the research is exploratory, the relevant research strategy was appointed.

A rationale for the selected research strategy and data collection methods was highlighted. Moreover, the adopted research methodology with reference to the research objectives was discussed, which covered four phases: Background Theory, Definition of lean design principles, Lean design framework development and Validation. The proceeding Chapter records the findings from the industrial field study.

# Chapter 4

# INDUSTRIAL PERSPECTIVES ON LEAN DESIGN

## 4.1 Introduction

This chapter presents the current industrial practices and perspectives on lean design which was an outcome of conducting an industrial field study. Section 4.2 describes the field study approach, a list of participating companies and some statistical information of the respondents. The design of the questionnaire based on the key areas of inquiry in presented in Section 4.3. A sample of the field study data analysis is presented in Section 4.4 followed by a discussion on the industrial opinions on lean design. The key findings from the field study are listed in Section 4.4 and Section 4.5 ceases the chapter with a summary and sets a pathway for the proceeding chapter.

## 4.2 Industrial field study approach

After conducting an extensive literature review and identifying the research gaps in Chapter 2, conducting an industrial field study to gain experience into workings of organisations and to become more conscience of industrial dynamics became necessary. The intent of the field study entailed the following: (a) become familiar with the current industrial practices, (b) capture the perspectives of lean design and validate the 'working definition' (c) engage with industry in the construction of the lean design principles and framework. In context, field study broadly defines a number of activities performed, which included: face-to-face interviews using a semi-structured questionnaire, site visits, informal discussions, observations and collecting data related to the current design practices.

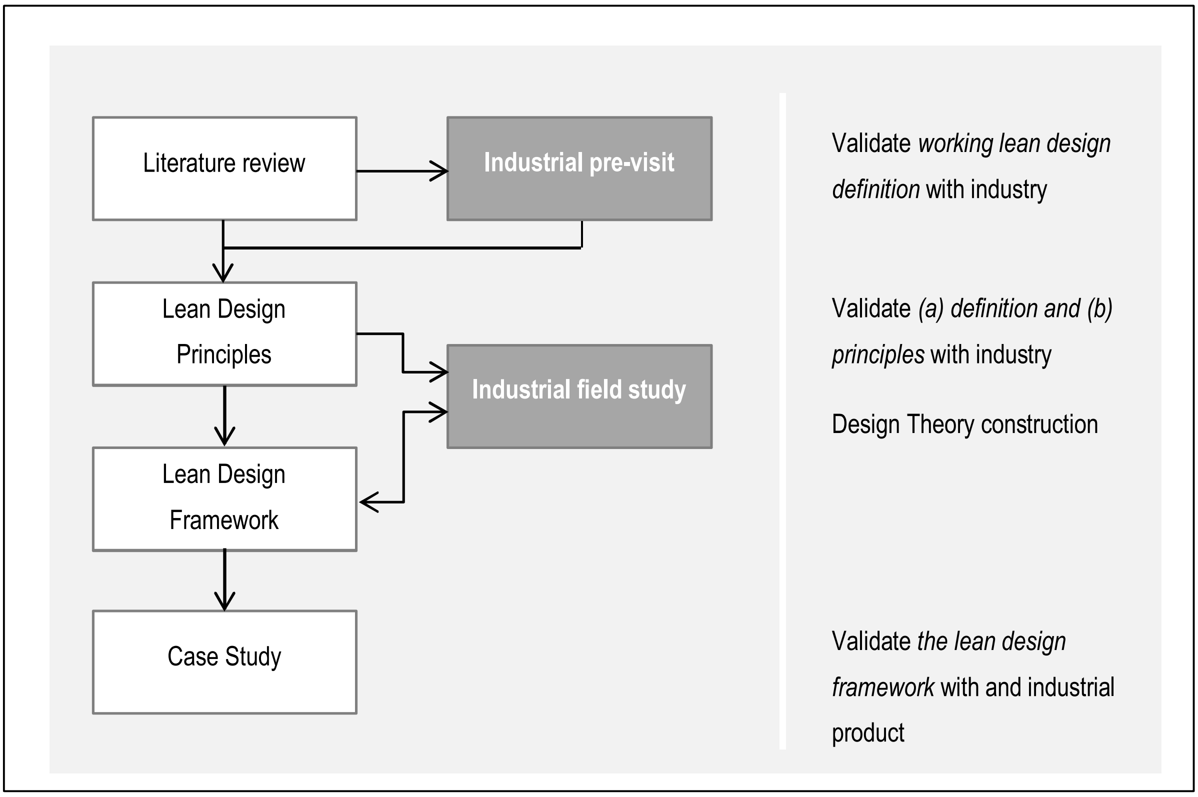



Figure 4-1: Overview of field study approach to get industrial perspective of lean design

The interaction with industry during the course of the research has been represented in Figure 4-1 Initially an industrial pre-visit was undertaken; as the research progressed a formal industrial field study was performed using a semi structured questionnaire and informal discussions with a range of manufacturing companies representing different industrial sectors, as highlighted in Table 4-1. A total of 34 interviews were performed; these included face-to-face and group interviews. The interviewees consisted mainly of designers and manufacturing engineers, 75% of which served the current position for 6-10 years, 5% possessed over 10 years of experience and the remaining 20% represented 1-5 years of experience. The interviews ranged from different levels of the business structure, for example 40% were working in middle management, and 15% held positions in senior positions and the remaining represented other business roles such as team leaders, technical support team or those directly engaged on the shop floor. Based on these statistics it can be induced that the results of the field study convey portray a substantial level of diversity, authenticity and reliability. The proceeding section details the design of the questionnaire based on the key areas of inquiry.

Table 4-1: List of companies involved in the field study and details of respondents

| No. | Companies | Sector | Position | Years of experience |
|---|---|---|---|---|
| 1 | EATON, (UK) | Aerospace systems | Design engineer | 5 |
| 2 | BAE SYSTEMS, (UK) | Defence | Middle management | 10 |
| 3 | BVT Surface Fleet, (UK) | Defence | Project manager | 10+ |
| 4 | ThermoFisher Scientific (UK) | Medical | Senior and middle management | 6 to 10 |
| 5 | METSEC Plc, (UK) | Construction supplier | Middle management | 6 to 10 |
| 6 | Visteon Engineering Services Ltd, (UK) | Automotive supplier | Senior and middle management, technical support team | 5 to 10 |
| 7 | Sitech, (Poland) | Automotive supplier | Senior and middle management, design engineers, manufacturing engineers | 5 to 10+ |
| 8 | VolksWagen (Germany) | Automotive | Middle management, senior designer, design engineers, manufacturing engineers | 5 to 10 |
| 9 | Rolls-Royce, (UK) | Aerospace | Middle management, senior designer, design engineers, manufacturing engineers | 5 to 15 |
| 10 | Indesit, (Italy) | Domestic | Middle management, senior designer, industrial designer, design engineers, manufacturing engineers | 2 to 15 |
| 11 | Getrag, (Germany) | Automotive supplier | Senior and middle management, | 6 to 10 |

## 4.3 Questionnaire design

In order to understand the current industrial practices related to product design a semi-structured questionnaire was designed. This was based on the inquiry of the findings from the literature review, as listed below:

1. The use of tools and techniques used as means of geometrical generation and enhancement during the course of product design (Chapter 2, Section 2.2.3)
2. Proactive consideration of resource and waste minimisation and harm elimination during geometrical styling (Chapter 2, Section 2.2.3 and Section 2.5.4)
3. The possibility of adopting lean manufacturing philosophies earlier in the design to ensure the lean manufacture of products (Chapter 2, Section 2.4)

This proceeding discussion presents the design of the eight key questions. The rationale of the questions in relation to literature is discussed; the design of the question and the intended projection of result visualisation are also discussed. The questionnaire can be found in Appendix A.1, a sample of the results analysis is provided in the proceeding sections, however a complete list of results and analysis can be found in Appendix A.2.

**Inquiry 1:** Tools and techniques used for design generation and enhancement

Chapter 2 initiated with a detailed discussion on the evolution of design practices and the use of design methods and theories as a means of design enhancement. As discussed in Section 2.2.2 there is an opportunity to extend beyond traditional methods towards a more modern approach that addresses the current demands and challenges faced by designers. In order to review this from an industrial perspective the following questions were generated.

---

(1) Which tool/techniques have you formally implemented during product design?
(2) What methods of product development do you currently follow and rate its effectiveness?
(3) What approaches do you use in assuring optimal values (as assigned in the design specification) are achieved in your final design?
(4) What sources do you consider during design to ensure key design attributes are achieved in your design?

---

The purpose of Question 1 is to identify the frequency of use and effectiveness of product design tools and techniques considered during concept generation. A predefined list of tools and techniques (selected from the literature review) was provided and the interviewees were requested to provide the relevant rating for frequency of use and the overall effectiveness as shown in Figure 4-2. The intent behind this design was to capture the frequency of use against the effectiveness of tools and techniques used during to design.

**Which of the following tools/techniques have you formally implemented as an aid during the design of the product? (Select as appropriate)**

| Tools/Techniques | Frequency of use | | | Effectiveness | | |
|---|---|---|---|---|---|---|
| | *Never* | *Sometimes* | *Always* | *Not effective* | *Somewhat effective* | *Effective* |
| 1. Design for Manufacture and Assembly | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 2. FMEA | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 3. TRIZ (Theory of Inventive Problem Solving) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 4. VA/VE | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 5. Design to Cost | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 6. Design for Sustainability | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| *Other* | | | | | | |

Figure 4-2: Question relating to tool/technique implementation during design

Question 2 develops upon the findings from literature and seeks to identify the current design approach followed by the design team. The questions seek to identify whether an over the wall approach is employed or a concurrent method whereby there is direct communication and integration between other departments in the design and development of the product. The layout of the question is very similar to the first question, whereby a predefined list is presented (based on the findings from the literature review) and the interviewees are requested to select the appropriate listings, as shown in Figure 4-3.

**What methods of product development do you currently follow and rate its effectiveness?**

| Method | Frequency of use | | | Effectiveness | | |
|---|---|---|---|---|---|---|
| | *Never* | *Sometimes* | *Always* | *Not effective* | *Somewhat effective* | *Effective* |
| 1. Concurrent engineering | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 2. Set-based concurrent engineering | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 3. Sequential manner | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| *Other* | | | | | | |

Figure 4-3: Screenshot of question relating to design methods

A detailed discussion in the importance of value and the scientific techniques used for value translation and representation has been provided in Section 2.5. Question 3 aims to identify whether mathematical or non-mathematical approaches in ensuring optimal values are realised in the final design by designers. A screen shot of the question and its design options are presented in Figure 4-4. The style of the question allows the interviewee to select the relevant approaches; the results would provide a numerical ranking of the most utilised approaches.

**What approaches do you use in assuring optimal values (as assigned in the design specification) are achieved in your final design?**

| Mathematical approach | | Non-Mathematical approach | |
|---|---|---|---|
| ❑ | Regression analysis | ❑ | Design Structure Matrix |
| ❑ | Multi-objective optimization | ❑ | Personal experience |
| ❑ | Other: | ❑ | Other: |

Figure 4-4: Question relating to value optimisation

Question 4 completes the first inquiry by asking: *What sources do you consider during design to ensure key design attributes are achieved in your design?* A predefined list is provided which the interviewees must select the most applicable listings. The intention of this question is to build a profile of the attributed listings which are essential to design and the most preferable sources that are employed in achieving them.

**What sources do you consider during design to ensure key design attributes are achieved in your design?**

| Attributes \ Sources | Design Rules | Design standards | Innovation | Personal experience | Other |
|---|---|---|---|---|---|
| Mistake proofing | ❑ | ❑ | ❑ | ❑ | ❑ |
| Manufacturability | ❑ | ❑ | ❑ | ❑ | ❑ |
| Critical to quality | ❑ | ❑ | ❑ | ❑ | ❑ |
| Performance | ❑ | ❑ | ❑ | ❑ | ❑ |
| Reliability | ❑ | ❑ | ❑ | ❑ | ❑ |
| Sustainability | ❑ | ❑ | ❑ | ❑ | ❑ |
| Waste minimisation | ❑ | ❑ | ❑ | ❑ | ❑ |
| Resource minimisation | ❑ | ❑ | ❑ | ❑ | ❑ |
| *Other* | ❑ | ❑ | ❑ | ❑ | ❑ |
| | ❑ | ❑ | ❑ | ❑ | ❑ |

Figure 4-5: Sources considered in achieving design attributes during design

**Inquiry 2:** Adopting lean manufacturing technique earlier in design

Having identified the opportunity to go beyond traditional design methods and theories, the possibility of adopting Lean Thinking was explored; this has been detailed alongside its benefits in Chapter 2, Section 2.3. This is further reinstated in Section 2.4 which suggests the success of Lean Manufacturing is on the strict enforcement and the integral use of tools and techniques that coincide with the lean philosophy. With this in mind, the second inquiry of the field study seek to identify if industry was in a state of adopting lean type thinking earlier in the design, during conceptualisation; therefore three consecutive questions were populated.

(5) Have you considered adopting lean manufacturing techniques as a means of improvement during conceptual design?
(6) During design do you consider incorporating error/mistake proofing for the product life cycle?
(7) Do you have evidence of cases when during design you incorporated error/mistake proofing features?

Based on the review of the Lean Manufacturing techniques in Section 2.4.1, three were identified as having the potential to be adapted earlier in to design, these included: Poka-Yoke (mistake-proofing), Single Minute Exchange of Die and Quick Change Over. The following question was posed: *Have you considered adopting lean manufacturing techniques as a means of improvement during conceptual design?* A graphical example of each technique was provided, as shown in Figure 4-6. The output of the findings from this question would give an insight in to what techniques are been used and which can be incorporated to further enhance conceptual design. Question 6 builds on question 5 and seeks to further identify the use of mistake-proofing within the Product Life Cycle. This is demonstrated in Figure 4-7. The layout of the question would provide a representation of areas within the life cycle where mistake-proofing is incorporated and areas in which it is less considered. Question 7 takes this further by asking for evidence of cases whereby mistake proofing was used. The purpose of this question was to populate a list of examples of mistake-proofing features used in commercial product (see Figure 4-8).

**Have you considered adopting lean manufacturing techniques as a means of improvement during conceptual design?**

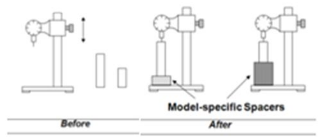
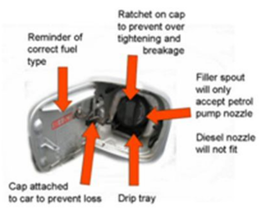
| Example | | Consideration | |
|---|---|---|---|
| | | Yes | No |
| Single Minute Exchange Die (SMED)<br><br>Replace 4 bolts that require 32 turns before the die is secure, with a clip-on attachment. |  | ☐ | ☐ |
| Quick Change Over (QCO)<br><br>Measuring different product models requires manual adjustment of the dial. By using model-specific spacers, adjustment time is reduced – allowing for quick change over. |  | ☐ | ☐ |
| Poke-Yoka (Mistake-proofing)<br><br>Apply mistake proofing mechanisms and features to prevent the loss of the fuel cap and remind the user to use the correct type of fuel |  | ☐ | ☐ |

Figure 4-6: Adoption of lean manufacturing techniques earlier in design

**During design do you consider incorporating error/mistake-proofing for the following areas of Product life Cycle?**

| User | Incorporation | | |
|---|---|---|---|
| | *Never* | *Sometimes* | *Always* |
| End User | ☐ | ☐ | ☐ |
| Prototyping | ☐ | ☐ | ☐ |
| Manufacture | ☐ | ☐ | ☐ |
| Assembly | ☐ | ☐ | ☐ |
| Testing | ☐ | ☐ | ☐ |
| Packaging | ☐ | ☐ | ☐ |
| Storage | ☐ | ☐ | ☐ |
| Distribution/sales | ☐ | ☐ | ☐ |
| Delivery | ☐ | ☐ | ☐ |
| Disposal | ☐ | ☐ | ☐ |
| Recycling | ☐ | ☐ | ☐ |
| Service/Maintenance | ☐ | ☐ | ☐ |

Figure 4-7: Incorporating mistake-proofing during Product Life Cycle

**Do you have evidence of cases when during the design you incorporated error-/mistake-proofing (features/elements/mechanisms) for the followings: (Select as appropriate?)**

| User | Incorporation | | |
|---|---|---|---|
| | *Never* | *Sometimes* | *Always* |
| 1. End user | ❑ | ❑ | ❑ |
| 2. Assembly/Disassembly | ❑ | ❑ | ❑ |
| 3. Service/Maintenance | ❑ | ❑ | ❑ |

Figure 4-8: Evidence of cases of incorporating mistake-proofing in design

**Inquiry 3:** Eliminating harm, minimising waste and resources

Theoretically formal consideration of harm elimination should be an integral part of any conceptual design project to ensure product safety and compliance to legislation as described in Section 2.2.3. Furthermore, as explained in Section 2.5.4 waste and resource minimisation as a means of value enhancement should never be overlooked by designers. Therefore the final question of the questionnaire was designed to investigate this.

(8) Do you have a systematic and formalised method of designing a product that ensures:

(i) Harm to the end-user and manufacturing is completely eliminated,

(ii) Waste and resources are minimised during manufacture?

The design of the question allows the interviewee to select the relevant options and provide a list of methods accordingly, as shown in Figure 4-9. The intent was to generate a list of formal methods used for the given options and identify a common trend amongst industrial application.

**Do have a systematic and formalised method of designing a product that ensures**

(1) Harm to the end-user and manufacturing engineer is completely eliminated,

(2) Waste and resources are minimised during manufacture?

| Design considerations | Options | | Details of method |
|---|---|---|---|
| | *Yes* | *No* | |
| Harm | ❑ | ❑ | |
| Waste | ❑ | ❑ | |
| Resources | ❑ | ❑ | |

Figure 4-9: Systematic and formalised method for harm elimination and minimisation of waste and resources

## 4.4 Field study results and industrial opinions on lean design

This section consists of a two part discussion, the former provides a sample of the data analysis and the latter dedicated to the industrial opinions on lean design.

### 4.4.1 Field study data analysis

A sample of data analysis is presented with graphical results, the selection of results are based on the three areas of inquiry mentioned in Section 4.3

**Sample 1:** Which tool/techniques have you formally implemented during product design?

Designers consider the utilisation of tools and techniques as an integral part of their activity and attest to their use as a compulsory custom; preference over the tool/techniques selection and utilisation is common and typically the response towards new untested methods is less welcomed. The design of the question required the interviewee to rate the levels of utilisation and effectiveness, and a three level rating was provided for each given option. The rate of utilisation was rated between *never, somewhat and always*. Effectiveness was rated between *not effective, somewhat and very effective*. The results were amalgamated and an average was produced. 0% represents never (utilisation) and not effective whereas 100% always considering utilising during design projects and very effective, as displayed in Figure 4-10.

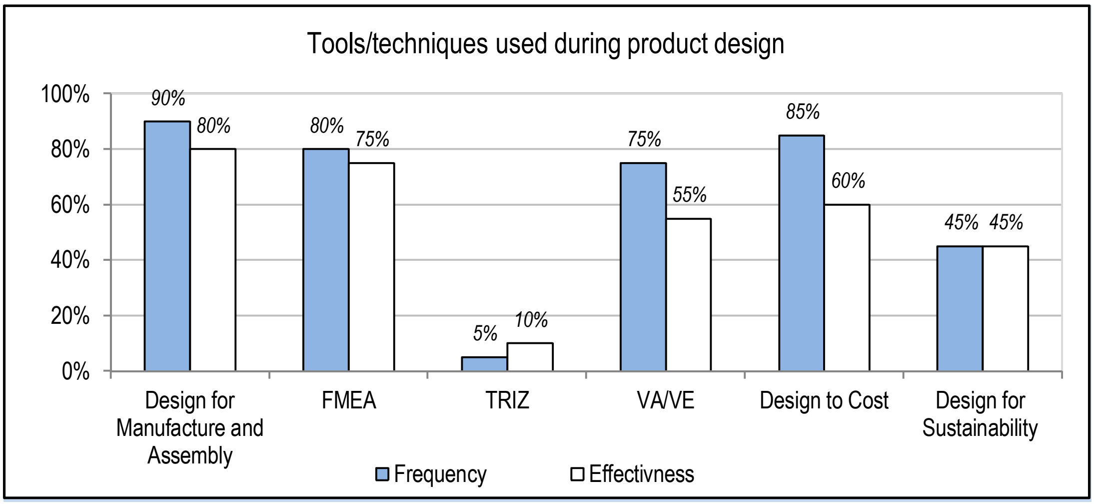



Figure 4-10: Results showing the frequency of use and rate of effectiveness of tools/techniques used in design

The findings demonstrate some interesting results, for example the frequency of use for DFMA is almost ‘always’, through the formal consideration of either Lucas or Boothroyd method, however it falls short of reaching the highest levels of effectiveness. Designers acknowledge the importance of critical analysis of the design through failure modes however the use of FMEA templates is considered a routine task and is least effective in generating the desired results. Theory of Inventive Problem Solving is not a favourite toolkit due to its repetitive nature, and in turn is not listed in the table of commonly used tools by designers. Instances been reported where the use of TRIZ has been made to generate creative solutions conversely with none to less effects. Informal consideration of Design to Cost is evident, not directly based on guidelines; designers rely on their expertise and judgement to address cost related issues, occasionally supported with an Excel based system. Designers are forced to consider sustainability issues due to pressure enforced from senior management however the tools used are not effective enough to reach a satisfactory level; this is due to the lack the in-depth knowledge possessed by designers pertaining to this field.

It can be concluded from the aforementioned results that manufacturability is important, sustainability is imperative because it is directly related to resource consumption and cost is essential however these aspects of design are tackled using a standalone approach. This highlights the possibility to have an approach where in addition to manufacturability, cost, harm, waste and resource minimisation related issues are addressed collectively in a wholesome approach, as opposed to employing numerous tools or techniques singularly.

**Sample 2:** Have you considered adopting lean manufacturing techniques as a means of improvement during conceptual design?

The possibility of adopting lean type thinking earlier in to design by considering lean manufacturing techniques which are directly related to the geometry was a key area of investigation. The general response received suggests there is an unclear understanding and appreciation of the lean techniques, for example designers were more familiar with the term mistake/fool-proofing as opposed to Shingo's Poka-Yoke and therefore were unable to relate to importance and the role of Poka-Yoke during manufacture. Same can be said for Single Minute Exchange of Die and Quick Change Over. From the entire sample, there were two notable cases, where designers and manufacturing engineers representing the medical and domestic appliance sector were aware of these techniques and had at some stage in the past considered incorporating SMED and QCO features in to the design; this can be clearly seen in Figure 4-11.

The general feeling received from the respondents suggests there is a lack of awareness amongst designers regarding these techniques. However, when graphical examples and possible scenarios were put forward the benefits that could be acquired from adopting these techniques was readily accepted. During a conjoint interview with manufacturing and design engineers, it was noted that meeting deadlines were halted due to the high levels of design rework, and this process is both taxing and iterative and continues until a satisfactory levels are achieved. One of the reasons for this is communication between the designers and manufacturing engineers. Additionally designers can undermine the effects of the design decisions (such as features) and the challenges faced by manufacturing engineers on the shop floor in realising them. This could be resolved through a proactive attitude by considering SMED, QCO and Poka-Yoke like techniques earlier in to design to ensure a smooth manufacturing transition.

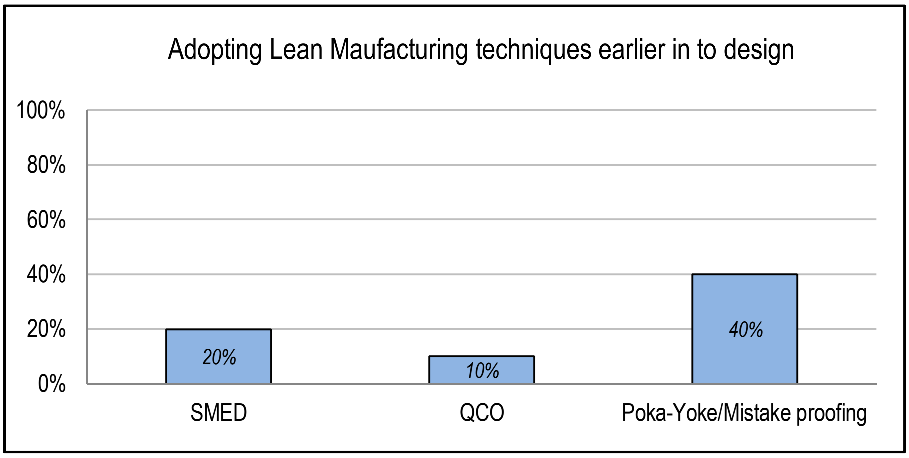



Figure 4-11: Results showing the adoption of lean manufacturing techniques in design

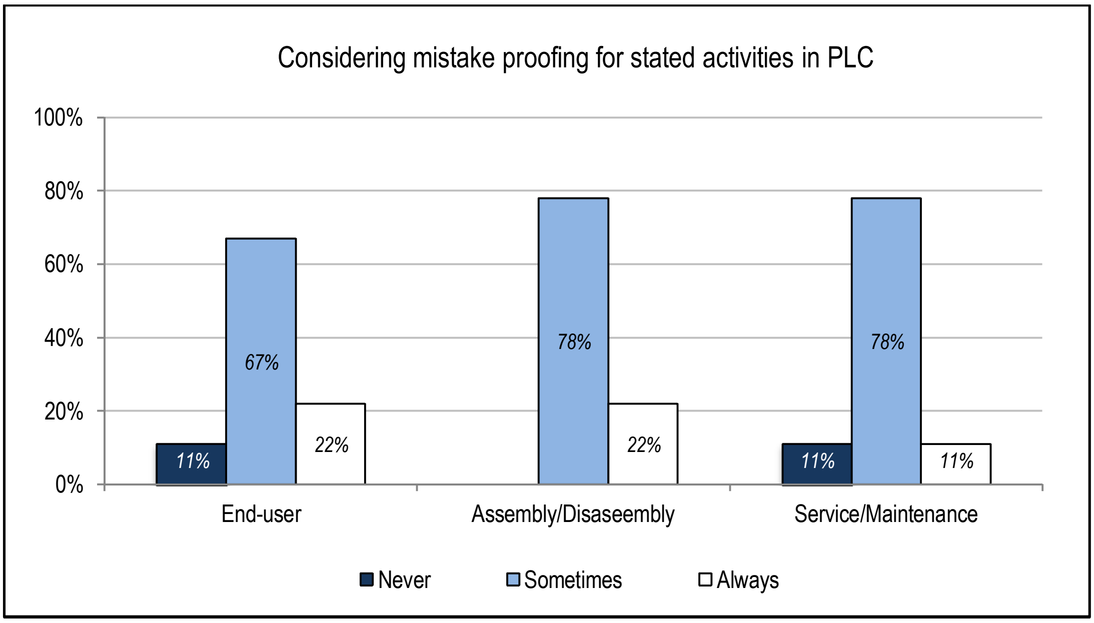



Figure 4-12: Results showing mistake-proofing consideration during design for PLC activities

Designers were posed with a question regarding the consideration of mistake-proofing during conceptual design for stated activities in the Product Life Cycle. All the interviewees acknowledged the impotence of considering mistake-proofing during conceptualisation, however only 'where and whenever' they felt necessary, as highlighted in Figure 4-12. Only a small percentage actually considered mistake-proofing as an essential element of geometrical design and made it part of routine to consider it always. Furthermore, 80% of the respondents relied on personal experience and initiative as opposed to using a formal method or technique to mistake/fool proof the design.

From these results it can be concluded that the consideration of lean manufacturing techniques earlier in design can be very beneficial, furthermore consideration of mistake-proofing for the relevant activities in the Product Life Cycle should be made an essential part of design.

**Sample 3:** Do you have a systematic and formalised method of designing a product that ensures: (a) harm to the end-user and manufacturing engineer is completely eliminated, (b) waste and resources are minimised during manufacture?

Product safety is a compulsory element of design and must never be overlooked or compromised; minimising waste and resources are equally important to ensure product competitiveness and should be controlled at source. Results from the filed study as shown in Figure 4-13 demonstrate that harm elimination, waste and resource minimisation are considered during design, however there is a mixed response with regards to methods followed. Personal experience, expert advice and design reviews are the common methods followed. However rational approaches such as tests results, simulations and guidelines which provide technical details should be given priority because harm elimination, waste and resource minimisation are very serious issues. Thereby the design decisions are based on factual and technical data as opposed to 'gut feeling' or personal experience and judgement.

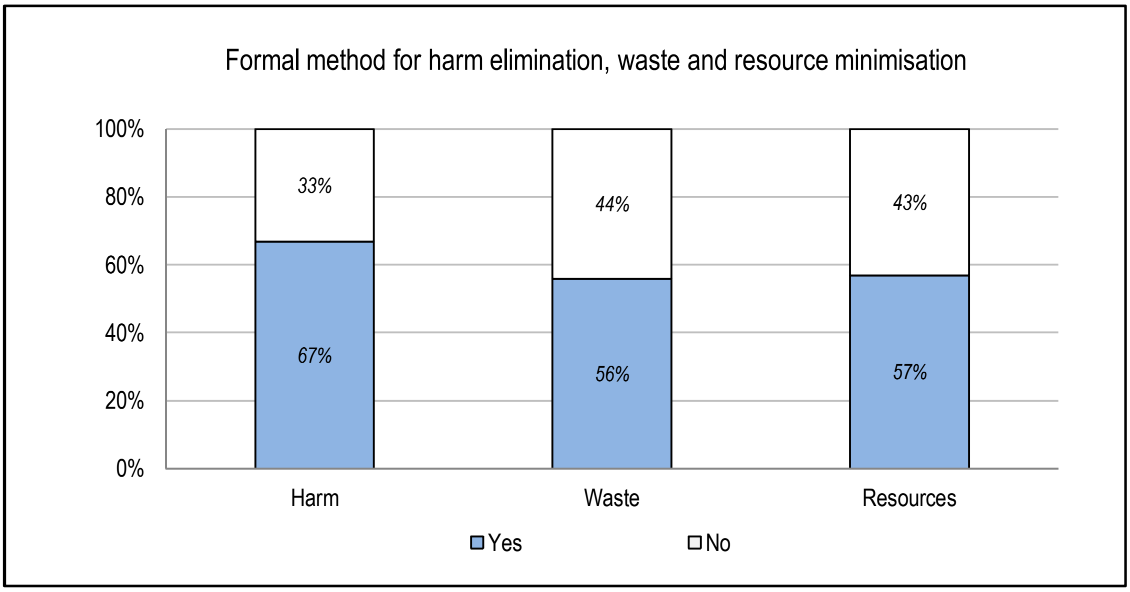



Figure 4-13: Results showing for formal consideration of harm elimination, waste and resource minimisation

### 4.4.2 Industrial opinions on lean design

The results presented in the previous section were based on the semi-structured questionnaire. This section discusses the findings from the open ended questions asked during informal discussions, and provides direct connotations of the responses received.

#### 1. What is your opinion and interest in lean design?

| | |
|---|---|
| **Senior designer** (Aerospace) | Lean design is not about the interface but it's about penetrating through the outer in to the inner i.e. manufacturability, serviceability of features etc. |
| **Senior designer** (Automotive) | Lean design would be to reduce ambiguous design intentions for manufacturing |
| **Senior Management** (Automotive) | A lean design product should reduce cost to achieve manufacturing target, time to delivery and be easy to maintain |
| **Manufacturing Engineer** (Aerospace) | Strip away unnecessary features and functions and manufacture it in the most cost effective way without causing interruptions to manufacturing procedure due to the health risks involved |
| **Industrial Designer** (Domestic appliances) | Offer a well-balanced product that contains features which our competitors do not have, these will exceed our customers expectations and it will result in the enhancement of our product brand |
| **Project Manager** (Defence) | Lean design would be to achieve a product performance threshold that is not hindered by internal/external circumstances such as obsolescence, fatigue, atmospheric conditions etc. |
| **Senior Designer** (Medical) | Eliminate non-conformance features that could pose a threat i.e. provide the wrong results to the client |
| **Manufacturing Engineer** (Medical) | A lean design would foresee the manufacturability and deliverability according to the customer's expectation and provide the most cost effective solution |

It can be inferred from the industrial opinions on lean design that there is no common understanding and agreement on the definition of lean design. The definitions provided by the respondents are based on personal understanding, position of duty and sector affiliation. This can be supported with the following presumption: the automotive sector co-relate lean design with manufacturing enhancement and its effects by means of reduction. The medical sector perceives lean design as a method of creating safer products. Furthermore, the domestic appliances sector foresees lean design as the co-development and enrichment of the outer form and inner functions which can be delivered to exceed the customer's expectations. It can be concluded that there is a need for a concise definition that specifically identifies the essential elements of lean design and predefines its boundaries to ensure it is not under or over defined.

**2. What implications do you see with lean design, and what advice do you offer?**

> Lean design is much more difficult as every product has a different objective by nature, whilst lean manufacturing has a stated objective i.e. waste elimination *(Senior Designer, Aerospace).*
>
> To be leaner we must target component level *(Senior Designer, Aerospace).*
>
> Lean design would need to consider the PLC i.e. service, disassembly, disposal etc. *(Designer, Aerospace)*

The challenge associated with lean design is that each product must be addressed objectively, common objectives might be found across a family of products. Nevertheless understanding the nature of the product and targeting it at the component level as opposed to the system level is requisite, as it set path for the quintessential activities in manufacture, service etc. Therefore designers must recognise and respond responsibly to ensure the spirit of lean type thinking is present in all design decisions.

### 3. What would be the most favourable method of representation that industry could use?

Designers already have a number of tools to perform their design activities, lean design should be a **way of thinking** not just another tool, *(Senior Designer, Aerospace).*

Generic lean design principles should prompt the designers **thought process** rather than apply constraints, *(Senior Designer – endorsed by Design and manufacturing engineers, Aerospace).*

A guidebook supported with visual examples that educates the designer on how to lean out a design, *(Designer, Aerospace)*

Generic Design Practice is the DNA of design – it is a tool set rather than a process used by designers, *(Senior Designer, Aerospace).*

The Generic Design Practise is essential but not fashioned logically; it is a collection of ideas but does not necessarily tell the designer what to use and to what extent, *(Designer, Aerospace).*

During the field study the author was given access to visit the shop floor, engage with individuals from different levels of the business, and given a number of live demonstrations of software used by designers. There is an attitude of accumulating tools and software within industry, and a large collection is available for resource, of which is ignored most of the time. Therefore, it was expressed that lean design should be *a way of thinking* that gives cognitive stimulation and challenges the designer from all possible aspects.

### 4. Validating the working definition – response and suggestions

Working definition: *"Lean design is the successful realisation of value, ensuring waste is minimised during manufacture as opposed to waste reduction in production."*

During the field study the author was able to validate the working definition which was generated as a result of the literature review. The overall response received was positive, however some suggestions for refinement were given, for example: a) lean design is not the successful *realisation*, rather is it a stage of representation and (b) the latter part '*as opposed to waste reduction in production* 'is explanatory of '*ensuring waste is minimised during manufacture.'*

## 4.5 Key findings from field study

The key findings from the field study can be explained as the following:

- Traditional design tools and techniques are used during product design and are not so effective. The tools and techniques are used singularly to address specific aspects of the design, such as manufacturability, cost, sustainability etc. However this approach is not effective and strenuous on time and resources.
- Many factors cause time and cost over runs; design modification is seen as one of the major contributors. Designers tend to over style, or design out of manufacturing capabilities reach and therefore are required to simplify designs. The use of lean type thinking earlier in design can substantially deter this to some degree.
- Harm elimination, waste and resources minimisation which are serious issues need to be addressed in a formal and systematic method rather than individual experience and judgement.
- There is no commonly shared definition of lean design amongst industry, nevertheless there is a common understanding that lean is to achieve the maximum attainable outcome with minimum, and to achieve this it must begin with design, precisely at the component level.

## 4.6 Summary

This Chapter has presented the current industrial design practices and perspectives on lean design in the European industrial sector. It initiated with a description of the field study approach, providing details of the participating companies and the individuals involved. This was preceded with a detailed explanation of the questionnaire development followed by an analysis of a sample of the results and industrial opinions on lean design. The commencing Chapter establishes the foundations and principles of lean design by drawing upon the findings from the literature and the industrial field study.

# Chapter 5

# THE FOUNDATIONS AND PRINCIPLES OF LEAN DESIGN

## 5.1 Introduction

This chapter predominantly focusses on the second objective of the research which defines the lean design principles that are to be used to generate conceptual design. Design research typically follows a scientific method of theory construction in order to assimilate an acceptable level of formalisation. The process for constructing theory is adapted by the author in Section 5.2 which is used to establish the foundation of lean design principles. In section 5.3 the methodology used to construct the lean design principles is discussed followed by a discussion on the contents of each principle. In Section 5.4, the application of lean design principles in relation to the product is explained. The chapter is summarised in Section 5.5.

## 5.2 Establishing the foundations of lean design

In the science of theory construction, there are theories for (1) analysing, (2) explaining, (3) prediction, (4) explaining and predicting. Gregor (2006) identifies design as a fifth class, which has been explained as theory for design and action. The distinctive characteristic of design theory as opposed to other theories is that they focus on *'how to do something'* where *'explicit prescriptions on how to design and develop an artefact'* is given (Gregor and Jones, 2007), design is both a noun and a verb, therefore a design theory 'can be about the principles underlying the form of the design and also the act of implementing the design in the real world' (Gregor and Jones, 2007). Design theories are generally sufficient in guiding the designer however the expression of output may vary. For example to Hevner et al. (2004) design theory can be illustrated in models, bodies of knowledge or frameworks. Codd (1978) and Simon (1981) can be considered pioneers of theory construction. Codd (1978) has provided a description of key components that must be considered in the construction a theory as highlighted in Table 5-1.

Table 5-1: Seven generic components of constructing a design theory (Gregor and Jones, 2007; Codd, 1982)

| Component | Description |
| --- | --- |
| 1: Purpose and scope | What is the motivation for the inquiry and what types of artefact to which the theory applies? |
| 2: Principle form and function | What is the underlying construct and what are the entities of interests? |
| 3: Artifact mutability | The change in state of the artefact anticipated in the theory |
| 4: Testable propositions | Truth statements about the design theory |
| 5: Justificatory knowledge | The underlying knowledge or theory from design science that gives basis and explanation |
| 6: Principles of implementation | A description of processes for implementing the theory |
| 7: Expository installation | A physical implementation of the artefact that can assist in representing the theory both as an expository device and for purpose of testing |

The author has adopted the seven generic components and made necessary rearrangements in favour of this research to establish the foundations of lean design; a brief description for each component is listed below:

**1. Purpose and Scope:** is threefold, (1) European manufacturing firms are seeking ways to advance the current practices by applying lean thinking in product development to design and manufacture a high value product at low cost. (2) An evolution in design research is preordained; consequently there is a need to go beyond traditional design methods and theories to address these challenges (as explained in Chapter 2, Section 2.1.2). (3) The current industrial practices can be improved through the incorporation of lean type thinking earlier at concept design stage to ensure leaner products are generated that minimise waste and resources, ensure the product is safe and can be manufactured in a cost effective manner.

**2. Principles Form and Function:** is to transpose and preserve the meaning of lean thinking in to product design as opposed to enforcing the methodology proposed by Womack and Jones to the design process, as identified in Chapter 2, Section 2.3.3. There is a tendency amongst practitioners as identified in Table 2-4 to selectively choose and apply lean thinking principles i.e. identify customer and specify value, create flow by eliminating waste etc. in to the design process as opposed to adapting lean thinking principles that are accustomed to design. Accordingly, the challenge is two fold, (1) preserve the essence of lean thinking (which is primarily focused on manufacturing) and adopt it to design and (2) ensure the principle form and function is directed to geometrical design as opposed to the singular focus on the design process.

**3. Artifact Mutability:** is an essential component, because consideration to the change in state of the artefact (product) must not be ignored at any stage. This has been identified and briefly discussed in Chapter 4, Section 4.4.2. For example, products differ in nature and the stated objectives vary from project to project, therefore there must be an acceptable level of mutability whilst not diverting from the primary objective which is to ensure optimal leanness.

**4. Testable propositions:** can be considered as the core 'truth statements' which are to be used as a rule of governance, to which the concept design must conform. In context, propositions refer to the lean design principles, which will form the basis of the lean design framework, these are the fundamental norms that represent what is required and aid in determining the conduct of decisions required by the designer in generating lean design. In theory the designer should be able to test the conformance of the design against the principles, based on justificatory knowledge and personal initiative.

**5. Principles of implementation:** will be achieved by encapsulating the lean design principles within a framework in a systemised method, which ensures the necessary actions are undertaken in order to output a lean conceptual design. Close consideration to the general activities in conceptual design are given to ensure a complete and cohesive implementation.

**6: Justificatory knowledge:** will form the pool of knowledge that is available to the designer to ensure the successful realisation of the lean design principles. This will be achieved through assistive guidelines, with reference to support material such as technical documentation which includes: design rules, standards, graphical illustrations etc.

**7: Expository installation:** is a complimentary component, and can be achieved by providing a selection of different lean design case studies. These can be used as a means of inspiration and practical references for the designers.

## 5.3 Lean design principles description and finalisation

The previous section detailed the essential components required for design theory construction in adopted them in establishing the lean design foundations in a scientific manner. The discussion in this section focusses on component four of Table 5-1 which will present and finalise the lean design principles. An initial description of the methodology followed in formulating the lean design principles is provided, followed by a description of each principle and its contents.

### 5.3.1 Formulating the lean design principles

The formulation of the lean design principles is a significant accomplishment which is a consequence of theoretical investigation and industrial collaboration. As delineated in Figure 5-1, the literature review provided the theoretical grounds; the field study gave an insight in to the current design practises and opinions on lean design. Through this, the author was able to collate the findings and refine the lean design definition and manifest the lean design principles.

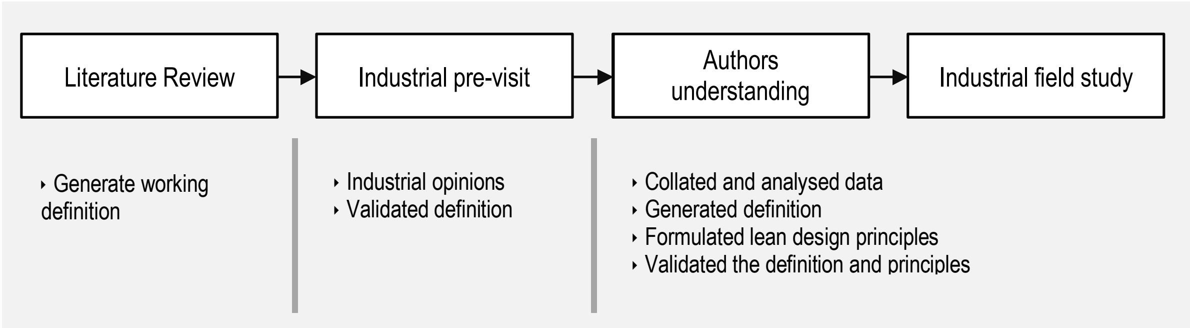



Figure 5-1: methodology followed in formulating the lean design principles

### 5.3.2 Lean Design Principle rationale

The lean design principles constitute the generic code that exhibit the characterisation of a lean design. These have been formulated by rendering the understanding of literature and industrial opinions, as shown in Table 5-2.

Table 5-2: Formulating the lean design principles

| Lean Design Principles | Literature and Industrial statements |
|---|---|
| Value maximisation | FS – 'Offer a well-balanced product that **contains features which our competitors do not** have, these will **exceed our customers expectations**'<br>FS – 'Complex and competitive product for a customer that doesn't know what they want'<br>LR – Value is an essential element of lean thinking<br>LR – Delivering value is imperative to the customer and is imperative to a company's success |
| Product simplification | FS – 'Strip away unnecessary features and functions and manufacture it in the most cost effective way'<br>FS – '…reduce ambiguous design intentions for manufacturing'<br>FS – '…foresee the manufacturability and deliverability according to the customer's expectation and provide the most cost effective solution'<br>FS – 'Simplify the design to reduce rework' |
| Simultaneously consider lean manufacturing | FS & LR – adoption of lean manufacturing philosophies to product design |
| Eliminate harm | FS – ...eliminate features that could pose a threat (physical/emotional) to the client<br>FS – eliminate the occurrence of health risk during manufacturing<br>LR – incorporate safety in design to eliminate the risk of product liability |
| Minimise waste | FS – Eliminate non-conformance geometrical features<br>LR – cost effective measures include minimising waste and resources during geometrical design<br>LR – anything that does not add value is considered wasteful |
| Minimise resources | |

**FS – Field Study** **LR – Literature review**

Lean design consists of six essential lean design principles, as illustrated in Figure 5-2. Each principle contains a set of considerations that must be adhered to in order to achieve maximum benefits. A discussion on the lean design principles is presented, explaining the (1) Principle Context and (2) Principle considerations, supported with graphical illustrations wherever applicable.

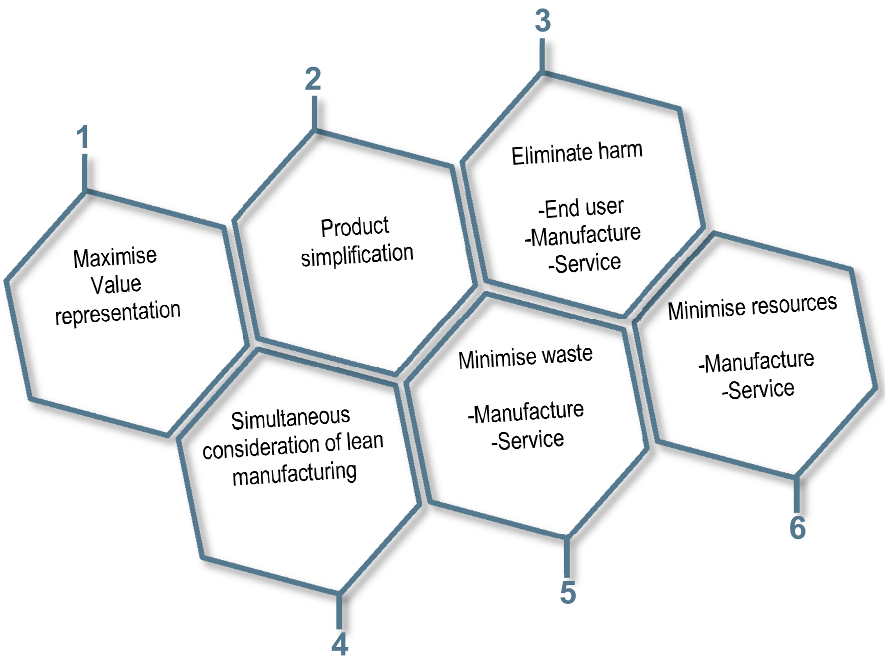



Figure 5-2: Illustration of Lean Design Principles

## PRINCIPLE 1: MAXIMISE VALUE REPRESENTATION

### Principle Context

The interpretation of value differs from customer to customer. What is common is a perceived characteristic relative to its cost. Value should not be confused with a product function; relatively it is a distinct functional characteristic that exceeds customer perception and is a means of attaining satisfaction.

Maximising value representation can be explained as: generating geometrical product characteristics (via form, function, mechanism) that achieve the 'higher allowable limit' (as by the circumstances of the particular case).

**Principle Consideration**

The basis of maximising value representation rests upon the following:

- Determining what is customer value (in relation to that specific case), by definition or extraction
- Endeavour to offer maximised value propositions that are conveyed through the geometry in a cost effective manner

**Maximising value representation example:** *GEAviation (2014)*

The example is based on the General Electric GEnx; the engine incorporates technologies that provide maximum value whilst ensuring operating efficiency, making it a reliable product.

Examples have been listed which demonstrate the striking innovations GE has incorporated in to the GEnx engine, making it a leading product in its industry.

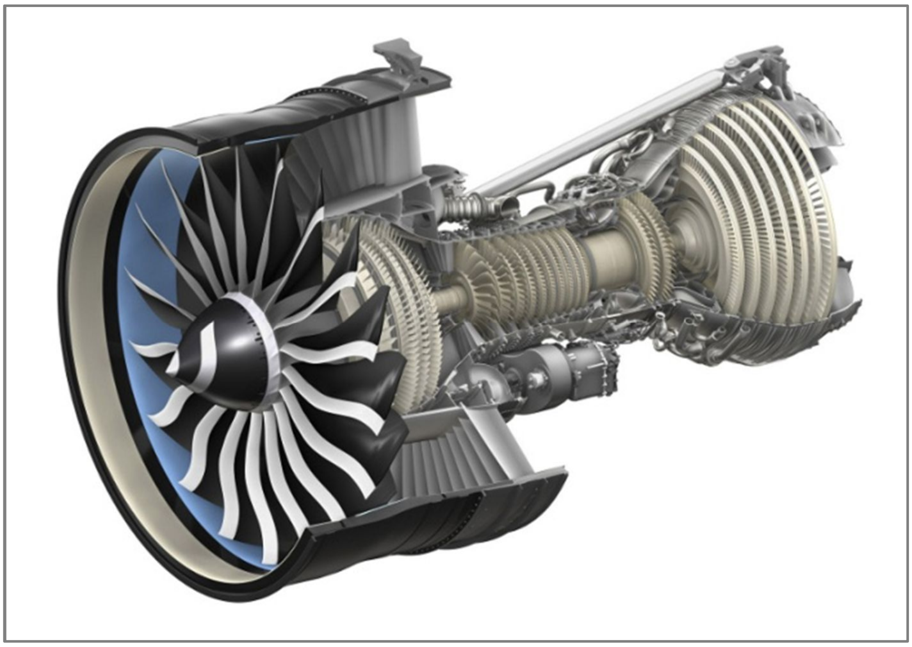


Figure 5-3: GEnx turbo jet engine

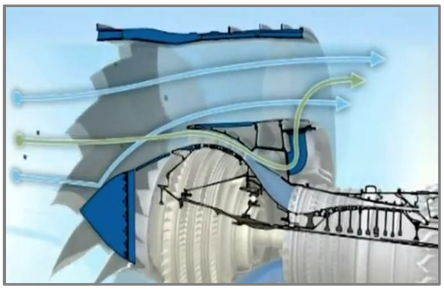


Figure 5-4: GEnx low pressure compressor

**VALUE 1:** The low pressure compressor incorporates the latest 3D aerodynamic improvements; it contains a *'debris rejecting system'* to keep foreign material from entering the compressor

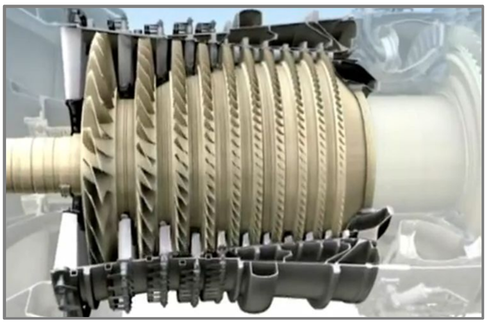


Figure 5-5: Genx high pressure compressor

**VALUE 2:** The high pressure compressor has ten stages, four fewer than previous engines – meaning fewer stages, fewer parts and lower costs. This efficient compressor delivers an astounding 23:1 pressure ratio while providing the same stall free operation in the previous GE engines.

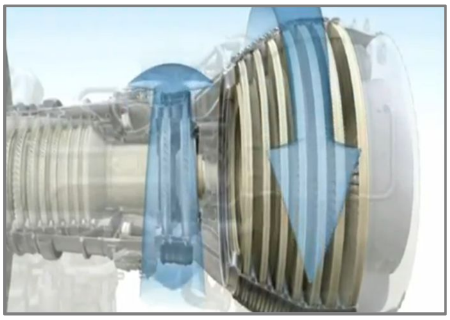


Figure 5-6: GEnx counter architecture

**VALUE 3:** Turbines extract energy from the core flow, by utilising advanced design, fewer blades do more work. In addition a counter architecture enables a more efficient extraction allowing for a 10% part reduction.

Figure 5-7: GEnx modular maintenance

**VALUE 4:** The innovative modular maintenance concept is designed to deliver significant savings in time and cost. The engine easily splits in to two modules, the fan and the propulsar. The propulsar can be removed and replaced with a spare one easily.

## PRINCIPLE 2: PRODUCT SIMPLIFICATION

### Principle Context

The primary objective of design is to conceptualise a functioning product that (a) meets a certain capability and (b) addresses an identified performance objective and design specification. This is usually within a number of constraints i.e. monetary, schedules etc.

The nature of design and technical skills of designer's means a product can be *designed in many ways*, with the primary objective of optimising the design.

Designers face two major challenges;

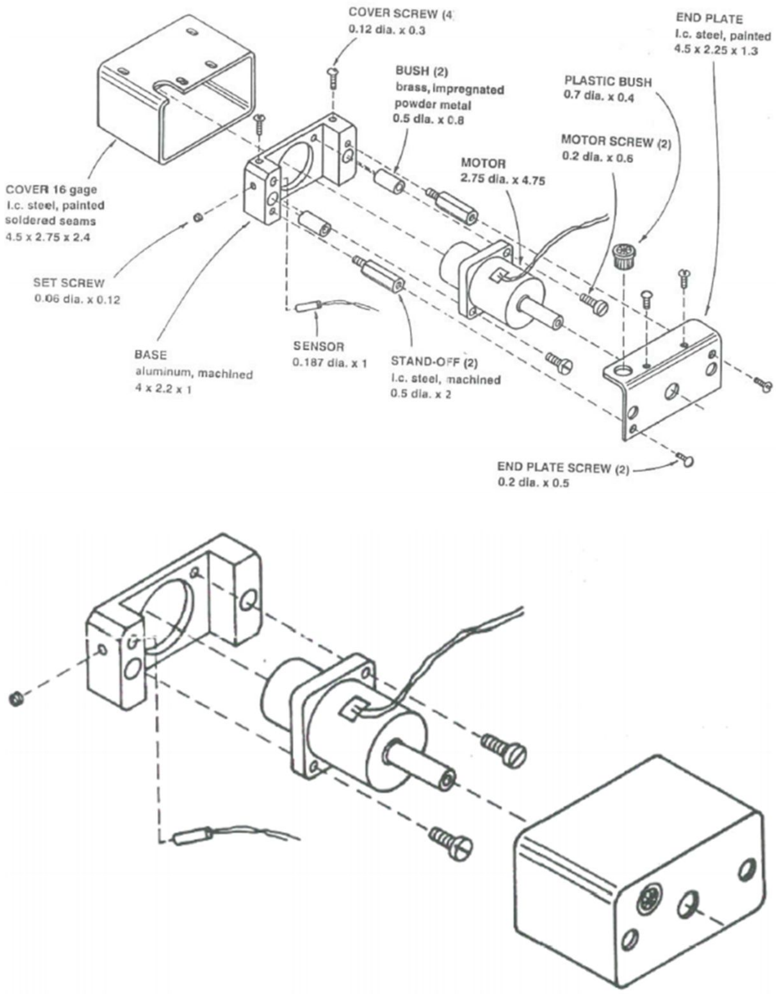
- Firstly designer's knowledge of what is required is vague during conceptualisation, during the process of creative design; excessive styling causes non-value adding features to be manifested in to the design.
- Secondly, the design must be optimised within the existing production system, which calls for the consideration of manufacturing processes, and labour force capabilities, suppliers etc. during design.

### Principle Considerations

The second lean design principle is product simplification; this broad term refers to the practical activities required by the designer/design team. This principle can be applied in to possible scenarios; (1) product simplification from the beginning and (2) simplification of an existing geometry. The following consideration must be taken in to account:

- Simplify the design and reduce the number of parts
- Standardise through the use of common parts and materials
- Minimise geometrical complexity and variation
- Design within process capabilities and consider specific Design for Manufacture
- Apply Boothroyd's Design for Assembly rules
- Consider Design for Modularity and Design for Serviceability

**Product simplification example:** *Motor drive before and after the application DFMA*




The impact of Design for Manufacture Assembly on Reticle assembly:

- Reduction in: parts to design, documents, revise, Bill of Materials cost, parts to receive, handle.
- Reduction in labour and energy to manufacture the product
- Minimised complexity
- Easy customer handling
- Simplified assembly instructions
- Higher quality

Figure 5-8: Reticle design before and after applying Design for Manufacture and Assembly rules (Boothroyd, 2005)

## PRINCIPLE 3: SIMULTANEOUS CONSIDERATION OF LEAN MANUFACTURING

### Principle Context

The ideal of lean design is the simultaneous consideration of lean manufacturing during conceptualisation. This principle seeks the development of the design in parallel to its associated manufacturing processes. Product and process co-development should be viewed as an opportunity for integration with substantial benefits. When the design undergoes an evolution and gains maturity, the manufacturing processes required to realise it should coincide accordingly.

The effects of product and process co-development can be illustrated as follows:

- Materials specified by the designers for the product coincide with the inventory, the suppliers catalogue and existing manufacturing capability
- The design tolerances adhere to the existing manufacturing capabilities and as result control the levels of defects
- The flow of assembly corresponds to the existing process flow

The success of lean manufacturing primarily rests upon the tools and techniques which are applied for specific situations. Significant benefits can be obtained through the simultaneous consideration of lean manufacturing, these include: (1) reduced waste, (2) improved quality through defect minimisation, (3) enhancing overall manufacturing flexibility, (4) reduced inventory and (5) improved lead times through quicker set-ups, fewer delays etc.

### Principle Considerations

During conceptualisation features and mechanisms are designed to address a particular functionality or customer value. Lean design encourages the introduction of 'lean manufacturing features' which might not directly offer a benefit to the customer but will ensure the lean manufacture of the product.

The principle considerations rests upon incorporating Poka-yoke (Mistake proofing) features and mechanisms and SMED/QCO features (or supporting geometry i.e. jigs, wedges etc.). Taking in to consideration these elements will ensure significant benefits during manufacturing.

## PRINCIPLE 4: ELIMINATE AVOIDABLE HARM

### Principle Context

Lean design considers product safety as an important and highly sensitive issue which should not be neglected or overlooked under any circumstance. It is essential to address safety during conceptualisation to ensure the associated harm occurrence during the product lifecycle is identified and sufficient geometrical features, functions or mechanisms are in place to ensure its elimination.

The two common circumstances where a product might become unsafe are:

- The product has not been manufactured as intended by the company; even though the concept is functionally safe however due to a defect caused during manufacture it has become un-safe.

*Possible scenario: the rotating mechanism in an office chair fails to engage causing the end-user to fall*

- The second circumstance is the product has been manufactured and functions as intended however the product is still unsafe due to a design defect.

*Possible scenario: when engaging the retractable lever of an office chair the end user traps their fingers unexpectedly.*

## Principle Considerations

Designers usually develop products based on pre-assumptions of who and how will use them. In order to create safe and easy to use products it is essential to gather information regarding the (1) user, (2) their behaviour and (3) the environment. This principle forces the designer to take in to account ergonomics, anthropometrics and specific harms associate with the manufacturing process and the extremes of the environment or operation and service. Features, functions and mechanisms are to be carefully embedded in to design to completely eliminate harm for the end-user, manufacturing/service engineer.

**Eliminate harm example:** *MedPro Passive Safety Hypodermic Syringe*

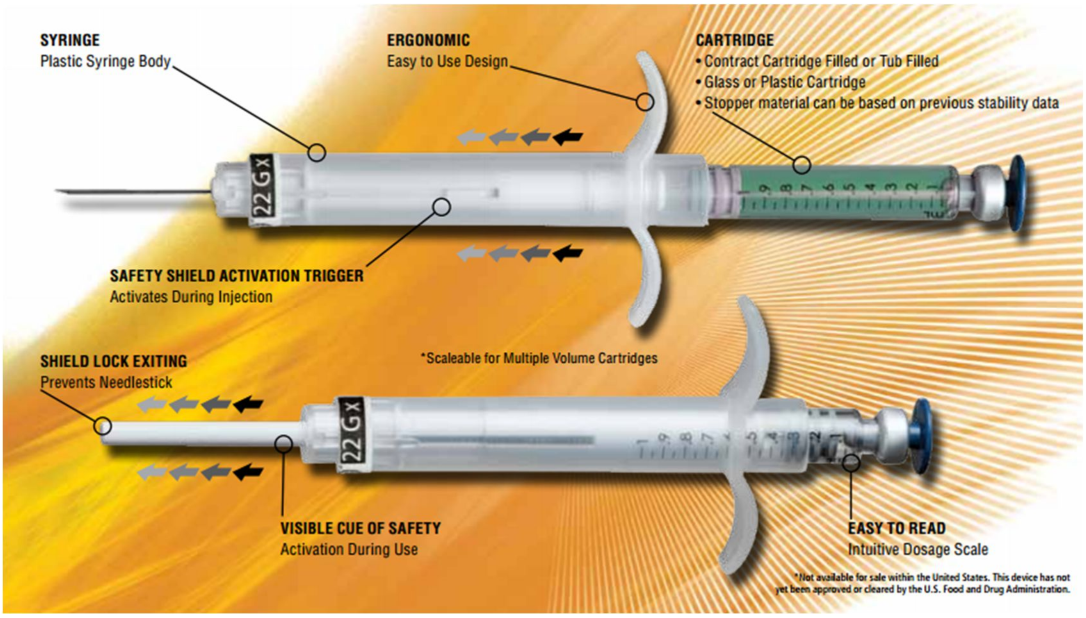



Figure 5-9: Passive auto release protection syringe design (MedPro, 2014)

This is a novel concept in drug delivery; the syringe has been designed to be automatically released only during injection of the drug. The safety shield provides immediate cover over the needle following drug administration to the patient. This design is a demonstration of elimination of harm occurrence, as stated earlier; it takes in to consideration the user, the behaviour and the environment in order to ensure all-round safety.

## PRINCIPLE 5: MINIMISE WASTE

### Principle Context

The fifth lean design principle is minimising waste or 'designing out waste'. By focusing on minimising waste during earlier parts of the design offers the greatest opportunity to control and minimise waste as opposed to managing and preventing waste during production. In context, minimising waste is the process of undertaking the required geometrical modifications in controlling the amount of waste generated during manufacture. Waste generation is inevitable during production however, through careful design there is an opportunity to control it 'at the source'.

Designing to minimise waste asks the following question:

*Can the amount of waste being produced as a result of realising this geometry be minimised, if not eliminated?*

Because lean design is concerned with the co-development of geometry with the manufacturing process, waste minimisation needs to be viewed from both perspectives:

| **Product design** | **Process design** |
|---|---|
| Eliminate non-value adding function/feature/mechanism<br><br>Eliminate non-conformance features/mechanism that generates an excessive amount of waste during manufacture | Seek to eliminate non-value adding activities required during the realisation of the geometry |

### Principle Considerations

Anything that does not add value to the end is considered wasteful and must be a target for elimination. The seven lean manufacturing wastes are used as governance criteria, which need to be addressed by the designer. The successful implementation of this principle rests upon the sound understanding of the manufacturing process and a strong communication between manufacturing engineers and designers to make conjoint decisions.

## PRINCIPLE 6: MINIMISE RESOURCES

### Principle Context

Lean design aims to produce cleaner product designs through the minimisation of environmental impacts; by reducing the resources required during production, in use and operations. The potential benefits of considering this principle during conceptualisation are as follows:

- Cost reduction during production
- Adherence to government legislations
- Improved design life

### Principle Considerations

Designers are responsible for collecting information regarding the product, its manufacturing and end-of-life options. Followed by in-depth review of the relevant legislations to identify the compliancy with current and future legislations. Designers must take in to account the impact of the product through out the product life cycle and aim to develop a solution that minimised the amount of resources required, these considerations include the following:

- Raw material
- Manufacturing
- Distribution
- In-use and service
- End of life (disposal and recycling)

The proceeding section will discuss the focus of lean design and the application of the lean design principles in relation to the geometry. The section also aims to clarify what is meant by: lean features, lean functions and lean mechanisms.

## 5.4 Lean Design focus: product geometry

Lean design is focused at the geometry level and the impacts of the different aspects of a working product. To simplify the process, the author bases the product breakdown using a similar approach as Qian and Gero (1996). They developed a concept of breaking a product in to three areas of function, structure and behaviour.

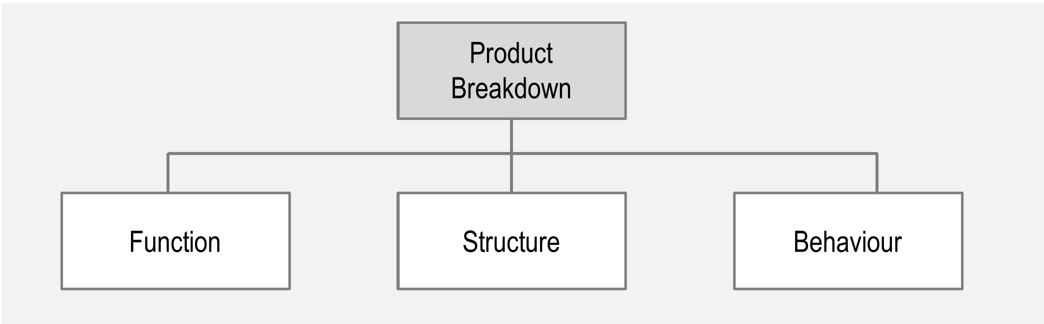



Figure 5-10: Product breakdown (adopted from Qian and Gero, 1996)

The three areas and their relationship to lean design are described in further details.

**Structure**

The simplest way to define the structure of a product is the physical elements that are used to make a product. Qian and Gero (1996) further break the concept of the structure down in to three further features:

1. Elements: a physical entity within a design
2. Attributes: the properties of an element i.e. the colour, material etc.
3. Relationship: the physical connection between two or more elements, this can be ‘fixed relationship’ e.g. the window structure, or a ‘changeable relationship’ e.g. a lock and key

The structure can be considered the most important aspect of lean design, because it is in a position to orchestrate the outcome of the product, i.e. the function and behaviour.

**Function**

The function of a design is a description of its purpose. Wirth and O'Rorke (cited by Qian and Gero, 1996) state that a function is "a relationship between the input and output of energy, material and information, or the manipulation of the fluxes of energy, material and information." Functions are defined using verb objectives, for example, the function of a tap is to control water flow. Understanding the function of a new design will help demonstrate its behaviour and thus, co-relate to its structure.

**Behaviour**

The behaviour of a design is the action of its structure. Qian and Gero (1996) consider two forms of behaviour:

1. Direct: a behaviour that is a fixed, direct result of a structure. The example that Qian and gero offer is that of a floor which is directly generated from the dimensions of a room's width and length.
2. Indirect: a behaviour that occurs when an element/structure is applied to another structure but is not considered part of the design make-up. The best example given here is the design of a tap water where water is an integral part of the performance but is not part of the taps design. However, the behaviour of the water is determined by the taps design.

The behaviour of a design is a critical part of understanding lean design, especially when considering that an indirect behaviour where an integral part of a design is could be the end-user, manufacturing/servicing engineer. The same structure/behaviour/function relationship has been modified and applied to Lean

Design. The terminology used is shown in Figure 5-10. Element has been replaced with a more specific terminology which include feature and mechanism. A feature can be explained as a prominent geometrical aspect of a product (or a collection of features combined to form associative features). A mechanism refers to the collection of multiple features working together for an intended function.

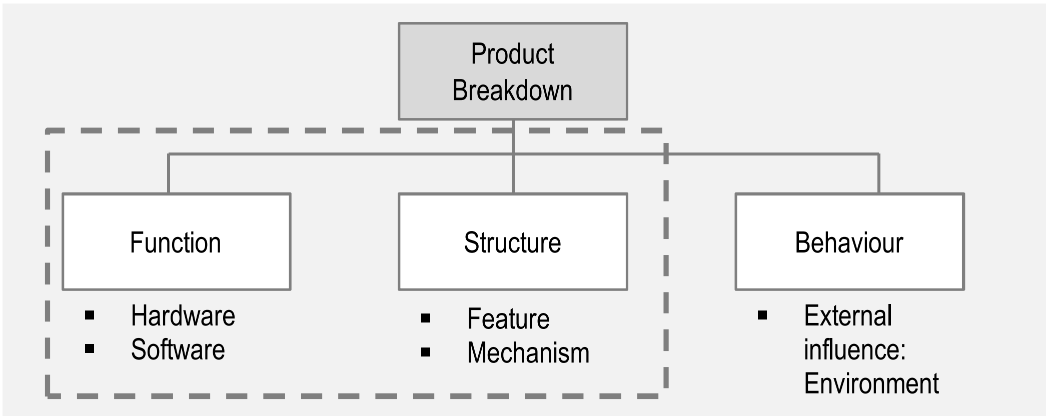



Figure 5-11: Modified product breakdown

This change offers a clearer scope of terminology when understanding lean design. The concept of lean design can thus be seen as:

*Lean Function + Lean Structure = Lean design*

Collective definition of lean feature, function and mechanism: working aspects of a product that ensure maximum customer value representation while ensuring the deployment of product quality with a safe transition to manufacture, operation and service.

**Lean function attributes:** encourage multiple functionality (reducing functions and combining/substituting function wherever possible) to ensure less geometry is required which is accordance with the lean design principles.

**Lean feature/mechanism attributes:** cost effective geometrical structure that achieves the intended function that is conceived according to the lean design principles.

## 5.5 Summary

This Chapter has achieved in establishing the foundations and principles of lean design by following a scientific process. Based on the findings from literature and field study the author was able to populate the lean design principles which can be considered the core of lean design. The principles are generic in nature and are to be considered during conceptualisation for the application of generating lean concepts. Details of a typical product breakdown were explained which clarified the meaning of lean feature, function and mechanism.

In order to apply the lean design principles effectively a systemised framework is necessary which ensures a logical sequence of activities needed to be followed in order to achieve a lean design. The details of the framework are illustrated in the form of guidelines that are to be used by designers during conceptualisation; this has been thoroughly discussed in the proceeding chapter.

# Chapter 6

# LEAN DESIGN FRAMEWORK

## 6.1 Introduction

The third objective of the research is to develop lean design framework which encompasses guidelines and it associated processes that will support the generation of conceptual lean designs. Details of how this objective has been achieved are explained in Section 6.2, a detailed description of the Lean Design Framework is discussed in Section 6.3. A summary of the chapter is presented in the final section.

## 6.2 Lean Design Framework development

The development of the lean design framework was achieved by following a logical sequence, which has been illustrated in Figure 6-1.

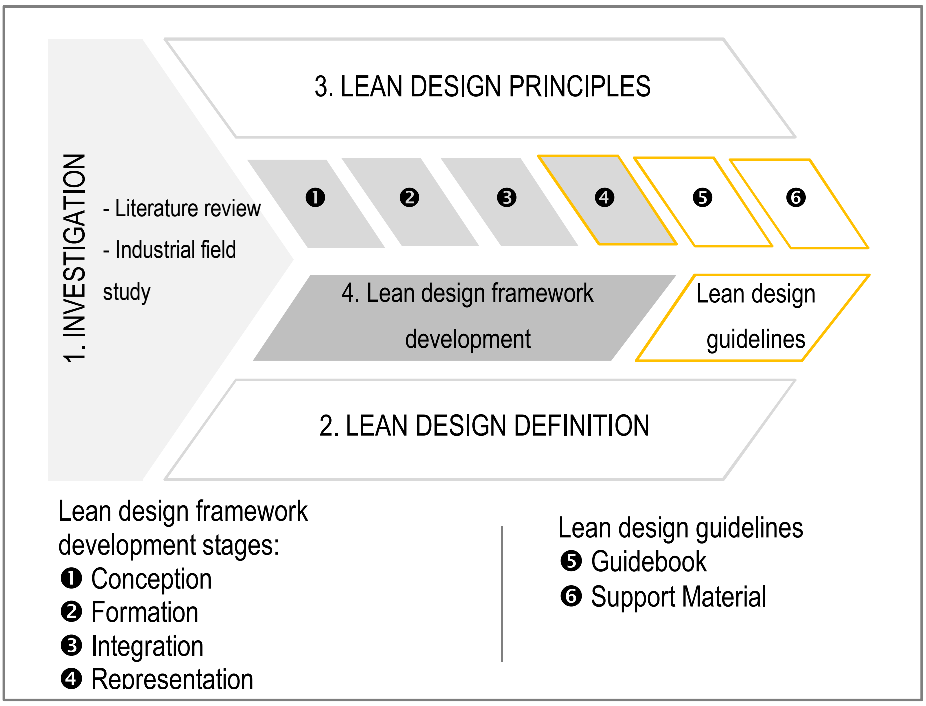



Figure 6-1: Lean design framework development process

The lean design definition and principles, which were an outcome of an extensive literature review and an industrial field study, alone, do not offer sufficient resource to the designer in achieving a conceptual lean design. It was therefore necessary to develop a lean design framework that would encapsulate the lean design principles and would cover the essential dimensions of lean design in a systematic process. The development of the framework consisted of four stages, as highlighted in Figure 6-1 and as an outcome of the development, lean design guidelines were generated, which consisted of a guidebook and its support material. A description of the lean design framework development stages is presented:

**Stage 1: Conception**

In the beginning, the following questions were posed: (1) what is the purpose of the framework? (2) Who is the target audience? And (3) what is the scope?

The purpose of the framework was to design and develop a framework that would be based on lean design principles, which would inspire designers to incorporate lean type thinking earlier at the conceptual design. The intended target audience was designers that are heavily involved in conceptualisation. The scope of the framework would be limited to the following: (1) providing sufficient educational resource on topics related to lean design, (2) give a clear direction of the activities and tasks required in a systemised method and (3) direct the designers to further sources for additional support or study.

**Stage 2: Formation**

The formation stage was comprehensively influenced with in-depth studies and conducting workshops with partners form the consortium. The intent of this stage was to identify and develop the contents of the framework and then to identify the most suitable method of organising it. During this stage it was decided that the lean design framework would be based on sequential phases, which would cover certain activities that would be required from the designers. This approach was adopted due to its flexible nature; it would cover pre and post activities pertaining to design. Pre-design activities would ensure familiarisation and preparation, and post-design activates would promote refining the design until a satisfactory level of leanness was achieved. A discussion on the contents of the framework is presented in Section 6.3.

**Stage 3: Integration**

The third stage of the framework development was associated with integrating the contents of the framework and achieving a balance. The flow between phases was made consistent, and unnecessary activities were as a result removed from the framework. Furthermore, the contents of the framework were thoroughly reviewed to ensure sufficient information availability.

**Stage 4: Representation**

The final stage of the development was to identify the most applicable representation of the framework that would suit its intended audience. From the available possibilities, it was decided the framework would be housed in an illustrative guidebook which would provide guidelines on how to generate a lean design. The lean design guidelines would make use of different type's information, for example: design rules, recommendations of tools/techniques, illustrative examples etc.

## 6.3 Lean Design Framework overview

The previous section described the four stages of the lean design framework development; this section presents the framework with a description of its contents. During the discussion references have been made to the lean design guidelines and support material which can be found in Appendix B.1 B.2, for example *P2-SM-PS*, refers to Phase 2 Support Material – Product Simplification.

## LEAN DESIGN FRAMEWORK

### Preliminary Phase

***Activity 1:** Scenario identification* → ***Activity 2:** Capture prerequisite information*

**Activity 1:**
- ☐ Selection from predefined lean design scenario

**Activity 2:**
- ☐ Capture product requirements and identify design objectives

Phase output: lean design pathway | *Proceed to Phase 1: Define.*

### Phase 1: Define

***Activity 1:** Product familiarisation & decomposition* → ***Activity 2:** Focus lean design efforts*

**Activity 1:**
- ☐ Lean out functions (supplementary/optional)
- ☐ Establish a value focus

**Activity 2:**
- ☐ Review geometry based on lean assessment
- ☐ Perform a cost breakdown

Phase output: (1) Clarified design objectives and (2) Un-lean product characteristics | *Proceed to Phase 2: Design.*

### Phase: Design

***Activity 1:** Generate/modify geometry based on Lean Design Principles*

- ☐ Maximise value
- ☐ Simplify product
- ☐ Simultaneous consideration of lean manufacture
- ☐ Eliminate associated harm
- ☐ Minimise waste
- ☐ Minimise resources

Phase output: Lean geometry that is in accordance with the lean design principles *Proceed to Phase 3: Refine.*

### Phase: Refine

***Activity 1:** Review design quality* → ***Activity 2:** Refine geometry*

**Activity 1:**
- ☐ Sub-system review against lean design principles
- ☐ System review and sub-system synergy

**Activity 2:**
- ☐ Refine geometry to ensure conformance of lean design principles

Phase output: refined geometry that complies with lean design principles | *Proceed to Phase 4: Finalise.*

### Phase: Finalise

***Activity 1:** Design autorisation* → ***Activity 2:** Finalisation and documentation*

**Activity 1:**
- ☐ Authorise the design through a design review

**Activity 2:**
- ☐ Freeze and document the concept in the lean design portfolio

Phase output: Finalised design that has been authorised and all geometry frozen

Figure 6-2: Lean design framework overview

Lean design is based on sequential phases which represent a distinct aspect of the framework; each phase consists of activities and tasks in order to achieve the required output. An insight in to the aim, objectives, activities and output of each phase is discussed in the proceeding subsections.

### 6.3.1 Preliminary phase and initial considerations

The aim of this preliminary phase is to identify the problem statement and select the required lean design pathway, which determines the proceeding design activities. Lean design is formed on possible design scenarios that are typically encountered at the start of design projects. As shown in Figure 6-3, there are three available scenarios: (1) lean out an existing design, (2) consider lean from the beginning or (3) lean out based on feedback from the Product Life Cycle i.e. manufacturing, tooling, service etc.

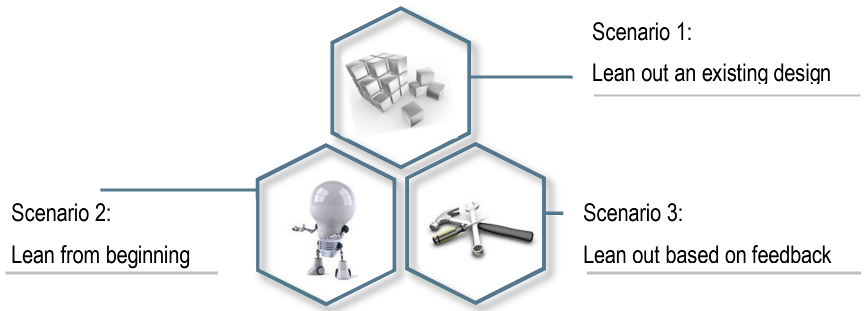



Figure 6-3: Predefined lean design scenarios

Due to time constraints this research was able to only formulate the required pathway for scenario 1: lean out an existing design. After selecting the relevant scenario, the next activity is: Capture prerequisite information. In this activity designers are required to capture customer requirements and identify design objectives ensuring ambiguity is resolved form the beginning. The purpose of this activity is to establish a clear focus at the beginning of the product. After completing these two tasks, the designers are required to proceed to the first phase, which is Define.

### 6.3.2 Lean Design Framework Phase 1: Define

The first phase of the lean design framework is 'Define', it aims to identify the problem statement and the required design efforts for the proceeding design phase. In order to achieve this, two key objectives must be accomplished, firstly to identify the design requirements and to lean out product functions which as a result will help to establish a clear value focus. Secondly, focus lean design efforts by performing a cost breakdown and relating values to sub-systems, as displayed in Figure 6-4. The level of information required in this phase is extensive; this is to ensure a complete understanding of the product and its principle objectives. This is achieved through the aforementioned sequence of activities.

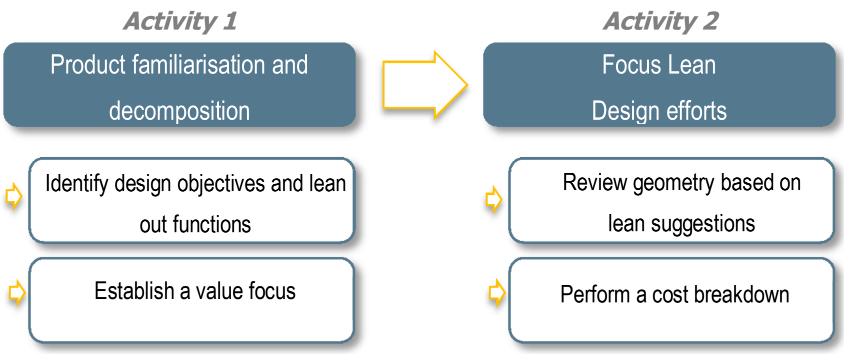



Figure 6-4: Phase 1 activity process

#### Activity 1: Product Familiarisation and decomposition

Failure to correctly define requirements can impact customer expectations and product reliability and could results in costly rectification. In this activity, the first task to be performed is: *identify product requirements and lean-out functions.* Designers are suggested to conduct a client participation focus group to capture the perceptions, opinions and attitudes of the stakeholders. Within the Lean Design Guidelines, as an aid to writing good requirements, '10 commandments of writing requirements' is provided furthermore a detailed list of steps to be followed during the focus group is also listed.

The second task is to *establish value focus*; this is achieved by drawing upon primary product functions and identifies essential customer values that will be maximised during the design phase. A detailed description of what is value in context and three examples of value maximisation proposition have been illustrated in P1-SM-03, as recorded in Appendix B.2.

**Activity 2: Focus lean design efforts**

In continuation from the previous activity, designers are required to engage with the existing geometry by focusing lean design efforts. The aim of this activity is to identify the lean design efforts required during design, this is achieved by performing two tasks: (1) relate values to the sub-system followed by a review of product geometry to identify un-lean characteristics, and (2) conduct a cost breakdown of the existing design to identify areas of improvement.

The first task is achieved by performing a brainstorming session that aims to relate the values directly to the product geometry and identify geometrical constraints and levels of feasibility. In continuation of this activity, the proceeding task is to identify the intent for geometrical reasoning and identification of un-lean characteristics by reviewing the sub-system; this is achieved using a checklist, which has been partly illustrated in Figure 6-5.

| Product Design | Yes | No | Partly |
|---|---|---|---|
| 1.The product has mistake-proofing designed in to it to ensure it is manufactured and can be operated without mistakes occurring | ☐ | ☐ | ☐ |
| 2.The product has been designed with manufacturing process simplification in mind | ☐ | ☐ | ☐ |
| 3.The design has made use of Computer Aided Engineering software for technical components to reduce test work | ☐ | ☐ | ☐ |
| 4.The product has unproven functionalities, technologies, software etc. that are not understood or fully proven in this specific application | ☐ | ☐ | ☐ |
| 5.The product uses many features to deliver the functions and there is an opportunity to combine functions and reduce parts | ☐ | ☐ | ☐ |
| 6.The sub-assembly architecture has been modularised | ☐ | ☐ | ☐ |
| 7.The product contains unpredictable features which are inconsistent and difficult to manufacture and maintain | ☐ | ☐ | ☐ |
| 8.The design has made use of standardisation (if no which parts could be standardised to enhance manufacturing without compromising performance) | ☐ | ☐ | ☐ |
| 9.Design features have been developed to ensure harm to the end user and environment of operation are eliminated | ☐ | ☐ | ☐ |
| 10.Have you had frequent exchange of information and co-design with suppliers to reduce expenses while preserving and improving product integrity | ☐ | ☐ | ☐ |

Figure 6-5: checklist for identifying un-lean characteristics

The checklist consists of generic statements related to product design, manufacture and service. The statements seek to challenge geometrical reasoning and aim to bring to surface any un-lean characteristics within the design, which can be given first priority during design modification; the complete checklist is listed under P2-SM-05, in Appendix B.2.

The second task in this activity is to set *a target cost* for determining the cost of the design, by taking in to consideration: specified functions, performance targets, value maximisation propositions and product quality to ensure profitability at the products anticipated selling price. The purpose of utilising target costing in this phase is the lean design journey is to control the design cost and design out excessive, undesirable costs as opposed to eliminating cost once the design is in production. This is achieved by conducting the steps listed in Table 6-1.

Table 6-1: Steps to be followed during target costing

| |
|---|
| (1) Determine a competitive price based on the customers requirements |
| The marketing department will need to establish a 'Target Price' which is competitive and market driven. Factors such as the companies position in the market, the business penetration strategy, competitors pricing for similar products etc. |
| (2.a) Deduction of an appropriate profit margin from the target price |
| Marketing department will establish a 'Target Profit' by deducing a profit margin from the target price |
| (2.b) Perform a cost breakdown of the current design |
| The design team is required to perform a cost break down of the product, identifying the areas of waste and resource consumption. Calculation of material, manufacturing, labour and other costs for each sub-system should be performed. |
| (3) Set a target price and cost target – taking in to consideration drifting costs |
| A target price and cost target should be set whilst taking in to consideration reasonable drifting costs. Drifting costs are short runs when a desired target is not achieved and a compromise is required. The design team must strive to achieve the target cost. |
| (4) Endeavour to achieve the target cost through redesigning the product with lean design principles |
| Using must base their design activities around the lean design principles and apply the tools and techniques to ensure a lean design is generated which is in line with the target cost |

After completing the two activities in the first phase, designers are expected to have a sound understanding of the product, the current design imperfections and what is required to ensure optimisation.

### 6.3.3 Lean Design Framework Phase 2: Design

Phase two can be considered the most critical aspect of the framework as it is directly related to the design. The principle aim is to explore design solutions through divergent thinking to generate a lean design that is based on the lean design principles. Its primary objective is to address un-lean characteristics from Phase 1, maximise value representation, ensuring manufacturability, elimination of harm, minimising waste and resources in a cost effective manner.

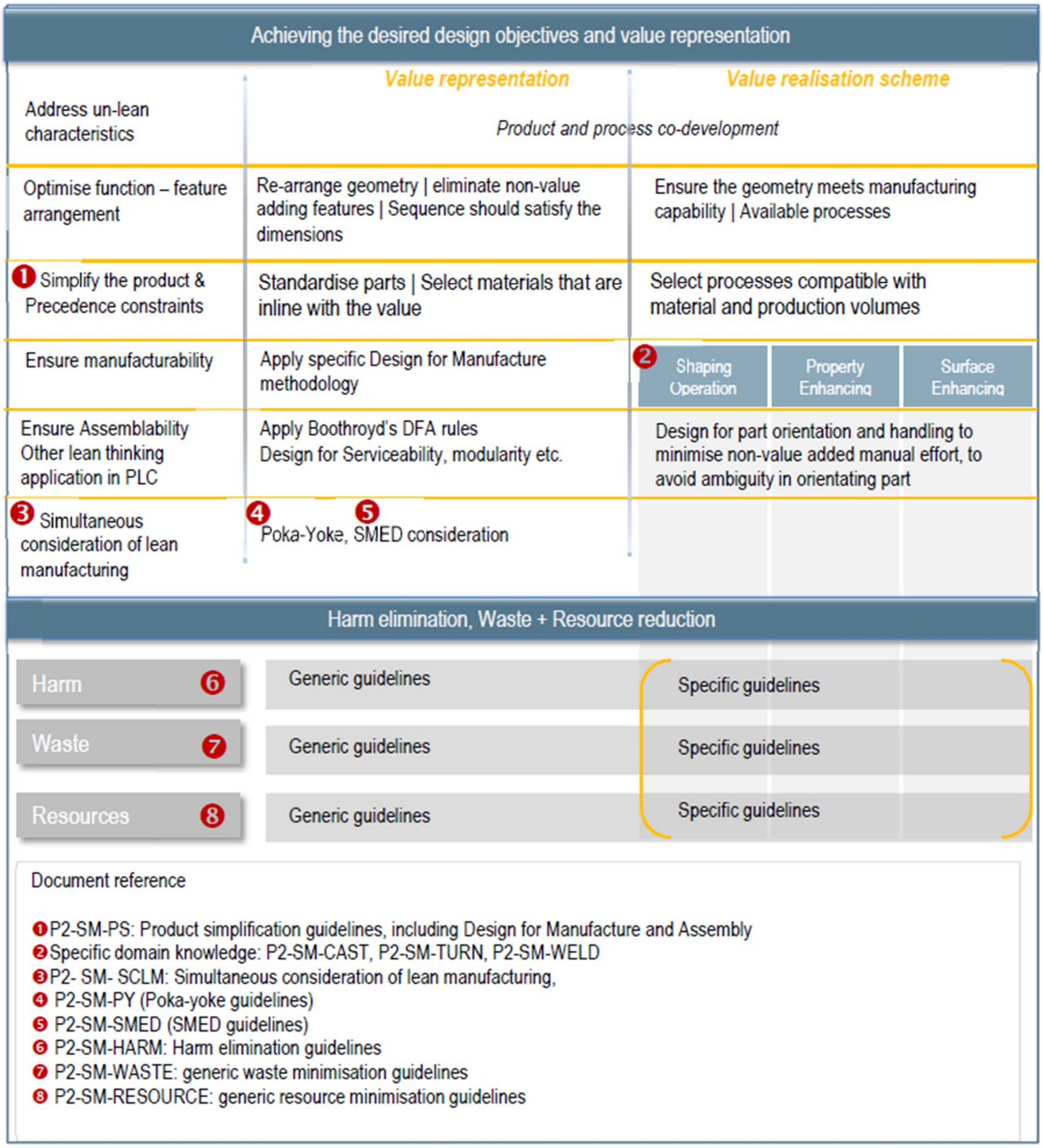



Figure 6-6: Phase 2 lean design navigator

The design phase seeks to implement the lean design principles to ensure a lean design is generated. It achieves this through the lean design navigator, which provides a sequence of design activities that must be employed; this can be seen in Figure 6-6, contents of the support material are listed in Table 6-2.

Table 6-2: Support material content description

| Document reference | Content description |
|---|---|
| P2-SM-PS | (1) Generic design rules for: product simplification, manufacture and assembly |
| P2-SM-CAST | (1) Specific Design rules (2) waste minimisation (3) resource minimisation (4) harm elimination |
| P2-SM-TURN | (1) Specific design rules (2) waste minimisation (3) resource minimisation (4) harm elimination |
| P2-SM-WELD | (1) Specific design rules (2) waste minimisation (3) resource minimisation (4) harm elimination |
| P2-SM-SCLM | (1) Checklist |
| P2-SM-PY | (1) Design rules for 7 types of mistake-proofing (2) examples |
| P2-SM-SMED | (1) Examples of SMED features |
| P2-SM-HARM | (1) Eliminating harm considerations (2) Harm elimination checklist |
| P2-SM-WASTE | (1) Generic design considerations for minimising waste |
| P2-SM-RESOURCE | (2) Generic design consideration for PLC resource minimisation |

The design initiates with addressing the un-lean characteristics identified from the previous phase, and aims to optimise the feature function arrangement. Using the support material P2-SM-PS, designers are required to simplify the design, ensure manufacturing capabilities are met and Design for Assembly rules are implemented. The nature of these rules and design consideration is generic. However, domain knowledge for shaping, property enhancing and finishing is more specific – furthermore details of minimising waste and resources and eliminating harm associated with these operations is also described in the relevant documents.

The current status of Simultaneous Consideration of Lean Manufacturing is still under-developed and requires further investigation to ensure all of its aspects as discussed in Section 5.3.2; however two key aspects i.e. Poka-Yoke (mistake-proofing) and SMED are addressed. It is compulsory for designers to consider Poka-Yoke and apply SMED wherever possible. Generic rules for seven categories of mistake-proofing supported with examples are provided in P2-SM-PY which provides sufficient guidance on ensuring the design is mistake-proofed. Consideration of SMED has been described in P2-SM-SMED examples of typical SMED features has been presented which can be incorporated in to the design to ensure set-up time is reduced.

Design considerations for specific domain knowledge cover waste and resource minimisation and harm elimination aspects; however support material for generic considerations have also been provided. For example P2-SM-HARM provides instructions on how harm can be eliminated in general design terms. Similarly P2-SM-WASTE and P2-SM-RESOURCE provide generic design considerations.

Successful generation of lean concepts is primarily associated with the correct understanding and execution of the information recorded in the support material. At the end of Phase 2, Designers are encouraged to review the design against the process map and its checklist (which has been illustrated in Figure 6-7). The purpose of this is to ensure the required sequences of activities have been followed and all necessary elements have been covered. For example, designers must initiate with product simplification and attest the recommendations for shaping, enhancing and finishing operations have been incorporated in to design. They must proceed by conforming the design has been verified against the mistake-proofing rules. This process continues to ensure the lean design principles have been considered, however in an instance of neglect or failure to conform, the design should not be able to progress further until the predicaments have not been resolved.

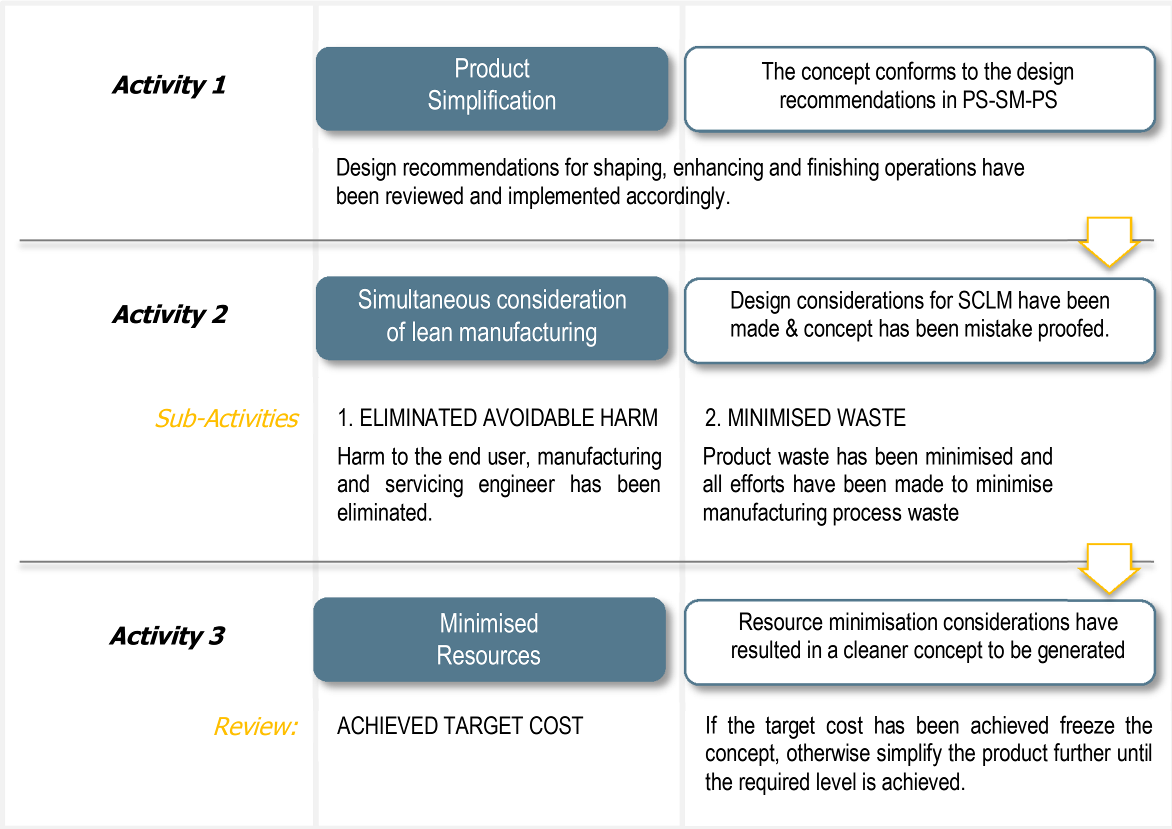



Figure 6-7: Phase 2 process map

### 6.3.4 Lean Design Framework Phase 3: Refine

Design refinement is an important phase of the framework, as it allows the designers to undertake necessary geometrical modifications to ensure the design conforms to the lean design principles. The three objectives of this phase are as follows: (1) review individual sub-system for leanness and further refinement, (2) bring together sub-systems to review the entire system for optimisation, which are to be completed in the first activity and (3) undertake necessary actions for lean design maximisation.

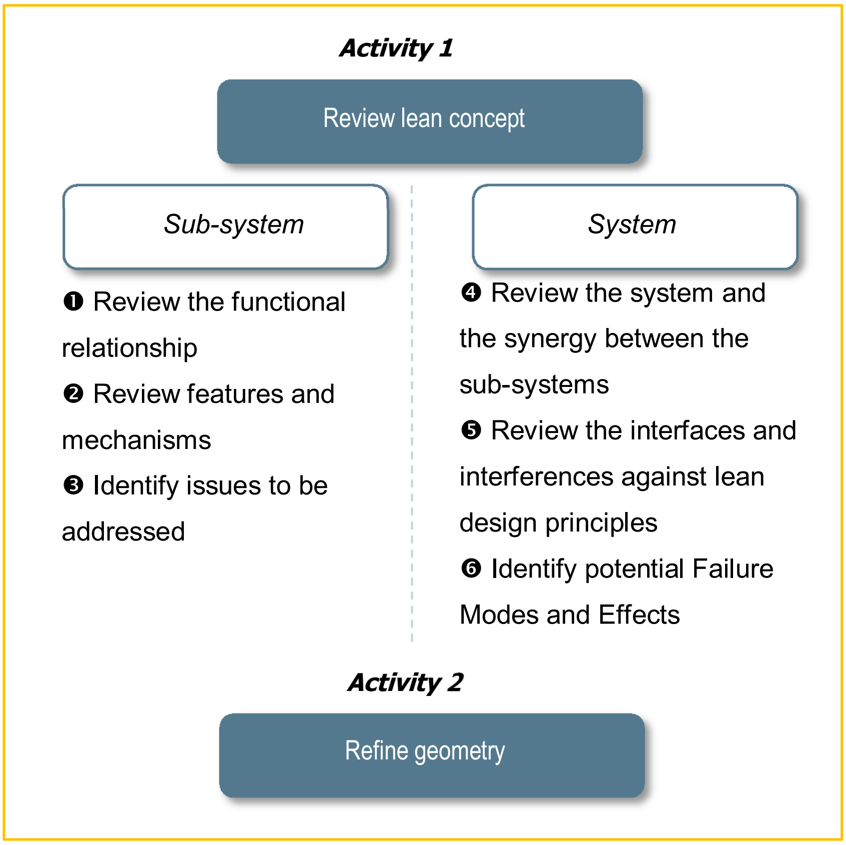



Figure 6-8: Phase 3 sequence of activities

Design refinement through design review allows designers to reminisce and communicate design intent, and aim towards improving the design. This is an opportunity to identify functional and geometrical inaccuracies with the design and provide a conflict resolution. The review initiates with the sub-system, functional relationships between features is evaluated through the application of lean design principle 1, the geometry is further simplified. This is then extended to the system level, synergy between sub-systems is essential to ensure consistency is maintained throughout the system. Complex systems such as the jet engine require substantial amount of effort to ensure design coherence and wholesomeness of the system. This is achieved by reviewing tolerances, interconnections between the sub-systems, the modularity and disassembly aspects of the design. The phase ceases with conducting a potential failure modes and effects. Designers are required to address all design predicaments before continuing to the proceeding phase.

### 6.3.5 Lean Design Framework Phase 4: Finalise

The final phase of the lean design frame work consists of two tasks; (1) design authorisation and (2) finalisation and documentation, as shown in Figure 6-9. The aim of the phase is to authorise the design, freeze and document geometry.

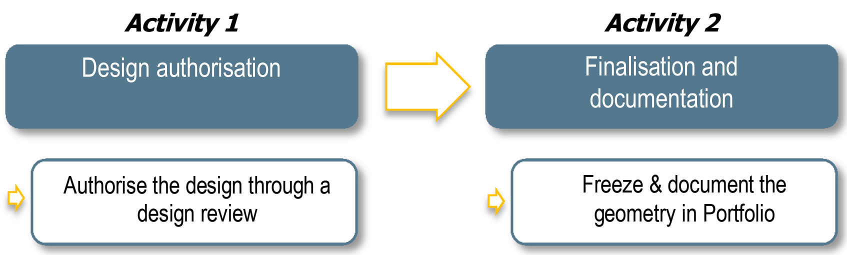



Figure 6-9: Phase 4 activity process

#### Activity 1: Design authorisation

The design review and authorisation is an evaluation process, which is to be conducted with an internal panel and later to be extended to stakeholders. The Design Review Process consists of three dimensions: conceptual design review, leanness review and creative direction review, as shown in Figure 6-10.

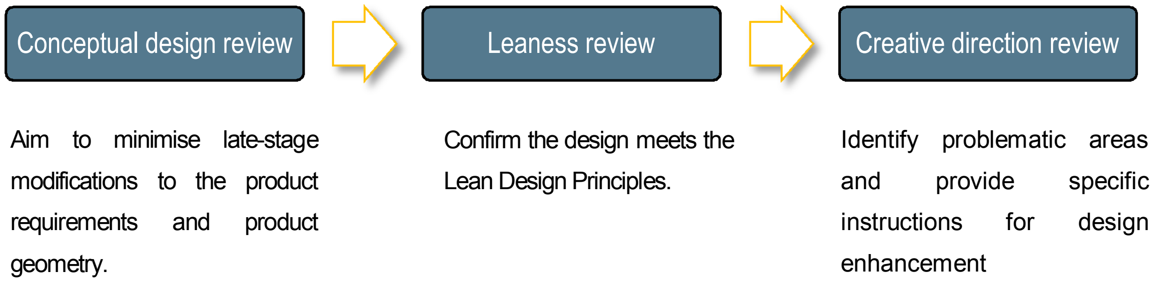



Figure 6-10: Design authorisation considerations

The lean design guidelines provides a detailed list of instructions for the three aforementioned dimensions and can be found in the support material under the document reference: P4-SM-01.

**Activity 2: Finalisation and documentation**

Once the design has been modified based on the suggestions from the previous task, designers are required to cease all design work and freeze the geometry, and document all the design work and document it in an executive report. An example of an executive report template has been provided in P4-SM-02.

## 6.4 Summary

The chapter has covered the third research objective by presenting the Lean Design Framework. A detailed discussion on the Framework has been presented, which categorically explains each phase, its activities and the tasks to be performed. The forthcoming chapter validates the lean design guidelines with an industrial case study to achieve a leaner design. The contents of the guidelines are also validated with expert opinion.

# Chapter 7

# VALIDATION OF LEAN DESIGN FRAMEWORK

## 7.1 Introduction

This chapter is presenting the validation of the Lean Design Framework which has been presented in Chapter 6, through the application of an industrial case study and qualitative validation through experts. The chapter has been organised in to five sections, after the introduction in Section 7.1, the case study plan is presented in Section 7.2. Details of the case study and theoretical background are explained in Section 7.3. In Section 7.4 the implementation of the Lean Design Framework with the case study to achieve a leaner design is discussed, and finally the chapter ceases with a summary in Section 7.5.

## 7.2 Case study plan

Based on the works of Neale et al. (2006), the author was able to devise a plan for the case study which consists of five phases, as shown in Table 7-1. The first phase was concerned with preliminary planning, the type of case study relevant for validation and the required information for successful completion of the case study were identified. Phase two was concerned with data accumulation i.e. performing necessary interviews and workshops. The analysis of the relevant material such as reviewing geometrical designs, engineering data and 2D drawings was performed in Phase three. Implementation of the Lean Design Framework to generate a leaner alternative solution was achieved in Phase four, and finally in Phase five the findings from the case study were documented and organised in the Lean Design Portfolio which can be found in Appendix C.1.

Table 7-1: Case study plan (adopted from Neale, et al. 2006)

| 1. PLANNING |
|---|
| Brainstorm a case study topic, considering the types of cases and why they are unique or of interest |
| Identify what information is needed and from whom |
| Identify any documents/materials needed for the review |
| List stakeholders to be interviewed or surveyed |
| Ensure research will follow international and national ethical research standards |
| **2. COLLECT DATA** |
| Gather all relevant documents |
| Set up interviews/survey/workshops with stakeholders |
| **3. ANALYSE DATA** |
| Review all relevant material |
| Review all interviews/survey data |
| **4. IMPLEMENT LEAN DESIGN FRAMEWORK** |
| Apply the relevant tools in Phase 1 of the Lean Design Guidelines to define the case |
| Apply the Lean Design Principles in Phase 2 to generate lean feature, function, mechanism |
| Generate a leaner alternative engineering solution |
| **5. DISSEMINATE FINDINGS** |
| Compile the findings in the Lean Design portfolio |
| Solicit feedback |
| Revise and disseminate |

## 7.3 Validation through case study

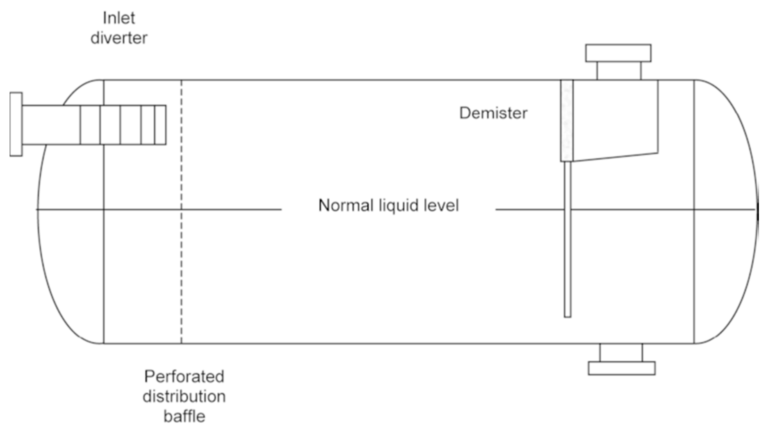
An industrial case study with a specialist design firm that develops equipment and offers practical solutions for improving production of oil and gas wells for the petroleum sector was selected. The study initiated with identifying a potential case study which would allow the author exercise the developed framework and principles, as a consequence an oil/water separator was selected. A team was organised which consisted of the collaborating company and researchers from the university. Each participant was given individual research topics for investigation. The researchers were given access to the companies' resources and were able to engage with the engineers and conduct workshops throughout the study. Ti (2011) and Kumar (2011) were responsible for identifying alternative design and manufacturing engineering solutions for the oil/water separator. The researcher adopted a traditional approach; by conducting a QFD workshop, applying Boothroyd's DFMA rules and evaluating alternative solutions with respect to cost and time. The author was responsible for the realisation of a leaner concept through the implementation of the Lean Design Framework. The discussion on the theoretical background for the oil/water separator case study is presented in the proceeding sub-section followed by a description of the problem statement and case study objectives.

### 7.3.1 Theoretical background of oil/water case study

An ongoing increase in global energy demands has caused the petroleum sector to expand its operations to multiple regions on the globe. Typically small amounts of natural gas and oil percolate through the earth's surface; majority of the oil and gas is extracted from the continental shelf or through underground reservoirs (Olah, 2005). Statistical information provided by the Oil Industry International Exploration and Production Forum (2015) highlights the significance of offshore production, for example it accounts for 30 percent of the world's oil and approximately half of the world's natural gas production. A study conducted by the U.S National Research Council reports that are over 8000 fixed or floating offshore platforms are currently in operation throughout the world and are expected to proliferate as the demand for oil and gas increases.

A pressure vessel known as an oil/water separator is used in the extraction process of gaseous and liquid components from well streams. The separators can be installed either on offshore or platforms of onshore stations for additional refinement processes. Oil/water separating vessels are typically divided in to horizontal, vertical and spherical build ups; the configuration is usually determined by the amount of operating space available (Bennett and Richards, 2013). The separators can be grouped in to gas/liquid two-phase separators or oil/gas/water three phase separators, based on the principle function the separators can be further classifieds as test separator, deliquiliser, degassers, high and low-pressure separators etc. an example of a two phase and three phase horizontal separator is shown in Figure 7-1.

A) Horizontal two-phase separator with inlet diverter, perforated distribution baffle and demister.




B) Horizontal three-phase separator with oil bucket and water weir, requiring no active interface control

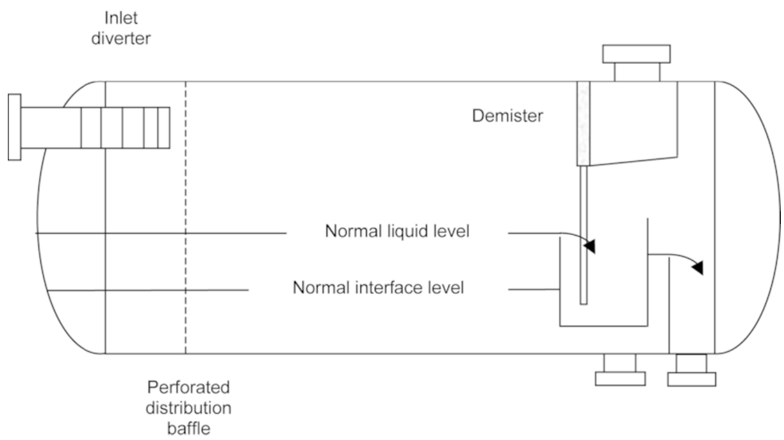



Figure 7-1: Horizontal three phase separator (Petrowiki 2015b)

In order to meet process requirements the separators are designed in a number of stages, the first stage is associated with preliminary separation, the second and third stage are associated with further treatment such as removing dispersed droplets from the gas stream or removal of contaminants from liquid streams (Petrowiki, 2015).

Statistical data provided by BP (2013) has identified the total world energy consumption at 8000 million tonnes of oil equivalent, the international community is relying heavily on oil and gas supplies as it accounts for 63 percent of the worlds energy supply. Coal provides 27 percent; nuclear energy is providing 7 percent and hydro electrical accounts for only 3 percent. In order to meet the world energy demands, exploitation of oil and gas reserves requires ecological considerations which provide a sustainable economic return.

Conventional production facilities have been used by the petroleum industry for low- risk to life-cycle operations. The effects of current downturn and unstable oil prices have motivated industry into evaluating technologies. Operators are seeking novel ways to increase production capacity of exiting facilities whilst driving down costs. Enhanced optimisation of operating space and system improvements as well as employing new separation technologies are expected to offer new developmental prospects,

The current research in to new developments of separation technologies has offered a cost effective alternative to traditional conventional separation methods that currently consume large surface areas. Some of the popular applications are lighter and more compact in terms of installation, require minimal planning as well as de-bottlenecking existing facilities layouts to accept production from new reservoirs. Furthermore, due to their reduced mechanical structure size they are considered suitable candidates for subsea and downhole processing, one of these new technologies is the cyclone which has been illustrated in Figure 7-2. Other alternative technologies include: downhole separation (DOWS), portable skids which are standalone-retrofits etc.

As a response to the aforementioned requirements of conventional separation methods, cyclone separation is starting to become more popular, which was initially introduced in mineral processing (Stone, 2007). Typically the word cyclone refers to a reverse flow cyclone, as illustrated in Figure 7-2 The cyclone consists of a conical chamber and an inlet connected to the top chamber, as the liquid enters in to the chamber from a tangential direction, it begins to rotate along the inner side of the chamber. Through the centrifugal force, during the spin the lighter fluid exits from the above chamber whilst the heavier fluid discharges through the underflow outlet.

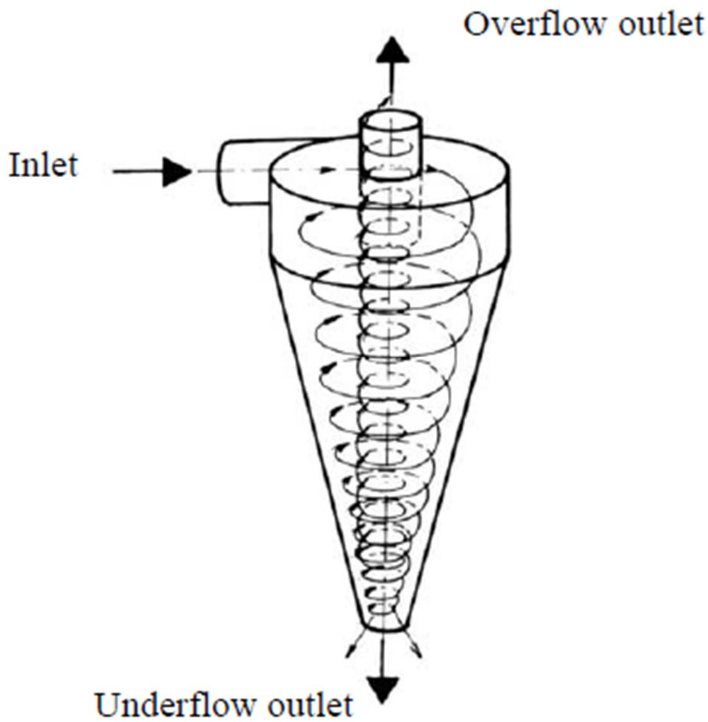
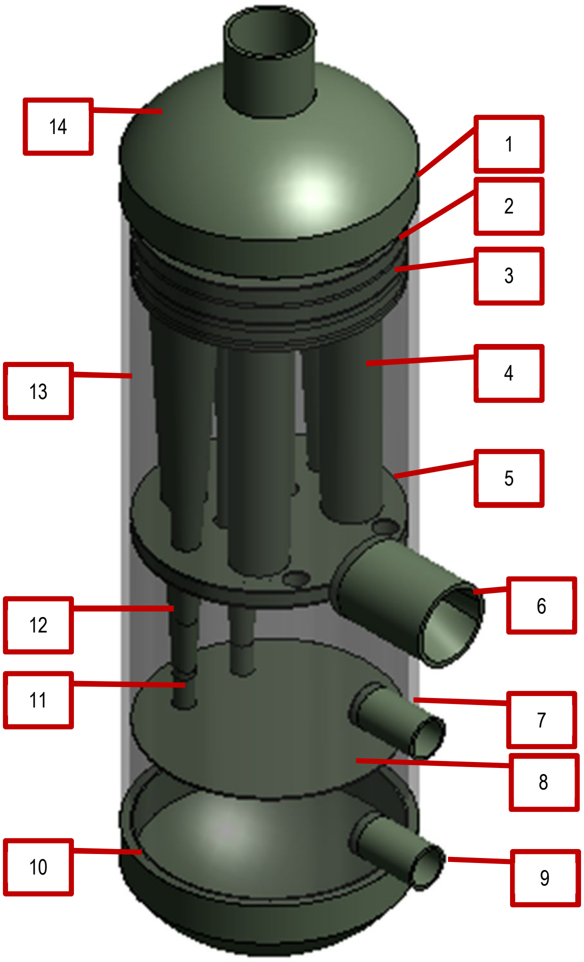



Figure 7-2: Example of a typical reverse flow cyclone

### 7.3.2 Description of selected case study

The current design of the oil/water separator provides satisfactory functional capabilities however falls short from achieving maximum attainable levels of reliability. Geometrically the current concept inhabits a number of ineffective design intricacies which can be resolved to ensure a leaner concept is realised; Figure 7-3 presents a product breakdown of the current standing concept. The following is an overall description of the initial concept.

- The compact structure ensures minimal surface area is utilised for operation
- As a standalone application, the separator requires minimum intervention in operation and maintenance as opposed to traditional separators that require human interference
- Due to its wholesome geometrical structure, pressure drops are minimised greatly ensuring a high level of oil is extracted




**Oil/water separator part breakdown**

| | |
|---|---|
| 1 | Top plate assembly |
| 2 | Oil plate assembly |
| 3 | Water plate assembly |
| 4 | Separation chamber |
| 5 | Inlet plate assembly |
| 6 | Inlet nozzle |
| 7 | Oil outlet |
| 8 | Divider plate |
| 9 | Water outlet |
| 10 | Base |
| 11 | Water cyclone |
| 12 | Oil Cyclone |
| 13 | Outer jacket |
| 14 | Dish end |

Figure 7-3: Oil/water separator part breakdown

## 7.4 Implementation of Lean Design Framework for application of oil/water separator

This section is presenting the step by step implementation of the framework, as explained in Section 6.3 to produce an enhanced design of an oil/water separator. For the purpose of the case study the preliminary, define and design stage of the framework will be considered, the refine and finalise stage deal with less technical details are not discussed. Furthermore, due to confidentiality reasons sensitive details relating to the case study have not been mentioned. The detailed case study has been recorded in the Lean Design Portfolio which can be found in Appendix C.1

### 7.4.1 Preliminary Phase

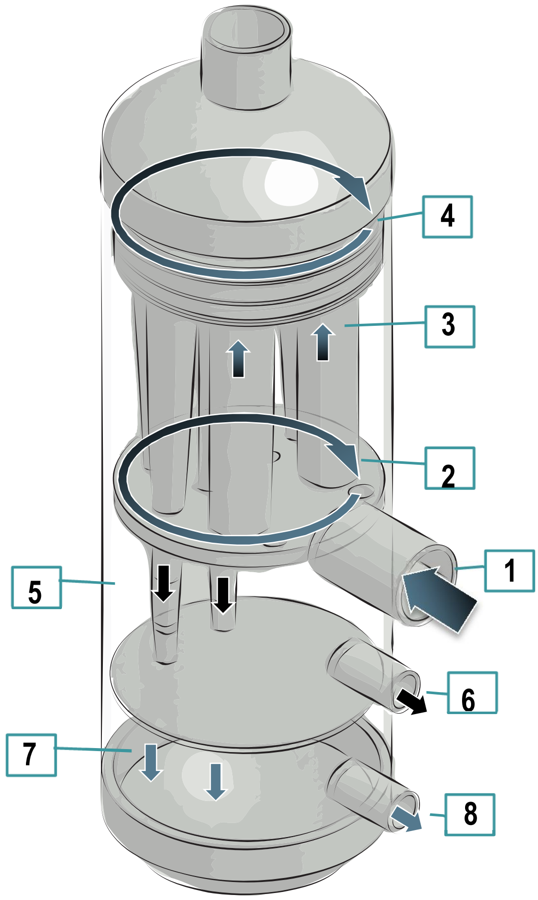
The implementation of the lean design framework for the application of the oil/water separator initiated with the preliminary phase.

*Activity 1: Scenario identification*

From the predefined list of lean design scenarios presented in Figure 6-2, Lean Out an existing design was selected. The circumstances of the case study were in accordance with the preconditions of this scenario, which included the occurrence of existing geometry and product reliability falling short of optimal achievable limits.

*Activity 2: Capture prerequisite information*

A technical workshop was conducted by the team, the functional aspects of the product was studied; customer and functional requirements were captured using a QFD Quality House (Kumar, 2011). Figure 7-4 provides a graphical illustration of mechanical mechanisms of the separator, of how the oil/water solution enters and follows the necessary paths until oil and water are separated and passed out through the outlets.




[1] Oil-water solution enters through the inlet nozzle

[2] The solution revolves in the inlet plate assembly

[3] The solution travels through the I-SEPs

[4] The solution is separated in the water and plate sub-assembly

[5] Oil travels through the oil cyclone

[6] Extracted oil exists through the oil outlet

[7] Separated water travels down the water cyclone

[8] Remaining water exists through the water cyclone

Figure 7-4: working mechanisms of the current oil/water separator

The functional requirements of the product are as follows: the internal flow path must have a surface finish of (1.6µm Ra), this is to ensure the fluid can circulate through the vessel without diverting its path and loosing momentum. The tolerance must be within the limits i.e. ±0.5mm, and the materials selected must be compatible within the temperature range of: -20 deg to 70 deg. In terms of pressure, the design must be 89 bar G and the differential pressure across thee device should be within the range of 0.5 to 1.6 bar. The separator has been designed for offshore production and therefore must be compatible with the atmospheric conditions; therefore the material must be resistant to salt water and oil and must show good resistance to erosion from sand. Furthermore the overall design must not exceed the internal weight of 432 Kg (approx.). Additional requirements include no change in basic geometry of flow which includes the involute curve, ease of installation, maintenance, inspection and cleaning.

From the workshop it was identified that it was in the interest of the case study to apply the Lean Design Framework to achieve the following design objectives: (1) maximise oil/water separation without compromising function and quality, (2) identify and alternative design solution to reduce cost and (3) seek to minimise the product surface area.

### 7.4.2 Phase 1: Define

Having successfully completed the implementation of Preliminary Phase, the study progressed by employing the necessary components of Phase 1: Define. This section provides an account of the implementation of the two key activities of this phase, which include: (1) Product familiarisation and decomposition and (2) Focus lean design efforts by reviewing geometry for un-lean characteristics.

*Activity 1: Product familiarisation and decomposition*

The primary objective of this activity was to establish a value focus. Through a discussion and brainstorming session the product attributes were thoroughly reviewed (i.e. performance attributes and the consequence of achieving desired goals from the oil/water separator) to derive values. The main value that was established was: Maximised oil/water separation, in order to achieve this the following considerations were necessary: (1) optimal separation would be achieved by reaching maximum G-Force (100), (2) Smooth internal finish, which must demonstrate adaptability to atmospheric conditions without causing obstruction during operation and (3) product surface area reduction by minimising product geometry shape and size whilst maintaining functionality to minimise operating costs. Detailed explanations of the findings from this activity have been recorded in Appendix C.1.

*Activity 2: Focus lean design efforts*

Task 1: The current design of the oil/water separator was thoroughly examined to identify un-lean characteristics; this was achieved based on the generic criteria, which can be found in Appendix B.2. The examination process consisted of reviewing the design elements and the manufacturing aspects of each sub-system. From the review the following un-lean characteristics were identified:

**a. Outer jacket**

The outer jacket encapsulates the inner components (as shown in Figure 7.3 as part 13) is currently built from a non-standard pipe, and the cost of manufacture is very high. Additionally, modifications (i.e. size and shape) have a cascading effect which impacts the internal components which are housed.

**b. Water cyclones**

The water cyclones are responsible for providing the different paths for oil and water, which have been illustrated in Figure 7-3 as part 11. Currently the cyclones are composed of six parts which are welded together to form the complete structure. Three of which are machined from solid bars and the remaining three are machined from pipes until the desired dimensions are achieved, as shown in Figure 7-5.

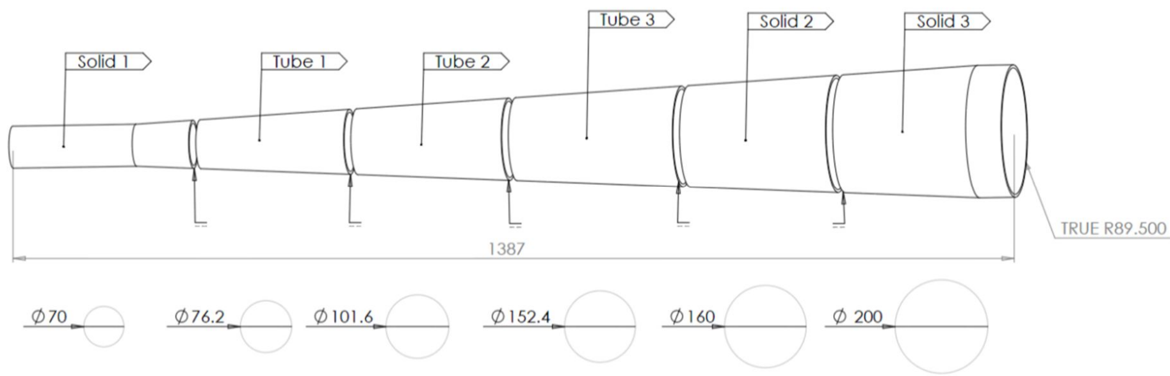



Figure 7-5: current design of water cyclone

There is currently a high level of waste due to machining, and the cyclones are prone to variation whilst welding the individual parts. The alignment of the six parts is essential to ensure the flow of the fluid is not hindered. The current design is manufactured from stainless steel; for optimal performance it requires a smooth internal finish and adaptability to atmospheric conditions.

### c. Inlet-Plate assembly

The oil/water solution enters through the oil/water separator through this sub-assembly and usually rotates up to 100G centrifugal force. The involute curve directs and separates the oil from the water. The plates are currently laser cut from non-standard sheet metal and then seal welded. This in turn generates a lot of material waste from the different sizes and should be minimised. The 'L Divider' is a weak component which acts as a separation for the dual involute curves. It can not withstand the extreme force and is prone to damage – as a consequence it impacts the functionality as well as cause potential harm.

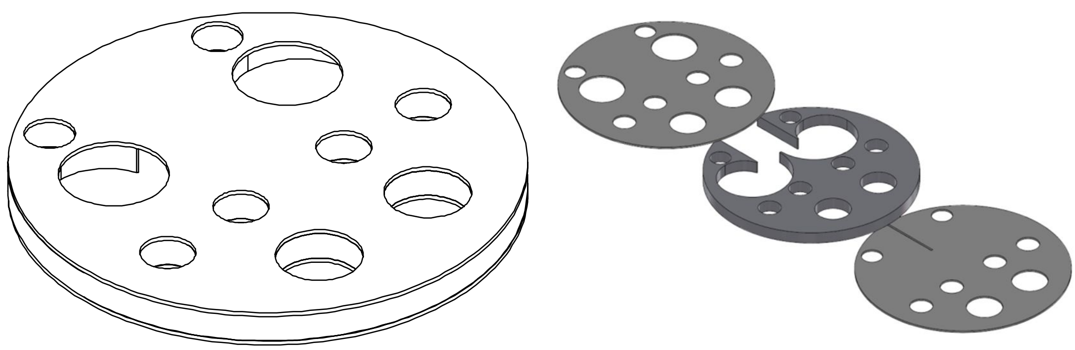


Figure 7-6: current design of inlet-Plate assembly

An illustration of the inlet-plate assembly is provided in Figure 7-5, the significant role of the inlet plate assembly can be viewed in Figure 7-3 (Part 5) which places it as the major subassembly to come in contact with the fluid after the inlet nozzle and can be considered one of the most important functional sub-assemblies of the oil/water separator.

**d. Water-Plate assembly**

The water plate assembly (as shown in Figure 7-7 and Part 3 in Figure 7-3) is responsible channelling water from the I-SEP to the water hydro-cyclone which then discards the excess water through the water outlet. Unlike the inlet-plate assembly, the water plate assembly contains two set of involute curves which consume majority of the parts space. Furthermore, the water-subassembly is composed of four plates which are laser cut and welded; some of the plates are non-standard sizes.

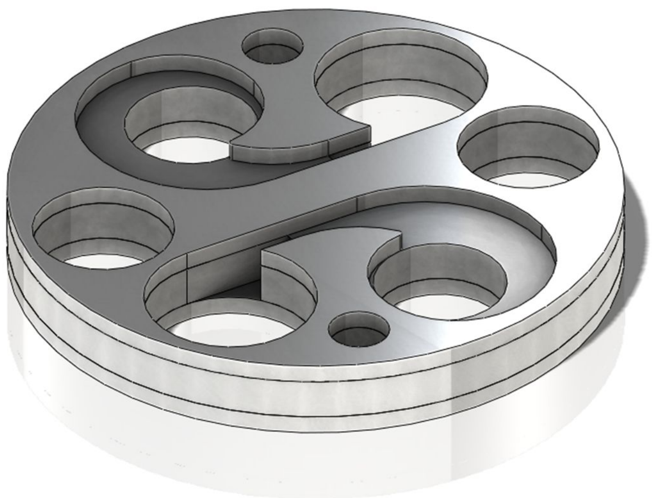


Figure 7-7: current design of Water-Plate assembly

Task 2: a manufacturing cost breakdown was conducted to identify the major areas of concern from a cost point of view (Kumar, 2011); Figure 7-8 delineates the results. It is evident that majority of the total cost is associated with the material, by leaning out the outer jacket, plates and cyclones the material cost can be minimised, which in turn should lower the cost of manufacture.

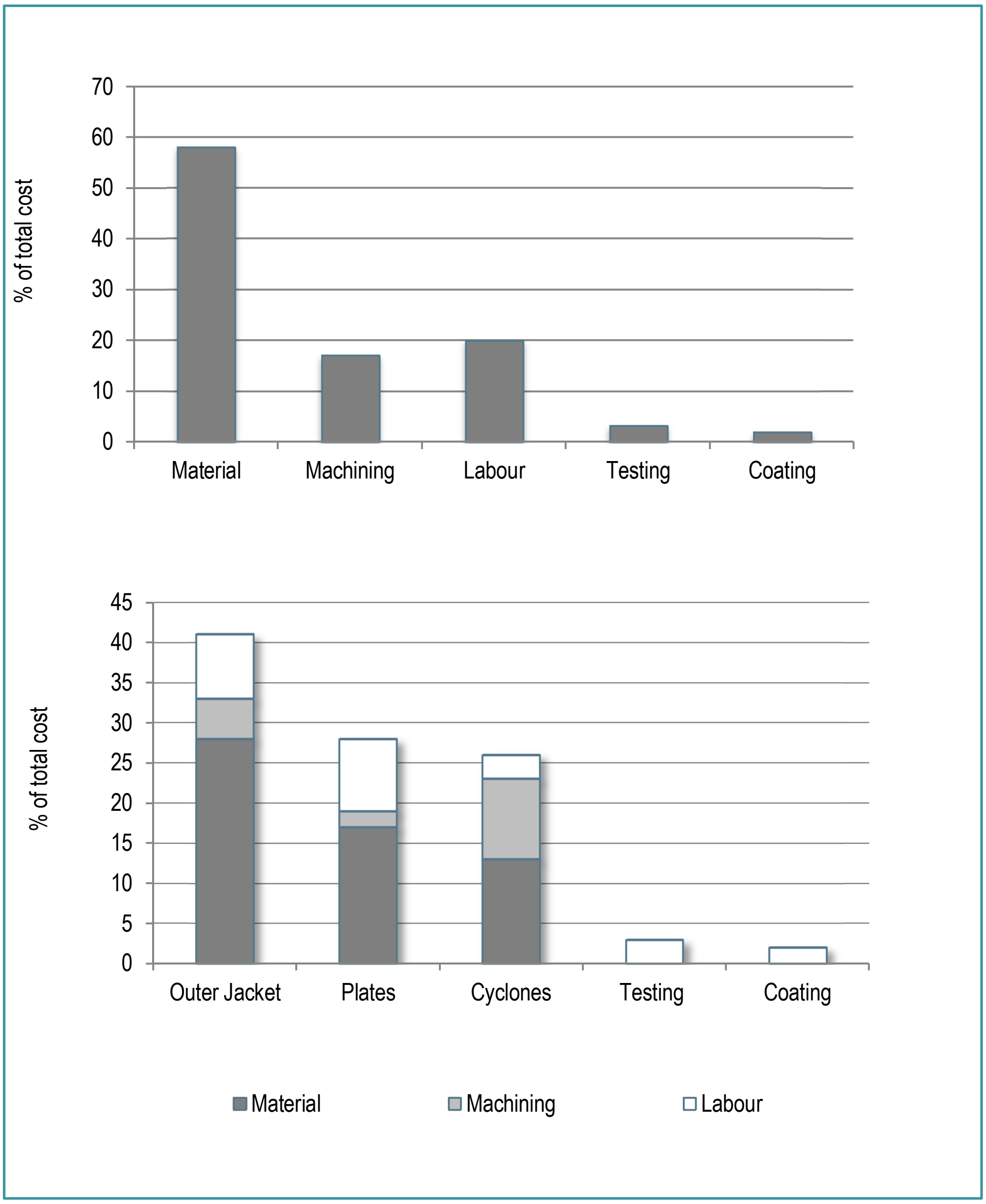



Figure 7-8: Manufacturing cost breakdown of oil/water separator (Kumar, 2011)

The completion of the two activities in the define phase has ensured the establishment of a value focus as well as the identification of un-lean characteristic. The proceeding section presents leaner alternative solutions which have been achieved through the implementation of the lean design principles. A discussion of each sub-system is presented.

### 7.4.3 Phase 2: Design

*Leaning out the sub-systems based on the lean design principles*

**Subsystem 1: Outer Jacket**

The outer jacket houses the internal components of the oil/water separator; it is currently built from a non-standard 28" pipe. The jacket has been reduced to a standard off the shelf 24" pipe (Steel Plate & Sections Ltd , 2011) this alone will provide a cost saving of 20% based on quotation from local supplier. The dish end has been removed (as shown in Figure 7-9) which eliminates the welding process, and a flange has been applied which will use standard screws to seal the jacket – this will ensure ease of access and maintainability of internal components. The current design of the outer jacket was manufactured from stainless steel. Based on the suggestions of Kumar (2011) Carbon steel has been selected with ceramic epoxy resin coating; this decision conforms to the Oil/Water separator material requirements and offers a significant cost reduction of 45%, based on quotation from Intercast Limited UK.

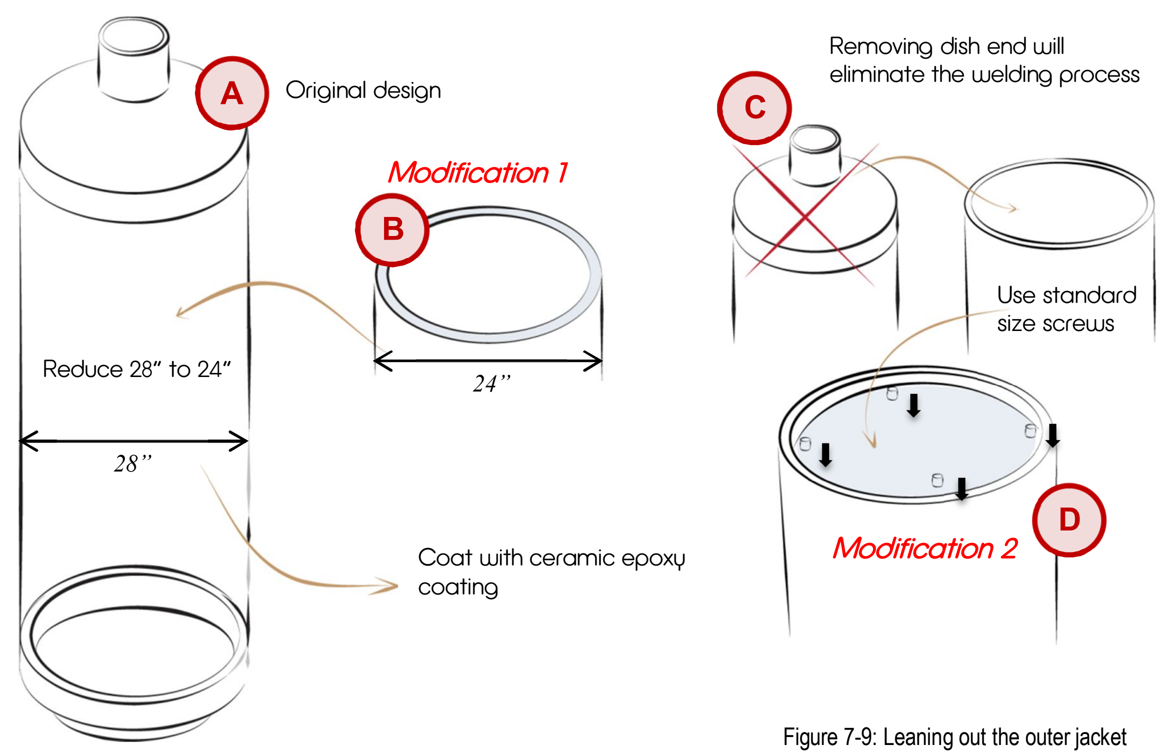



Figure 7-9: Leaning out the outer jacket

As a result of the modifications to the outer jacket, three lean design principles (which have been explained in Section 5.3) have been achieved, for example the value has been maximised, the product has been simplified and a waste has been minimised and because of it a significant cost saving has been achieved.

**Subsystem 2: Water cyclones**

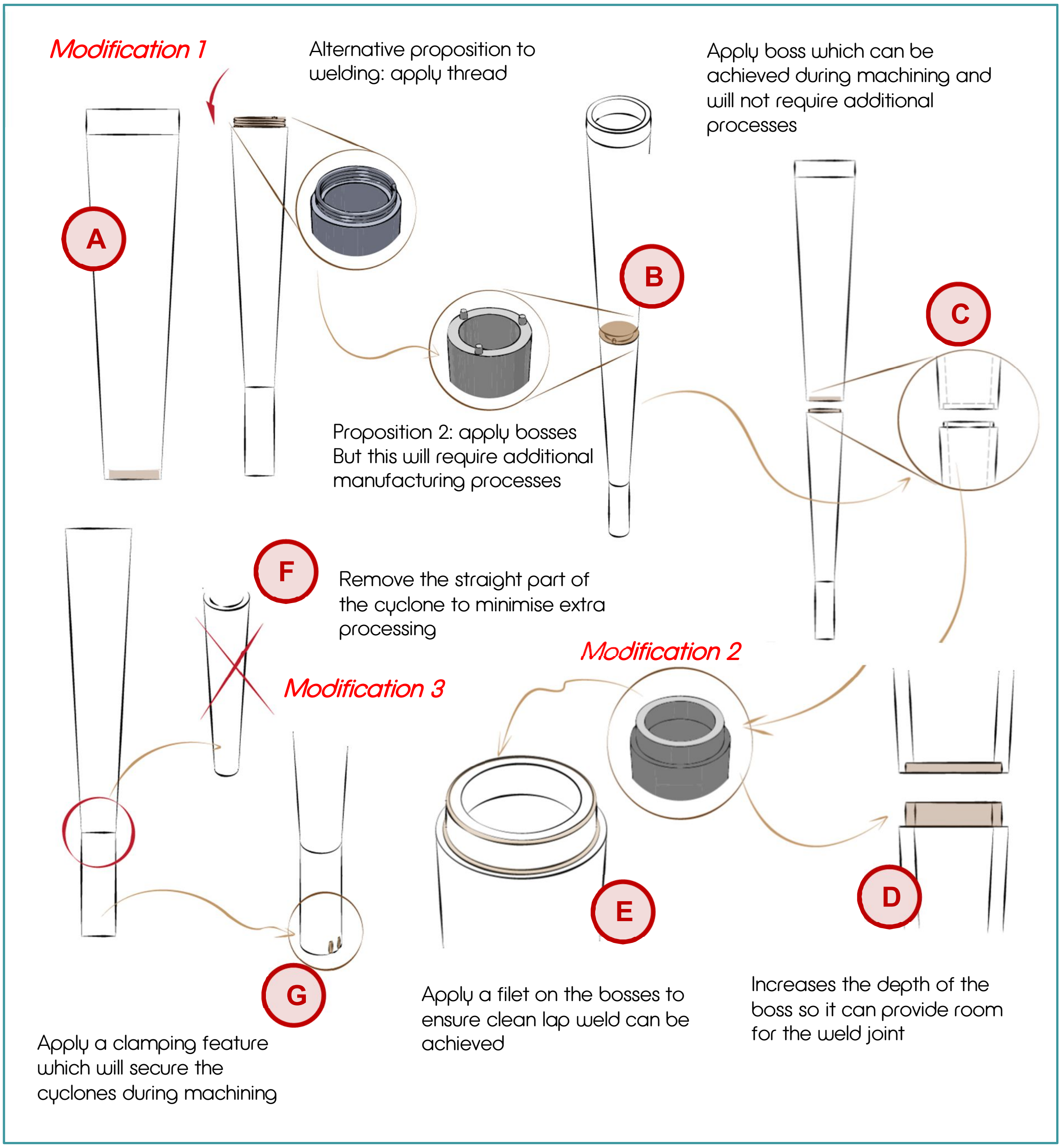



Figure 7-10: Design modifications of the water cyclone

The original design of the cyclone was machined from six non-standard parts (3 solid and 3 tubes) which were then welded together; the proposed design suggests sand casting two parts and machining them to obtain the required internal finish and thickness and then welding them. This proposal can potentially achieve a cost saving of 42.6% (Kumar, 2011 and Ti, 2011).

As highlighted in Figure 7-10, modifications were made to the structural aspects of the water cyclone, listed below are the modifications and references to the support material, for example:

- Modification 1: cyclone diameter was reduced; the dimensions are with design for sand casting rules: (1) cast with a length between 300mm and 1200mm is 13mm (Appendix C1: P2-SM-CAST)
- Modification 2: add a boss with rounded edges to ease the welding process, the depth of the boss is increased to ensure a Lap weld joint is achieved; this feature will eliminate the possibility of misalignment during welding (Appendix C1: P2-SM-WELD).
- Modification 3: introduced a clamping feature (within the cast design) to ensure cyclone (secureness) and the cyclones do not vibrate during turning machining (Appendix C1: P2-SM-TURN).
- Harm elimination: The cyclone will undergo machining to achieve the desired dimension and finish; the excess material (i.e. flash from sand casting) will be automatically trimmed and will not require additional effort by the manufacturing engineer (Appendix C1: P2-SM-TURN).
- By making the following geometrical modifications four of the lean design principles have been achieved, the value has been maximised as it will ensure the smooth flow of the liquid, the product structure and manufacturing processes have been simplified, harm elimination during machining has been avoided and a significant reduction in waste has been achieved.

**Subsystem 3: Inlet-plate assembly**

Original design: Design proposed

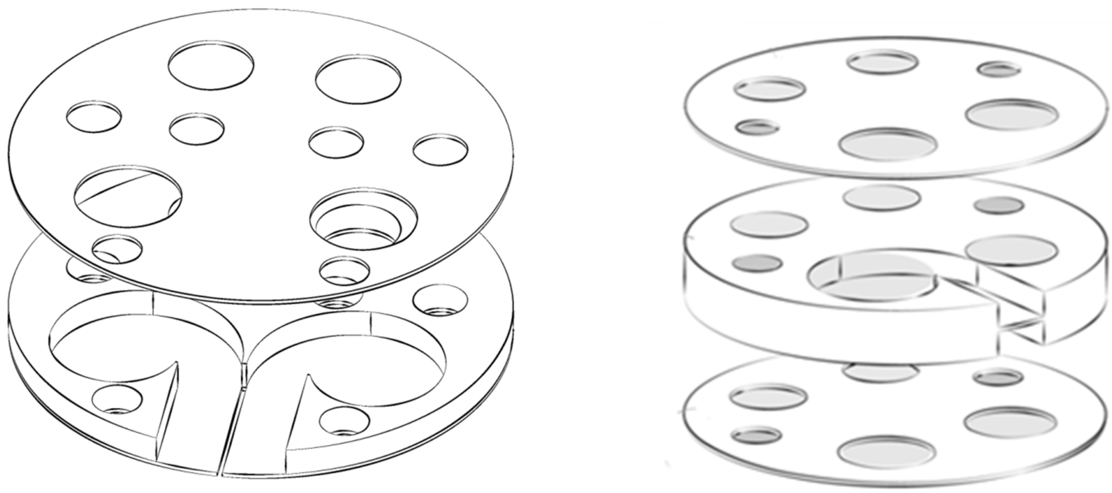


Figure 7-11: Inlet-plate assembly (original design & proposed design by Ti (2011)

Ti (2011) proposed a design by reducing the diameter of the sub-assembly from 657mm to 548mm and repositioning the involute curves whilst maintaining the key dimensions as shown in Figure 7-11. Furthermore by increasing the thickness of the middle plate he was able to eliminate a plate from the original design.

The manufacture of the proposed design included welding three non-standard stainless steel plates that are laser cut. Figure 7-12 highlights two key modifications proposed by the author, the first reduces the diameter of the top and bottom plate to ensure a V-butt joint weld can be achieved, as opposed to seal welding the side of the plates. However this is dismissed and a second modification is proposed which increases the middle plate from 38mm to 40mm, which is a standard off the shelf size (Steel Plate & Sections Ltd, 2011). Furthermore, the top and bottom plates are eliminated and the involute curve is sealed with a cover 5mm standard plate. A groove is applied to the involute cure to ensure the covers can be easily sealed using V-butt joint weld.

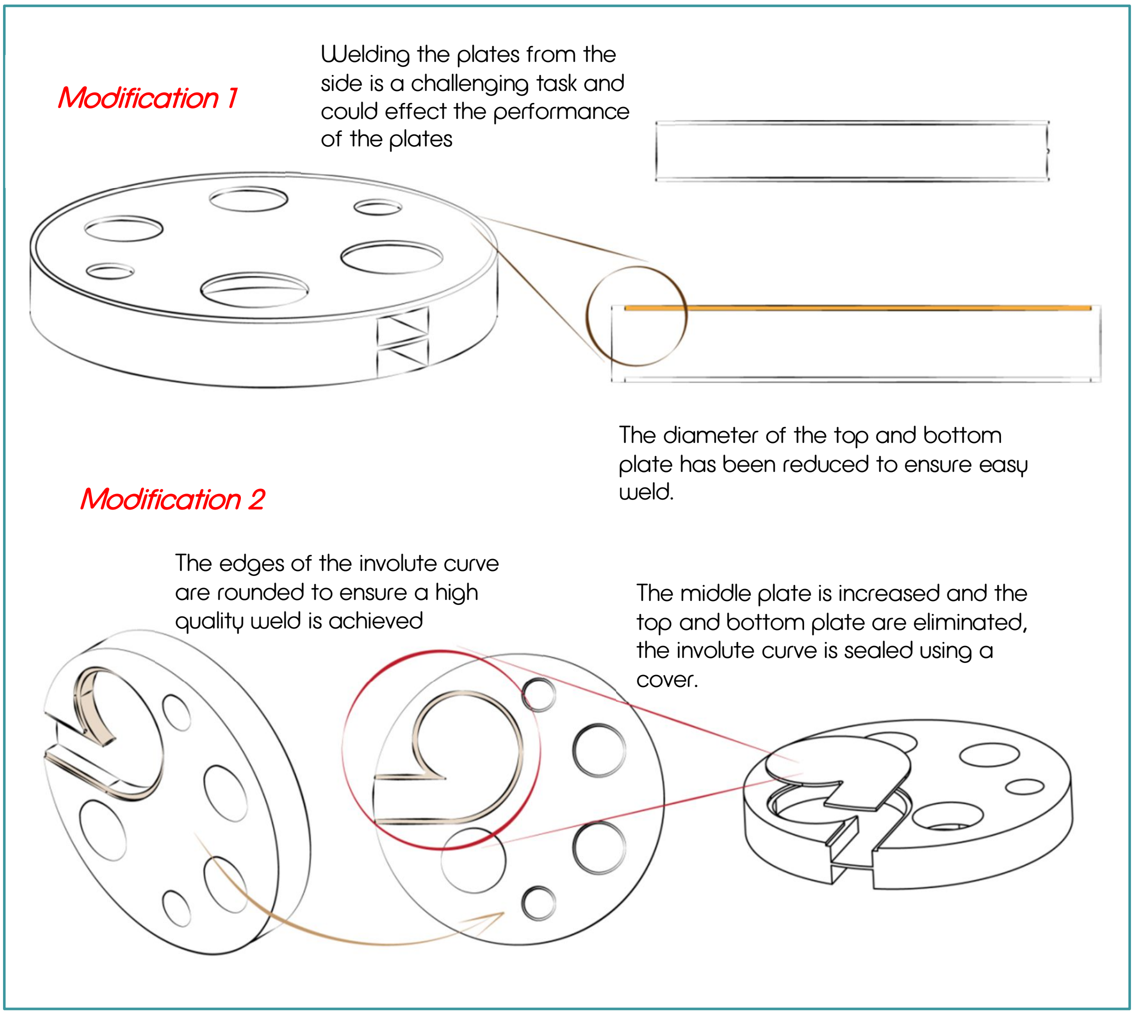



Figure 7-12: leaning out the inlet sub-assembly

By conducting the aforementioned modifications to the inlet-plate assembly four lean design principles have been achieved: value maximisation, product simplification, harm elimination and waste minimisation.

**Subsystem 4: Water-plate assembly**

The author was able to reduce the number of 8 non standard plates to 5 standards were all off the shelf plate. The manufacturing process of the original design and proposed design by Ti (2011) included laser cutting and seal welding the plates. A leaner proposition was made by the author; this would entirely eliminate the welding process.

Additionally the design proposition would ensure ease of maintenance of the plates. This would include using a split threat screws to secure the plates (inspired from SMED), this would minimise the occurrence of misalignment which could occur during welding as well as ensure the ease of maintenance of the sub assembly (Modification 2), and this has been illustrated in Figure 7-13.

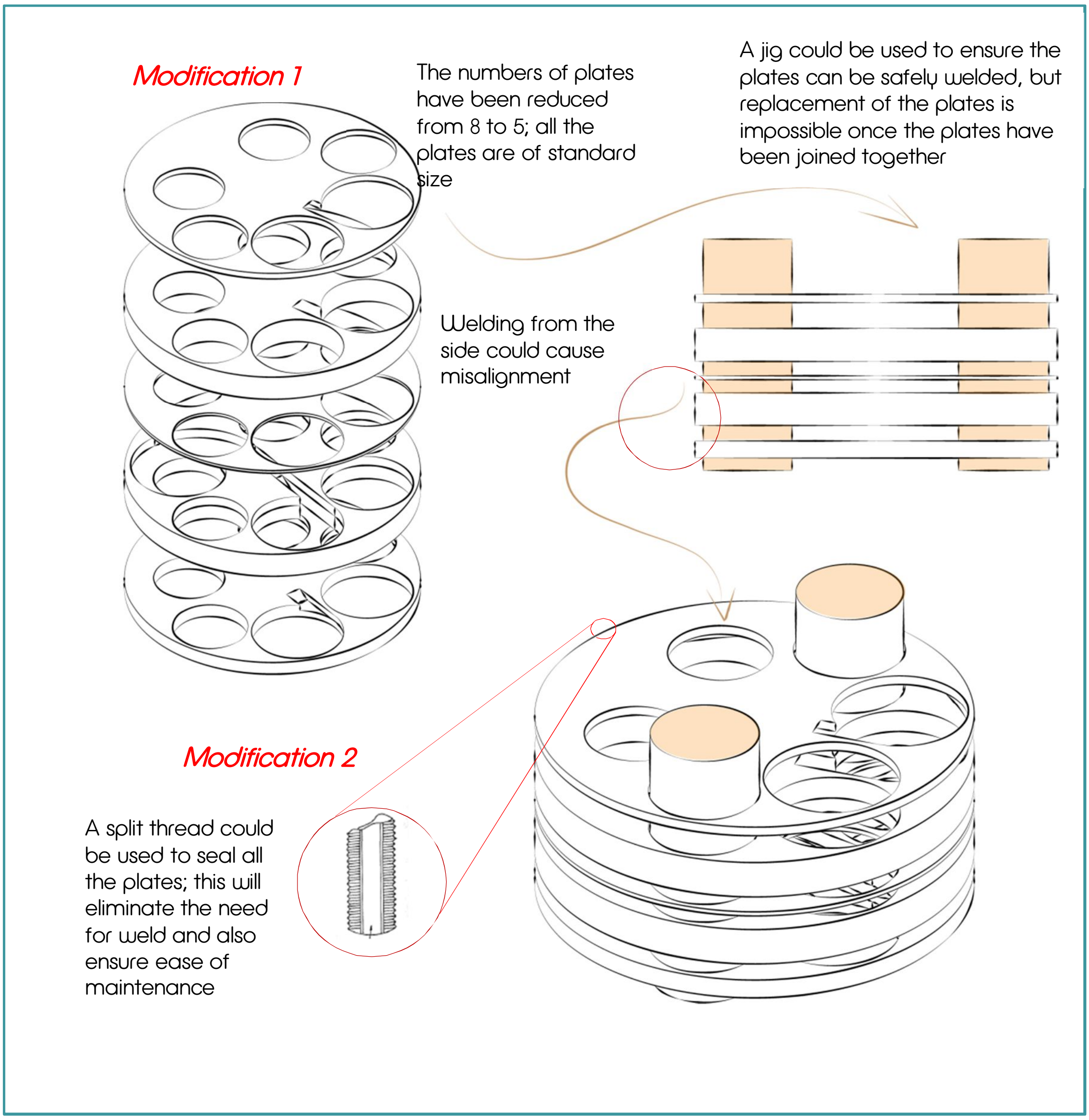



Figure 7-13: leaning out the water sub-assembly

## 7.5 Summary

The Chapter has detailed the validation of the Lean Design Framework through the application of an oil/water separator case study and expert opinions.

An industrial case study with a design firm that produces systems for the oil and gas sector was conducted. The case study was based on a systematic plan which ensured the necessary requirements in completing a case study were followed. Through the application of the lean design framework the original design was enhanced to ensure the design objectives were met, the design was enhanced through the implementation of the lean design principles and a significant reduction in cost was also achieved.

The validation of the case study is presented in the final chapter; the results of the oil/water separator are discussed followed by a review of expert's opinion of the framework. The chapter also provides a detailed explanation of the outcome of the research as a whole.

# Chapter 8

# DISCUSSION AND CONCLUSIONS

## 8.1 Introduction

The principle aim of this research was to develop a novel lean design framework for enhancing the application of product design. This was achieved through a methodological investigation consisting of tree phases. The first phase was based on academic investigation, intended to identify the evolution and trends in design research and the need to adopt lean type thinking earlier in to design. The proceeding phase consisted of performing an industrial field study to identify the current design practices and industrial perspectives of lean design. The final phase conceded with assimilating the totality of findings in the formulation and development of Lean Design Principles and a systematic Lean Design Framework. The author was able to demonstrate the application of the framework with an industrial case study, for which the results have been discussed in Chapter 7. This chapter the research outlined in previous chapters is discussed.

The format of thesis chapter is as follows:

Section 8.1 introduces the chapter, followed by a discussion of the results of the case study and expert opinion in section 8.2. An evaluation of the research presented in this thesis is discussed in section 8.3, which details the limitations of the research methodology and the fulfilment of research objectives. The key research contribution is discussed in section 8.4. Discussion on areas of future works in light of the thesis is presented in section 8.5 and finally in section 8.6 conclusions are drawn.

## 8.2 Discussion of research results

This section provides a discussion of the results from the oil/water separator case study; moreover it enlists and discusses the results from the validation of expert opinion.

### 8.2.1 Oil/water separator case study discussion

Chapter 7 has recorded the validation of the oil/water separator case study, for the purpose of this discussion; a primary focus will be placed on the results achieved as an outcome of implementing the lean design framework.

A summary of the validation process is presented

- Product requirements were not formally documented by the collaborating company, by implementing the first activity in the Preliminary Phase of the framework clear and concise requirements were documented.
- Through the formal decomposition of the product in Define Phase, a value focus was established which identified the necessary actions required to achieve the first lean design principle i.e. value maximisation
- A formal review of the geometry was performed against the lean design assessment in the Define Phase to identify un-lean characteristics of the sub-assemblies. The findings from this activity were astounding, and major areas of concern were instantly identified
- By performing a cost breakdown, which is the final task of Define Phase, a graphical representation of subassemblies and the different areas of manufacturing costs was identified
- The lean design principles were applied using the information provided in the guidelines to achieve leaner alternative solutions

Results obtained from the implementation of the lean design framework

**Outer jacket**

- From the cost breakdown in the Define Phase, the outer jacket was identified as the major contributor to cost; this constituted the material, machining and labour cost. The outer jacket was built from a non standard 28” pipe. By reducing the outer jacket to an off the shelf 24”, the machining and material cost was drastically controlled, however this would impact the geometry of the internal components. The cost benefits outweigh the implications of modification of internal geometry; therefore it was considered a beneficial design improvement. Furthermore, to assist maintenance the dish end of the outer jacket was removed and replaced with a flange which could be bolted down.

**Water cyclone**

- The flow of fluid within the system was crucial to performance, therefore achieving the correct levels of smoothness of the cyclones was necessary. The original method included machining three solid tubes and three hollow tubes of different dimensions and welding them to form the complete cyclone.
- An alternative solution was proposed which consisted of sand casting the cyclone in two parts and machining it to the desired dimensions and then welding them together.
- In order to eliminate welding, initially a thread was proposed however this would require additional manufacturing processes, therefore to minimise resource consumption a boss extrusion was suggested. This could be achieved whilst machining the cyclones to achieve the internal finish. Additionally the proposed depth of the boss would also ensure a complete weld would achieve and the risk of misalignment would be eliminated.
- Through he application of lean design principles significant cost savings were achieved with regards to the cyclones as well as the minimisation of parts, and the possible occurrences of design defects was minimised.

**Inlet-sub Assembly**

- The inlet-sub assembly is a crucial aspect of the separator, the key features and dimensions were preserved, and by implementing lean design principles the original design which consisted of four plates was reduced to one plate which required two small covers to protect the involute curve.
- Welding of circular plates was completely eliminated and the alternative leaner solutions could be easily manufactured and configured with minimal resource.

**Water-sub Assembly**

- Through simplification and standardisation the number of plates was reduced from 8 to 5 which were all standard sizes. Significant cost savings were achieved from this modification alone.
- In order to amplify the maintenance of the plates, it was proposed the welding process would be completely eliminated. The five plates would be sealed using a split threat screw (which was inspired from SMED). These design decisions minimised the number of manufacturing processes as well as provide a leaner design alternative.

Due to time and resource constraints the author was able to conduct a single industrial case study, however as a future prospect the following should be considered in order to capture more results:

- Perform multiple case studies with a number of products from different sectors, and conduct a comparative analysis of the findings to identify the general strengths and weaknesses of the guidelines
- Tailor the guidelines that are sector and product specific, for example customises the guidelines to suite electronic products. This will demonstrate the efforts required in adjusting the framework for adaptability of multiple business sectors
- Perform a live workshop and moderate the validation of each phase of the framework, because the guidelines are mainly textual which are subject to individual interpretation
- The Lean design Guidelines applied specific elements of the framework during the case study but did not cover all aspects due to the nature of the case study and time constraints. By applying all elements will demonstrate which aspects are compulsory and which can be overlooked

### 8.2.2 Validation through expert opinion

The Lean design Framework was also validated with experts in the field of product design and development, a total of five face-to-face interviews were performed during the validation, details of the participants has been recorded in Table 8-1.

Table 8-1: Details of participants

| Role | Years of experience | Areas of specialisation |
|---|---|---|
| Senior Designer (BMW) | 11 | Interior design |
| Team Leader (Epson) | 15+ | Manufacturing engineering |
| Researcher (Coventry University Design Institute) | 2 | Automotive design |
| Deputy Managing Director (Caltec Ltd) | N/A | Petroleum engineering |

The validation process initiated with presenting the Lean Design Framework through Microsoft SharePoint. The individual elements of the Framework were also explained with demonstrations of the case study. The key topics of the questionnaire are as follows:

- Logic of the framework
- Applicability of the framework to other business sectors
- Integrity of the framework to existing design processes
- Sufficiency of the guidelines
- User-friendliness of guidelines

The participants were requested to rate each of the topics from 1 to 5, one representing the least favourable option and 5 as the highest achievable rating. Figure 8-1 depicts the results from the study.

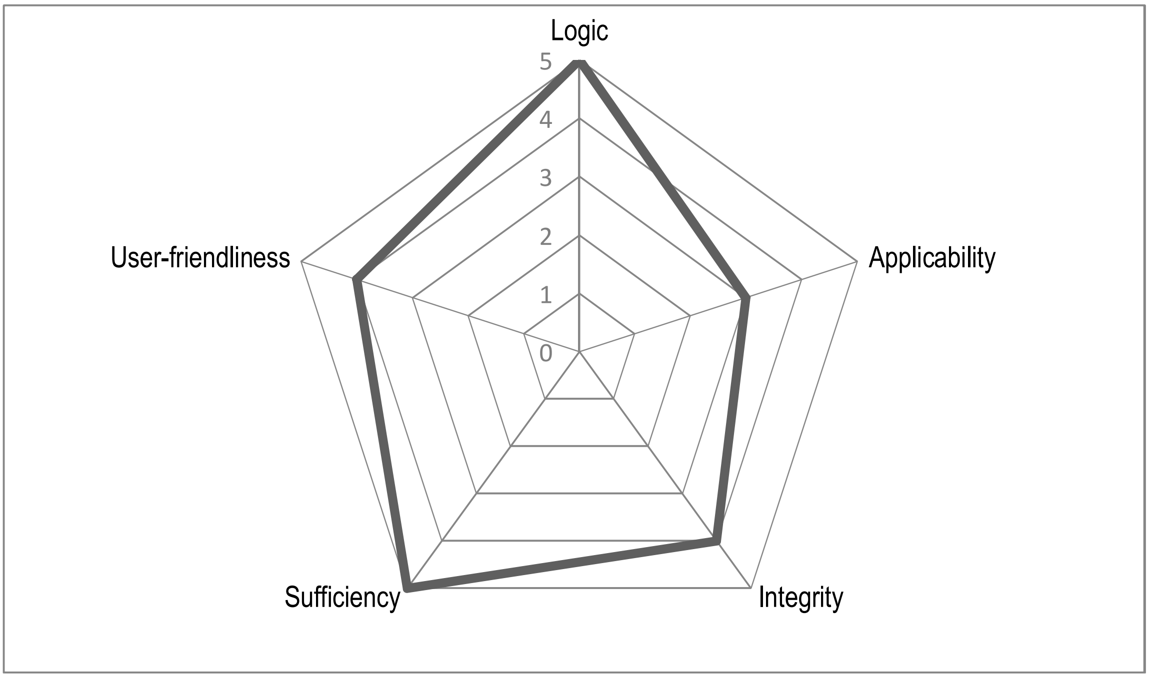



Figure 8-1: results showing expert opinion

- Experts were asked to rate the framework in terms of the logical sequence, there was a common consensus amongst the participants that the flow of phases and activities was valid and completely comprehendible.
- Applicability, in context refers to the possibility of application of the framework to multiple business sectors. The results averaged three, which is: somewhat applicable with minor deficiencies. Experts suggested the framework is too generic to be shared amongst multiple sectors and must be customised in terms of its activities in order to cater for multiple sectors.
- The possibility of integrating the framework for day to day design activities was discussed, the rating received was very positive and the experts suggested the framework would supplement and provide another perspective. However one participant suggested in order achieving complete integration, training would be necessary which the current framework does not consider.
- The guidelines contain a rich pool of different types of information to considering during the design process. Experts were asked to rate the guidelines with regards to sufficiency. All the experts agreed that sufficient material was available to conduct the required tasks without difficulty.
- The final area of discussion was related to the user-friendliness of the guidelines. The experts approved of the theme and design layout, however some experts suggested some of the fonts were difficult to read and a standard font should be used through out the guidelines.

## 8.3 Research evaluation

An evaluation of the research is presented in this section; it initiates with an examination of the lean design framework followed by a review of the research methodology highlighting its strengths and limitations. A discussion on the fulfilment of the research aim and objectives is also presented.

### 8.3.1 Lean Design Framework

The Lean Design Framework is a notable accomplishment in the research on lean design, which provides sufficient direction in generating lean concept designs. There is however a number of limitations with the current framework, which if addressed could further enhance the designer's experience. For example the current framework does not demonstrate 'the level of leanness' achieved. Ideally designers should be in position to benchmark the original design with leaner designs to evaluate the success levels. As a proposition, quantitative indicators which are based on the lean design principles could be used to ensure this. Furthermore, process indicators could be considered to identify the feasibility of the manufacturing aspects of the designs. Additional directional and actionable indicators could be utilised to specify effective design and the actions required to enhance un-lean characteristics of the design.

The current frame work is based on the 'Lean out existing design' scenario, additional research and modifications of the framework is required to achieve other scenarios i.e. (1) lean out from the beginning of the design project and (2) lean out based on feedback from the Product Life Cycle activities. The author believe the activities in the first phase of the framework will change significantly, however the remaining activities in Phase 2, 3 and 4 of the framework will remain intact with minimal changes.

The considerations of specific domain knowledge is limited in the current framework, additional knowledge must be incorporated to offer designers with a pool of knowledge. Furthermore a *smart comparative material and manufacturing selection* module should be included in the framework. There is also a possibility of incorporating a *cost analysis* and *lean design decision module* to encourage designers to base their design decisions using statistical methods such as trade-off curves as opposed to relying on experience and personal judgement.

### 8.3.2 The adopted research methodology

The research followed a qualitative strategy, theoretically which made it prone to inherent bias and possible concerns with the validity of the findings. A number of precautionary measures were undertaken by the author to minimise these issues. By considering multiple sources for data collection the probability of bias was neutralised, these included conducting interviews, first hand observation and conducting a case study. A range of interviews were performed which included different organisations from different sectors and personnel from different business positions. The results from the interviews were carefully analysed with the research theme in mind. The findings were collated and presented in the form of a presentation and report for review and feedback. Furthermore, during the course of the research industrial workshops were held which provided the ideal opportunity to present findings with industry that were involved in lean product development. The aforementioned measures ensured issues regarding validity and reliability of the research findings were dissolved.

### 8.3.3 Fulfilment of Research Aim and Objectives

The fundamental aim of the research was to develop a lean design framework that would support the generation of leaner product design. The derived framework enables the designer to adopt lean type thinking earlier at the conceptual design stage. The framework is illustrated in Figure 6-2. The research consisted of four objectives, which will be examined:

The first objective was to establish the evolution and trends in design research and investigate the status of lean thinking in product design through an extensive literature review. The author was able to conduct a scientific review of literature to grasp an understanding of the subject area and identify the research gaps. The research gaps included: the opportunity to go beyond traditional design methods and theories by considering lean thinking earlier at design. The current discussion of lean design requires more investigation and there is a tendency to address the design process as opposed to the design of the product. These research gaps were addressed by the author.

The second objective was to construct the lean design principles in a scientific manner based on the amalgamated information from the review of scientific literature and industrial field study. A common trend identified between scientific discussion in literature and industry was the lack of understanding of lean design, the need and importance however was evident. The author was able to amalgamate the findings from the studies to establish the foundations of lean design and populate generic lean design principles and define the technical considerations for successful applications. Through regular interactions with industry the principles were developed until they were matured.

The third objective was to develop lean design framework which encompasses guidelines and its associated processes that will support the generation of conceptual lean designs. Based on the lean design principles a systematic framework for realising a lean design was developed, this is referred to as the lean design framework. The framework is segmented in to phases which consist of activities and tasks which are to be performed by the designer subsequently. An illustrative guidelines was also develop to be used in conjunction with the framework, it contained all the necessary information such as rules, standards, technical domain knowledge and references to external information to ensure a lean design can be achieved.

The final objective was to validate the lean design framework through an industrial case study and expert opinion. An industrial case study of an oil/water separator was used which demonstrated positive results, and a clear contrast between traditional design and lean design was noticeable. Significant cost benefits were achieved as well a simplified and fully functional and operable design which could be manufactured easily. Valuable information was gathered from experts also. It was concluded from the study that the current framework is sufficient in achieving its primary objective however the availability of domain knowl3edge is limited and must expand for the utilisation of the framework for specific industries.

## 8.4 Key research contributions

The research has been successful in providing contribution to knowledge in a number of ways. Based on the authors understanding and awareness of existing literature on lean design the following contributions have been made:

1. Identification of fundamental elements required in lean design which has been translated in to a lean design definition.
2. Generic lean design principles, their individual considerations and the necessary knowledge to realise them in the form of generic rules, design considerations and technical domain knowledge has been developed
3. A novel framework that was based on the lean design principles which provides a systematic pathway segmented in to five incremental phases to generate lean design solutions
4. Illustrative guidelines based on the framework which provides the necessary information in order to systematically realise the lean design principles

Additional contributions to knowledge include:

- Current approaches to lean design have been reviewed, the author was able to identify the limitations and identify areas of investigation
- The industrial perspectives of lean design was established, the industrial needs for prompting the designers thought process and educating them through visual examples on how to achieve a lean design was uncovered
- The lean design framework has been validated with a real case study; the results attest to the benefits that can be achieved through the utilisation of lean design principles within an existing design process

## 8.5 Suggestions for future research

There is an opportunity for further research based on the research findings, which are as follows:

The current framework and its graphical representation through the guidelines are static; through the utilisation of media based applications a dynamic and customised solution can be achieved. This would entail the incorporation of the framework in a CAD based system that would provide intelligent lean design suggestions during design.

The current design scenario presented in the framework is 'Lean out an existing design' there is a need to develop the remaining two pathways: lean out from beginning and lean out based on product life cycle activities. This will allow designers to carefully select the relevant pathways based on the design projects.

Extensive research is required to ensure all of the lean design principles are further developed. There is a great opportunity to investigate and develop *Principle 3: Simultaneous consideration of lean manufacturing*. This will provide a revolutionary breakthrough in the direction of product and process co-development.

Another area of research that requires attention is the measure of leanness; the aim of this would be to provide a visual and numerical representation of the levels of leanness achieved and provide indications for areas that require redesign.

## 8.6 Conclusions

The theoretical proposition put forth in this study suggested that through the consideration of lean type thinking earlier at the conceptual design stage would allow for substantial benefits at the source whilst the design is in its premature stage. A number of academics have acknowledged this claim and have made individual attempts however were unable to provide a wholesome solution that would primarily focus on the design of the product as opposed to the design process. In order to address this, a methodological research was required to determine how lean type thinking could be executed relatively. Lean design principles which form the basis of the lean design framework have been developed and validated in this research. A number of conclusions from this research are drawn, which are as follows:

1. Design research and practise is evolving to address global challenges to introduce cheaper, competitive and more viable products, there is a need to adopt lean type thinking earlier at the conceptual design stage
2. The importance of lean design has been expressed by academics, however there is a shortage of research
3. The current discussion on lean design highlights its importance however there is no clear foundation, the extensive literature review and industrial field study helped to formulate a generic lean design definition, and a set of good principles
4. The lean design principles and theory construction have been used to develop a systematic lean design framework
5. The lean design framework consists of unique features and characteristics that provides a simple and effective method to generate lean design solutions
6. By implementing the lean design framework considerable benefits such as design enhancement and cost minimisation are expected which ensure the concept is functional, manufacturable ensuring avoidable harm is eliminated and waste and resources are minimised
7. The application of lean design framework demonstrated with an industrial case study addressed many design challenges and was able to offer alternative leaner solutions

The aforementioned conclusions are drawn from the research presented in chapter 2, 4, 5, 6 and 7. Conclusions 6-7 are primarily based on the single industrial case study of this research; it is most likely these will be applicable to other industrial sectors.

The thesis has successfully achieved the stated aim and objectives by demonstrating the application of the lean design framework; the author hopes this contribution to design research advances its evolution and brings about more awareness and appreciation globally.

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# APPENDICIES

## APPENDIX A: FIELD STUDY MATERIAL

A1: Provides the LeanPPD industrial field study questionnaire

A2: Records the field study results with a brief analysis of the results

## APPENDIX B: CASE STUDY MATERIAL

B 1: The final compilation of the lean design portfolio which presents the findings from the industrial case study.

# Semi Structured Questionnaire for LeanPPD Field Study

| | |
|---|---|
| ***Grant Agreement number:*** | NMP-2008- 214090 |
| ***Project acronym:*** | LeanPPD |
| ***Project title:*** | Lean Product and Process Development |
| ***Funding Scheme:*** | Large Collaborative Project |
| ***Date of latest version of Annex I against which the assessment will be made:*** | 20.02.2009 |
| ***Academic Supervisor names, title and organisation:*** | Dr. Ahmed Al-Ashaab & Dr Essam Shehab<br>Cranfield University |
| ***Tel:*** | +441234 750111 5622 |
| ***Fax:*** | +441234 754605 |
| ***E-mail:*** | a.al-ashaab@cranfield.ac.uk |
| ***Project website address:*** | www.leanppd.eu, www.leanppd.org, www.leanppd.net |
| ***Start date of the project:*** | 01.02.2009 |
| ***Duration:*** | 48 months |
| ***Responsible of the Document*** | Cranfield University Team<br>a.al-ashaab@cranfield.ac.uk |
| ***Due date of deliverable*** | n/a |
| ***Document Ref.:*** | *Questionnaire for field study* |
| ***Version:*** | 1 |
| ***Issue Date:*** | 29/February/2010 |

## CONTENTS

## 1. Product Development Process

1.1. Do you have a formal product development (PD) model (visual representation of the PD process, including the various stages, activities, mechanisms and supporting tools) and is it effective in guiding the PD operations? (select one option)

| Options | | Effectiveness | | |
|---|---|---|---|---|
| | | *Not Effective* | *Somewhat Effective* | *Very Effective* |
| ❑ | There is currently no PD model | ❑ | ❑ | ❑ |
| ❑ | The current PD model is developed by a central organisation that administer its implementation, but it is not followed | ❑ | ❑ | ❑ |
| ❑ | The current PD model is developed by a central organisation that administers its implementation, and it is followed | ❑ | ❑ | ❑ |
| ❑ | The current PD model is developed, and maintained by decentralised groups that administer its implementation in their respective areas | ❑ | ❑ | ❑ |

1.2. Do you have flexibility in how you do your job? (Or is it mandatory to comply to a process, that you do not have ownership of?) (select one option)

| Options | |
|---|---|
| ❑ | Engineers must complete defined tasks in the order of process documentation |
| ❑ | Engineers must complete defined tasks in process documentation but the order is flexible |
| ❑ | Engineers understand their responsibilities and are provided with company best practice information and complete key deliverables in accordance with project deadlines, but process documentation is not imposed on them |

1.3. Is there a technical leader who is responsible for the entire development of a product from concept to launch? (select one option)

| Options | | Effectiveness | | |
|---|---|---|---|---|
| | | *Not Effective* | *Somewhat Effective* | *Very Effective* |
| ❑ | No technical supervisor has responsibility for the entire development of a product | ❑ | ❑ | ❑ |
| ❑ | A project manager (non-technical) has responsibility for the entire development of a product while an engineer or a group engineers share some responsibility | ❑ | ❑ | ❑ |
| ❑ | A chief engineer with a team of engineers have responsibility for the entire development of a product | ❑ | ❑ | ❑ |

1.4. Every specification is a compromise between what customers want and what can be provided. How is a product specification stabilised in your product development process? (select one option)

| Options | |
|---|---|
| ❑ | Specification provided early on by customer or central organisation and must be adhered to |
| ❑ | Specification provided early on, but subject to engineering alterations |
| ❑ | Specification grows through continuous interactions along the stages of PD as the product understanding matures |

1.5. How do you select the design solution that will be developed? (select one option)

| Options | |
|---|---|
| ❑ | We only produce one design solution for each product |
| ❑ | We identify multiple solutions, and select the one that most closely matches the design specification |
| ❑ | We identify multiple solutions, and select the solution that has the lowest development costs |
| ❑ | We design multiple solutions for each product/component, and rule them out as more information becomes available (due to prototyping, testing, integration etc.) |

1.6. How are your current processes and work methods reviewed/improved? (select one option)

| Options | |
|---|---|
| ❑ | Processes are not regularly reviewed |
| ❑ | Processes are reviewed at regular intervals by experienced company members or a central organisation, but improvement suggestions are rarely incorporated |
| ❑ | Processes are reviewed at regular intervals by experienced company members or a central organisation, and there is a formal mechanism to capture improvement suggestions |
| ❑ | Engineers are encouraged to make improvement suggestions at any time and there is a formal mechanism to capture suggestions, but engineers are not confident that good ideas will be incorporated |
| ❑ | Engineers are encouraged to make improvement suggestions at any time and there is a formal mechanism to capture suggestions, and there is evidence that good ideas are regularly incorporated |

1.7. Do manufacturing (production) engineers play an active role in each stage of product development? (select one option)

| Options | |
|---|---|
| ❑ | Once the design is complete, it is communicated to the manufacturing engineers |
| ❑ | Once the detailed design is prepared, the manufacturing engineers are involved |
| ❑ | Once the final concept is selected the manufacturing engineers are involved |
| ❑ | Manufacturing engineers are involved in concept selection |
| ❑ | Manufacturing engineers provide design constraints to design engineers before design solutions are prepared and they are also involved and referred to throughout the development process |

1.8. Do your suppliers provide you with multiple alternatives for a single part (component)? (select one option)

| Options | |
|---|---|
| ❑ | Suppliers provide one part (solution) based on a detailed design specification that we provide |
| ❑ | Suppliers have flexibility to provide one (solution) based on a rough design specification that we provide |
| ❑ | Suppliers provide multiple solutions for most parts and we work with them to develop the solution |
| ❑ | Suppliers inform us on developments in what they can provide and we together develop multiple solutions and progressively eliminate weak solutions as the product design solution matures |

1.9. How are projects currently initiated, and the does the product development process flow? (select one option)

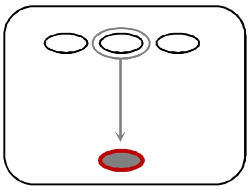
| Options | |
|---|---|
| ❑ | Project initiation is dependent on customer requests and projects often run late |
| ❑ | Project initiation is dependent on customer requests, but projects rarely run late |
| ❑ | Projects start at regular intervals, but do not have consistent standard durations |
| ❑ | Projects start at regular intervals, have consistent standard durations, and are composed of multiple project types (e.g. facelifts, major mods, redesign/breakthrough), but projects do run late |
| ❑ | Projects start at regular intervals, have consistent standard durations, and are composed of multiple project types (e.g. facelifts, major mods, redesign/breakthrough), but projects are always on time |

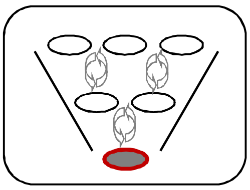
## 2. Product Design

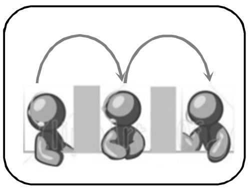
2.1. Which of the following tool/techniques have you **formally** implemented and utilise as an aid during the design of the product?

| Tools/Techniques | Frequency of use | | | Effectiveness | | |
|---|---|---|---|---|---|---|
| | *Never* | *Sometimes* | *Always* | *Not Effective* | *Somewhat Effective* | *Very Effective* |
| Design for Manufacture Assembly | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| FMEA *(Failure Modes Effective Analysis)* | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| TRIZ *(Theory of Inventive Problem Solving)* | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Value Analysis /Value Engineering | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Design to Cost | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Design for Recyclability | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Design for Modularity | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Design for Sustainability | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Design for Ergonomics | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Design for Maintainability | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Design for Aesthetics | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Design for Six Sigma | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Design for Reliability | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Design for Usability *(user-friendliness)* | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Design for Serviceability | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Design for Minimum Risk | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| *Other:* | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

2.2. From the diagrams below can you indicate what method(s) of product development do you currently follow and rate its effectiveness?


*Concurrent Eng*


*Set-Based Concurrent Eng*

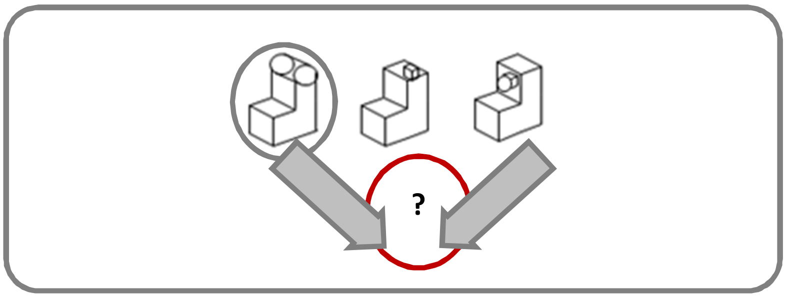

*Sequential Manner*

| Method | Frequency of use | | | Effectiveness | | |
|---|---|---|---|---|---|---|
| | *Never* | *Sometimes* | *Always* | *Not Effective* | *Somewhat Effective* | *Very Effective* |
| Concurrent Eng | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Set-based Concurrent Eng | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Sequential Manner | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

2.3. During design do you consider incorporating error /mistake-proofing (features/elements/mechanisms) for the following:

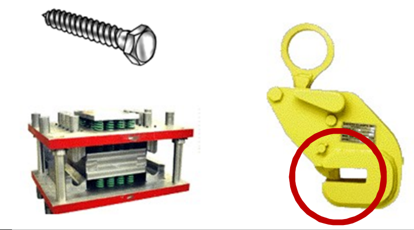
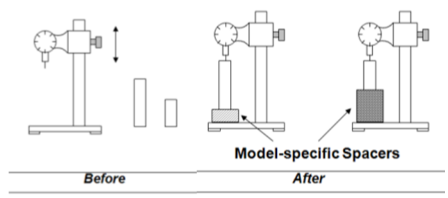
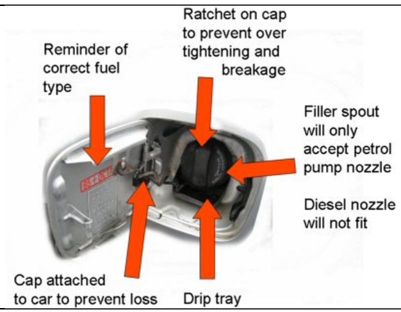
| User | Incorporation | | |
|---|---|---|---|
| | *Never* | *Sometimes* | *Always* |
| End User | ☐ | ☐ | ☐ |
| Prototyping | ☐ | ☐ | ☐ |
| Manufacture | ☐ | ☐ | ☐ |
| Assembly | ☐ | ☐ | ☐ |
| Testing | ☐ | ☐ | ☐ |
| Packaging | ☐ | ☐ | ☐ |
| Storage | ☐ | ☐ | ☐ |
| Distribution/sales | ☐ | ☐ | ☐ |
| Delivery | ☐ | ☐ | ☐ |
| Disposal | ☐ | ☐ | ☐ |
| Recycling | ☐ | ☐ | ☐ |
| Service/Maintenance | ☐ | ☐ | ☐ |

2.4. During concept selection which of the following criterions do you consider in reaching a final solution? *(select applicable)*

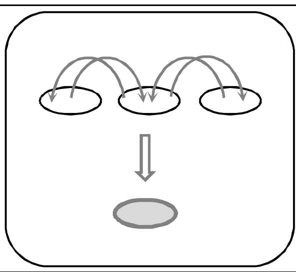



| Criterions | Considerations | | | Criterions | Considerations | | |
|---|---|---|---|---|---|---|---|
| | *Sometimes* | *Always* | *Never* | | *Sometimes* | *Always* | *Never* |
| Function | ☐ | ☐ | ☐ | Safety | ☐ | ☐ | ☐ |
| Critical to quality | ☐ | ☐ | ☐ | Sustainability | ☐ | ☐ | ☐ |
| Durability | ☐ | ☐ | ☐ | Ease of Manufacture | ☐ | ☐ | ☐ |
| Technology | ☐ | ☐ | ☐ | Portability | ☐ | ☐ | ☐ |
| Cost | ☐ | ☐ | ☐ | Enhanced Capability | ☐ | ☐ | ☐ |
| Performance | ☐ | ☐ | ☐ | Usability | ☐ | ☐ | ☐ |
| Featurability | ☐ | ☐ | ☐ | Reliability | ☐ | ☐ | ☐ |
| Ergonomics | ☐ | ☐ | ☐ | Recyclability | ☐ | ☐ | ☐ |
| Customisation | ☐ | ☐ | ☐ | Innovation | ☐ | ☐ | ☐ |
| Maintainability | ☐ | ☐ | ☐ | | | | |

2.5. Have you considered adopting lean manufacturing techniques as a sense of inspiration during conceptual design?

| Example | | Consideration | |
|---|---|---|---|
| | | Yes | No |
| <u>Single Minute Exchange Die (SMED)</u><br><br>Replace 4 bolts that require 32 turns before the die is secure, with a clip-on attachment. |  | ☐ | ☐ |
| <u>Quick Change Over (QCO)</u><br><br>Measuring different product models requires manual adjustment of the dial. By using model-specific spacers, adjustment time is reduced – allowing for quick change over. |   | ☐ | ☐ |
| <u>Poke-Yoka (Mistake-proofing)</u><br><br>Apply mistake proofing mechanisms and features to prevent the loss of the fuel cap and remind the user to use the correct type of fuel |   | ☐ | ☐ |

2.6. What approaches do you use in assuring optimal values (as assigned in the design specification) are achieved in your final design?

| | | | Mathematical approaches | | None Mathematical approaches |
|---|---|---|---|---|---|
|  |  | ☐ | Regression analysis | ☐ | Personal experience/understanding |
| | | ☐ | Multi-objective optimisation | ☐ | Design Matrix |
| | | ☐ | *Other:* | ☐ | *Other:* |

2.7. Do you have evidence of cases when during the design you incorporated error-/mistake-proofing (features/elements/mechanisms) for the followings: (Select as appropriate)

| User | Incorporation | | |
|---|---|---|---|
| | *Never* | *Sometimes* | *Always* |
| 1. End user | ☐ | ☐ | ☐ |
| 2. Assembly/Disassembly | ☐ | ☐ | ☐ |
| 3. Service/Maintenance | ☐ | ☐ | ☐ |

2.8. Do have a systematic and formalised method of designing a product that ensures

(1) harm to the end-user and manufacturing engineer is completely eliminated,

(2) waste and resources are minimised during manufacture?

(Select as appropriate and give example)

| Design considerations | Options | | Details of method |
|---|---|---|---|
| | *Yes* | *No* | |
| Harm | ☐ | ☐ | |
| Waste | ☐ | ☐ | |
| Resources | ☐ | ☐ | |

2.9. What sources do you use to ensure the following are considered your design? *(Select applicable)*

| **sources** / **Factors** | Rules | Design Standards | Inspiration | Innovation | Personal Intuition | Personal Experience | Design text books |
|---|---|---|---|---|---|---|---|
| Mistake-proofing | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Manufacturability | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Assembly | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Critical to quality | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Reliability | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Performance | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Sustainability | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Recyclability | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Innovation | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Ergonomics | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Cost | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| | | | | | | | |

2.10. Which of the following design optimisation techniques do you use to minimise variation (design noise) and to ensure a robust design is developed? How effective do you find them? Please list methods of application. (Select as appropriate and please give example for application)

| Tool/Techniques | Frequency of use | | | Effectiveness | | |
|---|---|---|---|---|---|---|
| | *Never* | *Sometimes* | *Always* | *Not effective* | *Somewhat effective* | *Effective* |
| 1. Regression analysis | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Application: | | | | | | |
| 2. Multi objective optimisation | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Application: | | | | | | |
| 3. Design of Experiments | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Application: | | | | | | |
| 4. Taguchi's Robust design method | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Application: | | | | | | |
| 5. Probabilistic design | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Application: | | | | | | |
| 6. Axiometic design | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Application: | | | | | | |
| 7. Design for Variety | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Application: | | | | | | |
| 8. Variation Risk Management | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Application: | | | | | | |

# 3. Knowledge Based Engineering & Environment

## Introduction:

Efficient usage of product life cycle knowledge can only be accomplished, if the knowledge is captured and structured in a way that it can be formally represented and re-used within an organisation to support engineering decisions in product design and development. These procedures are defined as a Knowledge Life Cycle.

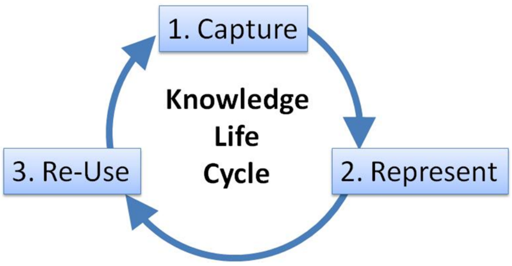



**Figure 1 Knowledge Life Cycle**

## Knowledge Capturing

3.1. From your personal experience, how important do you assess the following sources of Knowledge? *(Select one each)*

| Sources of Knowledge | Importance | | | | Comments |
|---|---|---|---|---|---|
| | *Not important* | *Important* | *Very Important* | *Essential for Competitive Advantage* | |
| Design Rules: | ☐ | ☐ | ☐ | ☐ | ☐ |
| • Heuristic Rules – Company own design rules | ☐ | ☐ | ☐ | ☐ | ☐ |
| • Published Rules e.g. from Books | ☐ | ☐ | ☐ | ☐ | ☐ |
| • Rules from supplier e.g. from Material Provider | ☐ | ☐ | ☐ | ☐ | ☐ |
| Design Standards | ☐ | ☐ | ☐ | ☐ | ☐ |
| Capability of current resources | ☐ | ☐ | ☐ | ☐ | ☐ |
| Capability of current process | ☐ | ☐ | ☐ | ☐ | ☐ |
| Previous Projects | ☐ | ☐ | ☐ | ☐ | ☐ |
| Tacit Knowledge (Expertise of Engineers) | ☐ | ☐ | ☐ | ☐ | ☐ |
| *Other* | ☐ | ☐ | ☐ | ☐ | ☐ |
| | | | | | |
| | | | | | |

3.2. Do you have formal initiatives or software(s) for capturing previous projects in a common database to provide a source of information and knowledge to support new product development? *(Select one each)*

| **Initiatives** | **Ratings** | | | | |
|---|---|---|---|---|---|
| | *No Initiative & Not Interested* | *Desired* | *Initiated* | *In Progress* | *Fully Established* |
| Lessons Learned | ☐ | ☐ | ☐ | ☐ | ☐ |
| CAD Files | ☐ | ☐ | ☐ | ☐ | ☐ |
| CAE Files | ☐ | ☐ | ☐ | ☐ | ☐ |
| Test Data | ☐ | ☐ | ☐ | ☐ | ☐ |
| BOM | ☐ | ☐ | ☐ | ☐ | ☐ |
| Technical Issues | ☐ | ☐ | ☐ | ☐ | ☐ |
| Cost Data | ☐ | ☐ | ☐ | ☐ | ☐ |
| Product Specifications | ☐ | ☐ | ☐ | ☐ | ☐ |
| Engineering Requirements | ☐ | ☐ | ☐ | ☐ | ☐ |
| *Other* | ☐ | ☐ | ☐ | ☐ | ☐ |
| | | | | | |
| | | | | | |

3.3. Currently what are the implemented mechanisms to capture knowledge in your organisation and how efficient do you asses them? *(Select one each)*

| **Mechanisms** | **Usage** | | | **Effectiveness** | | |
|---|---|---|---|---|---|---|
| | *Never* | *Sometimes* | *Always* | *Not Effective* | *Somewhat Effective* | *Very Effective* |
| Verbal communication | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Questionnaires | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Document Templates | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Web-Blogs/ Notice Boards | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| *Other* | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| ☐ We have no implemented mechanisms to capture knowledge in our organisation | | | | | | |

## Knowledge Representation and Re-Use

3.4. What technologies or functions are used in your company to realize that captured knowledge is re-used and shared during the product development process and how frequent it is used? In addition, do you think the knowledge content of the provided technologies are adequate in supporting decision taking in an efficient way? *(Select one for usage and one for efficiency if applicable)*

| Technologies and Functions | | Usage | | | Efficiency | | |
|---|---|---|---|---|---|---|---|
| | | *Never* | *Some times* | *Always* | *Not Supportive* | *Some Content is Adequate and Supportive* | *All Content is Adequate and Essential for decision taking* |
| ☐ | Knowledge Based Engineering System | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| ☐ | Check Lists | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| ☐ | Design Templates | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| ☐ | Design & Development Handbook or Manual | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| ☐ | Quality Gates | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| ☐ | Assessment and Judgement from Experts in your Organisation | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| ☐ | Wikis | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| ☐ | Web Servers / Intranet | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| ☐ | E-Books | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| ☐ | Reports | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| ☐ | *other* | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| ☐ | | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| ☐ | | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| | | | | | | | |

3.5. How do you assess the importance of proven knowledge (e.g. test results) to support decision taking in product design and development? *(Select one)*

| Not Important | Important | Very Important | Essential for any decision |
|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ |

3.6. In general any product development task consists of two key elements; routine tasks and innovative tasks.

- The routine tasks, is standard and done for all products; as most of the product are not developed from scratch rather they are successive from previous designs
- Innovative tasks distinguish the new product from previous ones and have not been considered before.

*The following picture represents a common distribution:*

**80%**
**Routine Tasks**

**20%**
**Innovative Tasks**

Please estimate in percentage how much of your work is related to routine or innovative Tasks? *(Select one)*

| | |
|---|---|
| ☐ | 100% routine - 0% innovative |
| ☐ | 80% routine - 20% innovative |
| ☐ | 60% routine - 40% innovative |
| ☐ | 50% routine - 50% innovative |
| ☐ | 40% routine - 60% innovative |
| ☐ | 20% routine - 80% innovative |
| ☐ | 0% routine - 100% innovative |

3.7. Please estimate how much, in percentage, do you rely on knowledge from previous project when designing a new product? *(Select one)*

| | |
|---|---|
| ☐ | 100% |
| ☐ | 80% |
| ☐ | 60% |
| ☐ | 50% |
| ☐ | 40% |
| ☐ | 20% |
| ☐ | 0% |

3.8. What specific knowledge domain do you need for your regular engineering activities? *(Select one each)*

| | **Importance** | | |
|---|---|---|---|
| **Domain** | *Not Important* | *Important* | *Very Important* |
| Injection Moulding | ☐ | ☐ | ☐ |
| Stamping | ☐ | ☐ | ☐ |
| Machining | ☐ | ☐ | ☐ |
| Casting | ☐ | ☐ | ☐ |
| *Other* | ☐ | ☐ | ☐ |
| | | | |
| | | | |

3.9. From your personal experience, which of the following activities would you consider to be important for engineering decision taking? *(Select one each)*

| | Importance | | |
|---|---|---|---|
| **Activities** | *Not Important* | *Important* | *Very Important* |
| Definition of Product Specifications | ❑ | ❑ | ❑ |
| Design for Manufacture and Assembly | ❑ | ❑ | ❑ |
| POKA YOKE – Mistake Proofing | ❑ | ❑ | ❑ |
| Tooling Design | ❑ | ❑ | ❑ |
| Cost Calculation | ❑ | ❑ | ❑ |
| Production Planning and Scheduling | ❑ | ❑ | ❑ |
| Testing and Simulations | ❑ | ❑ | ❑ |
| *Other* | ❑ | ❑ | ❑ |
| | ❑ | ❑ | ❑ |
| | ❑ | ❑ | ❑ |
| | ❑ | ❑ | ❑ |

3.10. Which commercial software do you use to support product development?

| Software for: | *Commercial Software (e.g. Catia V5)* | *Release (e.g. R14)* |
|---|---|---|
| Product Lifecycle Management (PLM) | | |
| Computer Aided Design (CAD) | | |
| Product Data Management (PDM) | | |
| Enterprise Resource Planning (ERP) | | |
| Knowledge Based Engineering (KBE) | | |
| Computer Aided Engineering (CAE), e.g. CFD, FEA etc. | | |
| Computer Aided Manufacturing (CAM) | | |
| Cost Calculations | | |
| Quality Management | | |
| Other | | |
| | | |

3.11. What is your experience in using the following acclaimed commercial Knowledge Based Engineering systems? *(If used select one and rate experience)*

| *Used* | **Knowledge Based System** | **Experience** | | | |
|---|---|---|---|---|---|
| | | Bad – Not Useful | Occasionally Beneficial | Very Good - Recommended | Comments |
| | AML - TechnoSoft Inc | | | | |
| | DriveWorks - SolidWorks | | | | |
| | Knowledge Fusion - UG | | | | |
| | Knowledgeware - Catia | | | | |
| | Expert Framework - ProEng | | | | |
| | Siemens Teamcenter – Enterprise Knowledge Foundation | | | | |
| | PACE KBE Platform | | | | |
| | *other* | | | | |
| | *I have not used any Knowledge Based Engineering system before* | | | | |

3.12. How and which of the following data is stored at your company for a specific product during the entire product life cycle? *(If used select one or multiple for storage)*

| **No.** | **Used** | **Data** | **Storage Form** | | | | |
|---|---|---|---|---|---|---|---|
| | | | Paper Form | PDM Database | ERP | Share Drive | *Other* |
| 1 | | QfD | | | | | |
| 2 | | BOM | | | | | |
| 3 | | Cost Calculations | | | | | |
| 4 | | Make or Buy | | | | | |
| 5 | | RfQ | | | | | |
| 6 | | Specifications Documents | | | | | |
| 7 | | CAD Models | | | | | |
| 8 | | CAD Drawings | | | | | |
| 9 | | CAE Files | | | | | |
| 10 | | DFMEA | | | | | |
| 11 | | Test Reports | | | | | |
| 13 | | Capacity Planning | | | | | |
| 14 | | PFMEA | | | | | |
| 15 | | PSW | | | | | |
| 16 | | PPAP Documents | | | | | |
| 17 | | Process Capability | | | | | |
| 18 | | Resource Capability | | | | | |
| 19 | | Change Requests | | | | | |
| 20 | | Customer Satisfaction Reports | | | | | |

## 4. Cost Estimation

4.1. What is the role of cost estimation in product development?
*(You may select multiple options)*

| | |
|---|---|
| ☐ | To target and reduce the overall development cost |
| ☐ | To compare the cost of product/component alternatives |
| ☐ | To support taking through cost visualisation |
| ☐ | Others (please explain) |

4.2. Please assess the following product development cost drivers

| Cost Drivers | | Impact | | N/A |
|---|---|---|---|---|
| | | *Major* | *Minor* | |
| 1 | Product complexity and size | ☐ | ☐ | ☐ |
| 2 | Technical difficulty | ☐ | ☐ | ☐ |
| 3 | Development team experience, skill level and attitude | ☐ | ☐ | ☐ |
| 4 | Method of communication among team members | ☐ | ☐ | ☐ |
| 5 | Tools used for design (computer assisted tools) | ☐ | ☐ | ☐ |
| 6 | Reuse factor | ☐ | ☐ | ☐ |
| 7 | Design partners involvement | ☐ | ☐ | ☐ |
| 8 | Pressure to complete the job | ☐ | ☐ | ☐ |
| 9 | Out of sequence work | ☐ | ☐ | ☐ |
| 10 | Initial vendor specifications | ☐ | ☐ | ☐ |
| 11 | Availability of customer-furnished information and /or equipments | ☐ | ☐ | ☐ |
| 12 | Drawing types (Basic, assembly, manufacturing) | ☐ | ☐ | ☐ |
| 13 | Formal process (Phase review or stage gate process) | ☐ | ☐ | ☐ |
| 14 | *Other* | ☐ | ☐ | ☐ |

4.3. What methods do you use to analyse the cost of design changes?

| Methods | Effectiveness | | |
|---|---|---|---|
| | *Not Effective* | *Somewhat Effective* | *Very Effective* |
| Previous projects are analysed to generate the cost of a new product | ☐ | ☐ | ☐ |
| Expert system for cost estimation | ☐ | ☐ | ☐ |
| Historical cost data to predict the future cost | ☐ | ☐ | ☐ |
| Parametric approach to estimate the cost | ☐ | ☐ | ☐ |
| Activity / feature based cost analysis | ☐ | ☐ | ☐ |
| Commercial software | ☐ | ☐ | ☐ |
| In-house developed software / technique | ☐ | ☐ | ☐ |

4.4. Who is responsible for cost estimation in product design?

| | |
|---|---|
| Finance personnel | ❑ |
| Design engineers | ❑ |
| Cost engineers | ❑ |
| Other | ❑ |

## 5. Additional Questions

5.1. What are the main problems with your current PD model? (you may select more than one option)

| | Options |
|---|---|
| ❑ | Too many sign-offs required (bureaucracy) |
| ❑ | Needs to be updated to meet changing demands |
| ❑ | Causes work to be delayed due to unnecessary tasks/activities |
| ❑ | Engineers are forced to spend time on lengthy documentation (reports) |
| ❑ | The model hasn't been well communicated to employees |
| ❑ | |
| ❑ | |
| ❑ | |

5.2. What are the main challenges that you face in product development? (you may select more than one option)

| | Options |
|---|---|
| ❑ | Products are not innovative enough |
| ❑ | We normally face cost overruns |
| ❑ | We are always overburdened with the quantity of work |
| ❑ | Downstream engineers passed optimised designs that require significant modification or redesign? |
| ❑ | |
| ❑ | |
| ❑ | |

5.3. What challenges do you face with regards to knowledge capture and representation? (you may select more than one option)

| | Options |
|---|---|
| ❑ | Often very time-consuming |
| ❑ | Incompatibility of knowledge formats between different software |
| ❑ | Unnecessary knowledge capture and over-crowded documents/figures/posters/databases etc. |
| ❑ | Designers find it difficult to extract knowledge from previous projects |

5.4. Do you think that mistakes in previous designs could have been prevented by the correct knowledge being provided at the right time? **(select one option)**

none ○ ○ ○ ○ ○ All

5.5. How are design problems currently resolved in your company (A3)? (please explain)

| |
|---|
| |
| |
| |
| |

5.6. Which of the following 'Lean Product Development' work are you aware of?

| Options | |
|---|---|
| ☐ | James Morgan and Jeffrey Liker |
| ☐ | Allen Ward, Durward Sobek and John Shook |
| ☐ | Micheal Kennedy, Kent Harmon and Ed Minnock |
| ☐ | Michael A. Cusumano and Kentaro Nobeoka |
| ☐ | Ron Mascitelli |
| ☐ | Donald Reinertsen |
| ☐ | Chris Mynott |
| ☐ | Mary Poppendieck and Tom Poppendieck |
| ☐ | Other |

5.7. Is your company working with any Lean consulting companies address the issue of product development? If so then what is the scope of their work?

| Options | |
|---|---|
| ☐ | Applying Lean 6 Sigma to product development |
| ☐ | Applying Lean manufacturing techniques to product development (e.g. 5 principles, 5s etc.) |
| ☐ | Applying Value Stream Mapping to product development |
| ☐ | Applying Set Based Concurrent Engineering (or SB design) to product development |
| ☐ | Other… |

# LeanPPD Industrial Field Study Results [Design Section]

| | |
|---|---|
| ***Grant Agreement number:*** | NMP-2008- 214090 |
| ***Project acronym:*** | LeanPPD |
| ***Project title:*** | Lean Product and Process Development |
| ***Funding Scheme:*** | Large Collaborative Project |
| ***Date of latest version of Annex I against which the assessment will be made:*** | 20.02.2009 |
| ***Academic Supervisor names, title and organisation:*** | Dr. Ahmed Al-Ashaab & Dr Essam Shehab<br>Cranfield University |
| ***Tel:*** | +441234 750111 5622 |
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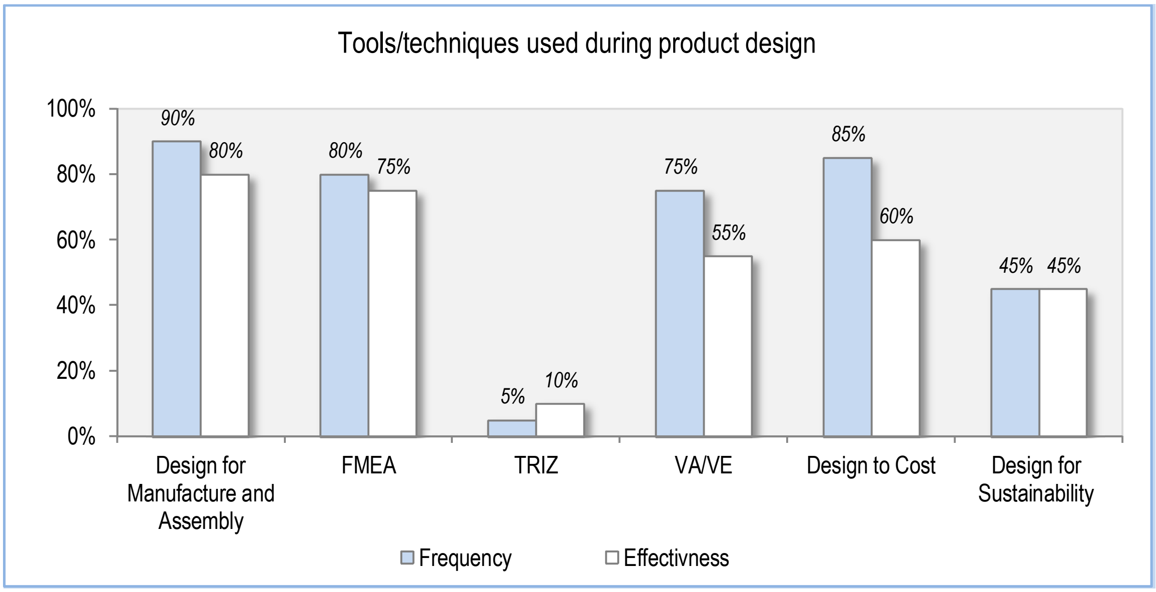
| ***Project website address:*** | www.leanppd.eu, www.leanppd.org, www.leanppd.net |
| ***Start date of the project:*** | 01.02.2009 |
| ***Duration:*** | 48 months |
| ***Responsible of the Document*** | Cranfield University Team<br>a.al-ashaab@cranfield.ac.uk |
| ***Due date of deliverable*** | n/a |
| ***Document Ref.:*** | *Questionnaire for field study* |
| ***Version:*** | 1 |
| ***Issue Date:*** | 29/February/2010 |

## PRODUCT DESIGN TOOLS/TECHNIQUES

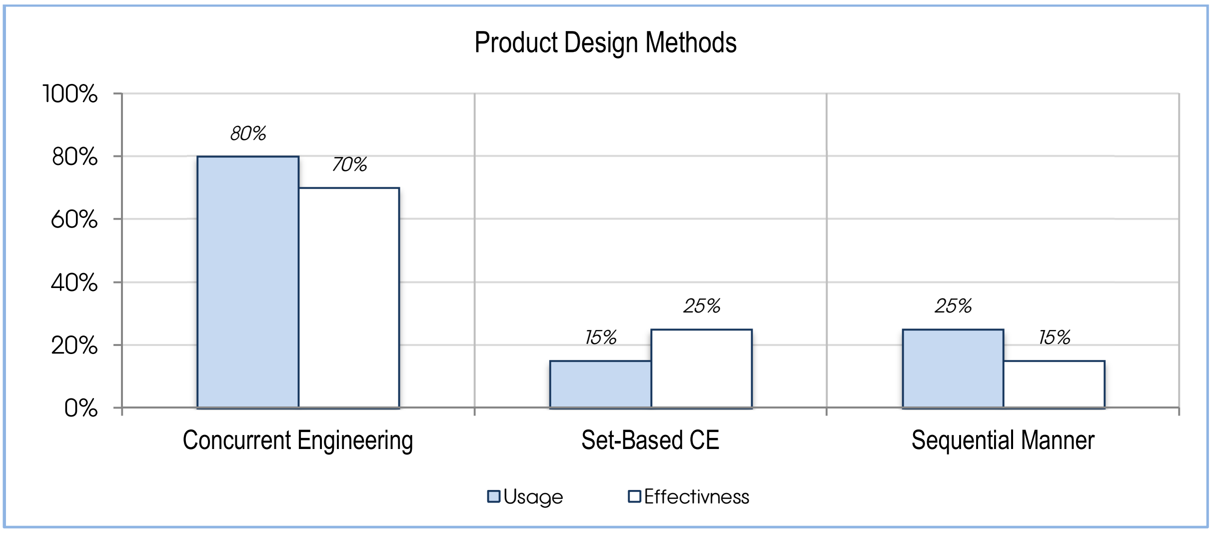
*Which of the following tool/techniques have you formally implemented and utilise as an aid during the design of the product?*




- DFMA, Design to Cost, Design for Minimum Risk and Reliability are considered in majority of projects.
- Designers will select DFX techniques based on project relevance
- For DFMA designers consider the Boothroyd or Lucas method but the DFX are all techniques developed in-house (and most have proven ineffective)

## PRODUCT DESIGN METHODS

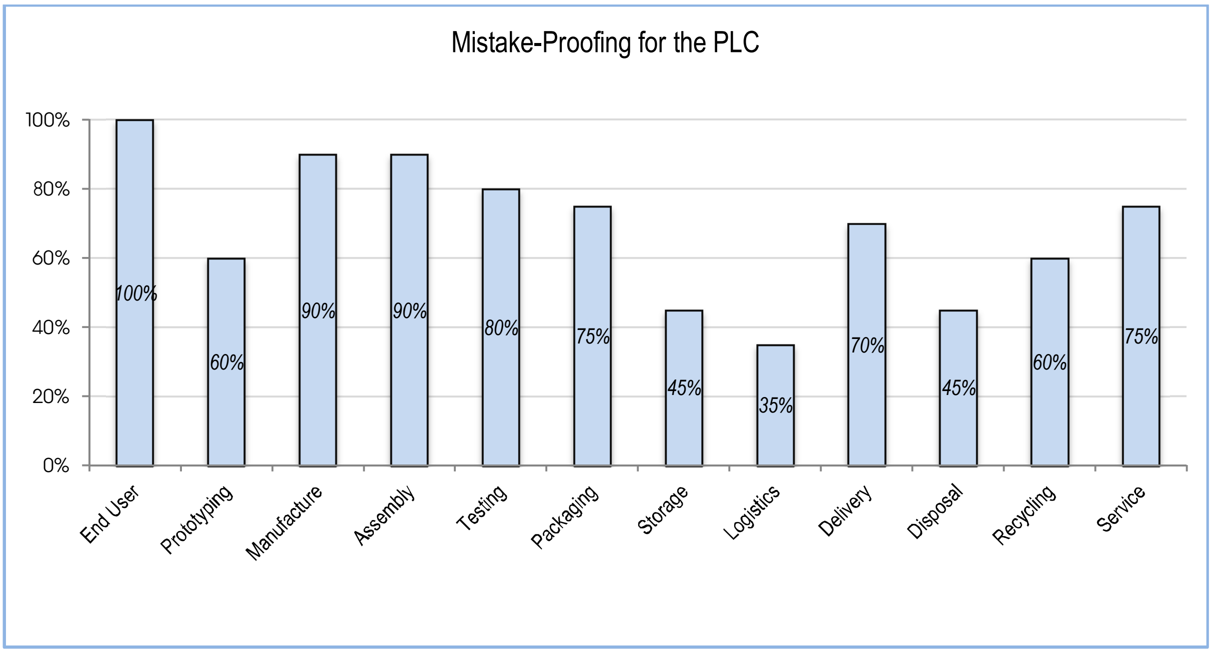
*What method(s) of product development do you currently follow and rate its effectiveness?*




- 25% of the interviewees reported to always follow the traditional method of 'over the wall communication' and express a high level of dissatisfaction.
- Concurrent Engineering is foreseen as the most popular method for product development (reported by 80% of the interviewees: 60% always and 20% sometimes) and shows a high level of effectiveness.
- Set-Based Concurrent Engineering method has not yet been fully implemented and accepted as a routine method – however there have been minor inducements at component level, and the cases of implementation showed good levels of effectiveness.

**MISTAKE-PROOFING FOR PLC**

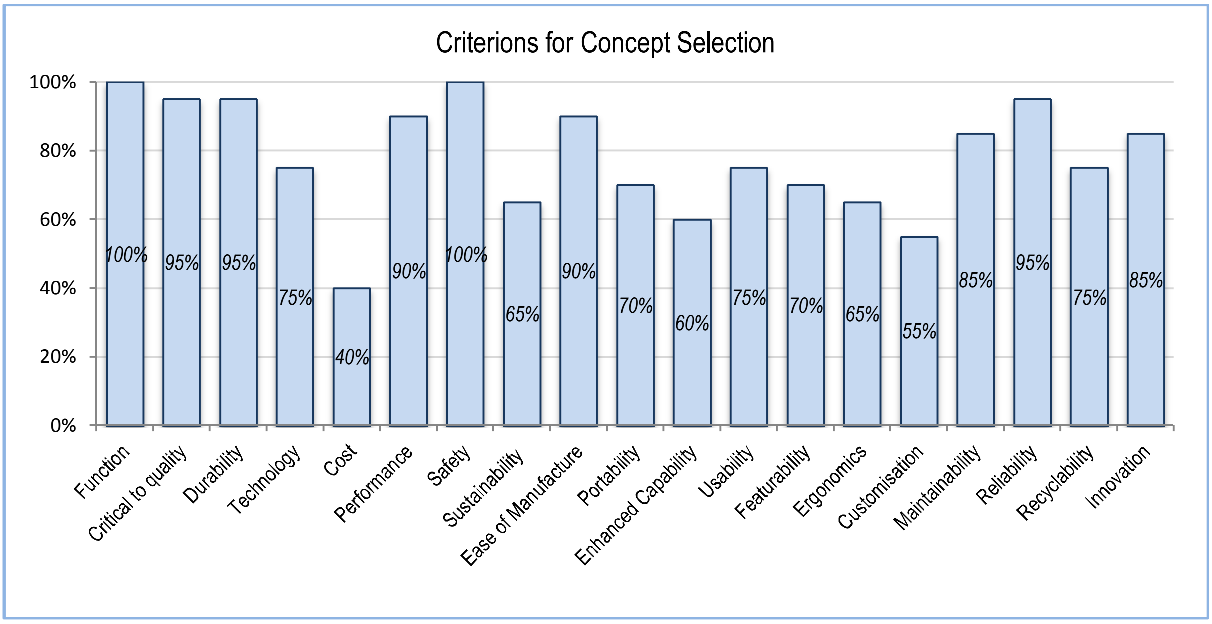
*During design do you consider incorporating error /mistake-proofing (features/elements/mechanisms) for the PLC?*




- There is minimal consideration of Poka-Yoke for the complete product life cycle: the results suggest designers consider mistake proofing for the end user, manufacture, assembly and testing (rating it between 100% -75%).
- All the interviewees acknowledge the importance of considering Poka-Yoke (or a similar mistake proofing ideology) during conceptualisation however 80% depend on personal experience instead of a formalised technique.

## CRITERIA FOR CONCEPT SELECTION

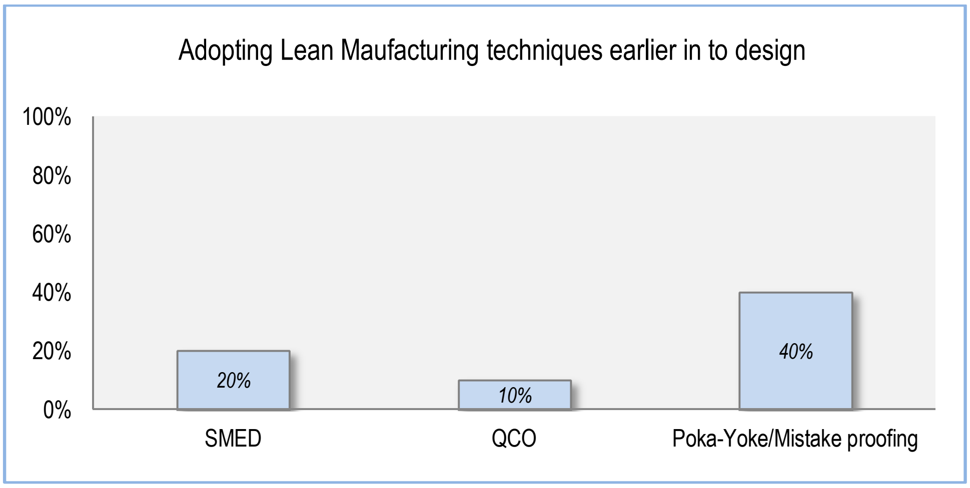
*During concept selection which of the following criterions do you consider in reaching a final solution?*




- Function, safety, performance and reliability are seen as the most important factors during concept selection; however other important factors which impact the product development such as cost are not given much attention.

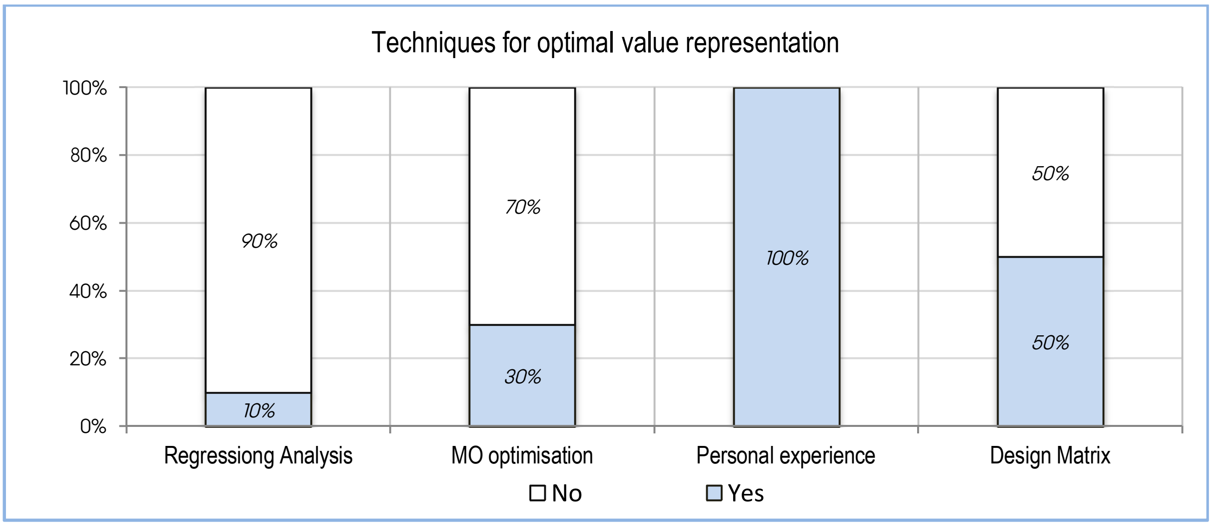
## ADOPTING LEAN MANUFACTURING TECHNIQUES

*Have you considered adopting lean manufacturing techniques as a sense of inspiration during conceptual design?*



**TECHNIQUES FOR OPTIMAL VALUE REPRESENTATION**

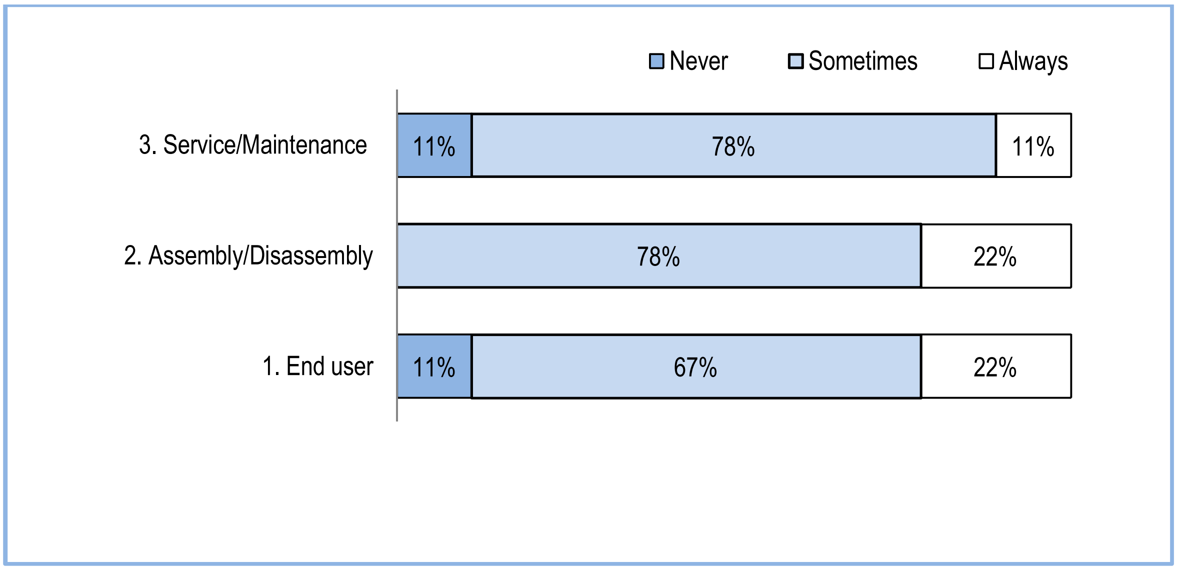
*What approaches do you use in assuring optimal values (as assigned in the design specification) are achieved in your final design?*




- Non-mathematical approaches are more preferred over mathematical methods in realising optimal values in the product.
- Designers solely depend on personal experience to make the necessary decisions as opposed to a more tangible technique.

**ERROR AND MISTAKE PROOFING ON THE FOLLOWING AREAS**

*Do you have evidence of cases when during the design you incorporated error-/mistake-proofing (features/elements/mechanisms) for the followings?*



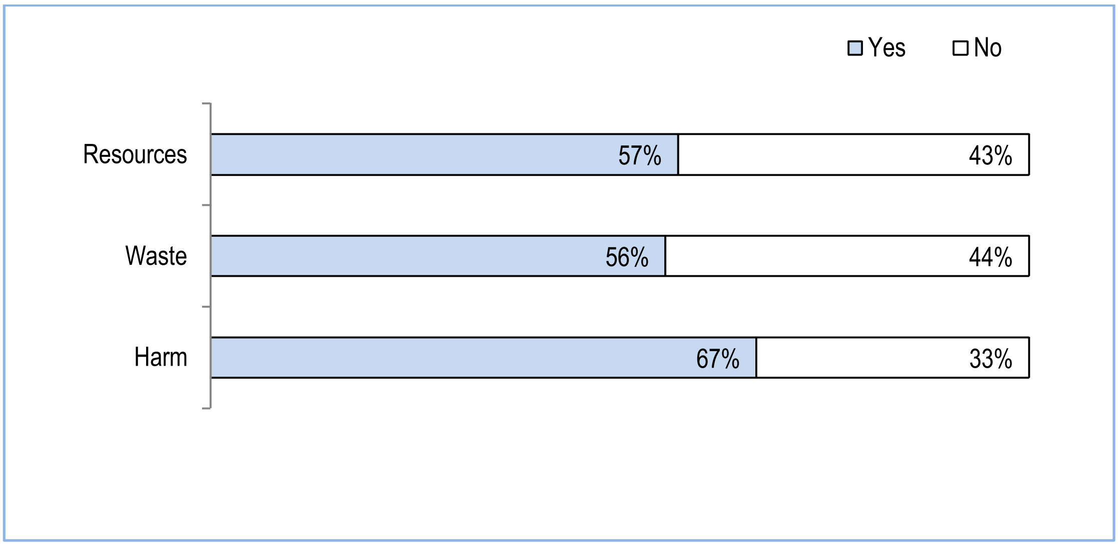
In general, mistake proofing concept is used during product design occasionally but not in a well defined or systematic manner, rather based on the individual’s experience/intuition.

**FORMAL METHOD TO ELIMINATE HARM/WASTE**

*Do have a systematic and formalised method of designing a product that ensures*

*(1) harm to the end-user and manufacturing engineer is completely eliminated,*

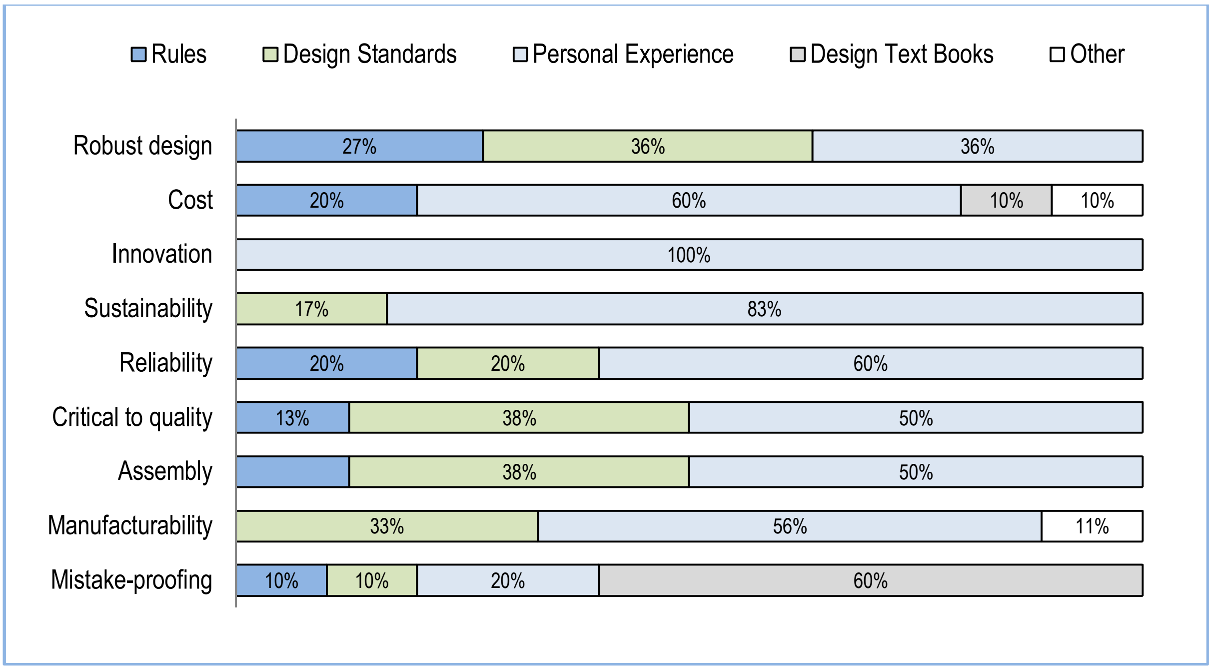
*(2) waste and resources are minimised during manufacture?*




The results demonstrate that design engineers consider harm to the end-user and waste of resources majority of the time, and this is subject to the individual’s ability, however it is not based entirely on a formal method supported by documentation. This therefore suggests there is a need to consider a more firm and technical method to guide the designer by instigating the required thought process.

## SOURCES USED TO DESIGN

*What sources do you use to ensure the following are considered in your design?*




Designers greatly rely on personal experience to do the different listed applications during product design. The aid of rules, standards and design textbooks are somehow considered however there is a need for a more systematic approach to perform those tasks during product design.

# **Lean** design | portfolio |

## oil – water separator

# WX-12

Compiled by: Rahman Alam

# Summary

This document depicts the results of an oil/water separator (wx-12) case study performed by Cranfield University and Caltec. The objective of this document is to present the results from the case study as outlined in the lean design guidelines.

The case study was undertaken by the research team at Cranfield University (CU) and Design Engineers currently employed by Caltec. The concepts and ideas recorded in this document came about by employing the LDG.

## Introduction to the Case study

The case study is based on wx-12, an oil/water separator aimed at replacing the conventional methods of offshore oil extraction. The product is a compilation of sub-assemblies that are currently welded together and housed in a tube to form the complete system.

Computational Fluid Dynamic (CFD) simulations have confirmed there is a good level of oil/water separation however there is an opportunity for further enhancement of the structural aspects of the wx-12.

## Design objectives

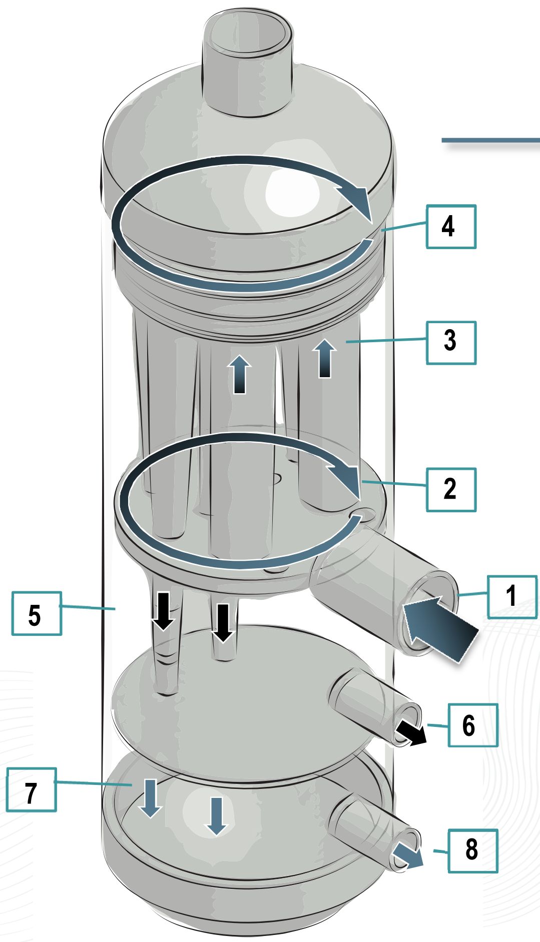
It is in the interest of this case study to apply the LDG to achieve the following outcomes:

- Maximise oil/water separation without compromising function and quality
- Identify alternative manufacturing engineering solution to reduce cost
- Product surface area reduction

PHASE 1:

# Define

# wx-12 | general description | **scenario**: lean out




## How it works

(1) Oil-water solution enters through the inlet nozzle

(2) The solution revolves in the inlet plate assembly

(3) The solution travels through the I-SEPs

(4) The solution is separated in the water and plate sub-assembly

(5) Oil travels through the oil cyclone

(6) Extracted oil exists through the oil outlet

(7) Separated water travels down the water cyclone

(8) Remaining water exists through the water cyclone

## Functional requirements

1. Internal flow path – N7 Surface finish (1.6μm Ra)
2. Tolerance, ±0.5mm
3. Operating Temperature -20 deg to 70 deg
4. Design Pressure 89 bar G
5. Differential pressure across the device 0.5 to 1.6 bar
6. Internal Weight 432 Kgs (approx.)
7. Material – Corrosion resistant to salt water and oil,
   Good resistance to erosion from sand
8. Ease of inspection, maintenance and cleaning
9. Ease of installation
10. No change in the basic geometry of flow

# wx-12 | value focus | three level brainstorm

## Value Extraction + Prioritisation

Values

Maximisation

### 1. Oil-Water separation ◈

#### 1.1. Optimal separation

Reach maximum G-Force (100) to ensure optimal oil separation from solution

#### 1.2. Smoot internal finish

Adaptability to atmospheric conditions without causing obstruction during operation

#### 1.3. Product surface area reduction

Minimise product geometry shape and size whilst maintaining functionality to ensure surface area reduction

### 2. Inspection + Maintenance ◈

#### 2.1. Increase ease of maintainability

Structural modifications to ensure the product can be maintained without causing major delays during operation

Priority
- ◈ High
- ◈ Medium
- ◇ Low

## Design objectives

- Reduce manufacturing cost
- Enhance performance

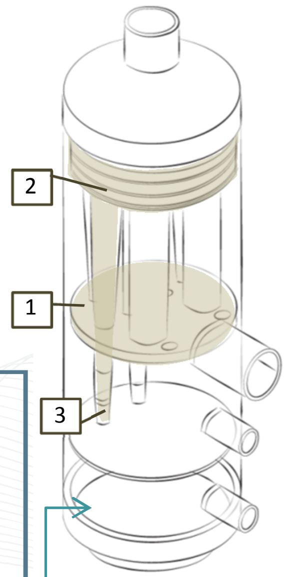
# Three Level Brainstorm: relate sub-systems to product values

Feasibility: ☝ | Design rework: ❶ | Constraints: Key features cannot be modified

Conjoint geometrical effect

The performance of the inlet plate (1) orchestrates the proceeding separation in the water subassembly (2) and the water cyclone (3) acts as a transmitter between the two sub-assemblies

The three sub-assemblies are constrained together




There is an opportunity for further investigation but key features cannot be modified. Therefore this element should be frozen

- The oil/water separation is achieved through the **involute curve** which is located in the inlet plate
- The oil/water separation is subject to **cyclones,** any turbulence or foreign debris could hinder the process of achieving maximum separation

Oil - water Separation

Values

Increase ease of maintainability

Value implications

Geometrical constraints

- The current design is currently all welded together, should a part fail – the entire product is scrapped
- The outer jacket is built from a non-standard size pipe hence the prices is much higher

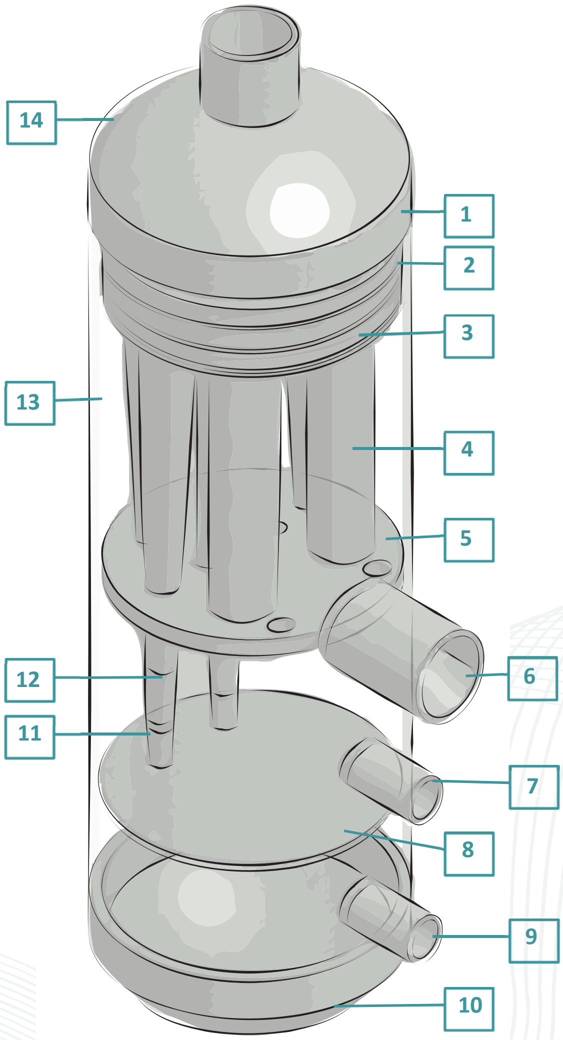
Find alternative method of manufacture to ensure ease of maintainability

Scrapping the entire product should be invalidated and a method for re-use of parts from disassembly should be considered in the new design

By enforcing a standard size of pipe will force area reduction as well as material waste and cost reduction

Feasibility: ☝ | Design rework: ❶ | Constraints: house internal components

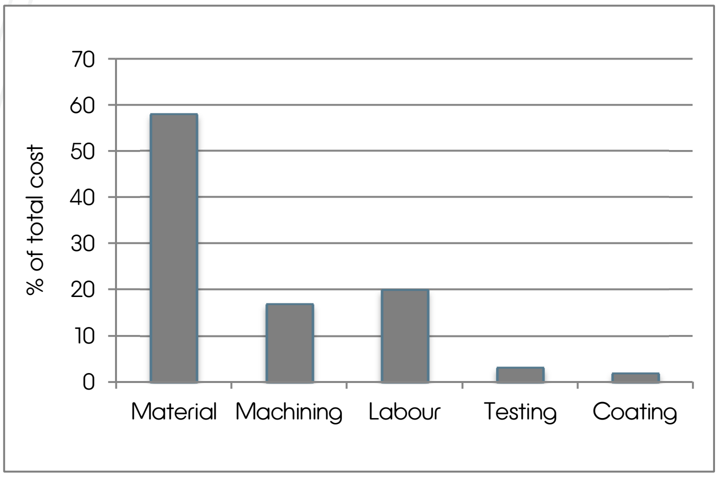
# wx-12 | Lean Design Review of sub-systems |

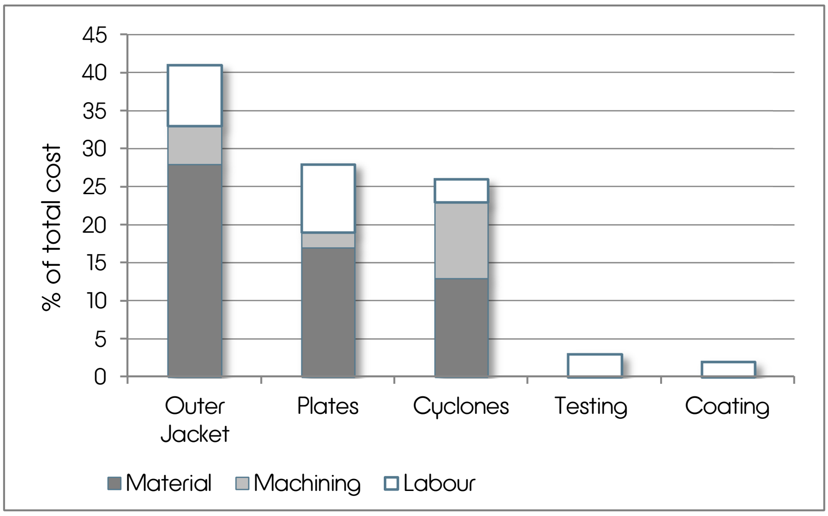



## Wx-12 part breakdown

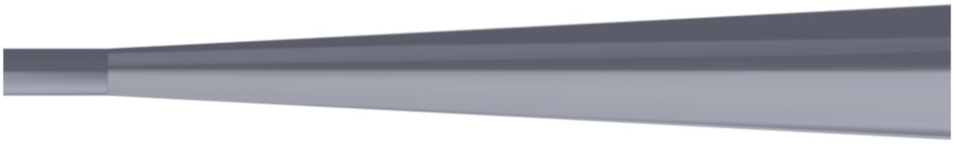
| | |
|---|---|
| 1 | Top plate assembly |
| 2 | Oil plate assembly |
| 3 | Water plate assembly |
| 4 | Separation chambers (I-SEPs) |
| 5 | Inlet plate assembly |
| 6 | Inlet nozzle |
| 7 | Oil outlet |
| 8 | Divider plate |
| 9 | Water outlet |
| 10 | Base |
| 11 | Water cyclone |
| 12 | Oil cyclone |
| 13 | Outer jacket |
| 14 | Dish end |

## Manufacturing cost breakdown



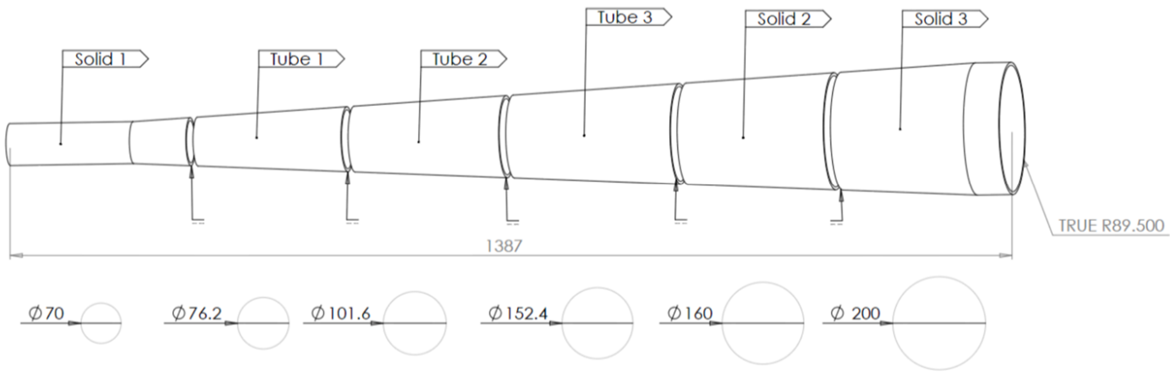



# wx-12 | water cyclone – design review |



| | |
|---|---|
| Function | The water cyclones are responsible for providing the different paths for oil and water |
| Current material | Stainless steel |
| Geometrical constraints | Ensure any modifications made to the dimensions should be inline with alternating geometry |
| Value | Smooth internal finish to prevent turbulence to the flow of fluid (1.6 μm internal and 6.3 – 12.5 μm external ) (2) adaptability to atmospheric conditions) |

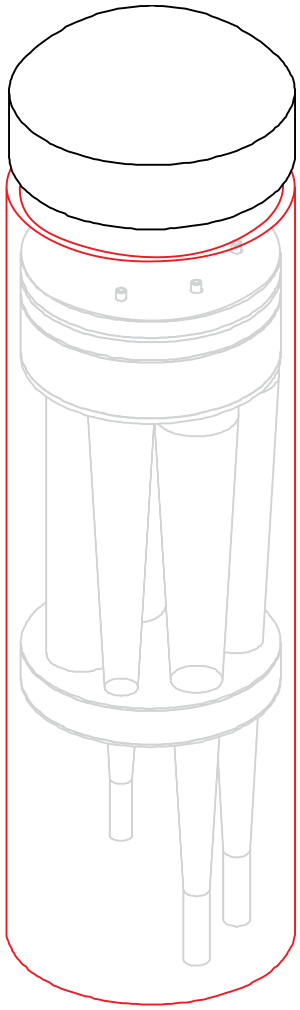
## Overview of un-lean characteristics




- The cyclone is composed of six parts which are welded together to form the complete cyclone
    - ↳ Three parts are individually machined from solid bars
    - ↳ Three are machined from pipe

- There is a high level of material waste due to machining
- Variation is likely to be caused whilst welding the six individual parts
- Alignment of the six parts is essential otherwise the flow of fluid could be hindered
- The overall manufacturing process is time consuming and very expensive

# wx-12 | outer jacket – design review |

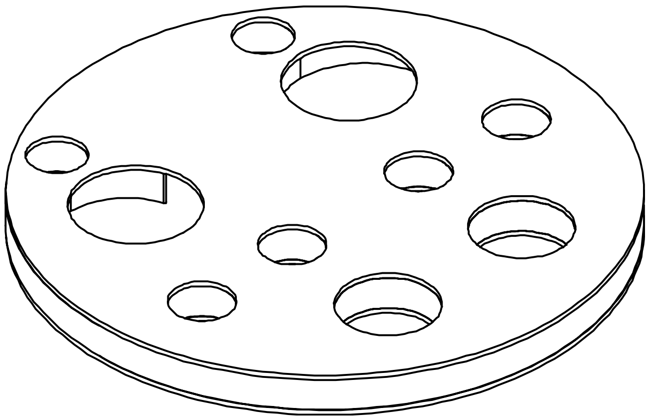


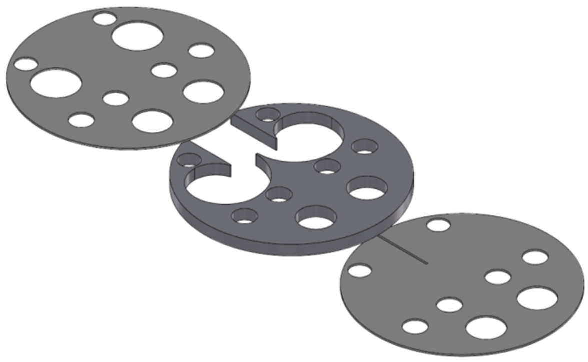
| | |
|---|---|
| Function | Encapsulate the wx-12 |
| Current material | Stainless steel |
| Geometrical constraints | The internal sub-assemblies of the wx-12 must be easily encapsulated in to the cyclone. Hence, reducing the circumference of the jacket will impact the internal components |
| Value | Reduced surface area<br>Ensuring ease of maintenance |

## Overview of un-lean characteristics

- The outer jacket is currently built from a 28 inch pipe (non-standard size)
  - ↳ The jacket is machined to the desired dimension and as a result a lot of material is wasted
  - ↳ Reducing the size of outer jacket will impact the internal components as described above; therefore this must be addressed first

# wx-12 | inlet plate assembly – design review |



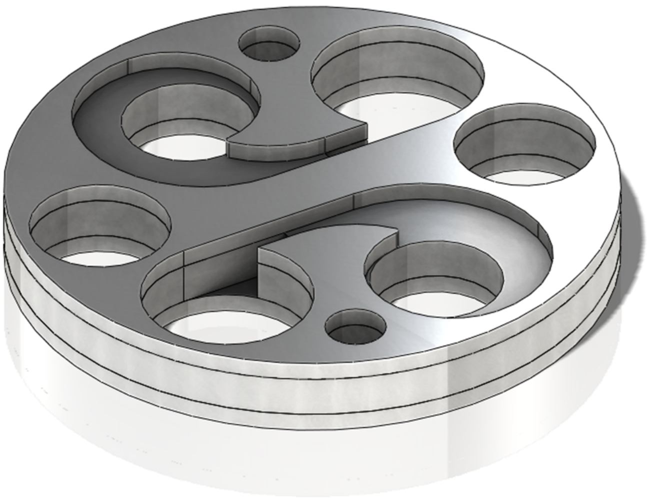


| | |
|---|---|
| Function | The oil/water solution enters through the wx-12 through this sub-assembly and usually rotates up to 100G centrifugal force. The involute curve directs and separates the oil from water. |
| Current material | 316 L |
| Geometrical constraints | The involute curve is a main feature and the dimensional proportions should not be modified<br>The size of the individual holes must be maintained throughout the plates |
| Un-lean characteristics | (1) Resize the plate plates, (2) the current manufacturing method generates a lot of material waste and (3) overall enhancement of geometry to ensure maximum separation of oil/water in the beginning |

## Overview of un-lean characteristics

- As a key sub-assembly in the wx-12, the inlet subassembly design must be enhanced
  - ↳ As a result of reducing the outer jacket the size of the inlet sub-assembly must be modified
  - ↳ The plates are currently laser cut from non-standard sheet metal and then seal welded. This in turn generates a lot of material waste from the different sizes and should be minimised.
  - ↳ The 'L Divider' is a weak component which acts as a separation for the dual involute curves. It can not withstand the extreme force and is prone to damage – as a consequence it will impact the functionality as well as cause potential harm.

# wx-12 | water plate assembly – design review |



| | |
|---|---|
| Function | The water plate assembly is responsible channelling water from the I-SEP to the water hydro-cyclone which then discards the excess water through the water outlet. |
| Current material | 316L |
| Geometrical constraints | The involute curve is a main feature and the dimensional proportions should not be modified<br>The size of the individual holes must be maintained throughout the plates |
| Un-lean characteristics | Unlike the inlet-plate assembly, the water plate assembly contains two set of involute curves. This part contains the most number of features within the Wx-12 |

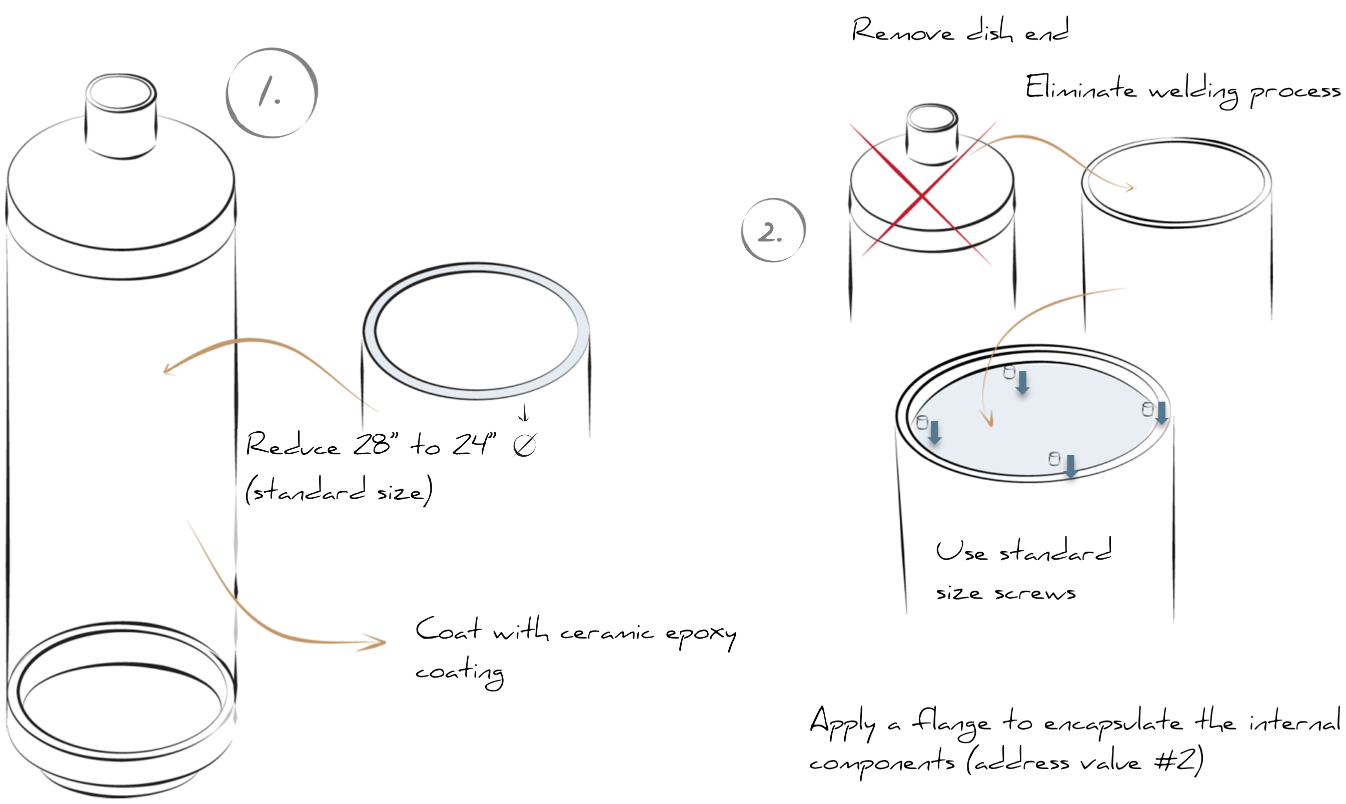
## Overview of un-lean characteristics

- As a key sub-assembly in the wx-12, the water subassembly design must be enhanced
  - ↳ As a result of reducing the outer jacket the size of the water sub-assembly must be modified
  - ↳ The part contains two involute curves which consume most of the parts space
  - ↳ The water-subassembly is composed of four plates which are laser cut and welded, some of the plates are non-standard sizes.

PHASE 2:

# Design

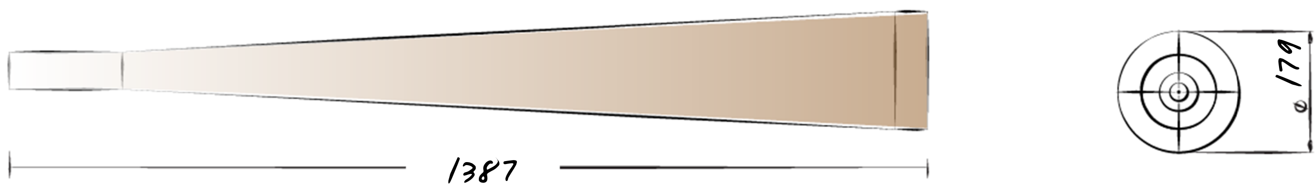
# wx-12 | outer jacket – lean out |



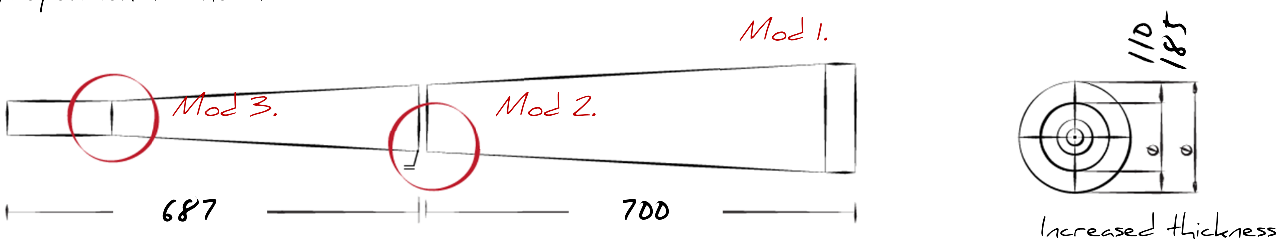

| | | |
|---|---|---|
| Modifications | 1. The outer jacket houses the internal components of the Wx-12 however it is currently built from a non-standard pipe. Therefore the jacket has been reduced to a standard off the shelf size, however it has direct implications on the internal components<br><br>2. The dish end has been eliminated which eliminates the welding process, and a flange has been applied which will use standard screws to seal the jacket – this will ensure ease of maintainability | |
| Current material | Stainless steel | Carbon steel |
| Cost saving | | 45% |
| Other details | Carbon steel has been selected with ceramic epoxy resin coating, this decision conforms with the Wx material requirements and offers a significant cost reduction | |

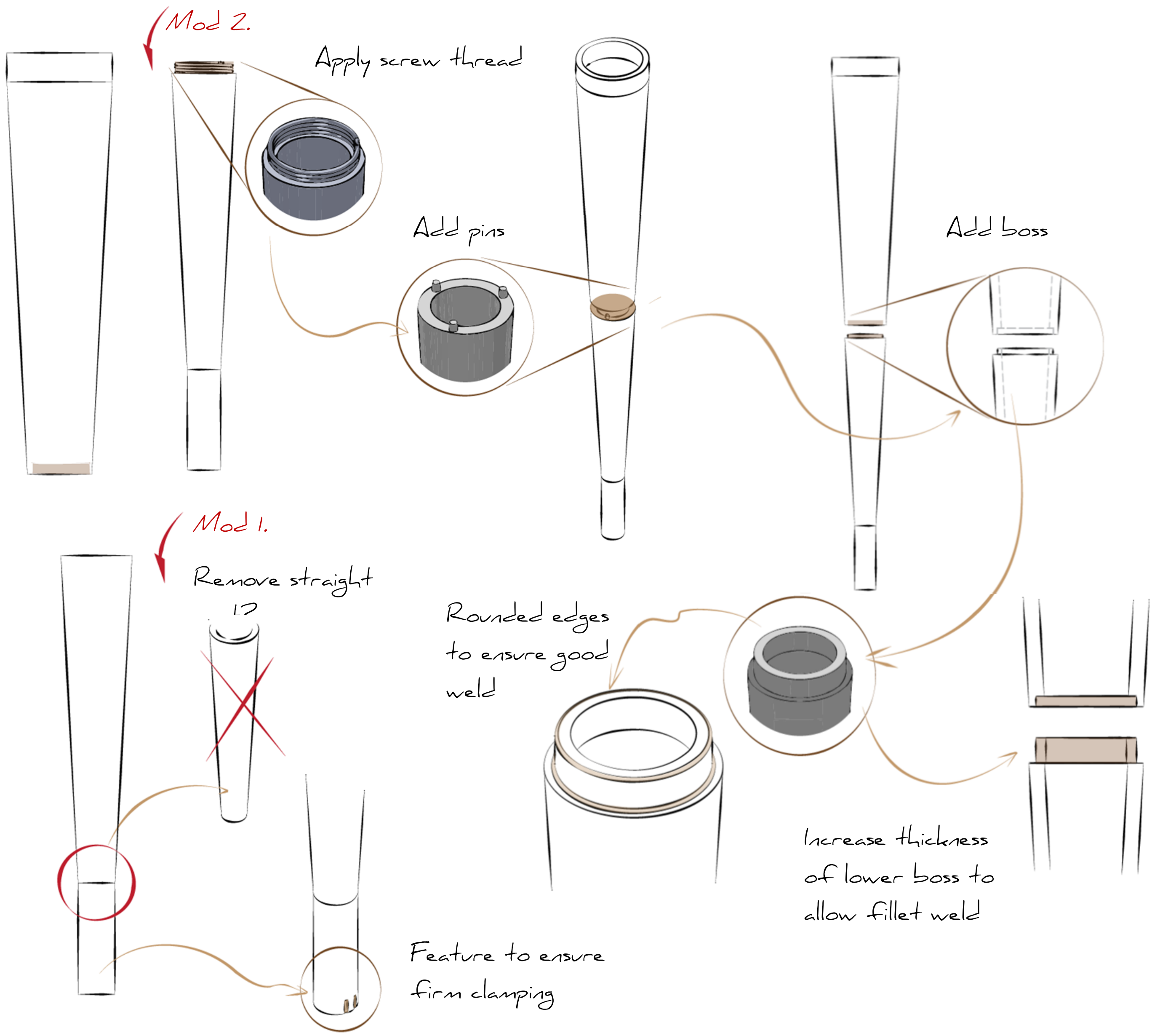
# wx-12 | water cyclone – lean out |

Original Water Cyclone Design




Design proposition: see notes



## General overview

| | Original design | Lean Design |
|---|---|---|
| Current material | Stainless steel | 316L Stainless steel |
| Number of parts | 6 | 2 |
| Manufacturing sequence | Machining → Welding | Sandcasting→ Machining (reduce thickness by 4 mm)→ Welding |
| Value realisation | Possible with implications | Feasible |
| Waste generated during Manufacturing | Very high | Minor as compared to original design |
| Cost saving | | 42.6% |

## Feature annotation

Modification 1: cyclone diameter reduction in accordance with design for sand casting rules: (1) cast with a length between 300mm and 1200mm is 13mm

Modification 2: add a boss with rounded edges to ease the welding process, the depth of the boss is increased to ensure a Lap weld joint is achieved; this feature will also prevent misalignment.

Modification 3: added a clamping feature (within the cast design) to ensure cyclone (secureness) and does not vibrate during turning operation.

Harm elimination: The cyclone will undergo machining to achieve the desired dimension and finish; the excess material will be automatically trimmed and will not require additional effort by the manufacturing engineer.

# wx-12 | inet sub-assembly – lean out |

## Original Inlet sub-assembly design

**Process:**

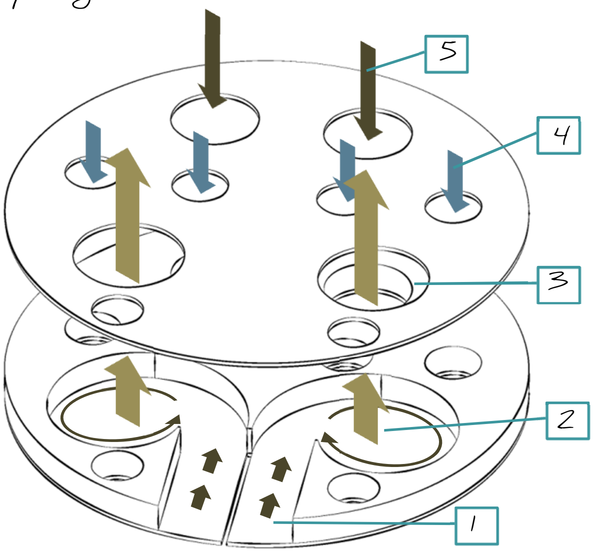
1: oil-water solution enters through the nozzle

2: solution revolves around the involute curve

3: extracted solution exits through I-SEPs to the water sub-assembly

4: extracted oil travels down the oil cyclone in to the oil chamber

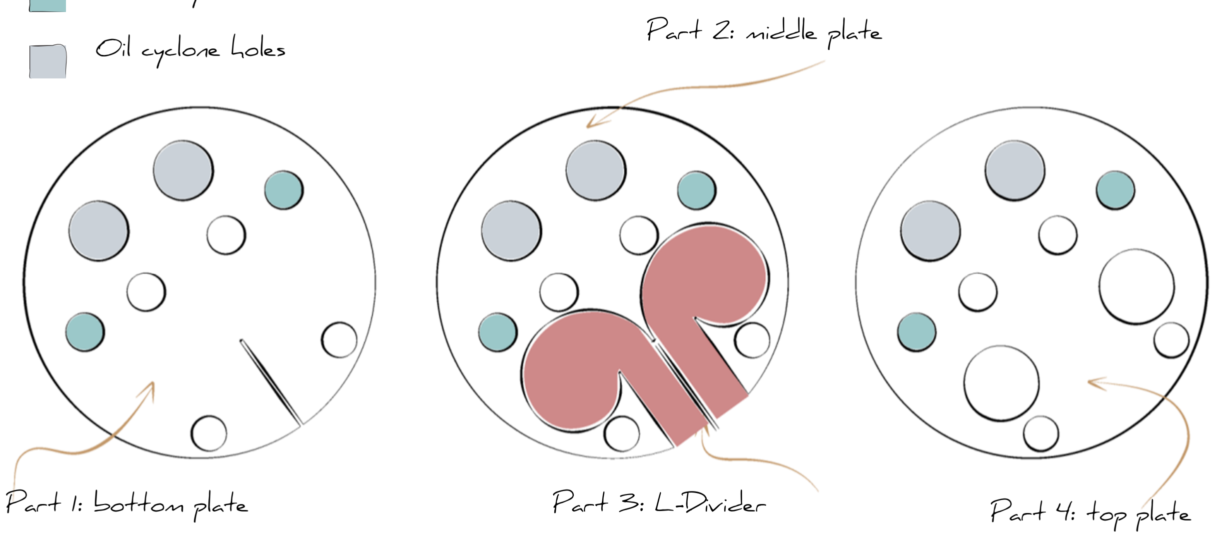
5: water exits to the water chamber




Involute curves

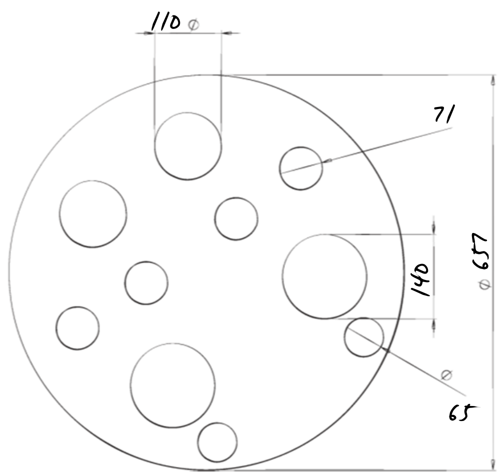
Water cyclone holes

Oil cyclone holes




**Dimensions**

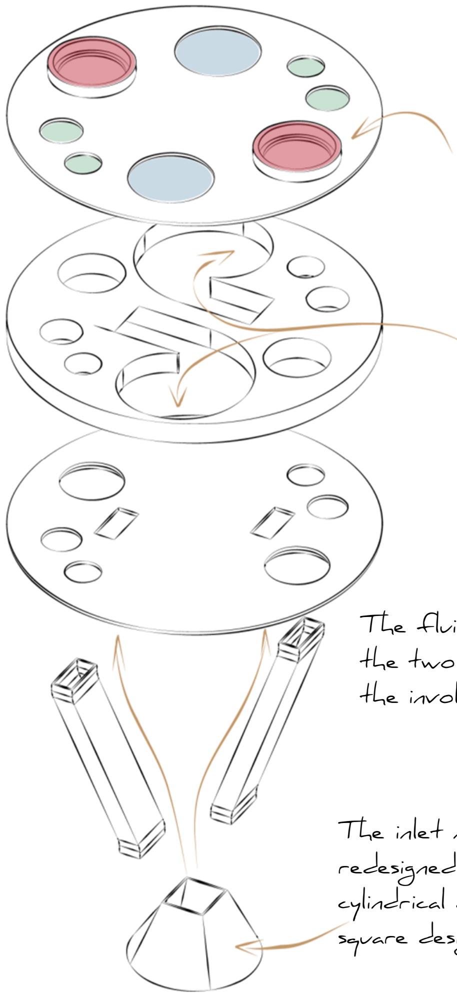
Assembled thickness of three plates: 60

# Design proposition 1

Oil cyclone holes
Water cyclone holes
I-SEPs

Principle dimensions have not been modified in the re-design

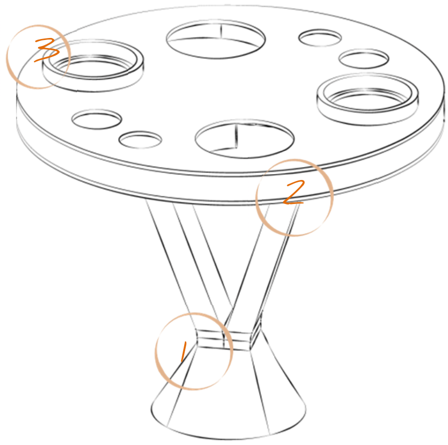


The holes have been repositioned accordingly

The involute curves have been re arranged
L-Divider is no longer needed

The fluid will enter through the two pipes directly in to the involute curves

The inlet nozzle has been redesigned from a cylindrical design to a conical square design



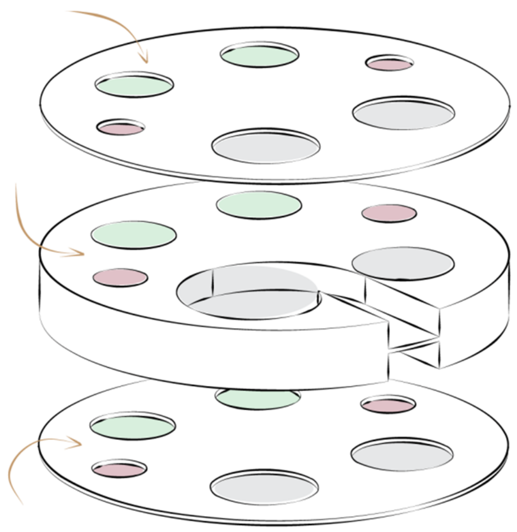

## Summary of design

1: The concept replaces the l-divider and modifies the solution entry from horizontal to vertical

2: The solution enters through the pipes in to the involute curves and the process of rotation continues

3: Additional material has been added to the I-SEP entry to prevent vibration

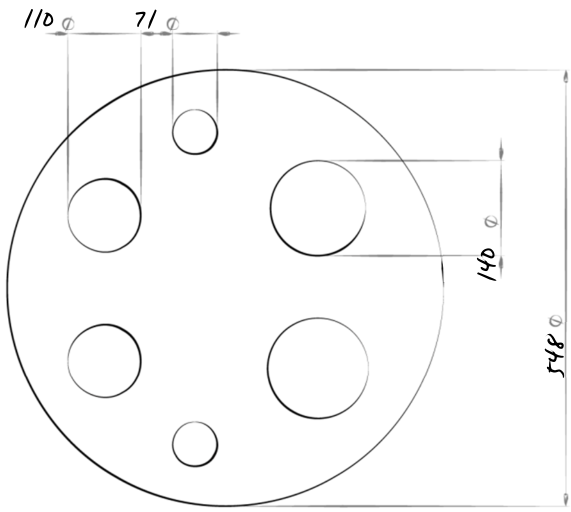
# Design proposition 2

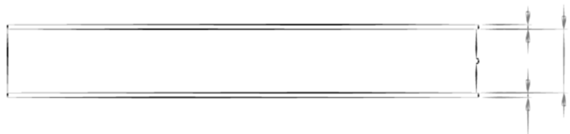


Involute curve

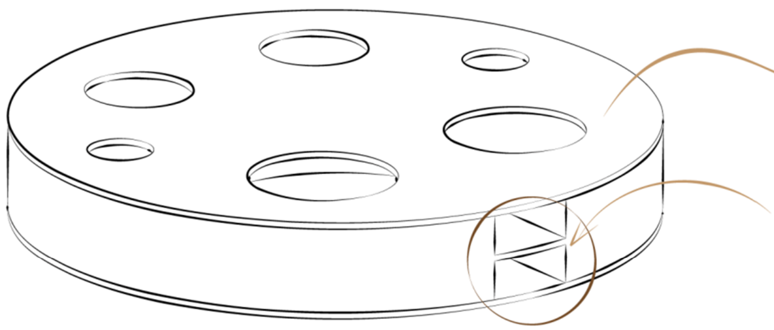
Water cyclone holes

Oil cyclone holes



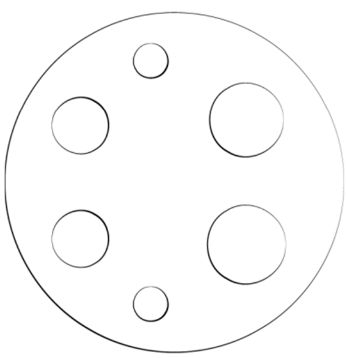




Principle dimensions have been maintained

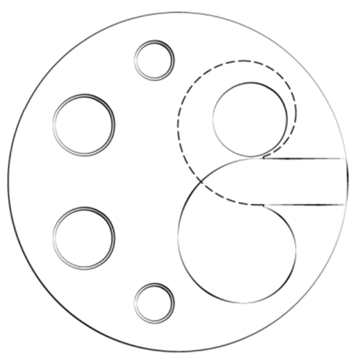


Design has been simplified; four I-SEP holes have been eliminated

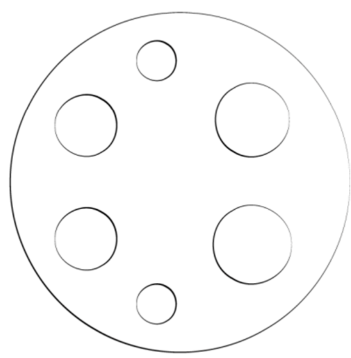
The involute curves have been re-arranged – 1 divider has been eliminated



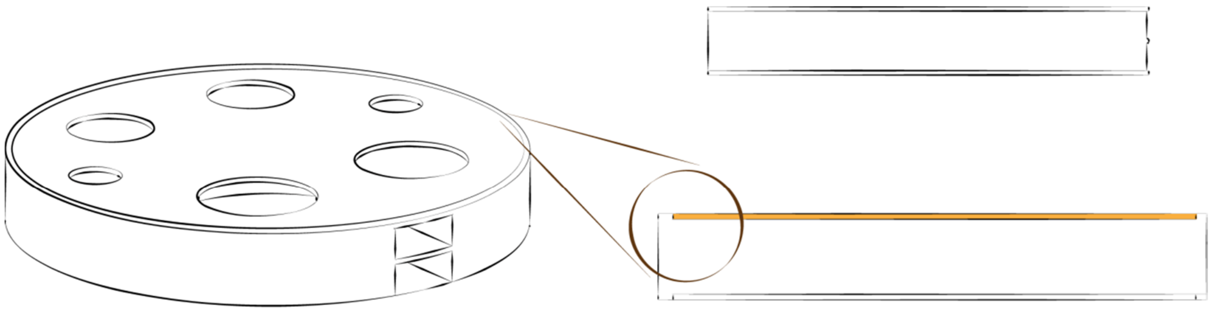
Top plate

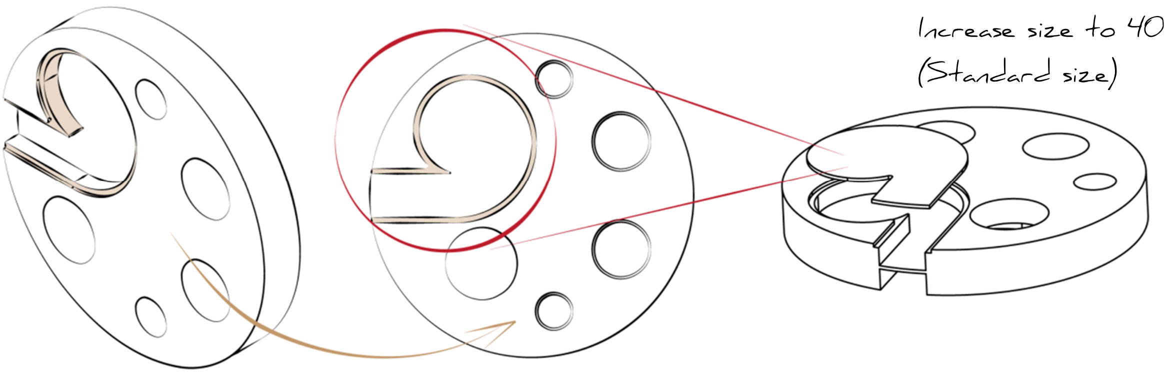


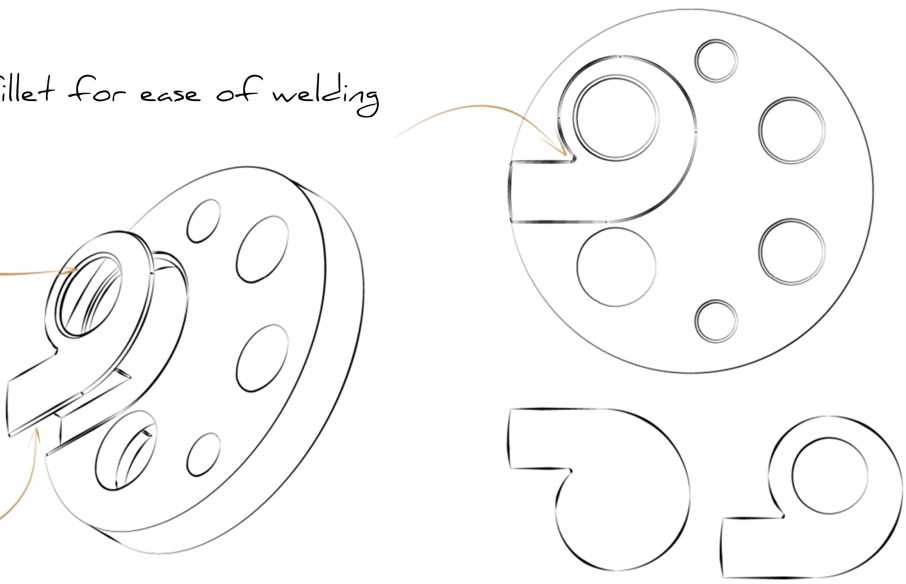
Middle plate



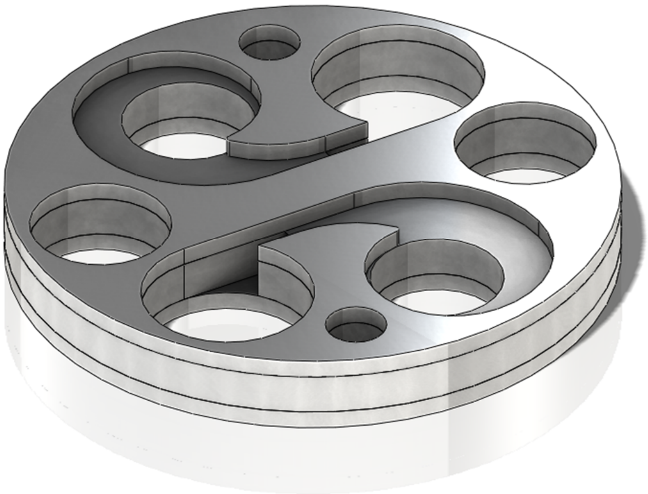
Bottom plate


Side fillet weld is difficult to produce
Reduce plate diameter to
V butt joint weld

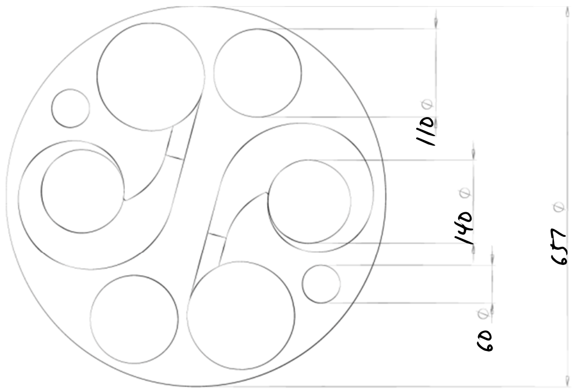

Increase size to 40 mm
(Standard size)
Eliminate the top and bottom plate and 5mm groove
for the involute cover


Create a fillet for ease of welding
Bottom cover
Butt weld
5mm standard plate thickness

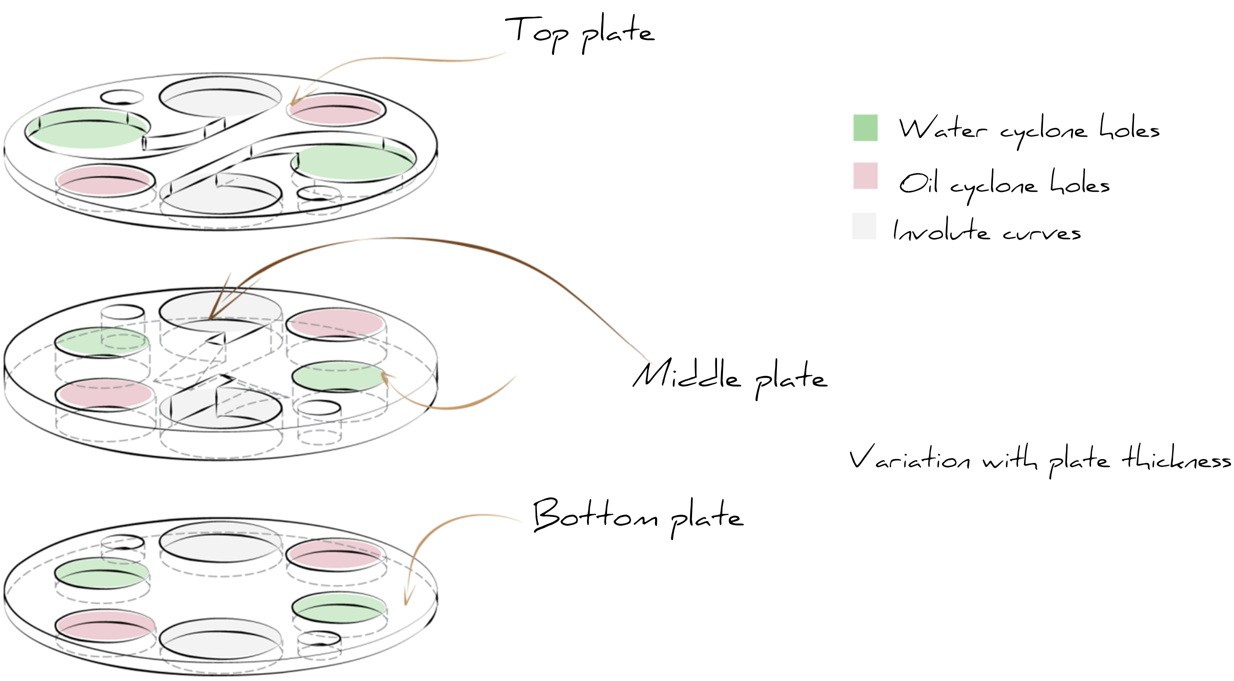
# wx-12 | water-assembly – lean out |



Original water-plate assembly design

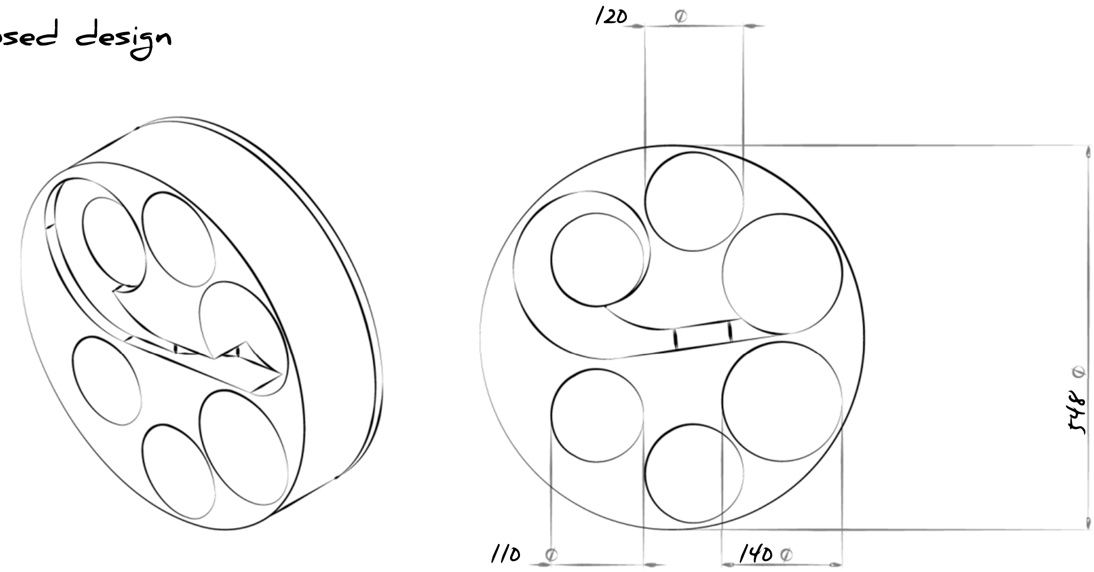


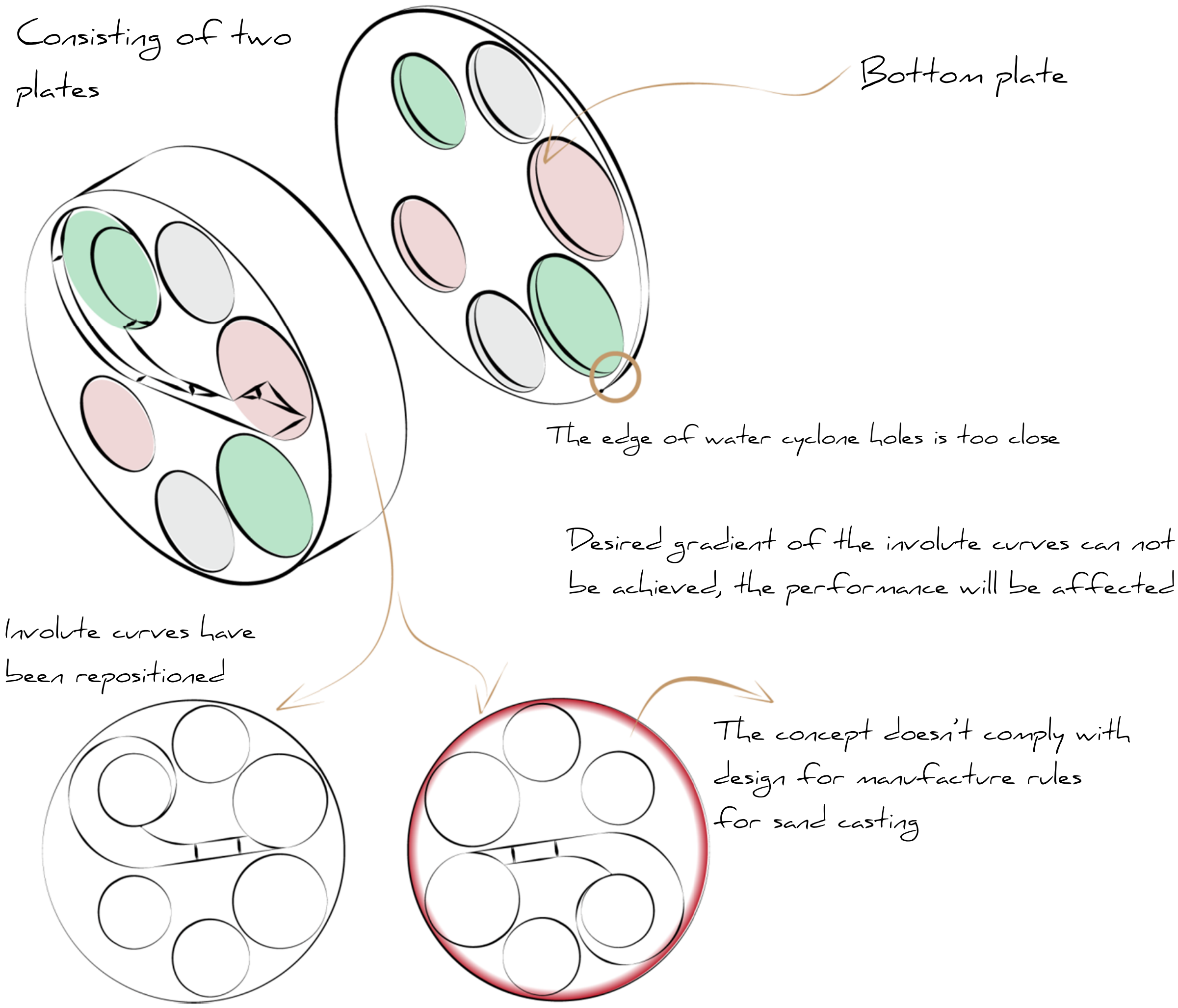

Currently the plates are wire cut from steel plates

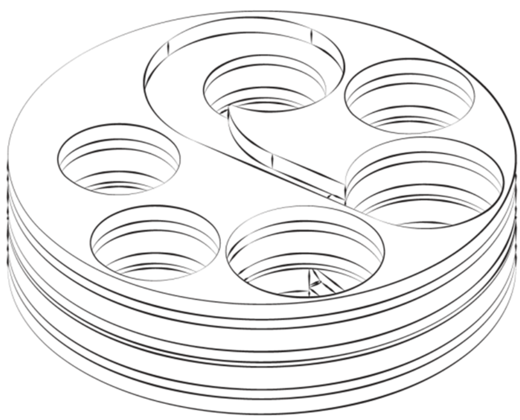



Variation with plate thickness

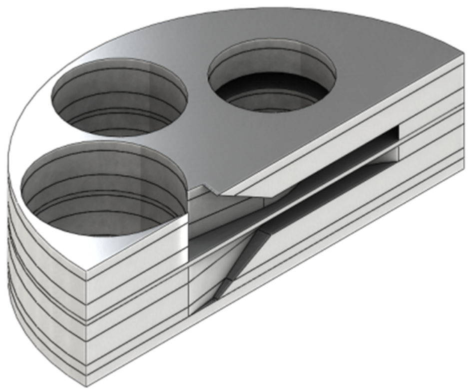
# Proposed design



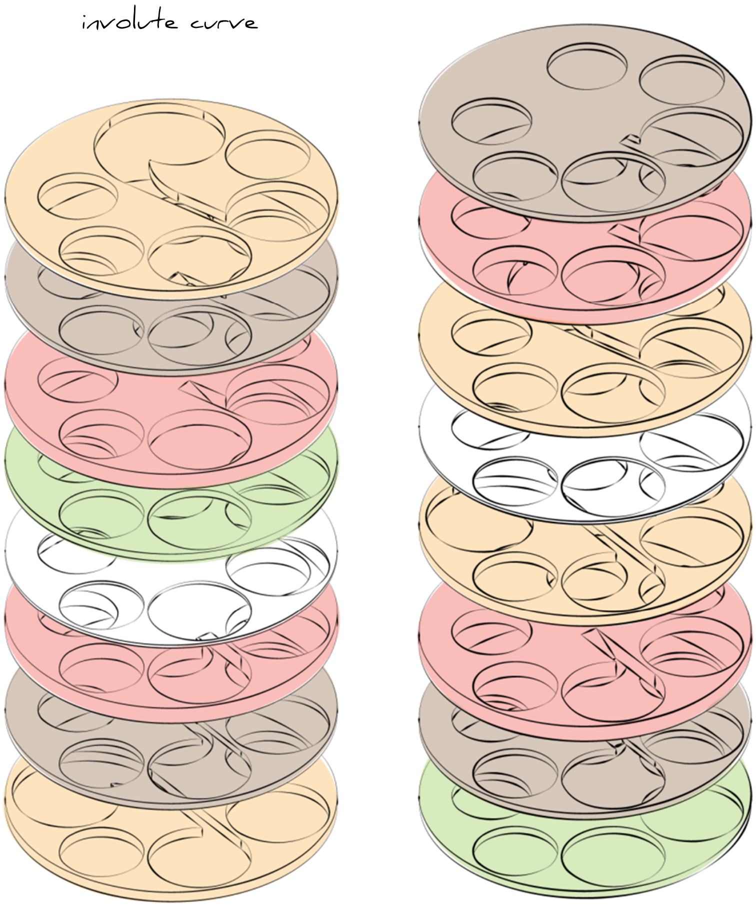


The number of plates is increased to 8

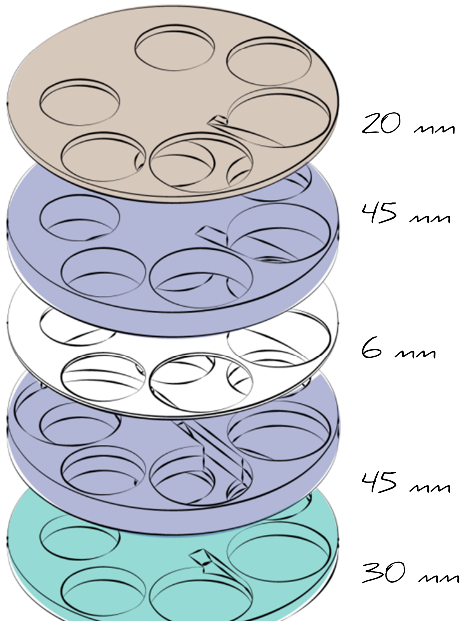


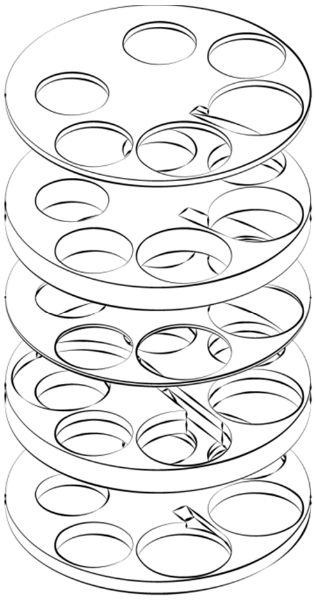
Middle plate has been re-positioned to ensure the gradient of the involute curves is maintained

Reposition plates to maintain gradient of the involute curve

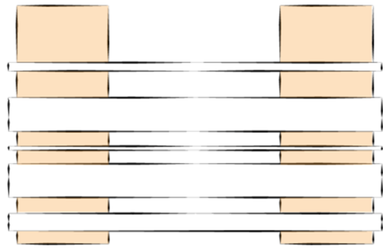


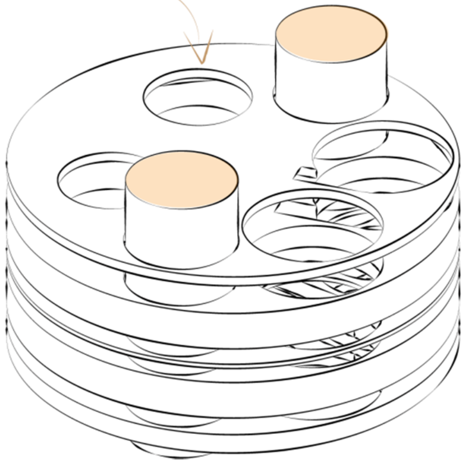
Group plates and use standard size steel plates





Create weld fixtures to prevent misalignment





Eliminate welding process by considering Split threat screws to enhance the maintenance of the plates