Sustainable Product Development in the Industrial Gas Sector

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Abstract

In the midst of the global recession many companies struggled to bring new products to market. There was a focus on cost optimisation, consumer searched for lower cost options in an effort to maintain profits while manufacturers responded by driving production costs down. The continuation of this short term approach is not sustainable. A new way of working is needed to develop sustainable products and to continue developing products. Some industries have reacted to this call and have found benefits in transitioning to sustainability. In the industrial gas industry a trend of lower costs has resulting in commoditisation of the market. This work investigates if there is a redirection can be found in moving towards sustainable practices.

An initial question asked in this work is if a more sustainable product can be beneficial to the industrial gas industry. A trial is conducted to investigate increasing the useable life of a gas cylinder. Two technical approaches are explored which deliver significant increases in life, upwards of 30%. To achieve the products, new mathematical models are developed for product design work which along with a focus on performance parameters leads to new developments in equipment and test methods. Business case models are developed to identify benefits for the manufacturer and consumer. The result provide potentially transformational changes in performance, identifying that sustainability can have strong benefits and be technically achieved. However it is found that the methodologies for development are a limiting factor, ultimately restricting the launch of new products. The trial finds the product development methods used need to be addressed if sustainable development is to be achieved.

Sustainable product development methods have been considered previously. The intent is that products are designed to be of low environmental impact, provide fairness in the supply chain and provide benefits to the consumer. However, the use of methods is not prevalent, typically due to an over focus on environmental impact, complex systems of assessment and methods. Investigations into best practices in product development highlight integrated techniques, disruptive innovations and portfolio management. A combination of knowledge in sustainable development and best in class product development methods provides the basis of a new sustainable product development methodology. The aim is to create and develop a system that enables sustaining product developments.

The new methodology developed uses an integrated product development framework merged with a definition of sustainability. The methodology is described by a framework, a process map and a guideline such that it can be easily followed and implemented. The framework introduces a strategic segment in technology to address a gap identified in the literature and in industrial gases of continued technical development. The work also includes an assessment method. This takes the form of a matrix which links the framework to sustainability factors. A rating method is developed for performance assessment and the calculation of a new indicator, the sustain index. The outputs are visualised and used for decision making at an individual development level and for portfolio management. The new methodology developed focuses on a balanced approach to efficiency, equity, and the environment.

Application of new technologies are explored in the industrial gas industry in order to test the technology strategy developed. A research approach is developed using three separate cases studies. The case studies investigate if similar benefits can be achieved in the application of new technologies as observed in other industries. The hypothesis is addressed along with queries on specific benefits and drawbacks identified for the industrial gas industry. It is shown that the application of new technologies can create step changes in products and processes. The results are seen in three pioneering products. The strategy enables differentiation and gives a competitive edge.

Implementation of the methodology is explored. A specific approach is developed from a literature search and interviews. Interviews are used to deepen knowledge on process change in research and development. A seven step action plan for transformational change is proposed. An example is then conducted. An increase in performance is observed, the sustainability measures improve, and the product development time halves.

In summary this work finds shortfalls of sustainable product development methods through literature and practice. It then considers the best processes for product development and creates a new methodology. This is achieved through a framework, a guideline, an assessment method and an implementation method. Developed areas are then tested. A strategy of new technologies is shown to promote sustainability. The methodology is then implemented though a case study and the transformation documented.

Acknowledgements

I would like to thank a number of people that have helped me achieve the work that is presented here. Firstly my supervisor Professor Kevin Neailey who without I would not have achieved the work, found the required level of rigor in my activities nor improved my writing abilities to the extent that I have. Kevin has been a wonderful sounding board through some challenging times particularly professionally for me. On a personal aspect I have enjoyed his stories and anecdotes. I have much to thank Kevin for.

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Declaration

This thesis is submitted the University of Warwick in support of my application for MSc by Research. It has been composed by myself and has not been submitted in any previous application for any degree.

The work presented was solely carried out by the author with the exception of:

- Modelling of gas cylinder filling
- Manufacturing a valve guard through additive layer manufacturing
- Building a virtual reality model and some of the CAD drawings required
- Initial development of the quartz sensor
- Engineering a circuit board for the electronic gas cylinder
- Coding a mobile application

1 Introduction

The supply of industrial gases is an essential part of the world we live in, they are used in the manufacturing of most every day products (from cars to electronics), in the food we eat (for freezing and packaging) and are essential in life support (medicinal gases such as Oxygen). However this industry supplies products in the same way it always has done and has been slow to adopt modern engineering methods. It is an industry that has struggled with product development and has experienced continued commoditisation. It is also an industry that recognises it has an environmental responsibility but has taken few steps towards sustainability. The concept for an investigation into sustainable product development in the industrial gas sector started with this background information. Following the global recession in 2008, a group of influencers within an industrial gas company started to question if there was an alternative way. They were experiencing tough business conditions and continued commoditisation post 2008. It was identified that there could be an alternative way to offer value to customers. The general products sold by industrial gas suppliers are limited in features and there is little differentiation between competitors (in terms of both product and supply options). Differentiation in product features may enable a positioning away from price as the main concern. Sustainability offers further potential, where the needs can be addressed without compromising the future, ensuring longevity of supply and continued benefits for all parties.

The start of the work presented here began through discussions on differentiation and sustainability in the industrial gas industry occurring in late 2010. There was a backdrop to these discussions of the global recession showing few signs of recovery. The external environment indicated that manufacturing was note recovering quickly and there would be continued cost pressure. A short term focus on efficiency was the strategy adopted by many of the large gas companies (Air Products, 2011).

Industrial gases are heavily used in manufacturing, such as in the production and processing of metals. As such the performance of industrial gas companies are heavily influenced by trends in manufacturing. Post 2008 manufacturing markets have been very slow to recover in volumes and may never. Those that survive the global recession may have an opportunity for growth, however the old norm will not return. Price is may still be the first line for negotiation (and needs to competitive), however, customers may start to look for increased value.

It is from this background that a concept to research and develop techniques of sustainable product development was created by the author and close colleagues. The idea was that if a company could focus on developing new products that provide benefits for all those who interact with the product. These products could provide a sustainable future for suppliers, consumers and others within the supply chain. Such a company would need to be agile to market conditions and able to avoid commoditisation through the rapid development of compelling products.

1.1 Aims and Objectives

The aim of this work is to explore if a new product development methodology will steer the Industrial Gases sector towards sustainable products.

This is to be achieved by the following:

- Conduct a thorough review of how other industries have achieved sustainable product design
- Research and critique relevant methods and best practices of product development
- Utilise a case study approach implementing the new methodology to identify where and how to change the current practices
- Evaluate the expected benefits and determine what would be required for wholesale change in the Industrial Gases sector

2 Background Review of the Industrial Gas Industry

The industrial gas sector is an industry serving predominantly manufacturing industries with products such as Oxygen, Nitrogen, Argon and Argon Carbon Dioxide mixtures (Downie N. A., 1996). These products are derived usually from air by an air separation plant. Air separation a the process of rapidly decompressing pressurised air over a restriction into a large volume that enables distillation of air into its constituent parts, see Figure 1 (Downie N. A., 1996). Such plants benefit from economies of scale. As such they are not frequently built and are often sited next to a large customer base (requiring pipeline quantities) for example to supply Oxygen for the steel industry. The plants are often sized to produce more than the requirements of the major customer base such that the overcapacity can be re-packaged into large cryogenic vessels and gas cylinders to be sold to many smaller users. This area of the business is typically called the merchant business sector (Air Products, 2013). The smaller users are span various sectors including electronics, automotive, food and medical (Downie N. A., 1996). However, the dominant base is still associated with manufacturing industries. Metals fabrication, accounts for 70% of sales (Air Liquide, 2011) (Air Products, 2013). Such customers are welding metals together using argon mixed with carbon dioxide (for carbon steels) or pure argon (for alloyed steel). Another typical activity is cutting metals using Propane and Air/Oxygen, or Acetylene and Oxygen (these gases can be used for some welding activities).

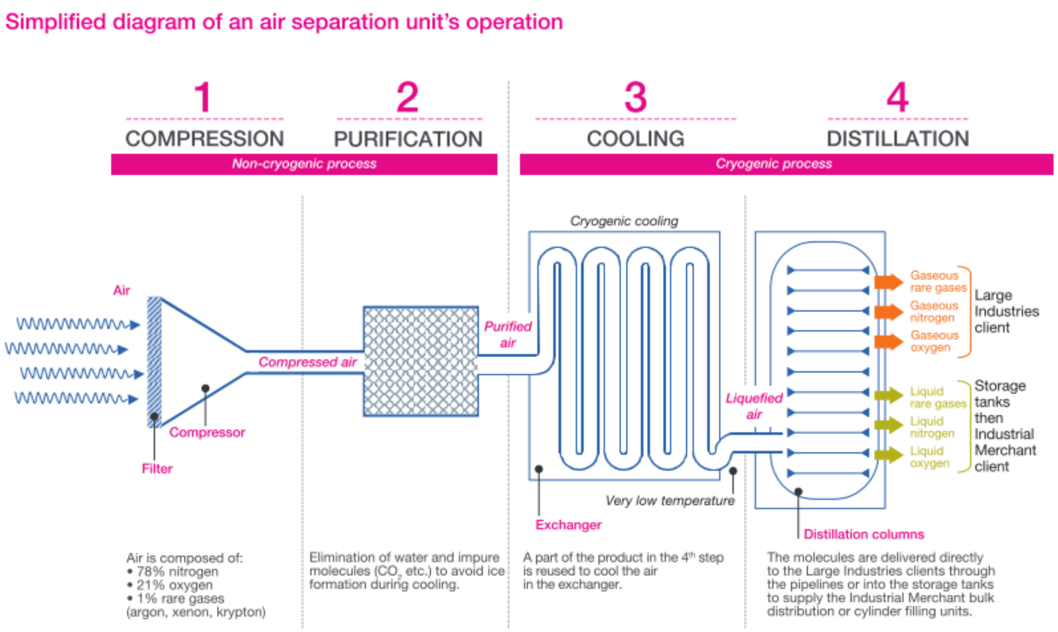

Figure 1: Simplified schematic of an air separation plant (Air Liquide, 2014)

The industrial gases industry shows a commitment to sustainability, all four of the major gas companies publish sustainability reports (Air Liquide, 2013), (Air Products, 2013), (Linde Gases, 2013), (Praxair, 2012). The industry directly has responsibilities in many environmental gases, it handles many tonnes of carbon dioxide, methane, nitrous oxide, ozone and some chlorofluorocarbons. However the industry is not identified as a major contributor to emissions of these gases. The major contribution of greenhouse gases is from energy production (regarding carbon dioxide) and agriculture (for methane and nitrous oxide), see Figure 2. Industrial gases forms part of the chemical industry which is often included in a group of Industrial process industries (U.S. Energy Information Administration, 2011), (Ricardo-AEA, 2014) (Department of Energy and Climate Change, 2015). The chemical industry and other industries contribution to climate change is expressed as "important" (Pachauri, Reisinger, & Core Writing Team, 2008).

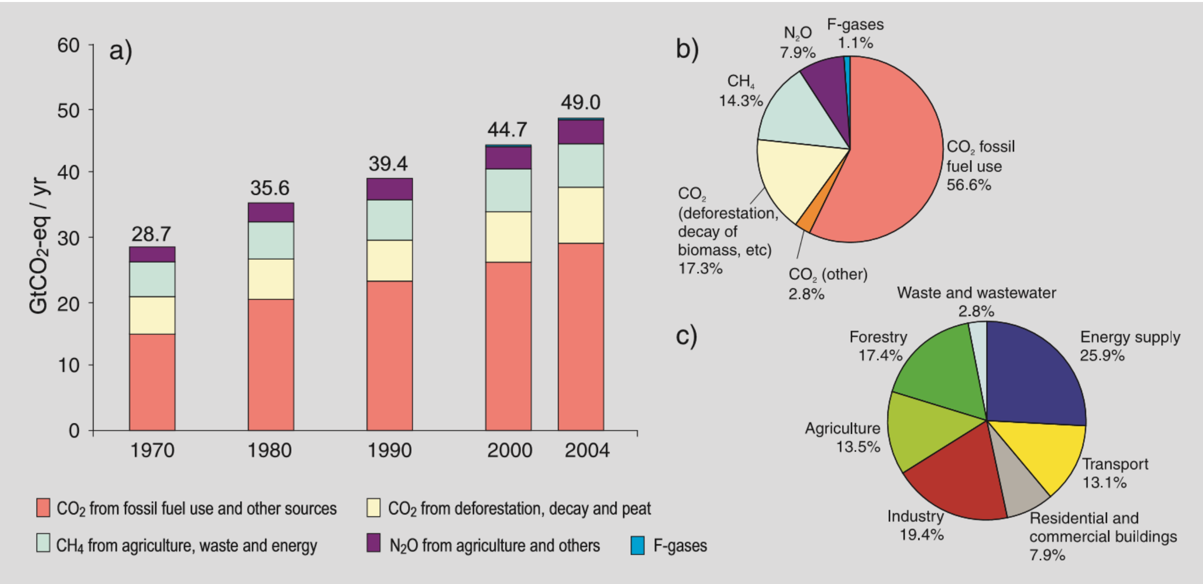

Figure 2: Global annual emissions of anthropogenic GHGs from 1970 to 2004 (Pachauri, Reisinger, & Core Writing Team, 2008)

The major consumed raw materials of this industry are electricity (in the production of air gases) and fuel (in moving the contained gas in liquid or high pressure phases), both are raw materials that contribute to greenhouse gases. It is in such a view (of the gases handled and use of gases) that the major companies in the industrial gas sector have a clear responsibility to the environment and the provision of a more sustainable world.

Reviewing the major gas companies' sustainability reports identifies questions of their commitment to sustainability. Air Liquide's report is a reissuing of their financial report with minor changes (Air Liquide, 2013), there is little focus on environmental performance. There are a few indicators to sustainable commitments, such as "*60% of the research and development budget is directly earmarked for the protection of life and environmental issues*". There is evidence of the use of environmentally focused tools for product development with a case study showing use of eco-design, life cycle analysis and carbon assessment (Air Liquide, 2013).

Air Products' sustainability report shows commitment with "*half of our products/offerings provide energy, environment and social benefits*" (Air Products, 2013). The report contains detailed information of activities (corporate headquarters "*recycled 57 tons of cardboard*" (Air Products, 2013)) but the commitment to sustainable products has some questionable areas. It is stated that 62 environmental products and process were introduced in 2012, a reduction from 84 in 2011 (Air Products, 2013). In 2012, 15 life cycle assessments were performed for key offering, if one life cycle analysis was used per environmental product development then only 24% (15 out of 62) of environmental developments have life cycle assessments (Air Products, 2013). This is the most generous way to look at the numbers, if life cycle analysis was used on non-environmental products then the number would be lower. What it does show is that while there is knowledge of life cycle analysis the adoption is low. In an expenditure of $126.4 million on R&D, some 1.3% of sales (Air Products, 2013), it is not clear how much of this is orientated to sustainability. The report could be improved with comments on expenditure and application of techniques towards sustainable products.

Linde's sustainability report much shorter than Air Liquide's and Air Products. It does contain some interesting information such as the corporation recognises a change in their shareholders with an increased focus on sustainability, "*Among Linde's shareholders, the proportion of SRI (socially responsible investing) investors rose from 4 percent at the end of 2012 to over 7 percent at the end of 2013*" (Linde Gases, 2013). There is a lack of information with regards to new product developments with a sustainability focus. The section on new product development details the expenditure level and number of patents. Only five key innovation projects are highlighted in the report are associated sustainability matter, in energy (Hydrogen and liquefied air) and carbon dioxide capture and re-use (Linde Gases, 2013). All of the projects are observed to be partnered projects, which could indicate a specific strategy.

From these insights it is observed that the major gas companies understand the need for sustainability but are yet to transition to sustainability. A driver is required to prompt transition, this could come from external sources, such as legislation or customers, or internally, such as the CEO's vision, cost position. Perhaps there is the start of a change in external drivers such as Linde's observation on an increase in shareholders focused on sustainability.

Considering the role of legislation it is interesting that the industrial gas sector has not been targeted with specific environmental legislation associated to production methods and use. For example the sector does not have any specific environmental legislation concerning the production and transportation of Carbon Dioxide. In the author's experience one small gas cylinder filling plant used to improve the purity of the Carbon Dioxide by venting 5 tonnes a week. This legally did not need to be accounted for or reported.

Industries such as the aviation and energy sectors are legislated as part of the European Union emissions trading system (European Commission, 2008). It is imaginable that there could be such legislation in future. An example would be setting targets for waste carbon dioxide in production or requiring offsetting of emissions by carbon capture.

Industrial gases has not been subjected to public opinion pressure to change. A comparative case close to the industry is seen with Coca Cola who was pressured into monitoring, reporting and targeting reductions in its use of water and carbon dioxide in drinks (Choudhury, 2013). This is a typical application for carbon dioxide supplied by industrial gas companies. Public opinion focused on Coca Cola as opposed to others in the supply chain, mostly due to the popularity of the brand. There are opportunities for industrial gas companies to take steps forward in their approach to such products before they are enforced to.

The industrial gases sector may have a more prominent role in a sustainable future. The supply of fossil fuels is limited and steps are being taken to use increasing amounts of renewable energy sources or lower carbon energy sources. In both these areas the industrial gas sector could be heavily involved. Many of the renewable energy technologies use gas products supplied by the industry. From simple shielding gases for welding in the construction of wind turbines (Messer, 2016), to the use of environmentally damaging gases (such as sulfur hexafluoride) in manufacturing solar panels (Mulvaney, 2013). In the supply of low carbon energy the industrial gases sector has an important role to play with Hydrogen (manufacture and distribution (Wall, 2015)), liquefied natural gas (manufacture (Scurlock, 2008)), liquid air (used as an energy vector (Strahan, 2012)) and even bio fuels (Oxygen can be used to improve the fuel burning efficiency, Nitrogen is often required as a blanket gas, such as, with wood chippings and often the gas companies are involved in the carbon capture technologies to process the Carbon Dioxide (Hochrinner, 2012)).

The products currently supplied in the industrial gases industry have hardly changed for decades. For example the general concept of the gas cylinder has remained the same since their introduction in the mid-1800s (Downie N. A., 1996) (Almqvist, 2003). Gas is held in a high pressure cylinder, which is accessed by the customer through a simple valve (acting much like a water tap). Typically, the customer will attach a gas regulator to the cylinder to reduce and stabilise the pressure and flow for the end application. The end application requirements varies, but the major applications share similar requirements, such as carbon steel welding which requires a pressure of approximately 3 barg and a flow between 8 and 20 l/min (Lyttle & Stapon, 2005). Alloyed steel welding requires a similar pressure of around 3 barg and a flow between 15 and 40 l/min (ESAB, 2015) (ESAB, 2015). For gas cutting applications a fuel gas is regulated to between 0.2 to 1.0 barg with a flow between 3 and 15 l/min, the oxygen is regulated between 1 and 10 barg with a flow between 10 and 750 l/min (Victor Technologies, 2015). Noting that the gas settings for a cutting application are highly dependent on the nozzle size and type used along with restrictions in the system such as hose length and flash back arrestors.

The typical gas products for a small industrial gas consumer are shown in Figure 3 and Figure 4. As highlighted these are much the same as those used in the 1900s, shown in Figure 5. The setup is shown in Figure 3 and Figure 4. The basics of the system has not changed for over a hundred years. The majority of the technological developments are concerning the electrical equipment used, the filler metals and the techniques to carrying out the welding. These developments have led to major process changes such as enabling robotic welding, which has revolutionised many areas of manufacturing. The gas delivery system remains largely the same for robotic welding, comprising of the same essential components of cylinders, valves and regulators. For robotic welding the configuration is more likely to be multiple cylinders manifolded together with a regulator and control valves mounted on a panel, typified in Figure 6.

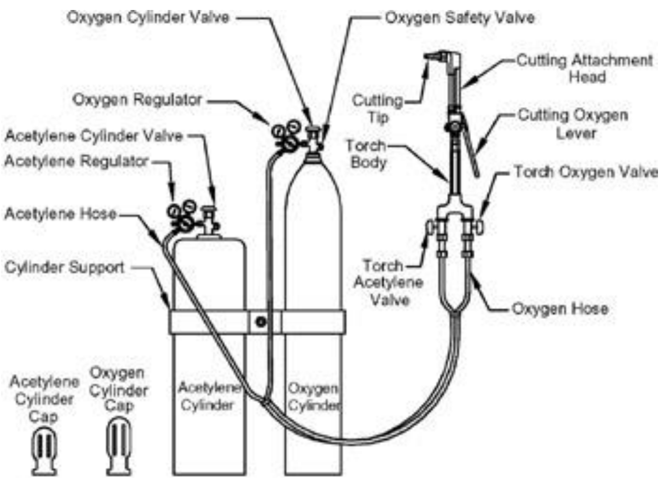

Figure 3: Oxygen Acetylene typical set up (Welders Universe, 2014)

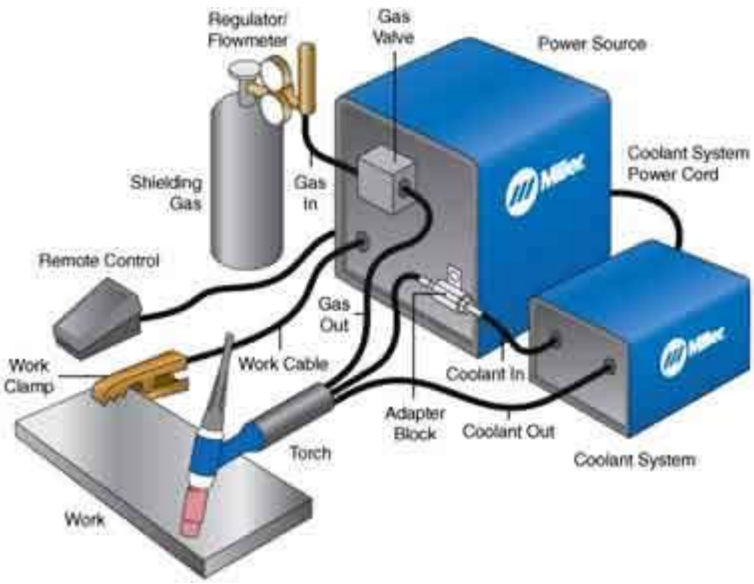

Figure 4: Gas welding typical set up (Miller Welding, 2015)

Figure 5: Acetylene welding in 1918 (Wikipedia, 2015)

Figure 6: Typical gas supply manifold (Midwest, 2015)

The major changes in the gas system have been associated to pressure and latterly the integration of the pressure regulator into the cylinder valve. The increases in pressure have happened in a stepwise progression from 100 barg in the 1930s to 200 barg in the 1970s then latterly 300 barg in the 1990s (Downie N. A., 1996). The major changes in the industry are set out in the timeline below for both welding and industrial gas applications, Figure 7:

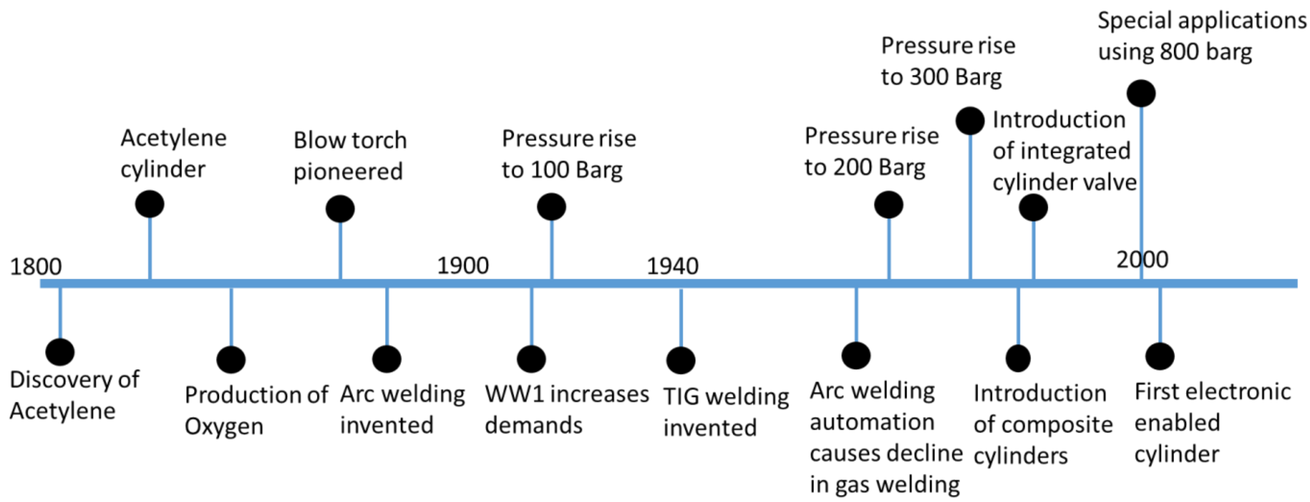

Figure 7: Timeline of cylinder gas milestones (Downie N. A., 1996) (Netwelding, 2015) (Almqvist, 2003)

From the timeline it is seen that there has been a steady frequency of new developments in welding. For industrial gases there has been recent advancements such as 800 barg cylinders now being possible (Züttel, 2003) and electronics on a cylinder valve. However, this chart does not visualise the market penetration of the products. For example, the market is currently dominated by 200 barg products; 300 barg is not typically standard. In the UK, BOC started introducing 300 barg for industrial products in 2015. The use of 800 barg is only within Hydrogen fuel systems where the pressure is required to minimise storage sizes, in particular for transporting applications (Harris, Book, Anderson, & Edwards, 2004). There is a similar story for integrated valves, composite cylinders and electronics cylinders. It is observed that while supporting industries adopt major changes in technology such as TIG welding and automation there is a inertia to adopt changes in the gas products.

The metals fabrication market has grown globally and continues to do so, albeit now at a lower rate. However the construct of the manufacturing geographies has changed dramatically. In Europe the production of steel has fallen, from 883 million tonnes a year in 2007 to 710 million tonnes a year in 2013 (World Steel Association, 2015). The subsequent effect is that the associated metals fabrication industries have struggled to remain competitive against a rising steel price. Unsurprisingly, much of the steel production and metals fabrication work has been relocated Eastwards, especially to China. China's steel production over the same period has grown and is still growing, see Figure 8 (World Steel

Association, 2015). What is left in Europe is an increasingly specialist market. This is natural as businesses in Europe struggle compete with China's prices and have to find other methods to survive such as, by offering customers specific grades and alloys. The current conditions show a slowing of the rate of decline, but this remains a very challenging market. The major gas companies' performance (see Figure 9) reflects limited growth in advanced economies (+5%) and stronger growth in developing economies (+20%). The growth for gas companies in advanced economies is from other market areas such as healthcare, electronics and alternative fuels (Air Liquide, 2011).

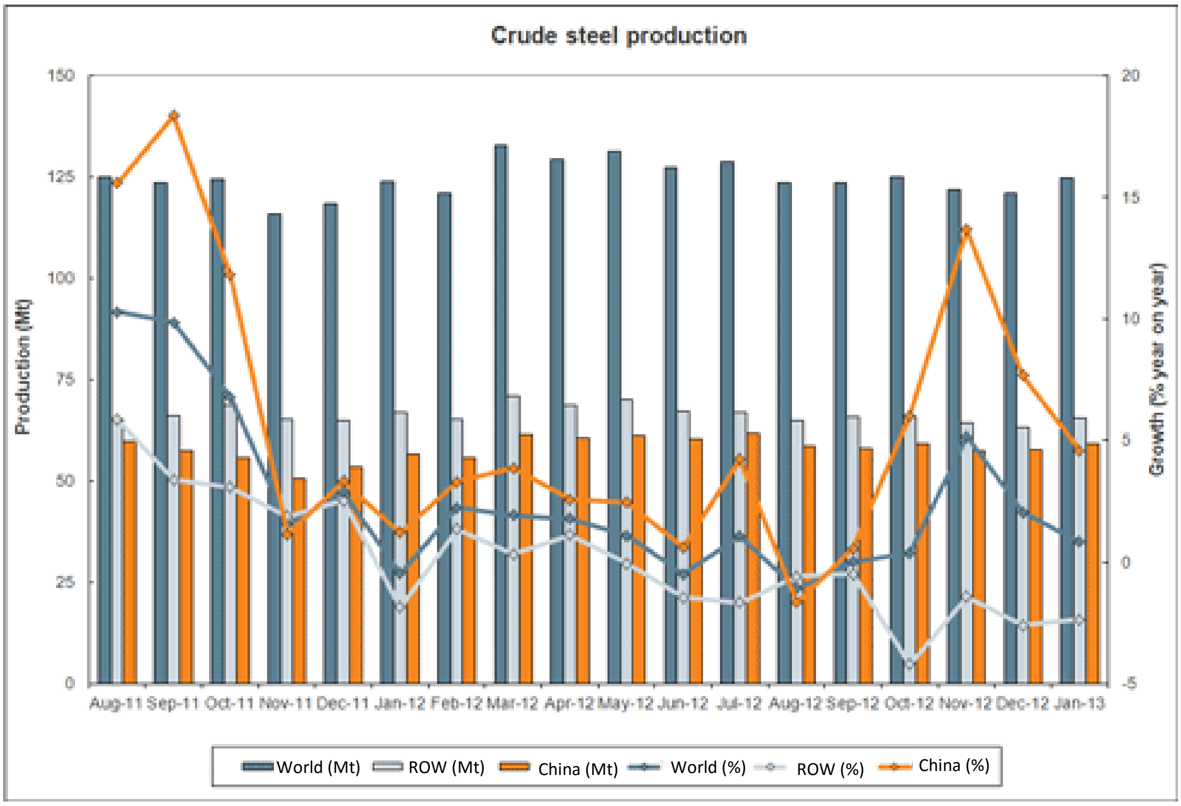

Figure 8: Global steel production showing China's growth (World Steel Association, 2015)

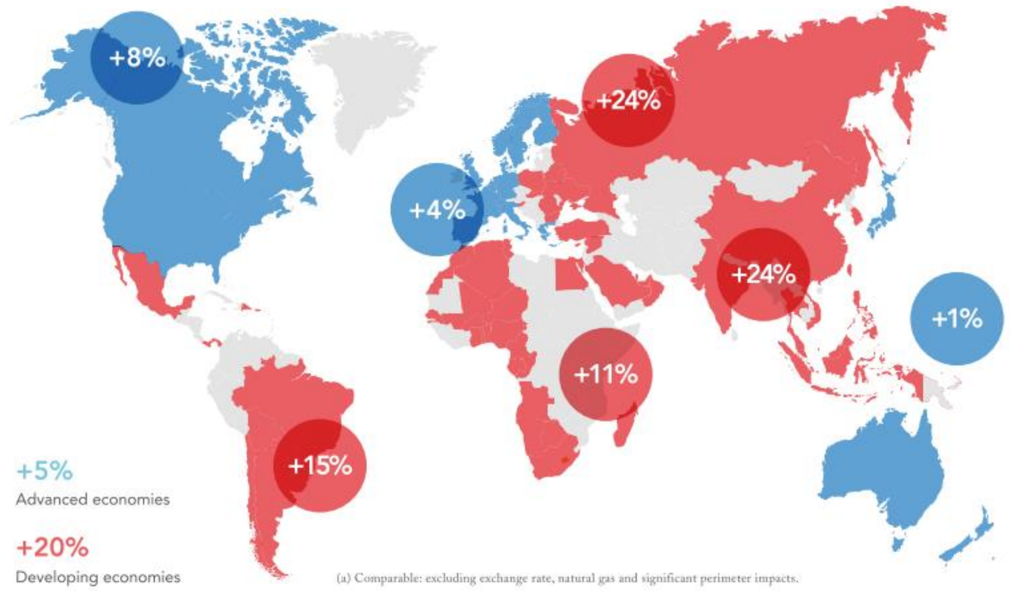

Figure 9: Air Liquide Sales Growth 2011 (Air Liquide, 2011)

However, the outlook does show signs of improvement. Recent research by *Rajaram Srinivasa* at BCC Research, indicates a small growth (Rajaram, Welding Equipment and Supplies: The Global Market for Various Types of Welding Technologies and Applications, 2014). Figure 10 shows that while the recent past performance in Europe has been stable, some top line growth is expected over the next years. This could be a result of pricing within the market increasing due to increasing specialism. Or it could be some base fundamental growth in the market.

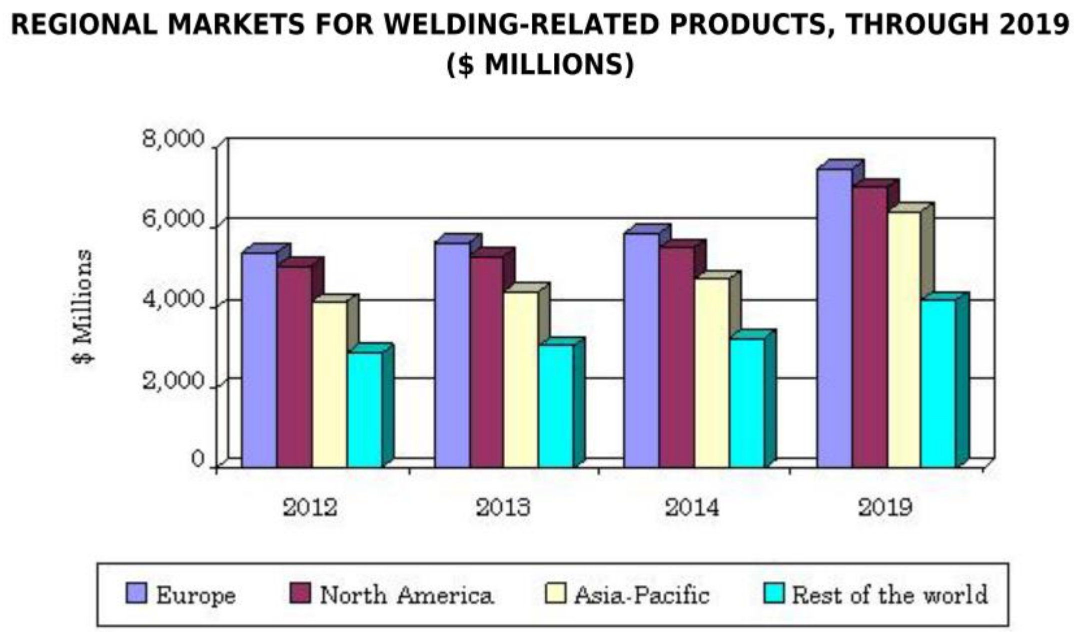

Figure 10: Market expectations for welding equipment (Rajaram, 2014)

The focus on research and development in the industrial gas industry is not as strong as in other industries. The industrial gas sector on average spends 1.0% of its sales revenue on research and development (Lewis, 2015). In comparison to other industries it is a very low value. Consider Figure 11, from a study of the worlds' top 1000 companies' expenditure on research and development. The average expenditure is 4.2% of sales with the lowest identified spend at 1.5% in the chemical industry (Veldhoen, 2015). The average industrial gas sector spend (1.0% of sales) is much lower than both the industrial average and the lowest spend identified in *Veldhoen's* survey. This indicates that the industrial gas industry could be spending more on research and development. The low level of funding also indicates opportunities for improvement, within product features and development processes. An average increase of 50% would only align the industry to the chemicals industry; a fourfold increase would be required to meet the industrial average. Consider the highest ratio in the industrial gas sector, 1.4% by Air Products in 2014 (Lewis, 2015) who are a Fortune 500 company. This places Air Products as one of the lowest spenders on research and development in comparison to the world's top 1000 companies (comparing to Figure 11). It is therefore fair to question if the sector has enough focus on product development. The figures indicate that increased expenditure in research and development could be a leading factor of transformational change (Veldhoen, 2015).

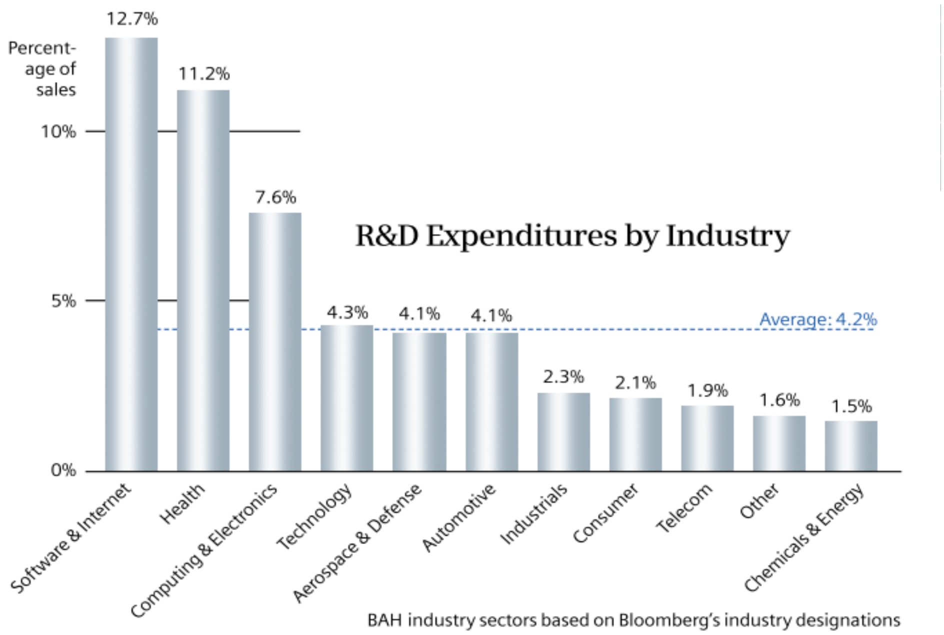

Figure 11: Research and development expenditure by industry (Veldhoen, 2015)

2.1 Consideration of the background information

From the background information presented the following observations are made:

- The industrial gases market is highly commoditised with standardised products
- Major companies in industrial gases are aware of sustainability but have not acted strongly to address sustainability
- There is a decline in European markets which is reflected with limited product developments
- The market is slow to react and change
- Technology improvements are possible but have made limited impact
- Low levels of growth are indicated in mature markets, higher growth is seen in emerging markets
- Expenditure and focus on new products is low compared to other industries

In comparison to other industries, there has been limited breakthrough moments for technologies in the industrial gas industry. Other industries have been completely turned around (and over), such as the introduction of digital images to the printing industry, the change in media formats for music and globalisation of the food chain. Whilst there have been clear incremental improvements, the market has been slow to change and adopt new developments.

There has been little change in process unlike other industries. For example, automation, which has enabled the automotive sector to make significant steps forward in efficiency. A further example for comparison is found in the airline industry where supply chain structures dramatically changed the industry. Consider the success story of Southwest Airlines where a start-up overtook the major players in the airline industry, breaking significant barriers to entry and outperforming the field in service and profit (Richard, 2004) (Freiberg, 1998). Southwest used the same planes, engines and airfields but changed how they managed these and how they served the customer. The is a good reflection to the industrial gas industry where one could continue to use the same equipment but still dramatically innovate.

There are new and potentially sustainable opportunities for the gas industry. New markets are starting to emerge in gases for energy (Hydrogen, Liquid Air, Liquefied Natural Gas), and new applications from a wide range of emerging industries (Oxygen for biogas, welding gases for wind turbines). The major gas companies do recognise that sustainability could provide a major revenue stream and are assigning resources towards such activities (Air Products, 2013) (Praxair, 2012).

A clarification of the thoughts presented above can be detailed in a strengths, weaknesses, opportunities and threats (SWOT) analysis. This is presented in Figure 12. Strengths for the industry are a large stable market with consistent technologies. The scale of investment required to take market share provides significant barriers to enter as a new major player. The weaknesses are that the market is focused on price and adoption of new products is poor. There are potential threats such as geography growth areas (the East) reducing demand in Europe. This threat could result in further focus on pricing as the main driver in the industry. The analysis also considers a threat of alternative technologies or step changes to existing technologies, such as gas generation. This technology may make a significant impact on the industry, it provides a threat to the barriers to entry and size of the market. However and unsurprisingly, the leading experts in gas generators are the major gas companies. The example does provide evidence of opportunities to innovate in the sector.

Other opportunities to develop are in the uptake of advanced engineering methods (such as lean and automation of production) which were identified to be just starting for industrial gases in 2008 (Cooper & Edgett, 2008). The uptake of advanced techniques is also low (such as computational simulation as seen in the investigation into new technologies (Pemberton G. , 2015a)). Even three dimensional CAD is not standard practice; at a major industrial gas equipment manufacturer only 60% of the design team could use such software tools (see interviews on users (Pemberton G. , 2015b)). An opportunity to drive change could be the current trend to re-patriate manufacturing to Europe. In the UK alone a manufacturing growth of £15.3 billion could occur over the next 10 years (Davidson, 2015).

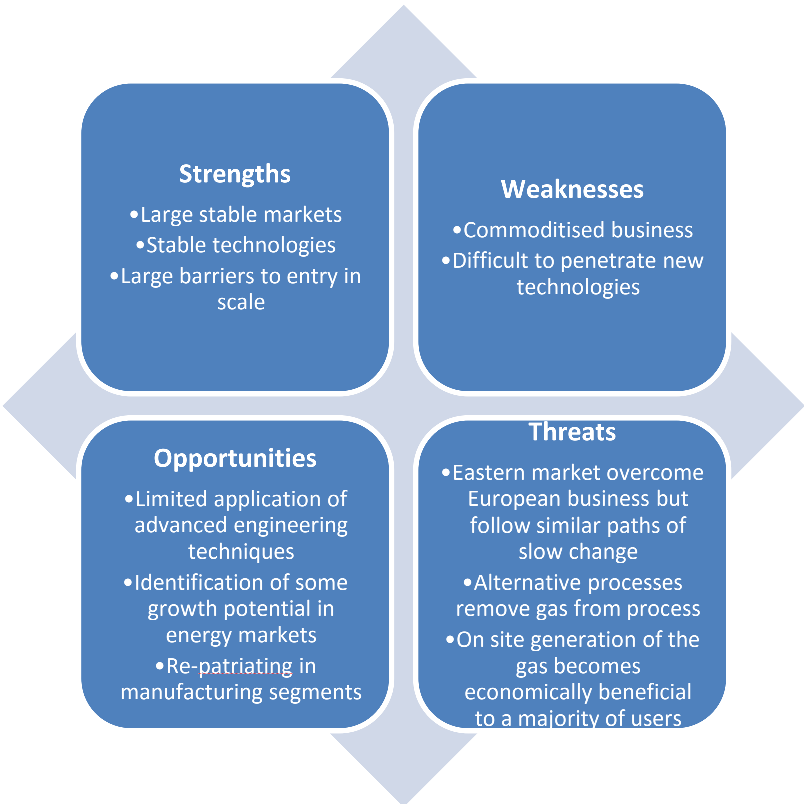

Figure 12: SWOT analysis of the industrial gas market

In this section recent new product introductions as considered, starting with integrated cylinder valves which are the largest change to the cylinder package. An integrated cylinder valve integrates the function of the standard valve with the regulator that is usually attached to the valve. The Integra cylinder (Air Products, 2013) or Vivantos (BOC a member of the Linde Group, 2015) are two examples of well known integrated valves that have been on the market for more than a decade. However both are of poor penetration (to the author's knowledge industrial integrated valve offerings currently account for only 5% of the market sales). It questions whether they have brought growth or even paid back their expenditure.

Identification and harnessing disruptive innovations is an area to consider; it could lead to revolutionary change. Air Liquide are looking for disruptive change setting up i-Lab (Air Liquide, 2015) which is a very small highly separated team from its main research and development function who have a remit to explore ideas (Meige & Schmitt, 2015). The environment presented is one of possible opportunities and benefits to change.

It may also be important to find technologies and products that disrupt the industry. Owing to the limited success of research and development activities it is recognised that new techniques may be required in order to advance such changes. It is also likely that there will be barriers to adoption.

3 Approach to Investigations and Development Activities in Sustainable Product Development Methodology Applied to the Industrial Gas Industry

This section considers how to develop a new methodology to product development that will address the identified aims and objectives. Recognising the major change that sustainable product development presents for industrial gases, a step-wise method was decided upon as the general method of approach. This bridges the gaps between current methods to the new concept in a palatable manner.

The approach to the development is presented through sections on concept development, development of an approach, defining a methodology for research and then presentation of the findings. In previous works regarding sustainable product development it has been found one large step- change often results in a failure to fully apply the method(s) (Byggeth, Broman, & Karl-Henrik, 2007) (Howarth & Hadfield, A sustainable product design model, 2006). A step-wise approach will provide more achievable changes and give opportunities to feedback what is and is not working. In conducting the development of a new method it was expected that there would be areas where new knowledge is required; these shall be explored through research techniques which are detailed later in this chapter.

In the method for new product development, activities and opportunities for innovation are to be identified and explored. It is expected that innovation will be found in improving existing methods and how to apply them in a new approach to industrial gases.

3.1 Concept of Approach

In order to develop a new methodology a set of followed are required in research, development and implementation. The first of these steps is to understand the current body of knowledge on the subject matter through a literature search. The main area of research conducted is associated to sustainable product development methods backed up with research on other successful product develop methods. Attention is given to successful examples of transition to sustainable product development methods. The research presented is focused on the methods in a process and how they work. It is not the aim to critique the products produced by the methods at a product performance level. The reason being is that sustainable products are often designed to specific goals in sustainability, such as improved environmental performance through use of recyclable materials. Therefore consideration of the individual product performance may not provide the input about general methodology successis the aim of the work here.

It is recognised that the literature search may not fully reflect the forefront of current research and best practices, but this shall provide a strong knowledge base with which to work with. The forefront of techniques may also be found at practising companies. Areas for further research (such as with companies) are likely to be identified through conducting the literature search. These areas can addressed with the use of other techniques such as surveys, interviews, and case studies which should capture current thinking and are all performed appropriately.

In order to develop a new approach a brainstorming exercise was conducted to draw on ideas about best practice in product development processes, business trends and sustainable activities. Ideas included conducting a survey of sustainable development practitioners, researching successful companies in sustainable development, testing sustainable design methods in an industrial gases environment, conducting life cycle assessment on products in industrial gases and conducting a trial of improving sustainability performance.

These ideas were then reviewed and through prioritisation an approach determined. The work identified a first phase of using a trial product development to explore sustainable products working in the industrial gas industry. Conducting a trial would act as a test to help identify gaps for further development phases to explore. Areas of success would be highlighted in the development and the product developed could be tested in the real world. This could then provide a convincing case that sustainable goals and benefits can be achieved.

In conclusion the approach shall be to explore the literature, looking for areas of successful transition to sustainability, then develop a basic method in order to conduct a product development trial. From this a new methodology can be developed.

3.2 Background Knowledge – Areas of Success in Sustainability

Consulting the literature for success stories in sustainability identifies companies and industries that have either developed from the outset with sustainability as a core value (such as alternative energy) or where transition has occurred to sustainable techniques. The latter is the primary area of concern for this work, as the industrial gases industry is not extensively using sustainable techniques. In the next paragraphs discussion of sustainable development in key two segments is given along with the tools used.

The two main industrial segments that stand out as examples of success in transitioning towards sustainability are the Aerospace and Automotive industries. These industries have both been subjected to scrutiny over their use of fossil fuels and the life cycle effects of the products (particularly for Automotive).

In the Aerospace industry sustainable techniques have been deployed throughout the business. There has been focus on the supply chain (Gopalakrishnan, Yusuf, & Musa, 2012) (Pagell & Wu, 2009) and assessing how sustainable is the business (Upham, Towards sustainable aviation, 2003). However the transition to a more sustainable future in aerospace is centred on aircraft design. Developments in design are strongly driven by changes in legislation for emissions (European Commission, 2008) (UK Government, 2008) and public pressure regarding fuel consumption and noise levels (Friends of the Earth) (International Civil Aviation Organization, 2012).

Techniques such as design for the environment and life cycle analysis have been successfully applied to identify how to improve the environmental impact of aircraft. Projects are in progress to significantly reduce emission and noise levels to achieve an 80% reduction in NOx emissions and 50% reduction in noise levels by 2020 (Parker R. J., 2006). Interim reports show a 62% reduction in NOx being achieved and 70% reduction in fuel consumption compared to a base line of the 1950s Comet (Parker R. J., 2006). These figures identify significant improvements. It could be questioned if the success is wholly due to use of sustainable design techniques. Would the same level (or higher) have been achieved without the use of such design techniques? In consideration of this question, the historical information identifies that limited change to reduce emissions was occurring prior to the use of sustainable design techniques and goals (Parker R. J., 2006). It is apparent that a higher level of focus on sustainability from companies such as Rolls Royce (who are a reference for many studies (Lazik, Doerr, Bake, Bank, & Rackwitz, 2008) (Rolt & Kyprianidis, 2010) (Azapagic, Perdan, & Clift, 2004)) and legislative change are key drivers in transition. This is well identified in Lee's publication titled "*Sustainable Aviation – The Way Ahead*". The paper develops the next level of depth in the transitioning to sustainability in its consideration of "*What role does Aviation have in a sustainable society?*" It is a pertinent question which opens further analysis of what does sustainability mean to society. It is observed that by tackling issues, such as noise and emissions, the aviation industry can take a step further and consider its wider role in society.

A focus on sustainability has become pronounced within the Automotive sector from design (Mayyas A. , Qattawi, Omar, & Shan, 2012) to production (Pusavec, Kramar, Krajnik, & Kopac, 2010) to supply chain (Koplin, Seuring, & Mesterharm, 2007) and business models (Bocken, Short, Rana, & Evans, 2014). Automotive's work towards sustainability is even discussed in popular television shows with acknowledgement that the industry is improving and developing sustainable solutions (Clarkson, Hammond, & May, 2016). It is well acknowledged that the automotive industry has to transition to a more sustainable future and has been acting on this with the introduction of cleaner engines, alternative powertrains, lighter materials, improved recycling and more sustainable ways to own and use vehicles.

The drivers to these changes are found in legislative changes such as the Euro 5 and 6 emission limits (European Commission, 2016) and legislation on reducing Carbon Dioxide from vehicle transportation (UK Government, 2008). Public pressure has been particularly strong towards the automotive sector not only in campaigning for improved environmental performance but also changing buying trends towards more sustainable vehicles (Price Waterhouse Coopers, 2014). More there has been rewards associated to transitioning to sustainability in the automotive sector, highlighted in higher stock market performance (McPeak & Guo, 2014). Another driver in this industry has been government backed schemes which have particularly assisted alternative fuels. Both electric and hydrogen powered vehicles have been promoted through government funding which included grants to low emission vehicle owners and funding for the provision of alternative fuel networks (UK Government, 2012).

In new product development for Aviation and Automotive industries there are several tools that are referenced as being well used in a transition to sustainability. In the next few paragraphs the key tools observed are outlined along with where and why they are successful. This then enables a reflection on what is necessary for transition in industrial gases.

Life cycle analysis, was introduced into the automotive industry with good success. The process assesses the environmental impact of a product during its manufacture, use, and end of life. *Ashby* and *Sundin* generally present a common set of phases of analysis in; raw materials, parts & manufacture, the use of the product, then re-use or recycling of parts and materials (Ashby, 2009) (Sudin, 2004). A similar method for life cycle analysis is further described and detailed in a series of international standards ISO 14040, ISO 14041, ISO 14042 and 14043 (International Standards Organisation, 2006). These provide a strong guideline which is well recognised in the automotive industry (Schmidt & Butt, 2006). Life cycle analysis is well suited to design engineers in that it highlights areas of focus to the designers, which align to the key drivers identified, such as, production efficiency (manufacture), improvements in emissions (use) and recyclability (end of life). *Mayyas, Qattawi, Omar and Shan* highlight life cycle analysis can give specific and needed areas of focus for automotive companies in material selection, vehicle design for end of life, fuel economy and air emissions. Within the application of life cycle analysis the need for quantitative analysis is highlighted, in particular for materials selection. The drawback is that to complete quantitative analysis often extensive amounts of data is often required.

Many of the design for X tools were pioneered and are prevalent in their use within the automotive and aerospace sectors. Some of these tools have been developed for sustainable design (for example design for recycling) or can be focused successfully towards sustainable goals (for example design for assembly). *Mayyas, Qattawi, Omar and Shan* identify design for manufacture, design for recyclability, design to minimise materials usage, design for durability and design for energy efficiency as key tools for sustainable design in the automotive industry (Mayyas A. , Qattawi, Omar, & Shan, 2012). In *Mayyas, Oattawi, Omar and Shan's* report, it is proposed that the design for X methodology can both analyse environmental impact and develop specific aspects of design. The work identifies areas of success such as BMW's use of design for energy efficiency and design for recyclability. This has reduced weight by increasing the amount of plastic while enabling 55% of the plastics in a BMW 3 series to be economically recycled (Mayyas A. , Qattawi, Omar, & Shan, 2012).

Steps forward have been made in the automotive sector, such as improving emissions. However the sector has been criticised for not going far enough. Furthermore the Volkswagen scandal undermines the improvements which are now viewed with scepticism. It is observed that while continued and increased levels of change are called for, there seems to be a shortfall in achievement for the automotive sector (Nelson, 2015 (28th October)).

Considering both the Aerospace and Automotive sectors there are several areas of commonality in transition. The first is in the drivers for change, these industries have had both legislative change and public pressure to improve. While the legislation is often highlighted to not be strong enough, it has brought a need for compliance and a reference point for public pressure. The public have reacted to key performance aspects such as Carbon Dioxide emissions with continued pressure for improvement. These two aspects are not present in the industrial gases industry and are unlikely to be in the near future. A major environmental incident would be needed to change this triggering either legislation and/or public pressure.

In Aerospace and Automotive industries public opinion has been clear that the environmental performance must improve, ultimately influencing a reason to buy. The industrial gases industry is not one of high public interest, the products are not commonly used by the general public and there is little media interest in the industry. It has been called "the invisible industry." In this respect it is highly unlikely that public opinion will be a driver for the industry to change.

Legislation is potentially an area where change could create a driver for change. Currently there is no specific legislation to restrict emissions or consumption of greenhouse gases by the industrial gas companies or users. For such legislation to be created a reason for change would be required by governments and national or international bodies. Such reasoning could come from international committees and continued target setting for environmental improvements.

In the transition towards sustainability both Aerospace and Automotive industries have applied specific tools focused on assessing and improving environmental impact. The key tools of life cycle analysis and design for sustainability have been deployed in both industries with success. These tools have brought benefits in materials selection, emissions reductions, efficiency improvements and end of life aspects, in particular recycling. It can be anticipated that these tools would be likely to bring improvements in the industrial gases sector. An area to investigate and understand further is if the tools can be successfully implemented.

In both Aerospace and Automotive segments, a complete and successful transition to sustainability cannot be claimed yet. The problems that both industries set out to address have not been resolved and the improvement targets not achieved. This highlights an area of concern for transition in industrial gases, it is likely to be a long term journey. In the investigations thus far conducted, a quick fix to sustainability was not found.

In both segments a key result of the drive to change is enhanced product development. In both industries long term research and development programmes were undertaken to make step changes in environmental performance. In these projects sustainable design techniques have been adopted such as life cycle analysis and design for sustainability. This observation provides a basic starting point for industrial gases. A transition to sustainability may require specific, long term research and development projects in which sustainable techniques are used.

In this background a driver to change has to come from other stakeholders in the industry or simply a company's own motivation.

In this discussion there is an uncertainty of the success of sustainable product development. It opens a question of how can a compelling case for change be built. A method to address concerns is to use trials and case studies, such that individual projects may be conducted with limited risk and their success or failure assessed. This would provide a method in which little commitment is required, but would enable exploration of challenges and areas of success. A test project would present itself as a first step to exploring sustainable product development needs in industrial gases. A test project would highlight challenges of implementation into real scenarios and develop evidence that success can been achieved in normal operating conditions.

An example for reflection outside of the discussed industries is found in the building sector. There is an urgent driver for more properties at lower costs (Marsden, 2015) which typically leads to lower technical performance, such as poorer heat retention, reduced amount of natural lighting, and reduced space. This is a risk to improving the environmental performance of buildings. Which appears to have been recognised by the UK government took active steps to counteract steps of lower costs and faster builds. The UK government only accepts bids for new building contracts from companies who meet specified improvements to the environmental performance of buildings. The improvements are published as national targets derived from climate change commitments (UK Government, 2015). In this arrangement the UK government has both set the improvement target and enabled it to happen through awarding contracts to those that meets or surpass its environmental requirements. The effect on the construction industry is that providing sustainable buildings is now an area of competition (the UK government is a major contract awarder). In this example the stakeholder had created a change to sustainability by introducing new market conditions (UK Government, 2015). Such a situation is unlikely for industrial gases, however elements may be possible in the provision of alternative energy gases. Governments could award grants and infrastructure contracts requiring an overall approach and performance on sustainability factors.

3.3 Development of the Approach

By brainstorming and the considering changes observed in other industries a list of areas to work on was developed and is summarised below.

1) Run a trial of a more sustainable product by conducting a development project. Then review the viability of the product and weaknesses in the process. From this work reasons as to why sustainable product development is not more prevalent should become clear along with the challenges to achieve sustainable development
2) Review the published knowledge base on sustainability, product development and disruptive developments. Consider how application to the industrial gas industry is relevant and applicable. This shall enable a critique of the literature, identify best practices, identify where there are gaps in knowledge and the shortcomings of current processes
3) Consider the findings from the literature review, the trial and the practices of the industrial gas sector to create a strategy for a new methodology
4) Develop a methodology that address the gaps in knowledge and that has a suitably applicable system. Assess the strengths and weaknesses of the proposal
5) Test the new areas of the methodology through a suitable method (for example a case study) in order to assess the applicability, benefits and best practices
6) Consider implementation of the methodology and create a process for implementation, which addresses the challenges identified from appropriate research

7) Implement the methodology through a case study. Review whether the expected benefits have been achieved, what the challenges were and does the methodology have further applicability?

These activities are reported upon through a set of submissions. The submissions are cross referenced to the above activities in the table below. In addition to the submission identification, the goal for achievement in each submission is given. The table presents the work as a set of steps each building on the last, following the general approach for this work.

Reference to above	Activity	Title	Anticipated achievements
1)	Conduct a trial of a more sustainable product	Improving the life of a gas cylinder	Identification of the areas for change, the challenges and the potential for success. Also potential for product innovations
2)	Review published knowledge	A Framework and Assessment Method for Sustainable Product Development Part 1: Literature review	Identification of best practices, learning from the literature and gap identification within the current process
3), 4)	Create a new methodology	A Framework and Assessment Method for Sustainable Product Development Part 2: Development	Development of a new methodology that brings sustainability into integrated product development. Potential for process innovations New knowledge is to be identified
5)	Test new areas of the methodology	Development and Application of New Technologies in the Industrial Gas Industry	Learning from application of the strategy. Innovation and knowledge creation potential in the products and technology applications.
6) 7)	Application and refinement of the model	A Framework and Assessment Method for Sustainable Product Development Part 3: Implementation	Learning how the methodology works in practice and development of a strategy for implementation that ensures the method is embedded.
1) to 7)	Summary of what was achieved	Thesis: Sustainable Product Development in the Industrial Gas Sector	Identifies what was achieved and how along with the innovations and new knowledge created

Table 1: Table of activities, submissions and achievements

3.4 Structure of the approach to the development of a sustainable product development methodology

In order to develop a new methodology an approach to the work is required. This section cover a review of different methods to approach the task and explanation of the chosen structure. Starting firstly with a method to structure the areas for investigation. The concept was to use activities that could be conducted in a learning process with individual steps that build up to create the whole system. There are many methods of learning published, from Lewin's original work in Planning, Action and Fact Finding, to models such as Kolb's experiential learning model (ELM) (Lewin, 1946) (Kolb & Fry, 1975). Other methods have developed since then such as Plan Do Check Act (PDCA), Define Measure Analyse Improve Control (DMAIC) and observe orient decide act (OODA) (Deming, 1952) (Wilson G. , 2005) (Osinga, 2006). These are currently some of the most utilised methods. The method chosen is to *observe*, *orient*, *decide* and *act* (OODA loops) (Richard, 2004). The OODA loop is a development to the traditional Deming cycle of *plan*, *do*, *check*, *act* method (PDCA) (Deming, 1952). The method is used for its advantage in being agile and that it is designed to follow a strategy as opposed to the Deming method, which is more focused at an activity level (Richard, 2004). The OODA loop is a method that uses learning cycles in each activity. The difference in *orient* and *decide* in OODA gives an advantage over *plan* with *Deming's* method. The step of *plan* is broken down into strategising (*orient*) then taking a decision as to what the *plan* shall be. It is also observed that *orient* is more aligned to an academic approach in which finding background knowledge enables this orientation. A weakness in the OODA method comparatively is that *Deming's check* step is not present. The *check* in OODA is aligned in the *orient* step through consideration of options. As the loop is progressed *check* is then considered in the *observe* step as review is conducted of the *act* step.

The approach used is to develop a sustainable new product development methodology through a series of work elements. Each work element is used as a learning loop built around the subject. In following a cycle each element of activity should identify a gap for the next work element to conduct further observation on.

The areas of development are split into four main areas, the product, the process, the method and the application, each work element being a learning opportunity.

The areas for investigation have been mapped to the work elements (submissions) that were identified in Table 1, giving:

- Product Gap – Trial improving sustainability (reference no. 1) in Table 1)
- Process Gap – Literature review and Development of methodology (reference no. 2), 3) & 4) in Table 1)
- Method Gap – Development of methodology and trials of new elements (reference no. 4) & 5) in Table 1)
- Application Gap – Implementation of the methodology (reference no. 6), 7) in Table 1)

The timing of the work elements has been placed into the following order. The start being the trial of a more sustainable product, then looking into the literature. This order enables the trial to identify where to look in the literature. With the product and process gaps understood they can be addressed by developing a new methodology. As the new method is explored it is likely to identify further gaps in process. Once the new methodology is created each new section is tested before implementing the whole method. This enables each new area to then be investigated in isolation. Once all the building blocks are in place the whole methodology can then be applied and learnings highlighted. The result should be a methodology grounded on testing.

Figure 13 presents the above discussion diagrammatically. It links the work elements to each other and identifies the gaps for each work element. The diagram shows a representation of the interaction of each of the individual submissions.

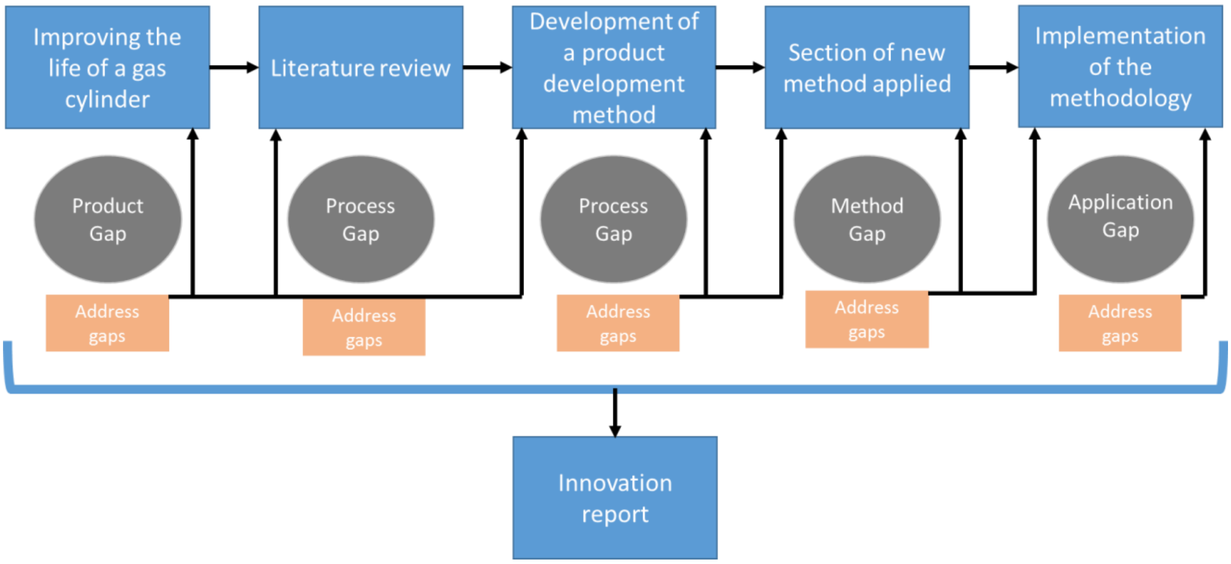

Figure 13: Activity structure for sustainable development in the industrial gas industry

Each of the activities is now expanded to identify the purpose and expected achievement. The first work element is a product focused test, considering how to make a more sustainable product. The concept shall be how to take a very typical product for the industry and develop it into a more sustainable product. The product will be improved from an environmental aspect and from an equity and efficiency aspect too. This must be considered in order for the product to have true sustainability (Clift, 2012 (November)). In conducting this work element, areas for improvement in terms of process shall be highlighted. The activity covers item 1 on the approach list (running a trial) and is the *observe* stage in an OODA loop.

The literature review (covering points 2 and 3 of the approach in Table 1) shall be focused on the process elements of product development. As the aim is to create a step change for industrial gases, the review will consider best in class knowledge from other areas. The work shall also consider step changes in techniques such as those required for disruptive product developments. Disruptive innovations can be highly sustainable in that they give rise to considerable benefits from user to manufacturer and often dramatically change product lifecycles. They are also typically challenging to develop, as typical product development processes do not enable nor encourage such developments (Wheelwright & Clark, 2011) (Cooper R. G., 2008). The step enables further observation, but will also *orient* the next phase of work.

With the knowledge base understood, next is to develop a new methodology, covering item 4 on the approach list (Table 1) and the *decide* step in OODA. Appropriate methods for the work shall be considered and research conducted as required. The development methodology is to be focused on the industrial gas sector and thus specific requirements for this industry shall be included.

New parts of the methodology will be independently tested to consider if they are valid and to provide a learning opportunity (act in OODA). The section covers item 5 on the approach list (Table 1). A set of test cases shall be conducted to qualify the new section(s) of the method. The test cases should provide a clear review of benefits and comparisons. This can then be iterated back into the methodology.

A full application of the product development method shall then be conducted with a company in the industrial gas sector, covering items 6 and 7 on the approach list in Table 1. To do this a best practice of implementation shall be developed and tested; this both returns the learning cycle back to observe, orient and decide but also provides a further stage of act in OODA. Effectively this work element provides a fast learning loop. It is expected that some research shall be required in order to find a best practice of implementation. The application shall then be conducted and learning identified for subsequent implementations.

One area of product development not covered in this process is creating new ideas, which is left out of scope for the work here. While this leaves a gap in generating new ideas it is believed that an improved process should manage the ideas in an improved manner and improve the selection of ideas. This in turn encourages further idea generation and steers the process. Application of a similar development to idea creation could facilitate a method to create a structured approach to ideation. While that is likely to have many advantages, it may also limit the creative process. For these reasons idea creation is left out of scope.

3.5 Methods to be used

Research through literature is essential to understand the current body of knowledge. However, it was known that there would be little published literature towards the industrial gas sector. This is not an area of industry that conducts or publishes research frequently. The reason is that little fundamental research is conducted in this sector. Work that has been conducted is also likely to be held as confidential by the parties involved due to the oligopoly found in this industry. The literature searches will focus on sustainable product development in other industries.

Within the work elements a variety of methods shall be used to conduct the research and development activities. The following techniques are used:

- Case studies
- Customer feedback
- Surveys
- Interviews
- Mathematical modelling
- Literature search
- Physical testing

Their application is summarised in the table below (Table 2) with further details explained below:

Research Method	**Submission**					
	Improving the life of a gas cylinder	**A framework and assessment method for sustainable development**			**Development and application of new technologies in the industrial gas industry**	**Thesis**
		Part 1: Literature review	**Part 2: Development**	**Part 3: Implementation**		
Case study	X					
Customer feedback	X				X	
Surveys					X	
Interviews				X		
Mathematical modelling	X					
Literature search	X	X	X	X	X	X
Physical testing	X				X	

Table 2: Table of research methods and submissions

A case study method is used in two of the work elements as the main method for research, see chapter 5.3 and 6 (Development and Application of New Technologies in the Industrial Gas Industry and A Framework and Assessment Method for Sustainable Product Development Part 3: Implementation). The purpose of the new technology work is to see is if a technology strategy works. Other techniques are discussed for application such as interviews and surveys but it is observed they do not provide the depth and concrete facts that a case study can provide (Gomm, Hammersley, & Foster, 2000).

In the new technology investigation, the work considers new areas for the industrial gas industry, this reduces the depth of knowledge available from interviews and surveys. Both methods have a risk of being opinion based and speculative. A case study method will provide factual information and develop experiences. As case studies are weak in their identification of repeatability (Gomm, Hammersley, & Foster, 2000), the approach undertaken is to use three case studies in three separate technologies. An option of using three or more case studies using the same technology is discussed in the report but not applied as the aim was to consider different technologies (noting if benefits and challenges are observed as similar as to other industries there is some evidence of repeatability). The case studies use a set of four generic questions plus specific questions on the technology investigated. The case studies are reported in the same structure to enable comparisons of the case studies. Replication of the same structured approach to technology applications enables comparisons to be made of the method.

The second application of a case study approach is seen in chapter 6 which reports *A framework and assessment methodology for sustainable development part 3: Implementation*. The case study tests an implementation method and the sustainable product development methodology. The decision to use a case study is driven by the requirement to see details of the application and generate results in a real world context. In this part of the work only one case study is used. The case study is based on previous research conducted and is used to test the overall methodology that the prior work has directed. A single case provides the opportunity for depth in investigation and identification of challenges. Repeated application would prove continued success. Further replication outside of industrial gases can test the hypothesis that the method could bring similar benefits to other industries. Repetition of case studies has not been conducted owing to time limitations.

Customer feedback is used within the product developments conducted, see chapters 4, 0, 5.5 and 5.6. This is the most appropriate tool to inform the product development team if the product is meeting the expectation of both the customer and the developer. In the first work on improving sustainability of a gas cylinder, customer feedback is sought to confirm that the products have tangible performance benefits. Customer feedback is utilised in the technology case studies (chapter 0, 5.5 and 5.6), in particular, in the case studies on additive layer manufacturing and electronics (chapters 0 and 5.6). Here a customer survey and focus groups are used in the design phase for both developments. The purpose of the customer feedback sessions is to assist in the decision of which concept should be advanced for development. The focus groups particularly assisted in gathering qualitative information which was desired on the electronics project owing to its radical nature. The focus groups provided a significant amount of information to enable clear and direct decisions. This resulted in a more tailored product to the customer needs.

Interviews are applied in the implementation work element (chapter 6). They are used to gather detailed opinions on change management in research and development. A generic structured interview process was used for fairness and comparison of the results. The questions were additionally set to be closed in style, such that quantitative results can be drawn, but enable a wider discussion on the subject matter. Interviews are used for this because little was directly seen in publications. This indicates such knowledge needs to be found from practitioners. An interview approach also enabled a deep conversation with the interviewees on the human aspects of transformational change and change in research and development teams.

It was expected that mathematical models would be required specifically for the product developments conducted. The reasoning is that improving the sustainability of the products would lead to highly different products and different approaches to their design. It was identified there would be a need to explore mathematically the performance of products before committing to development projects. In the first work element on a more sustainable gas cylinder (chapter 4.1) a need for five new predictive models is identified and fulfilled. The predictive models provided significant value to the project. The cylinder life model enabled design specification settings to be explored and optimised. The time step cylinder filling model identified new design specifications and prompted creative solutions such as cooling cylinders.

An iterative development approach is shown within this work on the regulator development for improved content (Pemberton G. , 2014a). An iterative approach is chosen owing to insufficient time to develop a real gas regulator mathematical model. Three iterations of the design had to be taken in order the product met the targets. While the process was successful it was time consuming and had failures during its process. A predictive calculation could have improved the time taken to conduct the development though virtual analysis of designs. The likelihood of success would have been improved through the knowledge built in virtually testing different designs.

Literature searches are used in all the work elements. The approach, identifies it is necessary to understand the background and published knowledge base in order to *observe* and *orient* before conducting development (following the OODA loop process (Richard, 2004)). The searches conducted are detailed below and in which submissions they can be found:

Research area	Purpose	Submission
Gas loses	Search for predictive models, potential benefits and current equipment	Increasing the life of a gas cylinder from a user perspective
Gas regulators design and market	Search for gas regulator behaviour and fundamental knowledge. Identify predictive models for gas regulators design and decide if they can be applied or further developed. Identify products in the market for suitability to develop	Increasing the life of a gas cylinder from a user perspective
Gas behaviour	Model accurately the gases for predictive calculations of life	Increasing the life of a gas cylinder from a user perspective
Cylinder filling	Develop a model to investigate parameter changes to fill at high pressures	Increasing the life of a gas cylinder from a user perspective
Sustainability in relation to the industrial gas industry	Investigate the potential and desire for change.	A framework and assessment method for sustainable product development
Product development methods	Investigate major areas of significance within product develop in order to identify improvement areas and opportunities	A framework and assessment method for sustainable product development Part 1: Literature Review
Product development approaches	Investigate how to design a product development system	A framework and assessment method for sustainable product development Part 2: Development
New technologies including case study areas	Investigate new technologies and application within the industrial gas sector and make recommendations. Specific focus on additive layer manufacture, virtual reality and electronics	A framework and assessment method for sustainable product development Part 2: Development
Approaches to implementation	Investigate how best to stabilise the process and give clear communication	A framework and assessment method for sustainable product development Part 3: Implementation

Figure 14: Table of research areas, their purpose and the relevant submission

Physical testing is the best method to evaluate a product to the design intent. Two main categories of testing are used in this work, in laboratory conditions and customer testing. The environment differences between the two methods are important to use in both understanding reactions in controlled conditions (laboratory) and uncontrolled conditions (customer). Physical testing was required in the product developments conducted to examine if the development met the expected specifications. Physical testing was conducted in all of the products presented in this work, see chapters 4.1, 0, 5.5 and 5.6.

3.6 Structure to Present Findings of the Investigations and Developments

In the next chapters of the thesis a summary of the work elements conducted shall be presented including the major findings in each of the activities. The submissions outlined in Table 1 and Figure 13 shall be covered namely:

- Increasing the Life of a Gas Cylinder from a User Perspective
- A Framework and Assessment Method for Sustainable Product Development Part 1: Literature Review
- A Framework and Assessment Method for Sustainable Product Development Part 2: Development
- Development and Application of New Technologies in the Industrial Gases Industry
- A Framework and Assessment Method for Sustainable Product Development Part 3: Implementation

These work packages build the concept of a sustainable development methodology in a series of steps from understanding the need, to developing a method, to testing and then implementing the methodology. This is covered through the following sections with the appropriate submissions:

- A trial in developing a more sustainable product
    - Increasing the Life of a Gas Cylinder from a User Perspective (section 4.1)
- Development of a sustainable product development methodology
    - A Framework and Assessment Method for Sustainable Product Development Part 1: Literature Review (section 5.1)
    - A Framework and Assessment Method for Sustainable Product Development Part 2: Development (section 5.2)
    - Development and Application of New Technologies in the Industrial Gases Industry (section 5.3, 0, 5.5, 5.6 and 5.7)
- Implementing the methodology, results and learning
    - A Framework and Assessment Method for Sustainable Product Development Part 3: Implementation (section 6.1)
    - Discussions on the development and implementation (section 6.2)
    - Further work in the methodology (section 6.3)

The implementation (chapter 6) covers, the development of a method for implementation (section 6.1.1 and 6.1.2) plus a case study of application (section 6.1.3). There is then a discussion about the learning of the work and further work that has been identified (section 6.2).

On the basis of the findings innovations, contributions, and a set of conclusions and recommendations are identified. The recommendations (section 7.3) focus on what can now be asked about sustainable product development due to the work that has been conducted.

4 A trial in developing a more sustainable product

The concept of the trial is to develop an existing product, improving its performance towards sustainable goals. The purpose of the work is to explore if a more sustainable product is a worthwhile pursuit and what are the current barriers to sustainable development. It is proposed that a more sustainable product will deliver benefits in competitive advantage, customer features and supply chain improvements. It is additionally proposed that such a focus for development has not been an activity in the industrial gas. It is expected existing product development methods do not identify nor provide methods to deliver sustainability performance sufficiently. Therefore the work shall challenge the current process and identify areas for improvement. In the product development it is anticipated that feedback and technical achievements shall provide evidence on the opportunities for sustainability within the industrial gas sector. The submission work element titled "*Increasing the Life of Gas Cylinder from a User's Perspective"* (Pemberton G. , 2014a) is summarised in this chapter (4).

4.1 Increasing the life of a gas cylinder from a user's perspective

The trial conducted takes a gas cylinder and aims to extend its useable life. The work started by exploring a product to be investigated, the most fundamental and most frequently used was chosen as it would provide a strong base case. What to improve in terms of sustainability performance was considered with a decision that working on the useable life could result in environmental benefits. There are potential environmental benefits from a reduced quantity of cylinders in the supply chain, reduced transportation emissions, reduced/avoided material and lower energy consumption (from the reduced quantity of cylinders), and a reduction in consumption of raw materials in manufacturing (due to reduced product loses). The end consumer benefits from an improved product performance, longer usage time, and lower operational cost. The manufacturer benefits from improved competitiveness with a more desirable product, and through efficiency gains in the supply chain.

Two main methods to increase the life were considered in this work, by first increasing the content and secondly by reducing product losses through improved control of the gas delivery. A first step in the approach was to review the impact on the business case for both methods. The aim was to identify if either of the approaches had significantly more impact. To do this a generic profit and loss model was built to explore the model, it is presented in Figure 15. A target for profit increase was set at 20%, a target of worthwhile impact and accounts for some inaccuracies in the model and the real world. An example of inaccuracy would be in the equipment costs and cost of goods sold, which remain in the model. In reality it is anticipated that both may slightly increase. The inputs for the model were then varied to simulate an improved content by using a higher gas price and longer rental periods.

It is identified that increases in gas price are more effective in improving profit than increasing rental. To achieve the same increase in profit, the gas price needs to be increased by 12% and the rental by 20%. To achieve this impact in the rental requires a cylinder remaining in use 30% longer. In both scenarios the costs of developing a product are ignored. An appropriate full cost model needs to be built for a more complete picture on payback. However, this analysis greatly helps in the consideration of the technical work. The results show that it may be easier to achieve a profit goal through changes to the gas content, as opposed to rental. This indicates changes in gas content to be preferable. However it shows that an improved package would be required to deliver significant increases in life (> 30%), this may be technically very challenging to achieve. In the next sections the model development and scenarios ran shall be explored to improve content and to reduce product loses.

		Standard	**Higher gas price**	**Improved time at customer**
Gas Price	**£/cylinder**	30	33.6	30
Rental	**£/day**	0.2	0.2	0.2
Depreciation	**£/day**	0.02	0.02	0.02
Product	**£/cylinder**	5	5	5
Other	**£/cylinder**	10	10	10
No. Days with customer	**days**	60	60	78
No. Customers a year		3	3	3
Revenue	**£**	126	136.8	136.8
COGS	**£**	-53.2	-53.2	-53.2
Overheads	**£**	-21.28	-21.28	-21.28
Profit	**£**	51.52	62.32	62.32

Figure 15: Simple financial assessment to explore cylinder life

4.1.1 Increasing the Content

The starting point to increase content was to review the fundamental gas laws and market trends to identify what would be a worthwhile target for increased content. For a gas cylinder there are two fundamental ways to increase content, either through volume or pressure. This work focuses on increased pressure, as volume increases have limited improvements to the sustainability performance (increases material requirements and incurs more transportation due to weight increases).

In considering pressure rises, a review of the modelling of gases was conducted. It was identified that the non-ideal behaviour of gases was of minor impact up to 200 barg, however non-ideal behaviour has increasing effects above 200 barg due to the compressibility factor of the gas. The impact is shown in Figure 16 which compares an ideal and non-ideal (Van der Waals) gas model for mass against pressure (for a fixed volume). As the models approaches 200 barg the ideal gas model becomes increasingly less accurate compared to non-ideal models. It is therefore not appropriate to use ideal gas laws when considering pressures above 200 barg. Historically the gas industry has generally operated at pressures where ideal gas laws can be used (200 barg is a standard operating pressure, 300 barg is now a maximum pressure). The trend has been stepped changes in pressure rise from 150 barg to 200 barg to 300 barg. Applying the Van der Waals model (Van der Waals, 1873) calculates the steps in gas content to be an improvement of approximately 30% in each step (using Figure 16). To continue this trend withe further steps of 30% increase would require pressures of 450 barg then 750 barg. The asymptotic trend of gas mass to pressure becomes increasingly significant above 500 barg, see Figure 16. There is a reduction in efficiency too, which is due to increased energy consumption in filling cylinders at increasingly higher pressures. Considering these factors a next step in pressure was chosen at 450 barg.

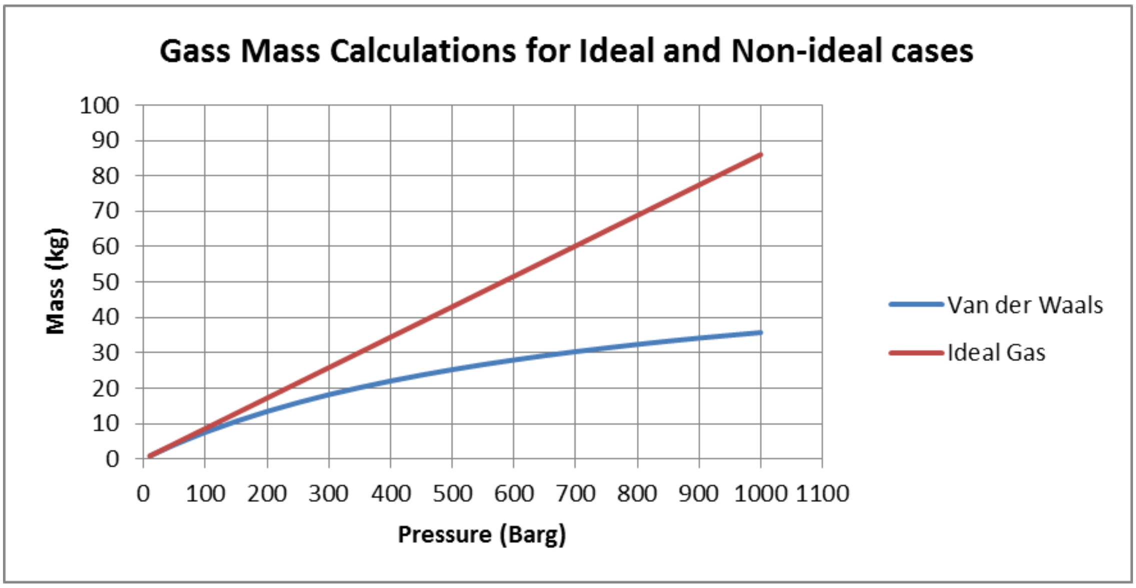

Figure 16: Gas mass calculations using Boyle's law & Van Der Waals

A pressure rise to 450 barg poses a number of technical challenges. There are limited standard practices for operating at this pressure. For instance the only recommended gas cylinder connector is from the American Compressed Gas Association standard (Compressed Gas Association, 2013). This is in contrast to lower operating pressures where every country has a different fitting. The American Compressed Gas Association identify a suitable thread form with metal to metal seal for inert and flammable gases up to 520 barg. The connection was primarily derived for Hydrogen use and some military applications of inert gases; it has not been used for mass market products.

Gas equipment operating at 450 barg was found to be limited. While cylinders are available with composite wrappings they are of limited (and often small) sizes, high cost and high maintenance. Only one manufacturer was found that offers a 450 barg rated seamless steel cylinder (seamless steel cylinders are the most common type of cylinder). Furthermore pumps to fill cylinders are not readily available for such pressures. These are the major pieces of equipment needed, the availability of minor equipment such as fittings, valves and pipelines was found to be restricted and specialist.

As there are gaps in the available equipment a review was undertaken to determine what the technical requirements would be. A first step was to consider the filling as this will define the main operating parameters of the cylinder, the valve (pressure, temperature and flow) and the supply system (filling equipment, filling time, pressure, temperature).

To understand the filling requirements further a predictive model for filling gas cylinders was needed. Research of publications found several articles on cascade filling, where a fixed large volume of high pressure is decanted into smaller volumes of a lower pressure. Basic predictive models were existing but it was identified by the publications that further work was required in higher pressures (above 300 barg) and predicting temperature (Dicken, 2001) (Dicken & Merida, 2007). The publications focused on alternative fuel applications using Hydrogen or compressed natural gas. It was also identified that published models were not applicable to the typical scenario of industrial gas filling when a pumped cryogen is used, there are added complications. The filling gas temperature is often below ambient conditions and there is a constant, and often rising, driving pressure. To address this a new time step thermodynamic model was built. The basis of the model is an energy balance for an unsteady system stating that the difference in energy incoming to outgoing is equal to the change in energy of the system (theory of energy conservation). This is developed into a model of energy transfer by heat, work and mass. The internal energy of the system is derived in two parts; the change in internal energy of the gas and then that of the steel cylinder. This gives, Equation 1;

$$dQ + \sum m_i\, h_i = m_{Cyl} Cv_{Cyl} \Delta T_{Cyl} + (mu_2 - mu_1)_{Gas}$$

Equation 1: Predictive model for cylinder filling

Where:

- m_{cyl} = mass of cylinder
- Cv_{cyl} = heat transfer coefficient of the cylinder
- T_{cyl} = change in temperature of the cylinder
- mu_2 = internal energy of the gas at end point
- mu_1 = internal energy of the gas at the start

The internal energy of the cylinder was calculated from two components; the pressure inside the cylinder and the temperature which is derived from a calculation of the heat of compression. A model was built into an excel sheet to enable ease of parameter change. Using the model a time step prediction can be made for the rise in cylinder pressure according to the cryogenic pump characteristics and the number of cylinders being filled. The model was validated against standard and high ambient condition fills at 200 barg and 300 barg.

The model was used to explore design parameters through predictive calculations. Filling to 450 barg resulted in a maximum pressure of 575 barg was in high ambient conditions, this derives a design pressure for the system at 610 barg in accordance and standard safety ratios (International Standards Organisation, 2014). It was found that raising the pressure to above 450 barg could lead to potential temperature issues. In warm to high ambient conditions (above 20 degC) filling to a pressure of 500 barg would create cylinder temperatures above 65 degC (International Standards Organisation, 2010). This would be above the operating boundaries of the cylinder. Which indicates that for such high pressures, additional control mechanisms shall be required.

Two methods to control temperature became apparent; either managing the fill gas temperature or managing the cylinder wall temperature. This led to testing a cold gas filling system and a system of heat removal from the external surface of the gas cylinder by using a sprayed glycol solution. This offered an opportunity to reduce temperatures below standard conditions, enabling higher fill pressures to be achieved by filling to a lower end pressure. Prototype testing enabled a standard filling system for 300 barg products to be increased to deliver 450 barg fills (Blisset & Pemberton, 2010).

A suitable product for 450 barg pressure was also developed. The first stage was the identification of a market and product requirements. This work identified that the offshore market presented an area where improved content would be highly valuable, particularly in reducing transportation space, gas change overs and redundancy stock. It is also an area where the customer had knowledge of higher pressure from hydraulic activities (often up to 1000 barg). There would also be a strong requirement for high safety standards and detailed testing. Customers were found to be open to increases in weight. Typical gas products for this market are “packs” of cylinders (such as 16, 48 or 64 cylinders) manifolded together and held in a frame. The products are generally moved by cranes with much higher lifting capacity than the current gas package weights of 3 to 8 tonnes (AGA, 2015). A design philosophy was developed in which the customer experience was not to be detrimentally changed but the package would simply last longer. The concept was to use the same gas connections for the customer and therefore a gas regulator was needed to reduce the now higher pressure to the level the customer would usually expect. To protect from failure, safety relief devices would be required. A general specification for a product was produced detailing a 16 cylinder gas pack with standard customer outlets, ultra-high pressure filling valves, a regulator and appropriate safety devices (Pemberton G. , 2014a).

A review of the equipment in the market and associated patents and publications was conducted to identify if useable components already existed, or if elements of the specification were achieved and products could be improved to meet the requirements. This work identified that a suitable cylinder, outlet valve and safety devices were available. No regulators or ultra-high pressure valves or frames were readily available so these would need to be developed. The most significant area for development was identified as the regulator. Although it was found that some products could be redesigned to possibly achieve the requirements, it was also identified that there were no clear design standards for gas equipment at these pressures.

The design methods for gas regulators have been researched and while it was identified that predictive models could be used, those published so far were not suitable for the scenario under investigation (ultra-high pressure and high flowrates). Essentially the real behaviour of gases is not accounted for in published models (Shahani, Esmali, Aryaei, Mohammadi, & Nahar, 2011) (Zafer & Luecke, 2008) (Jury, 1972). Non-ideal behaviour becomes increasingly important as pressure and flow are increased. Regulator design would benefit from predictive models which work for real gases. Developing such a model requires a longer term programme than could be followed in this work, so an alternative step-wise approach was applied. The development was conducted by achieving the flow specification, then the pressure specification and lastly the stability and response requirements. The step-wise approach worked but did require design iterations, which a predictive model may have avoided. A dynamic model of regulator behaviour would have identified the required spring characteristics and could have shown the initial disc spring as an incorrect choice. The resulting regulator is a compact, high performance and a relatively low cost product (Pemberton G. , 2014a). The resultant performance is visualised on a full flow test of the new 450 barg pack compared with a 300 barg pack. The 450 barg pack maintains a higher flow rate for a longer time period and delivers larger volume of gas see Figure 17. The additional performance is highlighted by the light blue coloured area between the two lines of results. The graphic presents well that the new offering is a step-change in performance.

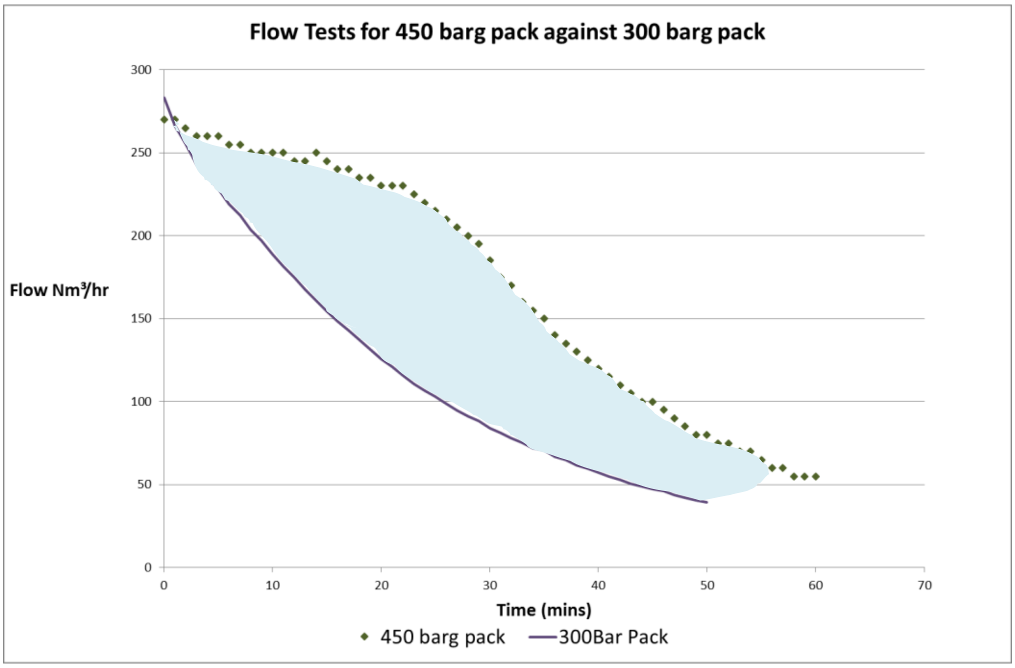

Figure 17: 450 barg pack performance against a 300 barg pack

The end product was prototyped and taken to an initial customer applications for feedback. The overall product fulfils the original aims of improved content (33%), but also has improved performance (higher flows available for longer) and no requirement of change for the user. However the product struggled in its launch phase. When additional capital funding was needed to be spent on equipment the business delayed the investment prioritising traditional equipment investments. Investments were not strongly linked to the product development programmes. Further problems arose as the marketing team decided they wanted to reconsider the specification. The supply chain team wanted to review other options for the filling process. In essence the project stalled. A number of new inputs were highlighted for consideration by the supply chain, purchasing and operations teams as they became increasingly exposed to the project. There was a mix of resistance to change and opportunities for improvement. The development process had failed to engage important areas of the company and gather their feedback.

4.1.2 Improving the gas consumption characteristics

The alternative method to increase the usage life of gas cylinder is to reduce the product losses and improve the consumption characteristics. To consider this, a model for the predictive life of a gas cylinder was built by modelling consumption, see Equation 2. In considering the gas losses (M_{SV}) two main areas were identified to model, the surge of gas as a system starts to flow and the stability of the flow rate during the use of the cylinder. Whenever a pressurised gas system transitions from a static condition to a flowing condition, a surge of gas is experienced as the gas flows into the low pressure regions (Pemberton G. , 2014a). In such a scenario the gas regulator opens in order to meet the flow demand and in doing so it will over-compensate (as no previous flow existed). The result is a surge of gas. This phenomenon is not well published, although it is identified in the field of metals fabrication as a source of gas loses. The term '*weld surge'* is used to describe lost gas due to triggering the gas flow. A calculation model for the gas surge loss was built, Equation 3.

$$Useage\ time\ (mins) = \frac{(M - (M_{SV} * n))}{(f_{AVG})}$$

Where M – Initial mass of gas (for a full cylinder) in Kg; M_{SV} – Gas loses due to surge in Kg; *n* – Number of gas openings; f_{AVG} – Average flow rate (Kg/min)

Equation 2: Model of gas consumption

$$V_{GS} = \int_0^t f dt \; - \; (f_{SET} * t)$$

Where V_{GS} – Volume of gas due to surge (*l*); f – instantaneous flow rate (*l/min*); f_{SET} – flow rate set for application (*l/min*); t = total application time (*mins*)

Equation 3: Quantification of excess gas

Considering the stability of flow at the same time as the surge effect builds a predictive model for gas cylinder life, Equation 4. The model is then used to review design parameters by simulating real life gas flow scenarios when welding. By varying the model's parameters, it is found that a gas surge volume between 0.2 and 0.4 litres is optimal, see Table 3 and Figure 18. Less than 0.2 litres brought little additional user savings but increased the technical difficulty and product costs. In terms of stability a target of +/- 15% was found to give the most user benefit without making the system difficult to technically achieve, see Table 3 (Pemberton G. , 2014a).

$$x = x_i - [(f_i T_i) + (S_i T_i)]$$

Where x – current cylinder content; xi – initial cylinder content; F – flowrate; T = time step; S = surge loss; f = f_i.f(x_i) [flowrate is a function of cylinder content]; S = S_i.f(x_i) [surge volume is a function of cylinder content]

Equation 4: Predictive model of cylinder life

Case	Duration	No. Openings	Gas on time	Gas consumed by surge	Gas consumed by flow
			Hrs	Litres	Litres
Base case	Short	6000	5.00	9000	5140
Base case	Std	1980.0	11.0	2970	11320
Base case	Long	750.0	12.5	1125	12840
Perfection	Short	18600.0	15.5	0.0	13950.0
No Surge	Std	2760.0	15.3	0.0	13800.0
No surge	Long	930.0	16.8	0.0	13950.0
No flow variation	Std	2220.0	12.3	3330	11100
No flow variation	Long	870.0	14.5	1305.0	13050.0

Table 3: Table of results for cylinder life calculation by performance variation

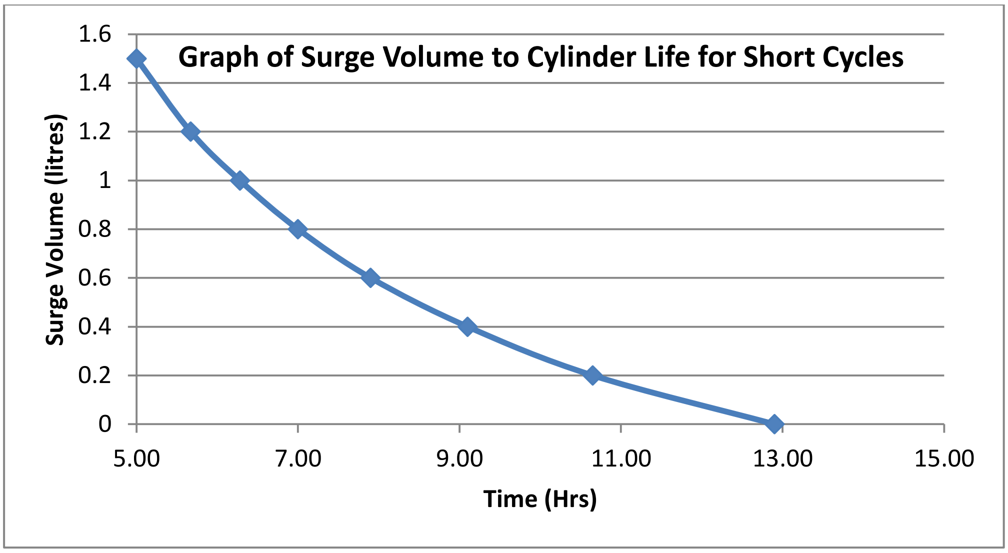

Figure 18: Graph of surge volume against usage time for short cycles

Research was then conducted into devices which reduce surge and/or improve stability. So called gas economisers' are available in the market and were found mostly in the metals fabrication area. Although some exist in medical Oxygen delivery systems (Barker, Burgher, & Plummer, 1994). The current product base has impressive claims about potential savings of up to 50% (Fit Up Gear, 2014). However the actual cost impact maybe limited as gas costs are a small contribution to the overall production costs, typically, between 1% and 6% (Cambell, Galloway, Ramsey, & McPherson, 2012).

The economisers found can be categorised into four technical solutions; flow regulators, fixed orifices (flow limiters), pressure regulators and quick acting valves. Each has their specific benefits and drawbacks, for instance, fixed orifices perform well at restricting the maximum flow and are low cost, but the gas loss due to surge is not well addressed. Flow regulators are an improved product, exhibiting good stability but are expensive compared to other options. Therefore their overall monetary saving can be questionable. While quick acting valves (i.e. solenoid valves) do achieve minimal pressure build up and good flow control, these systems are often more than ten times the price of other solutions. A gap was identified for a product, with an ability to control the pressure build up and manage flow at reasonable costs. An ideal device would have similar performance to quick acting valves and be of comparable costs to other devices.

The other main contributor to gas losses, is flowrate variation. As a gas cylinder is used, the outlet flow will vary as the pressure reduces in the cylinder; typical regulation equipment do not compensate for this variation. There were no directly marketed '*gas saving*' products found in this aspect. However, it could be conceived that the use of a two stage regulator, or pressure regulator in conjunction with a flow regulator is an available solution to minimise losses. These methods are often applied when a high stability in flowrate is required sych as TIG welding. It is recognised that the most common method to address losses through flow stability is simply to adjust the flow as the cylinder is being used.

Considering this view on product losses, it identifies an opportunity to address issues of surge and flow variation at the same time.

The requirements for a product were then built and a list of parameters created:

- Steady pressure delivery
- Steady flow rate delivery
- A useable pressure range for the application
- A useable range of flow rates for the application
- Quick closing of the system when gas demand is not required
- Control of the initial pressure release to limit the initial flow and manage the gas surge
- Simple to use
- Low cost

An idea generation event was held to create a starting point for a product development. Eight ideas were chosen to have enough technical and commercial benefit for further work. This led to the selection two position valve system which can be adjusted depending on whether the use was for long or short duration welds. During the ideas session the concept was explored of optimising the valve for different welding conditions. Two main areas of welding were identified tack weld, short in duration and being most sensitive to surge, then penetration welds, long duration and more sensitive to stability. The two position system provides an opportunity for an optimal solution, minimum surge for tack welds (short duration) and improved flow stability for penetration welding (longer duration). Once developed and tested the system was compared to other offerings, including with gas economisers. Significant performance benefits were seen with the new system. From a base case the cylinder life (time used) could be extended between 11% and 142% depending on the user profile, see Figure 19. Compared to the best in class set up of an economiser, the developed system out performs this by a significant margin (an economiser saves between 5% and 50%). Additionally as the new system was integrated with a cylinder valve it provides a lower cost solution than using an add on economiser.

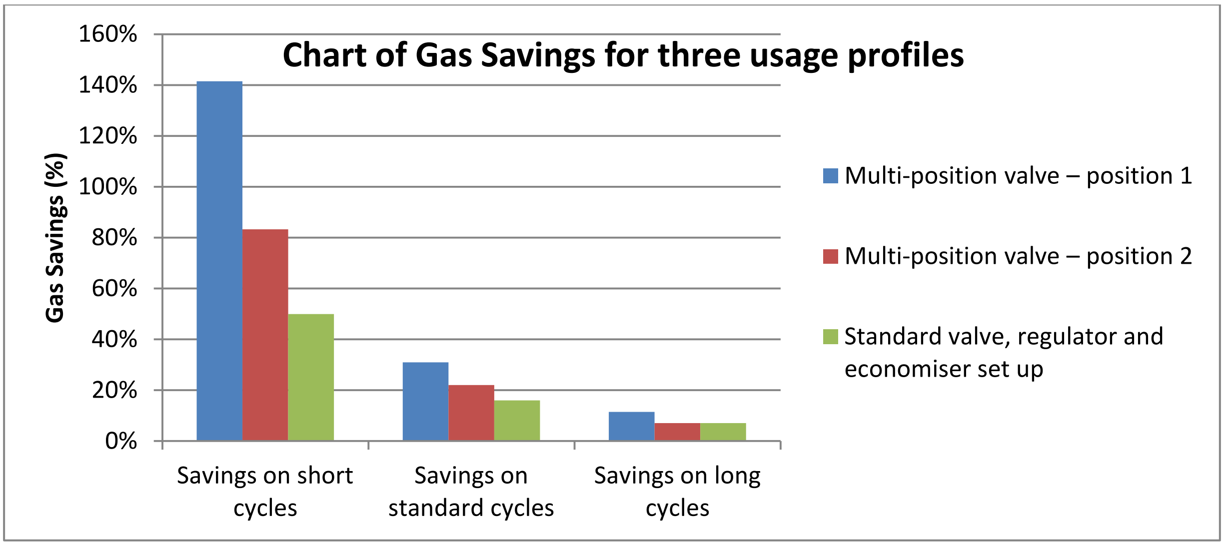

Figure 19: Chart of gas savings for three usage profiles

The comparison tests of the new system show several benefits from a sustainability view. The first being that the cylinder will last on a customer site between, 11% and 142% longer in time used. Using a generalised approximation of a customer consumption pattern, 1 cylinder per 2 weeks, then over a year the number of deliveries may be reduced from 24 to between 10 and 21. Similarly the number of gas cylinder change overs would reduce by the same amount. The number of cylinders required in the fleet can be reduced by 1 to 2 depending on the processing time of the cylinder plant.

Testing of the product produced positive customer feedback, many commented on the usefulness of the two positions for welding and that the cylinder lasts longer. However, as the time came to launch the product the business managers took a decision to postpone a full launch and take some further time to improve stability in the tack welding mode. The business managers also decided they wanted to take more time to develop the business case and sales approach. Lastly and also very importantly funding was not made available for capital purchases required to further the project due to other priorities. Capital expenditure was limited due to overarching tough business conditions and focused on essential replacement of assets. Funding for all new products was essentially put on hold.

4.2 Summary of increasing the life of a gas cylinder

Two main methods to increase the life of a gas cylinder for a user have been explored, firstly by increasing content (by pressure) and secondly by reducing product loss (through surge and stability). The identified concepts were advanced through two new product developments. In both developments by considering how to improve sustainability more time was spent on modelling. In particular modelling of the gas effects enabled designs to be virtually explored. Four key new models were developed:

- **The economics of a gas cylinder** – a model was built and explored to investigate the business benefits and areas of sensitivity in the supply of a gas cylinder from both a user and producer point of view
- **The filling of the gas cylinders** – this required a new thermofluids model to accurately predict temperature conditions and explore different temperature filling profiles.
- **The behaviour of the gas handling equipment** – required a new model to predict gas losses and real gas equipment behaviour. The model for a non-ideal gas regulator was not fully developed due to the complexity and time required for the work being greater than that available for the product development. The required scope of work has now been planned and an initial study conducted with Rouen University.
- **The predictive life of the cylinder** – a new model was required to estimate the time based life of a cylinder from user activities. This model was developed and inspired a two position gas valve that led to a patent application which is its review stage.

The models have been used for design work and exploring the sensitivities of the systems. The insights gained have been highly beneficial, for instance, in modelling the product losses, an optimal target for surge volume and stability was found. This gave clear design goals which were proven in product benefits.

There is still further work required in the aspect of modelling, in particular, for the non-ideal behaviour of gas regulators. Moving away from a step-wise approach to a predictive model should streamline the design process.

The innovative elements of the products developed were enabled through the approach of identifying gaps and setting targets. This led to creative solutions, such as the multi-position valve. The low temperature filling method is another example.

Both products struggled with in adoption and launch. While the financial side of the business cases met the necessary requirements, the supply chain and sales support was not strong enough to drive a launch. A major reason for this was that the whole of the supply chain and sales team were not involved through the development. There was involvement at the start and at the end but limited input during the development. Furthermore, the business had not budgeted the required capital expenditures and as a capital expenditure freeze was imposed during the development, the investment was delayed as regular business took priority. Planning with the rest of the organisation would have reduced the impact of this issue (or delayed the project). It highlights the importance of interfacing and integrating with the rest of the organisation.

In summary the development process failed to address:

- Cross functional communication in decision making
- Business planning
- Stakeholder support
- A lack of strategic objectives to drive sustainability

The development process could be improved by:

- Further use of computational modelling
- Use of lean design tools, especially those targeting sustainability
- Integrating marketing team members in the design process

The areas of success were:

- Use of virtual analysis in the design process
- Prototyping to gather feedback on design options as early as possible
- Exploring options at the start of the design process
- Setting clear technical goals and targets

5 A Methodology for Sustainable Product Development

The previous chapter found it was possible to improve the sustainability performance of a standard product in the industrial gas industry. Two methods to extend the useable life of a gas cylinder were identified and conducted. The result was increased useable gas by upwards of 33% by improving the content and gas deliver, and between 10% and 140% by reducing product loses. These figures highlight improvements in the supply chain are to be realised too in reduced transportation, material consumption which can provide benefits such as, reduced costs to the customer and improved profitability to the provider.

A direct analysis of enhancements to environmental factors was not completed within the projects. This is a shortcoming in the work. Understanding the environmental improvement is likely to have identified further successes in the work. Environmental improvements are indicated by the anticipated reductions in deliveries to the customer (reduced emissions), reducing the assets required (reduced material consumption) and improving the efficiency in production (reduced consumption and emissions). These could be quantified in environmental terms, such as reduction in carbon dioxide emissions or energy consumption. Such an analysis would provide clearer information to stakeholder. In developing a new methodology for sustainable product development a goal should be to target projects with environmental improvements and report performance in a quantifiable way.

Considering the technical improvements of the projects it could be expected that the products would be implemented and become highly successful. This was not the case. In both developments challenges were met in terms of internal support, along with funding support for launch. Teams outside of Research and Development were not involved during the project, there was little cross functional planning and limited interaction outside of the core team. The result, unsurprisingly is a full launch did not occur. As it has been identified the industrial gases business is reluctant to change, so there is a high likelihood of difficulties in bringing a transformational change to the industry through the product alone. It is proposed that the processes needed to be reconsidered. The investigation into increasing the cylinder life found the product development method failing in several areas. Such failings in process has led to a very conservative approach in launching products. It is proposed a stronger development process is required to make step changes.

Considering there was limited activity in the industrial gas sector towards sustainability, it was important to take a review of best practices in other sectors, which had gained knowledge in sustainable product development. Looking at other industries' successes and challenges would provide valuable insight into how to improve the product development process.

A new view on how to approach product developments is be considered in this work. It is clearly not enough just to make the product more sustainable; the process needs to support sustainable product development and guide the product to a successful launch. In this chapter the aim is to address the process for product development through an exploration of product development processes. This is achieved through three steps research, development and test. The approach focuses on the same philosophy as used previously of conduct research, find gaps, make informed decisions on what to do next, then test and check for further improvement (effectively and OODA loop). Over the next three sections the three submissions are discussed to address the steps identified:

- Research: A Framework and Assessment Method for Sustainable Product Development Part 1: Literature Review
- Development: A Framework and Assessment Method for Sustainable Product Development Part 2: Development
- Test: Development and Application of New Technologies in the Industrial Gases Industry

5.1 A Framework and Assessment Method for Sustainable Product Development Part 1: Literature Review

In the trial of increasing the life of a gas cylinder challenges were met in the process for development. The process used was a company specific method based on a modification of Stage-Gate®. It had been in use for over ten years predominantly in the United States and operated with isolated teams. The process had been set as a global method which all Research and Development teams worked to. In these actions several common failings of Stage-Gate® are seen, firstly operating with isolated teams and secondly not customising the process to business/team needs (Cooper R. G., 2008). It is proposed that a fresh review of the product development process too best practices should achieve improvements.

In the field of product development there is a niche area of sustainable product development. This area is obviously of interest to investigate and should provide areas of learning. However, it is also important to understand why there has not been a significant transition to sustainable product development methods. This may identify how a methodology can be best developed for the industrial gas industry.

The two products developed in the investigation to increase the life of a gas cylinder were highly different from a technical view to those currently in the market. Both developments utilised new enabling technologies and it could be argued that they would advance the market from its current position. The products would enable higher pricing (in gas and/or rent) than current products and would attract users who understood the life time benefits. In this respect the product would be likely to create initially a niche in the market. The two products developed are potentially disruptive in that they have a strong element of new technology and an element of entering or creating a new market (Tidd, Bessant, & Pavitt, Managing Innovation, Integrating Technological, Market and Organizational Change, 2006). Disruptive innovations are identified as an area for research as they may be a significant contributor to the long term future of a company. It is envisaged that to develop successful disruptive innovations different ways of work may be required.

In summary the key areas for literature review were identified to be in sustainable product development, best practices in product development and disruptive developments. Through literature searches a knowledge base shall be obtained, along with directional content as to how to develop an improved method for sustainable product development.

The context of sustainability in industrial gases is first explored such that the scope and gap to sustainability is understood. The starting point for this is a consideration to the definition of sustainability. The definition can then be used in the development activities.

5.1.1 Defining Sustainability

There are many definitions of sustainability and one is needed to base the work on and for consistency of understanding. There can be misunderstandings with the term sustainability, according to *Meenakshi and Leela* over three hundred definitions (Meenakshi & Leela, 2014), each with their own focus. In this section a definition of sustainability will be explored and presented. An understanding of sustainability and its importance has been discussed since the 1970's (United Nations, 1972) (Ward & Dubos, 1972). The traditional approach to sustainability identifies three factors to consider social, environment and economic (van Weenen, Towards Sustainable Product Development, 1995) (Goore, 2006) (Steffen, et al., 2005). While it is not the purpose to redefine sustainability, it is proposed it is worth considering if a different definition could be more suitable to product development.

The traditional three factors describe three distinct areas for performance assessment. Social factors are those that affect the well-being of society, this includes providing suitable conditions for work, ensuring that societies are sustainable in provision of food, housing and transport. It is also concerned with there being equity, and empowerment of people such that societal improvements are accessible to all. Measureable social factors can be difficult to define but *Norman and MacDonald* propose factors such as percentage of employees covered by collective bargaining agreements, number of workplace deaths, percentage of pre-tax earnings donated to the community and the percentage of senior executives who are women. The metrics identified cover five areas namely; diversity, industrial relations, health and safety, child labour and community (Norman & MacDonald, Getting to the Bottom of "Tripple Bottom Line", 2003). This approach is practical and would certainly provide a good basis of performance and improvement measurement for companies working in areas where discrimination and exploitation are of concern. These may not be so valid for European based centres where industrial relations, health and safety, and child labour are well legislated. The intent of social sustainability appears to be more than just these areas of metrics, it is far reaching, providing a platform for cultural identity and institutional stability.

Environment factors are those that typically identify damage to the environment or miss-use of natural resource. Examples include carbon dioxide emissions, air quality measurements, temperature changes, embodied energy, waste generation, consumption of natural resources and the type of fuels used for energy. An emphasis for environmental factors is that recycling and reusable resources is promoted, this is often achieved through specific design techniques such as Eco-Design (Luttropp & Lagerstedt, J, 2006). Environmental factors are well identified, although an exhaustive list would be difficult to produce. There are internationally recognised environmental factors which focus on two main areas, in pollution and the use of natural resources and assets. The factors are well defined with recommendations for performance measurement such as Air Quality by Sulphur Oxides levels and Nitrogen oxides levels (Organisation for Economic Development and Co-Operation, 2008). The aim with environmental factors is to minimise harm to the environment, these are often a starting consideration for companies on the journey to sustainability. A drawback in respect to product development has been observed in developing reliable measures that are relevant and possible to influence in the product development being undertaken (Hassini, Surti, & Searcy, 2012).

Economic factors are those associated to funding and growth in monetary terms, along with productivity and the distribution of wealth. The aim is to achieve sustainable economic growth that is fairly distributed. This requires consideration of natural, social and human impact when making monetary investment decisions (Basiago, Economic, social, and environmental sustainability in development theory and urban planning practice, 1999). Classic economic factors are profit, gross margin, payback, return on investment, net present value. These factors are well-known economic factors for most companies who will be using their own preferred economic measures. When considering economic factors for sustainability supporting information is likely to be required such as the impact on natural resources and social effects. Such supporting information is less well documented.

One of the most frequently quoted definitions of sustainability comes from the *Brundtland* report. It summarises sustainability as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, 1987). This definition expresses two key concepts, that of *needs* and *limitation*. In *needs* it is in particular towards those who need most help. Then there is the concept of *limitations*, which may be imposed by technology and/or social organisation. In this definition an understanding of compromise is clear. In achieving sustainability it is important to address just the *need* without incurring *limitations*.

Product development is a lever of growth and referenced in the concept of sustainable growth. Sustainable growth is well stated by *Pearce, Markandya and Barbier* in their definition,

> "Sustainable development involves devising a social and economic system, which ensures that these goals are sustained, i.e. that real incomes rise, that educational standards increase, that the health of the nation improves, that the general quality of life is advanced." (Pearce, Markandya, & Barbier, 1989)

An important difference in this view is that limitations are not highlighted. Here the focus is continued improvement, perhaps growth is not bounded by limitation if conducted sustainably.

There are limitations to growth, a more balanced opinion is expressed by *Holdgate and Synge* in,

"Development is about realising resource potential, Sustainable development of renewable natural resources implies respecting limits to the development process, even though these limits are adjustable by technology. The sustainability of technology may be judged by whether it increases production, but retains it over environmental and other limits." (Holdgate & Synge, 1993)

In considering all the above, sustainability shows a responsibility of thought, that a holistic consideration of purpose and others is conducted. Such that there is no intentional harm by actions and that those actions optimise the good that can be created towards the economy, social values and the environment.

The concept of the triple bottom line is built from such definitions of sustainability. The common definition of the triple bottom line is a measured and reported performance of sustainability through social, environment and economic factors. The triple bottom line view recognises decisions in the past have been made without consideration for environmental impact (Bruntland, 1987). Another idea of triple bottom line for sustainable product development considers the interactions of a product which are with people, profit and the planet (van Weenen, Towards Sustainable Product Development, 1995). The use of a triple bottom line approach has been shown to help convey the value of sustainability to shareholders (Willard, 2012) (Slapper & Hall, 2011). A further challenge is defining the social element in terms of value and quantitative assessment.

Product development requires a consideration of the whole life cycle and impact of a product, from its initial use to its end of life requirements. In this respect a focus on social and economic factors could be miss later effects. For example the economic factor should consider not only the profit for the initial seller but also the fairness of profit distribution over the product's life. Similarly the social aspect of the product should be considered from the end user view and the entire supply chain from product initiation to end of life including recycling or repurposing.

Another definition of sustainable product development comes from the UK Government who published a definition of sustainable development to be the means by which four objectives are acted on at the same time. The four objectives are:

- Social progress that recognises the needs of everyone
- Effective protection of the environment
- Prudent use of natural resources
- Maintenance of high and stable levels of economic growth and employment (Department of the Environment, Transport and the Regions, 1999)

This approach starts to develop some of the wider concepts provided by the terms economic, environment and social. The social element is explored in the first and fourth objective, in that sustainability is about providing social improvements (progress, growth, and employment) for all. The second and third terms highlight a practicality in *effective* and *prudent*, an understanding that consumption and technologies can provide specific benefits but may cause other damages. This rounded and interlinked view gives an improved description of sustainability.

A further development, and a current preference of thought is the *five capitals* method. This model is developed from original work by economists at the World Bank (the four capital method) and the Form for the Future (a UK charity) in partnership with Keele University (Ekins, Dresner, & Dahlstrom, 2007) (Forum for the Future, 2014). The model aims to represent the resourcing available to society though five areas of capital, natural, human, social, manufactured and financial (Parkin, Sommer, & Uren, 2003). Each area of capital is then treated as investment areas. The model can be seen as an expansion to the terms of environment, society and economy. The five capitals method uses a separate model for human and social aspects to cover the traditional society term. The manufactured and financial terms consider the traditional economy term. The natural capital is in-line with an environment term but is more focused on the planet's eco-system as opposed to connotations to the living environment. The living aspects of environment are included within the human and social terms. The use of the natural capital also places a greater emphasis on valuing and nurturing natural resources. The five capitals model provides a practical, broken down, view on how to address sustainable development. It encourages investments in all five areas bringing in turn their specific benefits.

In the five capitals approach practitioners look to answer where effort should be spent and how benefits flow from that area of capital. Practitioners are advised pay attention to the primary resources identified in the natural and human capitals. These must not be under invested as they provide a key enabler to social, manufactured and financial capitals. User guidance is provided in ways an organisation can enhance their performance to each area of capital (Forum for the Future, 2014). The role of stakeholders is then to approve proposals in a balanced way, thus providing sustainable investment (Paramanathan, Farrukh, Phall, & Probert, 2004) (Parkin, Sommer, & Uren, 2003).

An aim in the five capitals approach is to change the path of capitalism so that sustainability is seen as answering the challenge of living within natural limits. This is a quite different direction to the acknowledged economic and politically driven world (Porritt, 2007). In this view the five capitals method is taking on more a challenge than so far considered in this review of sustainable development.

In looking for a well suited definition of sustainability for product develop a model was found that considers the task of development well. In Clift's definition of sustainability *Environment, Equity and Efficiency,* (Clift, 2012 (November)) two new terms are introduced (equity and efficiency) that are well suited to product development activities in particular the life time view of a product. Equity addresses the fairness of economic and social aspects. It is a measure of the aspects of well-being in monetary, political, health, technological and educational terms (Gretchen & Ehrlich, 1996). Equity prioritises where the needs are greatest, enforcing that minorities are not discriminated. It addresses profiteering which can arguably be encouraged with a purely economic view. By working with both equity and efficiency an ensuring economic benefit is provided throughout the supply chain and more so to where they are needed most. Equity considers a continued and benefitting human interaction (Dempsey N. , Bramley, Power, & Brown, 2011). In these aspects equity follows Bruntland's definition (Bruntland, 1987). Equity is a term well suited to product developments as product features, supply chains and the life cycle can be designed for equity.

The efficiency term is also well suited to product development activities. Efficiency is concerned with the process and product features. In *Clift's* approach efficiency is used to highlight engineering's role in sustainability, which currently is to take decisions to improve efficiency often at the cost of environmental and equity aspects, see Figure 20. The concept is to balance efficiency, equity and environmental aspects. One drawback of the definition is it may lessen the focus on social aspects and this should be strongly considered when considering product features to positively address social aspects.

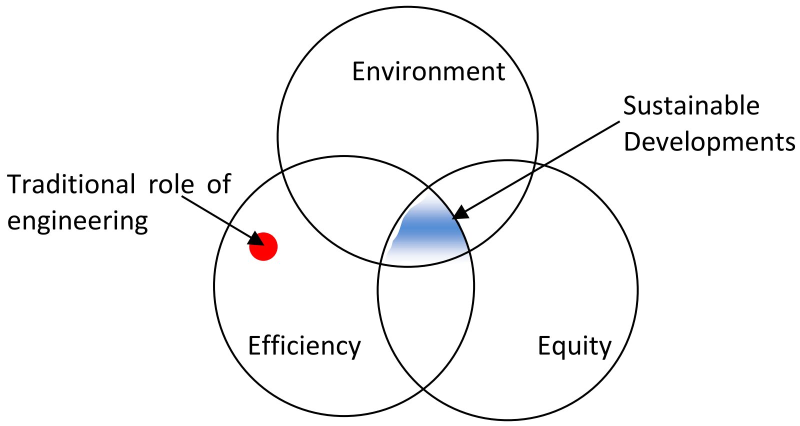

Figure 20: The relationship of efficiency, equity and the environment (Clift, 2012 (November))

5.1.2 Sustainable Product Development in Other Industries

The adoption of sustainable product development practices is an area highlighted in the literature with some complexity. It is typically highlighted that specific drivers are needed to adopt sustainable product development such as changes in legislation, company leadership, stakeholders, customer requirements, and public opinion. *Smith and Sharicz* identify common areas in the successful adoption of sustainable practices to be, governance (a necessity to comply), leadership (setting direction, resources, measures, reports and culture) a business plan (a justification to shareholders) and a learning organisation (Smith & Sharicz, 2011). There have been steps made by many companies and industries to develop sustainable products, *Kiron et al* identify a management trend that a sustainability focus is becoming a competitive strategy and companies are profiting from sustainable product development. They argue a tipping point is being approached in which companies see the need and feel the benefit from sustainable actions (Kiron, Kruschwitz, Haanaes , & Velken, 2012). In specific areas best practices are evident, and in particular where the needs of legislation, customers and stakeholders combine. The U.K.'s construction industry is a good example of this. The U.K. government has signed up to international environment targets such as the Kyoto agreement giving clear stakeholder requirements, this in turn ensures the H.M. Treasury creates legislation to force improvements (such as energy efficiency requirements on buildings). Lastly the U.K. government is a large customer for the construction industry and looks for not only for compliance but competition on sustainable factors (Parkin, Sommer, & Uren, 2003). The UK government has created a need and market for sustainable product development.

A further example is the aviation industry where emissions legislation, public opinions and technical developments have combined to transition the industry towards sustainability (Lee J. J., 2000). The industry is one of significant impact, such as Airbus' with a turnover at €65 billion, 136 574 employees, reducing their CO2 emissions by 45% and water consumption by 8%, and an impressive set of environmental targets to be achieved through product developments (Airbus Group, 2015). The industry is not directly comparable to industrial gases, the scale is much bigger in aviation (Airbus' turnover is more than the four major players in industrial gases combined ~€50 billion) and as has been demonstrated there is little focus on environmental targets let alone proven performance. Learnings can be taken from the industry and comparisons more readily drawn with other similar sized companies in the industry, such as Rolls-Royce at a £15 billion turnover (Rolls-Royce, 2015) which is comparable to Linde or Air Liquide. The approach at Rolls-Royce is heavily technology focused using sustainable development tools such as life cycle analysis, design for the environment and clean technology developments (Lee J. J., 2000). These have been combined in an approach that considers the environment, economics and society as part of the "design philosophy" (Lee J. J., 2000).

5.1.3 A view on Sustainability

In reflection of the above it is observed that defining sustainability is not a simple task and has been discussed at length in many literature sources. In order to develop a system for sustainable product development it is important to define sustainability as a reference is needed. Using accepted terms and general agreement of what those terms mean is a route forward. Although it was observed that there are some deficiencies in the traditional Economic, Environment and Social terms of sustainability when applied to product development. To address this it is proposed to use a definition of sustainability through the terms of Equity, Efficiency and Environment. This suits product development well as they are all terms by which a product development can be measured.

The definition of sustainability that will be carried forward in this work, is a view based on discussion above, wider reading and the environment of today. That is, sustainability is the responsibility of everyone, in their actions and decisions. Consideration is to be given to others, to the future and if there is an alternative way that could lessen the negative aspects of such actions and decisions. Sustainability is the active process of making a decision that positively addresses the terms of Environment, Efficiency and Equity without deficiencies in a long term view.

In relation to product development there are several aspects where sustainability can substantially influence decisions. A primary aspect of this is the product itself, which should show benefits to the environmental, society, supply chains and economics. A further view, is that the strategy of product developments may enable a focus on specific areas of sustainability with each product development.

5.1.4 Sustainability in relation to the Industrial Gas Industry

From the definition of sustainability consideration is now given to sustainability in the industrial gas sector. In this section an overview of the impact on sustainability is given from an industry perspective. The industry's activities and commitment to sustainability shall also be explored. In completing this review the opportunity and potential impact of sustainable product development shall be highlighted.

The first aspect of this review considers the context of sustainability in the industrial gas industry. Using the definition outlined in the previous section, key areas to consider can be mapped to the definition terms. It is found:

- Environmental – Key aspects are the environmental effect of the gas itself, the manufacture of products and equipment, as well as the production and supply chains.
- Equity – Key aspects are the sourcing and production methods (in particular for large equipment e.g. plants), contracts for customers (length, equipment rental and gas prices) and the way business is conducted (in particular the trading of chemicals and the oligopoly of the industry)
- Efficiency – Key aspects are the development efficiency for new products, production efficiency (in production and processing gases), supply chain material movements (typically by road) and product performance

Research of activities with a sustainable product development in industrial gases was conducted and then the search was then extended to include any sustainable activity in the industrial gas industry. Two specific pieces of work were identified in the literature. One was focused upon the Hydrogen economy (McDowell & Eames, 2007) (Stankiewicz & Moulijin, 2005) the other on new air separation plant design. *McDowell & Eames* identify that the hydrogen economy is dependent on many more factors than the economic and environmental benefits of hydrogen (McDowell & Eames, 2007). *Stankiewicz & Moulijin* consider the use of sustainable product design techniques to plant design, re-considering material and construction choices. Both works highlight the need for further work in sustainable product development in industrial gases. Both works identify that the wider environment is important and may hold key reasons as to why there has been limited transition towards sustainability (Stankiewicz & Moulijin, 2005) (McDowell & Eames, 2007). The next paragraphs explore the overall interest in sustainability with industrial gases.

The industrial gas sector is a large oligopoly with four key players; Linde, Air Liquide, Praxair and Air Products. All four have turnovers in excess of €10 billion, produce billions of tons of gases and consume huge amounts electricity as their main raw material in the production of industrial gases. Each company produces a sustainability report and each of these along with their other activities were investigated. Air Liquide was found to see sustainability as a "*new*" subject in 2013 (Air Liquide, 2013). Within their one hundred and seventeen page sustainability report only three pages considered products, the rest mirrors the financial report. These facts indicate a lack of commitment to sustainability from Air Liquide. It was observed from the report that there was little focus on how new products could change behaviours or address unsustainable consumption.

Air Products' report highlights two new products developed for sustainable performance Hali (an oxygen waste water treatment product) and Amcamide® (a curing agent made from renewable materials) (Air Products, 2013). The report is an improvement compared to Air Liquide. However, it only talks about two new products, which, for a company as large as Air Products its budget for research and development at €101 million in 2013, (Lewis, 2015), these two products are representing a small addition to the business.

Linde provide a review of the environmental benefits of their products along with a focus into key areas of sustainable benefits; Hydrogen for energy, carbon capture and biomass. A goal for Linde is stated as "*Development of products and technologies that unite the goals of customer value and sustainable development*" (Linde Gases, 2013). This goal strongly places additional emphasis on customer value. Which indicates Linde see this to be different to a sustainability target. Three flagship projects are highlighted in the report as sustainable new product developments being undertaken that are highly important for the company. Again as with Air Products when the expenditure and number of employees for new product development are considered (€92 million and 367 employees) the three flagship projects are put into context. They represent a small amount of the overall research and development activities.

Praxair was the only gas company to show some long term vision using a sustainable materiality assessment chart to map out a prioritisation of projects focused on specific areas of benefit. They classified areas to focus on as environmental, economic & governmental and social (Praxair, 2012). The link between economic & governmental is interesting as it indicates Praxair are prepared for some form of external influence on sustainable projects effecting the economics of the projects. This may be a recognition that many of the projects associated to energy would not be conducted without government support as they have limited economic benefit. The report then discusses a number of improvements through *sustainable productivity* (Praxair, 2012). These activities compared to the definition of sustainability used here could be classed as efficiency activities. In Praxair positive statements of sustainable productivity are made. However, Praxair may find deficiencies in other aspects owing to the efficiency focus. It is also interesting that Praxair have issued a report with non-traditional classifications it shows evidence of thinking in a different way about sustainability.

The major four gas companies' approach to sustainability and the general conditions of the industry can be summarised using a political, economic, social and technology analysis (PEST). The diagram is presented in Figure 21. The PEST analysis highlights macro-economic issues that face the industry, ongoing commoditisation of products and little organic growth owing to manufacturing slowdowns. Politically, the industry has a number of barriers in scale, but it is not heavily legislated in production, waste or mis-management of environmentally damaging gases. It is recognised that some growth in the industry may occur if government support mechanisms are in place, such as the use of Hydrogen for energy. Social aspects are not a strong influence for this industry (it is known as the invisible industry), except in the use of medical Oxygen. Here the aging population and increased diagnostics (and treatment) of pulmonary dieses will demand a greater use of medicinal Oxygen (Chronic Obstructive Pulmonary Disease is one of top five causes of death).

The industry while being a major handler of carbon dioxide is not seen in the public view as being associated with negative aspects of environmental issues. For instance, Coca Cola have had a lot of pressure to reduce their use of Carbon Dioxide, but nothing is ever said about the producers of Carbon Dioxide (Air Products, Air Liquide etc) who are not restricted and vent much more to atmosphere than Coca Cola (El Amin, 2007).

There has been few changes in the technologies used in the industry. The industry lags behind other industries for speed in technology change, there are barriers to change. A major challenge is associated to infrastructure items like air separation plants and the years of investments made in cylinder fleets. In this analysis the industry has little incentive to change. Therefore, in the creation of a new sustainable product development methodology the benefit proposal and implementation must be strong elements for adoption.

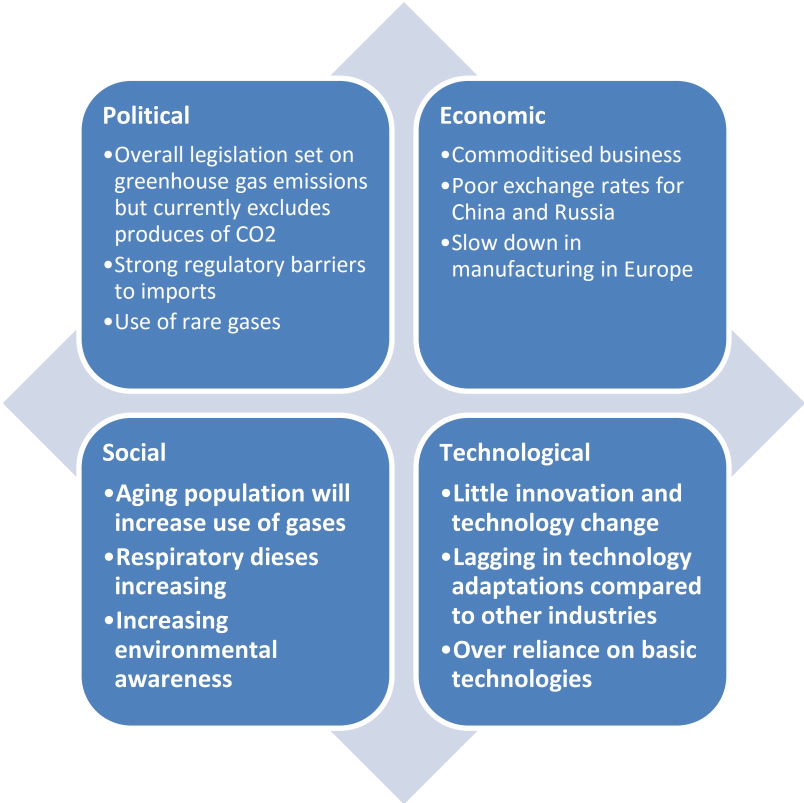

Figure 21: PEST analysis of the industrial gas industry

5.1.5 Product Development Methods

Highlighted in section 4, increasing the useable life of a cylinder, the method used for product developments lacked a cohesive structure and did not include the sales, supply chain or business teams collectively in the development until the completion of the product. As such the products struggled to be implemented. Specific areas identified for further investigation, included integrating the people and processes, developing a manageable system, and engaging senior management with the process. These gaps are to be addressed by investigating best practices in product development such as Stage-Gate®, portfolio management, product family design and disruptive innovations.

Best practices in product development were investigated with several areas proving to bring benefits in particular the integrated product development model (Macintyre, 2010), the Stage-Gate® model (Cooper R. G., 2008) and portfolio management (Wheelwright & Clark, 2011). The integrated model for product development brings together a wide number of areas in a company to break down the traditional silos of activity associated to product development work (Rainey, 2005). The integrated model focuses on the customer and then uses a cross functional team to develop new products. In its fullest intent the team has freedom to go across the company to conduct the work necessary for the development. The senior manager of such a team is there to provide the enabling factors (resource and funding primarily) and the business strategies (product positioning, time to market and financial goals). The rest of the work is then about connecting the customer to the business drivers.

Within the integrated product development approach a process to conduct the development is required. Stage-Gate® systems provide such a process describing how to move from idea, build the business case, development, testing and validation then to launch. Stage-Gate® is a well-documented process recommending five gates. In each gate the development team brings the product for review and senior management are required to take a decision of advance, stop or recycle. The method is designed to stop projects that will not work in the market as early as possible and to ensure those that do pass through the gate have achieved the required levels in performance and quality. The advantages and potential areas of failure are well published (Cooper, Edgett, & Klienschmidt, 2004). A main advantage in the use of Stage-Gate® is the robustness of the process to advance activities and ensure that decisions are jointly made. Application of Stage-Gate® has been reported to not always fulfil the potential benefits. In such cases it is owing to the process being applied with too much rigidity and not enough customisation to the company (Cooper & Edgett, 2008). These findings are evident in the trial conducted (section 4), such as not involving the whole organisation or having clarity on project phases and timing.

Portfolio management is extensively used in the world of finance and banking. These methods can be transferred into product development processes. Using a performance evaluation calculation, projects can be assessed in terms of their achievements and deviations from goals. The results can then be plotted and an efficient frontier drawn, which is a goal for the portfolio to achieve. The calculation of the efficient frontier requires the use of some relatively sophisticated mathematics. It requires the calculation of a common return parameter to which a goal is set and the variation in performance found. The variations are then used with the goal in a predictive calculation of how much risk is acceptable on new projects (Trippi & Lee, 1996). The efficient frontier is a visual indicator that can be used for project selection, portfolio decisions and driving company strategy. However, a simple standardised system for portfolio activities although desired has not yet been presented (Tidd, Bessant, & Pavitt, Managing Innovation, Integrating Technological, Market and Organizational Change, 2006).

Portfolio management in research and development is not as well documented as other best practices in product development. A number of works on portfolio management focus on the financial side of portfolio management in research and development projects. Financial benefits are considered and decisions taken as to whether the company should be continuing with the project or what steps can be taken to improve the situation. Financial analysis of the portfolio is found to be the most frequently applied method of portfolio management. Typically three or four of the following are used; net present value, internal rate of return, profitability index and payback (Brigham & Ehrhardt, 2002) (Arnold, 2013) (McWatters, Zimmerman, & Morse, 2008). From the financial performance decisions are taken to advance, stop, or recycle the product development.

There are other simple methods to conduct portfolio reviews that focus on non-financial aspects. In particular *Wheelwright and Clark* present a process for product development in which a series of charts are used (Wheelwright & Clark, 2011). A main view presented is a timeline with additional columns to give insight to the resource allocation and the type of project (Breakthrough, platform, derivative, partnered). *Wheelwright and Clark* also highlight that in portfolio management care is needed in resource allocation to ensure maximum productivity of engineers, recommending assigning two projects per person (Wheelwright & Clark, 2011).

A scorecard approach to portfolio management is presented by *Morris and Pinto*. The scorecards are developed for general project portfolio management and are not research and development specific; however it is a highly applicable method. Two main scorecards are recommended; one with an investment view and the second a more general view of the portfolio. *Morris and Pinto* use financial criteria in the investment view the customer, process and technology assessments. The portfolio view the structure of the portfolio (types of projects), relationships with key partners and stakeholders, organisational performance and strategic performance (Morris & Pinto, Project program & portfolio maangement, 2007). *Morris and Pinto's* scorecards consider some of the concepts seen in the definition of sustainability, in that investments need to work for the whole supply chain (a sense of equity) and that a portfolio needs to work with positive contributions towards the environment. These scorecards have a resemblance to the five capitals model, in that they consider the performance from several key aspects in groups of data. They both use financial and non-financial data in a quantitative assessment. There is probably scope to merge the five capitals method with a portfolio scorecard approach.

A best practice in portfolio management for research and development identified by *Cooper Edgett and Kleinschmidt* is the use of bubble charts in portfolio reviews for research and development projects (Cooper, Edgett, & Klienschmidt, 2004). They propose that a number of bubble charts may be required to present the required information for a specific company. One chart they recommend covers the relationships of reward (x-axis), probability of success (y-axis) and allocated resource as the bubble size. Projects that feature in the top right are typical projects using known technologies and which should be strategically planned. The top left of the chart identifies the "*pearls*", projects which could transform the company with high impact and high probability of success. Below these are projects named as "*Oysters*" as they could provide a "*pearl*", see Figure 22. These are projects with recognised high potential but have technical challenges. Care and attention is required to manage these projects and nurture the technical developments. In the bottom right quadrant are the projects with low return and low probability of success. As such they should be stopped or understood as to why they are important to complete (Cooper, Edgett, & Klienschmidt, 2004). The chart gives a good visual indication as to where the resource is being directed by reviewing the collection of projects in each segment and the bubble size (showing resource allocation). Over focus on standard projects (bread and butter) will only drive incremental benefits. Conversely over focus on high potential projects may lead to a low success rate of completion. There is a balance to be achieved.

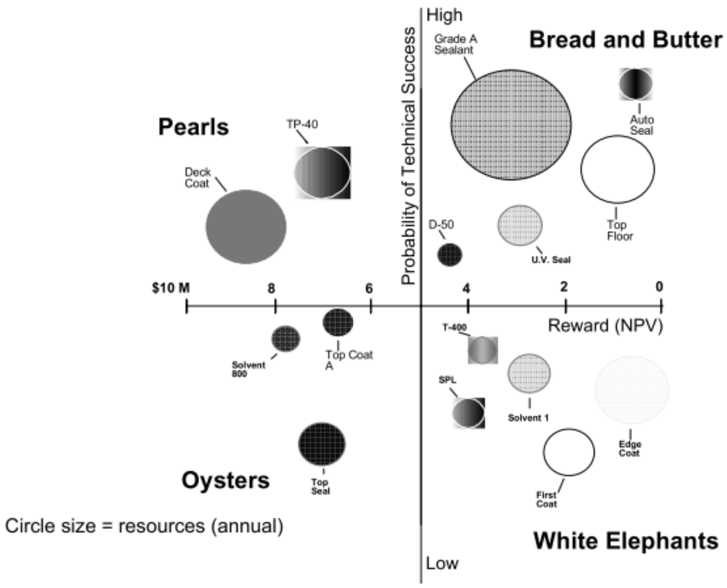

Figure 22: Risk and reward bubble diagram (Cooper R. G., 2008)

Product family design is a method by which a range of products is conceived from a common platform. The development is conducted so that a complete range of products is considered and links are made between them so that consistency in design can be achieved. It is a design approach that considers sustainable aspects. In efficiency terms, benefits are reported 30% less engineering hours, 20% reduction in investment costs and 20% reduction in costs (Potsch, 2011). Additionally product family design has an impact on environmental and equity aspects through increased standardisation, less transportation and reduced material consumption. The use of common platforms may restrict customisation, although there has been development in the method to enable areas of customisation in the early stage of design concept (Haung, Li, & Schulze, 2008). The disadvantage of product family design is that highly niche products can out-perform those designed by product family design owing to compromises. The optimisation opportunity with product family design may be restricted in order to meet the requirements of the full range. However, it is concluded that product family design is a best practice that can enable more sustainable product developments.

Disruptive technologies are those that challenge the normal way to do business. They can be highly powerful, opening new markets, breaking down existing markets and providing dominance for the inventing company, such as the *iPod* by Apple (Isaacson, 2011). Techniques to manage such innovations are of interest. While disruptive innovations account for a small portion of developments, typically 6% to 10% (Tidd, Bessant, & Pavitt, Managing Innovation, Integrating Technological, Market and Organizational Change, 2006), they often define the long term future of a company. Techniques for disruptive innovation were explored (Christensen & Overdof, 2000) (Kostoff, Boylan, & Simons, 2004) (Linton & Walsh, 2004), however there was not a clear best practice. It was recognised that typical models used for product development may block disruptive development and stop them prematurely. An example would be at a prototype review where the market is not clear (as maybe it has not been created yet) the project may be stopped so that the team can work on other priorities.

5.1.6 Sustainable product development methods

Sustainable product development methods promote the consideration of environmental aspects for a product. They are top level approaches that have developed from the application of environmentally focused tools, such as EcoDesign and Life Cycle Analysis (Maxwell & van der Vorst, 2003). Sustainable product development promotes an integrated approach that considers ecological destruction, social integrity and the neglect of future generations (Siebenhuner & Arnold, 2007). Sustainable product development is a system which provides a mechanism to manage performance towards sustainable goals. Existing systems typically take the form of either a framework, a guideline or a process map (Holmberg & Robert, 2000) (Hallstedt, 2008) (Maxwell & van der Vorst, 2003). Guidelines are the most popular with several published models. These are often built using question-sets to open discussions and ensure wider considerations are understood as part of the product development process (Hallstedt, A Foundation for Sustainable Product Development, 2008) (Byggeth, Broman, & Karl-Henrik, 2007) (Maxwell & van der Vorst, 2003). However, guidelines were found to be cumbersome and over prescriptive in practice (Kaebernick, Kara, & Sun, 2003). A framework approach is used to provide a more generalised view and a less prescriptive system. Frameworks have an advantage of setting strategies and using a structure to develop these into product criteria (Choi, Nies, & Ramani, A framework for the integration of environmental and business, 2008). A systems approach is used by *Gehin Zwolinsji & Brissaud* in the development of a framework with a design tool (Gehin, Zwolinski, & Brissaud, 2008). A practical method seen in the literature comes from *Howarth and Hatfield*. They develop a relatively simple overview matrix through which the elements of environmental, social and economic performance can be evaluated. The system considers ratings of risks and benefits for the three elements against performance aspects of raw material and design. The output is viewed through spider diagrams which highlight the focus areas (Howarth & Hadfield, A sustainable product design model, 2006).

Feedback from product development practitioners found the need for new and sustainable methods to be unclear. Work has been conducted in linking traditional methods to sustainable product development methods, which identifies the transition areas well (Kaebernick, Kara, & Sun, 2003). However failures in adoption of the methods is common place in literature associated to sustainable development. Usually this is due to over complex systems and lack of senior management support (Kaebernick, Kara, & Sun, 2003) (Hallstedt, A foundation for sustainable product development, 2008). Considering a seeming practical tool such as that by Howarth and Hadfield still shows issues in adoption. The tool requires a response to 109 questions to assess a single development project through a software tool owned by Bournemouth University. These are significant barriers to uptake (Howarth & Hadfield, A sustainable product design model, 2006). There is a need for a simpler system that can be easily communicated and adopted to provide proven benefits.

5.1.7 Sustainable Product Development in Other Industries

In this section a review of how other industries have adopted sustainable product development is undertaken to give learnings as to how the industrial gases industry may transition to sustainability. Literature associated to sustainable product development enabled identification of appropriate industry segments to consider. Three industries that appear to have made significant steps towards sustainable product development are Aviation, Automotive and Construction. *Hassini et al.* identify the automotive industry as having the most publications associated to sustainability (Hassini, Surti, & Searcy, 2012). Other key industries identified by *Hassini et al* are Agriculture, Construction, Electronics Healthcare and Transportation. Within the Transportation industry further research identified the Aviation industry to be prevalent in activities associated to sustainability. The last area considered is the Construction industry, as interactions with social sustainability are greater than that of typical engineering industries which might provide an alternative angle to consider.

In the Aviation industry there has been significant changes to legislation (Department for Transport, 2015), political and public opinion (European Environment Agency, European Aviation Safety Agency, Eurocontrol, 2016). The main focus of the external drives is to reduce the environmental impact of flying. It is a well published trend that passenger numbers are increasing and will continue to increase (International Air Transport Association, 2012) (Airbus, 2016). People are also traveling further (Airbus, 2016) which highlights equity considerations associated to travel, such as distribution of wealth, conditions of work, and infrastructure considerations (such as road networks, water and power supply). The aviation industry through both tourism and business activities has resulted in significant effects to many communities both positively and negatively. It is questionable that the industry considered these impacts in a sustainable manner. For example in offering low cost flights to holiday destinations, did the industry promote equity and efficiency benefits to passengers at the expense of environmental impact? Did the industry consider what actual improvement in carbon dioxide emissions is required to off-set the impact? Further the product (low cost flights for holidays) is questionable from a sustainability view, is a family holiday better to be had at home or flying to a distant country? Is the environmental impact of these choices as clear to customers as the price?

The Aviation industry has focused development activities on reducing carbon dioxide emissions from jet engines (Foust, Thomsen, Stickles, Cooper, & Dodds, 2012) (Peeters, Gossling, & Becken, 2006). This has typically been achieved through efficiency improvements, following the traditional role of engineering where a specific parameter is improved. The main driver for this is legislative compliance and political agendas based on reducing carbon dioxide emissions (European Commission, 2008). It is arguable that other environmental targets may have driven an improved overall environmental performance. Factors such as embodied energy in the manufacturing of a plane, consideration of the consumed natural resources in maintaining and operating flights, and the end of life environmental impact are also important considerations. There are companies within this industry who take a holistic view to sustainability. Rolls Royce, the engine manufacturer, is a strong example of a company who has taken significant steps forward in both performance, reducing NOx by 50% (Parker R. , 2009) and regarding sustainability in a wider view (Upham, Maughan, Raper, & Thomas, 2003). Others in the aviation industry are also applying sustainable design techniques into their engineering processes, using methods such as design for the environment and life cycle analysis. Although the highest level of maturity, sustainable design is not achieved due to lack of partner integration (Lee J. , 2001). Business models have also changed in the aviation industry, again, Rolls Royce provide an interesting example as they moved to a service model as opposed to a pure product purchase. This is arguably a more sustainable business model as it addresses the customer needs of reliability and lower capital outlay, while offering improved profitability to Rolls Royce (Smith D. , 2013).

It is observed from the consideration of the aviation industry that legislative, political and public drivers can change industries. While the main driver has been environmentally focused, it has achieved improvements that may not have occurred without the drivers. It is likely the environmental impact of flying would have been significantly higher if nothing had been done and the rate of passengers increased as it has done. The legislative changes have been tackled largely by technical developments using sustainable design practices. This has delivered strong performance improvements, although the journey to sustainable development is not complete.

The automotive sector follows the main trends seen in the aviation sector, that emissions targets (largely carbon dioxide and nitrous oxide based) are driving environmental improvements. These are set in legislation and are on the public and political agenda. In the automotive sector a similar approach is seen as in aviation, the emissions target is met by developing existing technologies to meet lower emission requirements. In the automotive industry there is less evidence of an integrated sustainable development approach compared to the aviation industry. However there is evidence of integrating environmentally focused techniques into the design process, (Luttropp & Lagerstedt, J, 2006) (Mayyas A. , Qattawi, Omar, & Shan, 2012) (Schmidt & Butt, 2006). There is evidence of sustainability as a focus in the manufacturing process (Hassini, Surti, & Searcy, 2012) (Amrina & Yusof, 2011). From an emissions point of view the industry is improving (BIELACZYC, WOODBURN, & GANDYK, 2016) and the industry is considering alternative technology such as batteries (Fabian, Hirz, & Krischan, 2014) and hydrogen (Rizzia, Annunziata, Liberati, & Frey, 2014). Both technology options have been incentivised through tax benefits (US Department of Energy, 2016) and grants (US Department of Energy, 2016). Environmentally there is also focus on improving operational and end of life impact, again legislation is a key driver (UK Government, 2016). Other sustainable considerations, while less publicised are apparent for example, a self-driving car is a significant efficiency improvement (Wadud , 2016) and increased localised production brings equity benefits (Niedermeyer, 2014) (Tang , 2009). Both of these activities are driven more from a financial and performance benefit than from external factors (although it is recognised external factor may influence the decision of manufacturing locations and provide barriers to self-driving cars).

The automotive industry provides a further important learning in what can happen when there is an over focus on key drivers. The Volkswagen incident of falsifying carbon dioxide and other emission results in legislative tests (Texin, 2016) indicates sustainability was not a consideration, the ethical issues of the incident need not be explored here but they were clearly ignored. The learning is that legislation is not always a positively influencing driver.

There is a significant amount of literature associated to sustainability and the construction industry, it is observed that "sustainability of construction has become a key aim of countries aspiring to follow the path towards sustainable development" (Holton, Glass, & Price, 2010). Key stakeholders driving sustainability are identified as legislators, customers and investment groups, (Holton, Glass, & Price, 2010) (Basiago, Economic, social, and environmental sustainability in development theory and urban planning practice, 1999) (Heffernan, 2013). In their role the stakeholders set development policies and it is the role of the construction industry to deliver on these policies. In this respect the industry is playing a pivotal role strongly linked to sustainability (Dempsey N. , Bramley, Power, & Brown, 2011). The construction industry's links to government policy is arguably stronger than other industries. The reason behind this is that buildings and living environments have more non-physical factors to be aware of in their design when compared to other products (Dempsey N. , Bramley, Power, & Brown, 2011).

In similarity to the automotive and aerospace industries, construction legislation has been set to reduce global warming by reducing green-house gasses (UK Government, 2015). This is achieved through improved energy efficiency of buildings, but also in reducing the embodied energy in constructing the building (Hammond & Jones, 2008) (Mehta & Meryman, 2009). These design goals are important to consider along with social goals such as more and lower cost accommodation. Although this can lead to direct compromises between environmental performance and social performance (Constructing Excellence, 2006). The drive for zero carbon homes (and eco-towns) is a holistic approach towards global carbon dioxide targets and social mobility, while integrating with existing infrastructures (Heffernan, 2013). There have been significant areas of success in the construction industry in particular around new cities in South America where a strong social benefit is observed (Basiago, Economic, social, and environmental sustainability in development theory and urban planning practice, 1999). In this respect the construction industry is displaying a high degree of understanding of sustainability, well described in the commentary of Curitiba's success,

> "Curitiba has thrived by building an efficient intra-urban bus system, expanding urban green space, and meeting the basic needs of the urban poor. It suggests that economic sustainability requires planning for people, making the city more 'green', and, hence, more liveable, for people" (Basiago, Economic, social, and environmental sustainability in development theory and urban planning practice, 1999)

However there has been a lack of adoption of more radical designs such as Zero-Carbon homes due to the construct of the volume building industry. It is identified by *Hoffman* that it is possible to drive more zero-carbon homes by increasing public pressure, stronger regulations and improved supply chain integration (Hoffman, 2007).

Industry guidance for sustainability can be found in two international standards as BS 8900:2006 Guidance for managing sustainable development and ISO 14001 Environmental management (British Standard Institution , 2006) (International Organisation for Standardisation, 2015). Both guidelines develop a management system for identification of performance factors, reporting, review and decision making against the performance factors. In BS 8900:2006 a framework is presented to integrate sustainable decision making as part of everyday work. ISO 14001 provides a compliance focus and promotes a natural transition to corporate sustainability. However it lacks a focus on social aspects and broader sustainability concerns.

A strong factor in all three industries has been legislative requirements to improve environmental performance. It is generally observed that, "companies are hesitant to commit to sustainability, as long as they are not forced to by law" (Hassini, Surti, & Searcy, 2012). This is accompanied by companies placing a focus on environmental management to address legislative compliance (Holton, Glass, & Price, 2010). A transition to sustainability occurs in several stages, identified as, rejection, non-responsiveness, compliance, efficiency, strategic pro-activity, the sustaining corporation (Dunphy, Griffiths, & Benn, 2014). While out and out success is not observed in any of the discussed industries, there has been clear performance benefits for all three industries in all areas of sustainability. Environmental performance is observed as being the dominant improvement area. While the construction industry appears to have had more success on social performance, this is likely to be due to the product having a tighter interaction with people. In contrast the automotive and aerospace industries showed a greater maturity in product design and efficiency, which is likely to be due to those industries having a stronger focus on engineering techniques.

The industrial gases sector has lacked activities in sustainability, particularly in terms of environmental performance. There are no active environmental targets for this industry set either by legislation or industry bodies. Three main aspects of legislation apply in Europe, that is, the pressure equipment directive (European Parliament, 2012), the transportable pressure equipment directive (European Parliament , 2010) and the carriage of dangerous goods (Accord européen relatif au transport international des marchandises dangereuses par route, also known as ADR) (United Nations Economic Commission for Europe, 2013)). There are industry bodies at national and international levels, examples are the British Compressed Gas Association (British Compressed Gases Association, 2017), the European Industrial Gases Association (European Industrial Gases Association, 2017) and the Compressed Gases Association (Compressed Gas Association, 2017). These bodies are actively participating with other bodies and governments to ensure safe trade of industrial gases (for example standards for gas connections and pressures) and lobby on external changes that impact the industry (an example would be fuel tax).

At an individual company level activities in sustainability are present in industrial gases. These have been explored in the background to this work, see section 0, finding sustainability could be a stronger focus with improved funding. Industrial gases is perhaps in a similar situation prior to legislative changes in the aviation, automotive and construction industries. Considering the exploration of sustainability in other industries in relation to the current activities of the industrial gases industry, a set of learning can be taken from the above discussion:

- Environmental improvement often triggers the transition to sustainability, this happens when environmental performance becomes an important element of an organisation's strategy. Companies working in the field of industrial gases should consider environmental targets as a starting point for transition.
- An emissions based target set in legislation is likely to drive environmental performance improvements. While it is unclear as to how such legislation may come into force in industrial gases, increased political and public awareness of the industry may provide a trigger.
- Legislation has been used to drive an industry wide approach and promote competition through targets. However, care should be taken policing performance. The representative bodies for industrial gases should consider this and how legislation could be brought in for a positive effect.
- Technology alternatives can be encouraged through funding methods and other externally influenced provisions. The industrial gases industry would benefit from both seeking more funding and lobbying for more funding. An opportunity is with Hydrogen and LNG as energy sources.
- Public opinion can be a strong driver for change, it may be beneficial for the industrial gas industry to promote itself more to the public.
- Companies should consider setting strategies aligned to sustainability performance factors, in particular environmental factors.
- Companies could deploy best practices in sustainable product development from other industries pro-actively. This could include activities such as best practices in design for the environment, through to embodied energy assessments and life cycle analysis.

5.1.8 Summary of Findings and Approach

There is a need for a new simpler sustainable product development system that focuses on all elements of sustainability and promotes a balanced performance. Additionally a new sustainable product development system needs to address the shortcomings in product development techniques employed in the industrial gases industry. For example, managing disruptive developments (which can be highly sustainable) and using portfolio management.

The architecture of a sustainable produce development system has been considered through the assessment of currently applied methodologies (see section 5.1.6). The result is a recommendation to use a framework as the description of the methodology. A guideline can then provide support in how the activities are be conducted. A guideline may also provide the practise details, for example, in how to conduct portfolio management. Furthermore, in a guideline there can be best practices such as a process map and how to adopt techniques to a company.

Many of the sustainable product development methods focused on environmental improvements and also struggled in implementation. It was identified that this is partly due to underestimating the needs of the business in areas other than environmental aspects, but also the methods were over complex in comparison to the current practices. Therefore recommendations in best practices for sustainable development shall be required in the new methodology. A focus on ease of use and providing business benefits may aid implementation.

In the previous chapters the area for improvement in product development processes were identified as:

- A best practice for sustainable product development
- A best practice for the use of portfolio management
- How to successfully manage disruptive product developments

In order to make a strong step-wise change in methodology it is proposed to apply portfolio management and actively manage disruptive innovations. A best practice for portfolio management can be considered, based on the literature search conducted (Pemberton G. , A Framework and Assessment Method for Sustainable Product Development Part 1: Literature Search, 2014b). This identifies a need for a guiding process map to be used for project performance and management. The process is required to be to be flexible with appropriate company customisations. One particular area for customisation is how to manage disruptive innovations. Current product development processes often result in rejecting these products before they have had opportunity to show their potential. In the proposed process map a specific provision can made for disruptive innovation.

The effect of disruptive innovation on teams was observed to be an under discussed area within literature. Wider still, the human aspects of research and development teams is a general area where there is limited information. The information that is available highlights an uncertainty and reluctance to change. In the development work, an opportunity is presented to look at how to provide provisions for managing the team, especially post product development when there is a higher likelihood for burnout and seclusion. As the sustainable produce development methodology is developed implementation is to be considered along with the human aspects of the process.

5.2 A Framework and Assessment Method for Sustainable Product Development Part 2: Methodology Development

Following the literature review a separate work element was conducted on the development of a methodology for sustainable product development. The work commenced by considering the identified gaps and how to approach the overall subject matter. The need for a descriptive system is identified in a number of works as a necessity to manage product development activities (Choi, Nies, & Ramani, 2008) (Maxwell & van der Vorst, 2010). It was highlighted that a number of approaches are found in literature to define product development, the traditional method being a process diagram (Coyle, 2006) (Tidd, Bessant, & Pavitt, Managing Innovation, Integrating Technological, Market and Organizational Change, 2006). It has been popular in sustainable development to use a framework to describe the overall system which has an advantage of providing a more holistic view of activities (Howarth & Hadfield, 2006) (Hansen, 1999) (Rainey, 2005). In other cases guidelines have been used, which give a greater depth in the description of activities (Byggeth, Broman, & Karl-Henrik, 2007).

In reflection to the aims of the new sustainable product development methodology, a reasoning was developed as to the suitability of the different methods. A review was conducted focusing on the aspects of sustainability (environment, efficiency and equity) which is presented in Appendix 1: Assessment of approaches to a new methodology for product development. There are three identified approaches explored, frameworks, guidelines and process maps. In Appendix 1 these are critiqued for advantages and disadvantages. This also covers specific gaps observed in the methods for new product development when linked to sustainable approaches. Table 9 (in Appendix 1) is a view of the purpose and core strength of each approach, which has been used to highlight different aspects. In this view each approach is seen to contribute positively and therefore elements of all three approaches are desirable. A combination of all three approaches was identified to provide an improved method for sustainable product development.

Howarth and Hatfield develop a sustainable product development method that links to sustainability and provides a potential base to build on. They develop an eight by three matrix to evaluate aspects of product design towards sustainability risks. Each area of sustainability is viewed in association with risk through an assessment, for example environmental risks includes items such as noise, hazardous waste and emissions. However to complete the assessment each area has a set of multiple questions to be answered, a total of 109 question sets. The derivation of the list could be questioned; a simplified format might have had increased levels of acceptance. The degree of assessment, and at times, abstract nature in the assessment (due to the criteria) results in a very low adoption of the process (Howarth & Hadfield, 2006). This highlights the importance of building a sustainable product development method that is user friendly.

In this regard it has been considered if a five capitals method would work as part of framework. The five capitals of, natural, human, social, manufactured and financial could be used in a similar approach as *Howarth and Hatfield*. Considering *Howarth & Hadfield's* model this would add an additional 2 areas of assessment, effectively 16 further points in the assessment, or an expected increase in question sets to 182 (using the same ratio of questions to assessment points). This is moving further away from the requirement of simplicity. The linkage of product to five capitals does have logic although it may create some abstract assessment areas, for example product performance linked to *social* investment. At a higher level view than product development, the use of the five capitals method seems to make more sense, as it then captures the work that companies do outside of product development. The use of the five capitals method is not taken further into the new sustainable product development methodology but it is acknowledged that further work in this area might deliver useful insights.

Going back to the approach, a framework with a guideline which contains a process map is the chosen approach. This gives a balance of an overall view (framework) with detailed instructions of boundaries and activities (guideline). The framework can support a sustainable view enabling an understanding of how stakeholders and strategies are connected and how decisions are made. A process map is recognised as being a useful way to depict the process, the interactions with other departments and how to work within the framework and guidelines. A process map is included in the methodology and helps to address a weakness of frameworks in showing the timing and interaction of tasks. A guideline then acts like manual giving best practices and examples of how to conduct tasks.

The performance aspects for a new sustainable product development system were explored and are detailed in A Framework and Assessment Method for Sustainable Development Part 2 (Pemberton G. , A Framework and Assessment Method for Sustainable Product Development Part 2: Development, 2014c). It is expected that key performance indicators need to be developed to assess the system and the work being conducted (Wheelwright & Clark, 2011). Practices in monitoring performance are identified as, basic value reporting, multi-criteria analysis and guidelines/statements (Sattay, 1990) (Heijungs, et al., 1992). From a review it is proposed that a multi-criteria assessment is the most aligned technique to the method in development. A multi-criteria assessment shall quantify the data and enables several views of the data. It is this method that is recommended for the new methodology. The details of the key performance indicators can then be built into a new assessment method for the process.

A key aspect observed in the transition to sustainability is a focus on Environmental performance. In the development of a new sustainable product development system for the industrial gases industry, where there is limited Environmental focus, the system must promote improvement in Environmental performance. In other industries a focus on emissions has been successful, however in industrial gases the link of emissions to product is not as strong as the other areas observed (automotive, aerospace). An indicator for carbon dioxide emissions or embodied energy at a product level is a gap too far to immediately achieve. A prescriptive system on Environmental performance may restrict adoption. An alternative route would be for the system to require Environmental performance factors and that an organisation decides what they should be from guidance. Examples at a product level would be; a measure of consumed energy in a product, a measure of the emissions associated to the supply of the product, a measure of the waste associated to the product and a measure of the ability to recycle a product. Special performance measures could be given to the handling of products containing environmentally harmful gases such as carbon dioxide, nitrous oxide, methane, carbon monoxide and refrigerants. In particular releases from production and activities to recapture and recycle these gases should be encouraged.

The best practice of using lean tools in product design is typically part of integrated product development models, lean is also seen as general best practice (Cooper, Edgett, & Klienschmidt, 2004). It is identified that the new product development methodology could follow application of lean tools at an activity level and monitor how they assist in achieving goals. A guide for the application of lean tools in product development process has been developed based from previous work (Warwick University, 2010) (Wilson G. , 2005) and is presented in Table 10 in Appendix 2. It is proposed to these recommendations.

An additional consideration for the sustainable product development method which may help trigger transition as a focus on new technologies (Pemberton G. , A Framework and Assessment Method for Sustainable Product Development Part 2: Development, 2014c). Technology road maps were found to be a best practice but often not integrated into methodologies (Phaal, Farruh, & Probert, 2004) (Rinne, 2004). This observation has led to the proposal of a technology area within the product development methodology. Roadmap techniques can be applied and opportunities for technology implementation identified across the portfolio of product developments being conducted. This should encourage a strategic approach to technologies for the company.

Implementation of the methodology is considered from a systems aspect. It is recognised that implementation should be considered in the design and development stage. This is a similar approach as conducting product design with an understanding of the end environment, which has been shown to bring benefits to product development (Rainey, 2005). *Siebenhuner and Arnold* identified that companies often customised systems during implementation to improve their fit with the company culture and to find additional process benefits (Siebenhuner & Arnold, 2007). The learning here is that the new methodology must have enough width in its design to enable customisation.

In the approach it was decided to include a study of implementation and conduct an implementation to test the ability of the sustainable product development methodology to work in a specific company. As there was little literature an initial exploration of implementation with a survey was deemed a logical approach. A set of questions was created about change in product development methods. Alongside the change related questions, responses are explored on expectations, risks and what mitigating actions could be taken. A table is presented from this work which includes the questions, actions, outcomes of actions and how to measure if the actions are effective. This table is shown in Appendix 3: Table of actions and expectations from a new product development methodology. This work assists in clarifying the needs for the system and areas for customisation.

Consideration of application to the industrial gas sector was undertaken. There are few drivers for significant product or process changes identified. Most product development activities centred on continuous improvement (Pemberton G. , 2014b) (Pemberton G. , 2014c). While sustainability was a clear concern for all the major gas producers, the commitment varies considerably. Furthermore, actual actions were seldom of significant impact (Pemberton G. , 2014c). There is an opportunity to advance product developments and to apply best practices from others (Cooper, Edgett, & Klienschmidt, 2004). The new methodology must take on these challenges and combine both clear areas of sustainable product development and where customisation works.

5.2.1 The Framework

The development of the framework considers the use of the three terms of sustainability from section 0. It follows the review on different aspects of product development and methods used (Pemberton G. , 2014c). A key finding was the best practice for product development was to use an integrated development model, this could be used as a structure the rest of the method. An integrated development model identifies boundary aspects such as customer needs, business drivers, business strategies, enablers, organisation, the interacting departments for product development and the process for product development. These areas of activities can be reduced to the following groups; business drivers, enablers and process. Business drivers also includes customer needs and business strategies. The enabling element also includes organisation considerations. A specific process area is proposed to ensure continued focus on process. A weakness identified in these groups associated to the integrated model is that technical step changes are not naturally promoted as the input is focused upon the business drivers. It was also observed that new technologies should be encouraged to achieve step changes in the industrial gas segment. To address this, a new technology area is considered. This should identify technology changes but ensure a continual development of technologies used within a company. A technology focus should improve the product features, the supply chain and end of life considerations. The area also enables the identified best practice of technology road maps (for product development) to be applied.

The framework can then be formed using the above areas of discussed identified. These are the three terms of sustainability (efficiency, equity and environment) and the methodology for product development (in business drivers, enablers, process and technology). With these a framework can be built. The groups form a methodology for product development acting as boundary conditions for activities. Furthermore, as seen in the integrated product development model each of these areas has interconnections. For instance, if a business driver is to expand into a different geographical market, the enablers' node requires knowledge of local practises and legislation. The methodology sections act as points where information is transferred and shared back to other areas. They are therefore analogous to nodes, much like a finite element analysis model where an input causes an effect in the node that is then transferred to the adjoining node through an interconnection. This structural connection can be visually represented as a border for activities. This covers how to do product development, it is then required to focus on sustainability. The nodes there need to link to how sustainability is defined. It is proposed that inside the product development boundaries the correct balance of performance shall lead towards sustainability. This means that sustainability is needs to be central to everything undertaken within the framework. Visually it is logical that sustainability sits central to the frame.

These descriptions can be presented graphically in Figure 23. It shows the working boundaries, how to do product development, and that the focus is on sustainability. To detail how to work in the framework a guideline of best practice has been developed and may be viewed in appendix 4. The guideline builds on the information described in section 5.1.8, detailing how to develop products using the best practices identified, see Appendix 4: Guideline to the Sustainable Product Development Framework. Within the guideline a 5 step process map, based on Stage Gate® is presented as a generic process which can be customised for use within a company (see appendix 4).

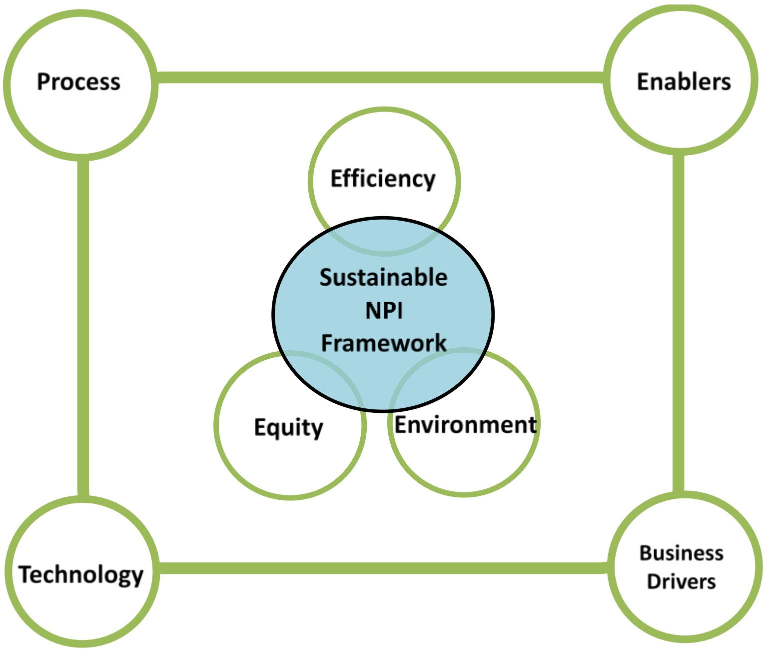

Figure 23: The Sustainable Product Development Framework

5.2.2 The Assessment

As part of the new sustainable product development methodology a requirement was identified for performance measurement. To address this a sustainability assessment method was developed. Using the learning from previous works on sustainable development systems, key requirements were identified (Pemberton G. , 2014c). These included a numerical result, a simplicity in completing the assessment and the use of a rating system. By considering the framework nodes and the definition of sustainability, the method (of process, enablers, technology and business drivers) can be mapped to sustainability (efficiency, equity and environment). This directly correlates the performance of a product development to sustainability. The concept of this mapping enables the performance of each element of the framework to be considered in terms of sustainability. This type of linkage resembles some previous literature where sustainability is linked to product attributes (Howarth & Hadfield, A sustainable product design model, 2006) or environmental performance with product design aspects (Choi, Nies, & Ramani, A framework for the integration of environmental and business, 2008). It is proposed that linking the product development method to sustainability will drive more than product improvements enabling a more holistic view on the product being developed.

At this point either qualitative or quantitative assessment could be conducted. As a numerical result is called for, an approach is to use a scoring system, the framework nodes can be scored against the sustainability factors. This results in a concept of assigning numerical values to show performance, for example scoring process performance in terms of efficiency aspects. The development now needed to address how to score or rate performance to sustainability aspects.

There are alternative methods available for numerical assessment, one option is to use performance indicators. An example would be using an environmental performance indicator (such as tonnes of Carbon Dioxide emitted) to set an overall objective for the company it could be cascaded to enable a quantitative assessment at a product development level. An equity example might be to employee a specific percentage of the work force from minority representations, which again could be assessed in a scoring method. The concept appears to work on a single line assessment. It is desired to look at collective performance of the new product development method. Performance factor are unlikely to result in comparable numbers. A method to address this, is to use a common scoring system for all data points. Scoring system are well used in other literature regarding product development, such as scorecards (Morris & Pinto, Project program & portfolio management, 2007) risk assessments (Howarth & Hadfield, A sustainable product design model, 2006), sustainability assessments (Kaebernick, Kara, & Sun, 2003) (Choi, Nies, & Ramani, A framework for the integration of environmental and business, 2008) and tools such a (eco) quality function deployment (Kuo & Hsin-Hung, 2005) (Kaebernick, Kara, & Sun, 2003). There are various scales available for scoring systems, simple ones such as 1-2-3 are popular (Wheelwright & Clark, 2011), as are scales such as 1-10 (Howarth & Hadfield, A sustainable product design model, 2006), in some cases scores are set with deliberate weighting (High = 0.735, Medium = 0.199, low = 0.065) (Choi, Nies, & Ramani, A framework for the integration of environmental and business, 2008). However the chosen method is to use a scaling system of 1 to 9 along with a standard weighting factor of 10 (Saaty, 1990). This scoring method has been shown to be robust in giving significant separation and determination of performance (Saaty, 1990) and it has been used in other rating methods in sustainable development processes (Heijungs, et al., 1992). This provides a known working method, which may be improved on following feedback.

A method to complete the scoring has also been developed. Options were explored for this including question sets, performance parameters and industry comparisons. Question sets have been used in sustainable methods previously but have been found to become cumbersome due to the quantity of questions required (Howarth & Hadfield, A sustainable product design model, 2006) (Byggeth, Broman, & Karl-Henrik, 2007). Quantitative performance indicators, such as tonnes of Carbon Dioxide or productivity targets, are a good method if a company has a set of performance parameters that map to the new sustainable product development method. As this is unlikely, then development of performance indicators would be required from one business to next. A potential downside to performance in limit the cross comparison of results. This may limit adoption.

A simpler method would be to use a guideline based on industry descriptions, much like a doctor's assessment method of a patient. In this approach descriptions could be used to define a variation from poor to excellent. It is proposed to use such a method and review if alternatives are more appropriate following an implementation. The assessment descriptions have been built up for each assessment area. For example, in assessing the rating of lean tools in the process node, the scaling of 1 to 9 is between companies not using lean to companies using multiple lean tools and have a lean culture. Further details are in Appendix 5: Rating guidance for assessment method. It is recognised that there is subjectivity in this approach, and it is expected with several implementations the rating guidance can be revisited for improvements.

A method to conduct the assessment is required. This presents options such as self-rating, using a specific person/team or a group of people responsible for the project. It is proposed to use the steering committee for the project. This reduces bias in the assessment, as it is not the individuals working on the project conducting the assessment. The steering committee has a responsibility to be objective through the development process and there is expected to maintain its objectivity in the assessment. For each assessment discussion, evidence of performance is to be presented in order that a decision of the score can be made. In some cases it may be suitable to refer to performance indicators for the project. An example using the enablers area regarding funding is if the project is on budget and that the required on-going funding is available. It is recognised that in using a 1-9 scale with three points of reference the granularity of the response is a weakness, such as what is the exact difference between a score of 7 or 8. This is to be best addressed when conducting the assessment by comparing the proposed score to previous performance and to other projects. Implementation and practice should be used to assess this and look for opportunities to improve. The assessment can be completed by an individual providing the higher level of subjectivity is understood. Such issues of bias in the assessment method may be possible to identify in detailed analysis of the results, looking for patterns or inconsistencies.

A weakness in the system described so far is that there is no method to place a strategic emphasis on a particular area of the methodology. A further enhancement to the assessment can be built in. A weighting system would enable aspects of the performance to be deliberately emphasised. As has been observed earlier in sections 5.1.6 and 5.1.7 that often environmental improvements are the initial focus in transition to sustainable product development. A weighting system enables the focus to be biased to environmental factors. An alternative would be to place a weighting system on the framework nodes which would enable biasing to the nodes (business drivers, enablers, process and technology) which require improvement for a specific organisation. This weighting could also be added in addition to the sustainability weighting. However this may be overcomplicating the system and could cause challenges in comparison assessments of data, such as the effect of the weighting would need to be considered. For initial use the proposal is to use a weighting system only on the sustainability factors. It is anticipated it may be most desirable to use the weighting against the environmental factor in order to promote environmental performance.

From this the full assessment can be built. It takes the form of a matrix in which the frame work nodes can be assessed against the sustainability factors, noting the nodes have been split down into key elements. The assessment matrix developed is shown in Figure 24.

The assessment matrix can be used to create a single indicator of performance for the sustainability factors and the development process nodes. Summing each row's results gives a value of performance in each area of sustainability, this is has been named the *sustain index* which provides a method of relative assessment at each stage. The *sustain index* enables performance evaluation to occur at an individual project level and across a portfolio of projects. At an individual level the matrix can be used to identify where improvements are necessary and where there are areas of strengths. A more holistic view is seen when comparing several projects within a company. This view provides an indication of current and future areas of strengths and weaknesses. For example if the sustain index for efficiency was currently the lowest number across all projects that would indicate an area for improvement. Using previous data would also give insight, such as if the preceding trend was of higher performance appropriate actions can be identified and taken. Inspection of the individual rating assessments within each node should provide insight into the causes of performance and where to assign actions.

		Process			Enablers			Technology			Business Drivers			
	Weighting factor	Lean tools	Gate checklist	KPIs	Team	Suppliers	Funding	New technology	Intellectual property	Differentiation	Performance to requirements	Business financial goals	Business strategic goals	SUSTAIN INDEX
Efficiency	10													0
Equity	10													0
Environment	10													0
Total weight		0	0	0	0	0	0	0	0	0	0	0	0	
		Process	0		Enablers	0		Technology	0		Business Drivers	0		

Figure 24: The sustainability assessment matrix

The assessment matrix is developed as a tool for project and portfolio assessment within a company. The rating method is based on benchmarking to descriptions, therefore it could be possible to compare scores between different companies and different sectors. This would require further research and examples to substantiate. For example, the sustain index may be able to provide industry and company level benchmarks if further work was conducted. It is envisaged part of such work may require the removal of the weighting factors (as these are used for specific company level biasing).

An opportunity with the assessment matrix is to identify areas of weak and unbalanced performance. In doing so actions may then be taken to positively level/improve performance. It is not intended that the matrix is used to identify what to do less of.

A portfolio of product developments can be reviewed using the matrix to provide a holistic view of development strategies. Regular portfolio assessment enables insight to trends and general performance. A further advantage of using a portfolio approach is that a lower performance in certain aspects (by specific projects) can be balanced by a stronger performance in other projects. For instance a highly efficient project with reduced environmental performance may be balanced with a lower efficiency, but a higher environmental perfomance project. Such a review can be conducted using portfolio analysis techniques, particularly those with visual representations. An example of such a review is shown in Appendix 6.

A popular visual method in sustainability assessments that also works well here is that of the spider diagram (Carrillo-Hermosilla, del Rio, & Konnola, 2010) (Howarth & Hadfield, A sustainable product design model, 2006) . This can be set up to view the performance of sustainability factors at both an individual level and multiple project level. In the first view presented, Figure 25, an individual project is shown. The coloured areas represent the performance to sustainability factors. The larger the area the stronger the performance. In this view the areas of strength for individual and collective factors of sustainability are clear. In the example the *business drivers* node, is a clear strength in all aspects of sustainability for this project, seen with its overlapping areas. While in the enablers mode *suppliers* is a particular weakness in efficiency terms and does not have strong performance in equity and environmental terms either. This indicates the suppliers chosen have room for improvement and a supplier improvement strategy should be applied or look for new suppliers. Insight into the product development methodology is also possible from the diagram. Figure 26 is used to visualise this by removing the general terms of assessment and showing the specific nodes (business drivers, enablers, process and technology). In this view the project requires strengthening in *business financial goals* and *funding* while it is strong in *intellectual property, differentiation* and *key performance indicators*.

In these views collective and individual strengths and weaknesses of performance towards sustainability and product development methodology is shown.

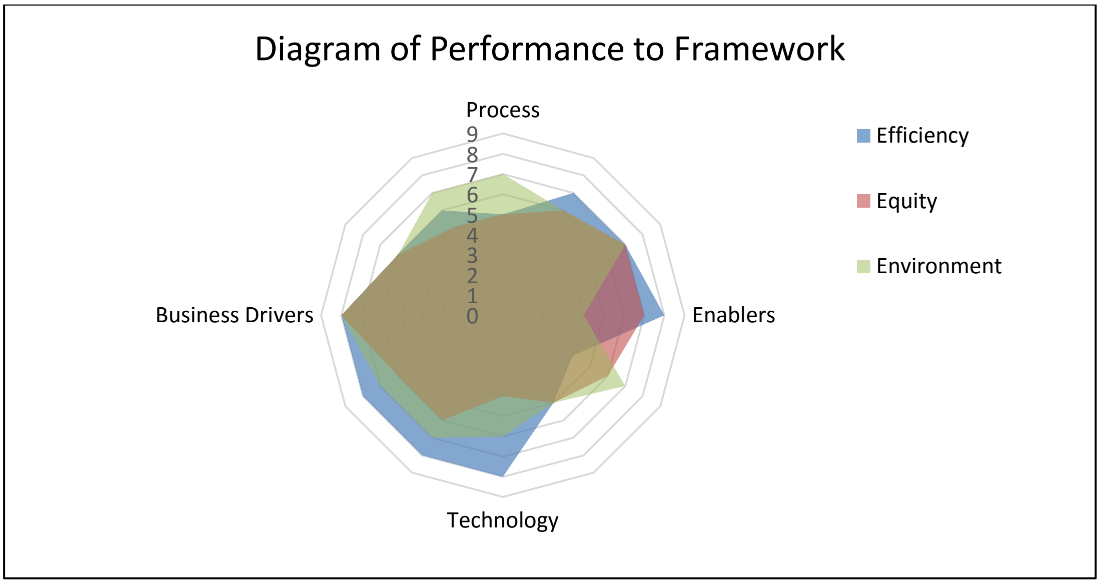

Figure 25: Example Diagram of Project Performance

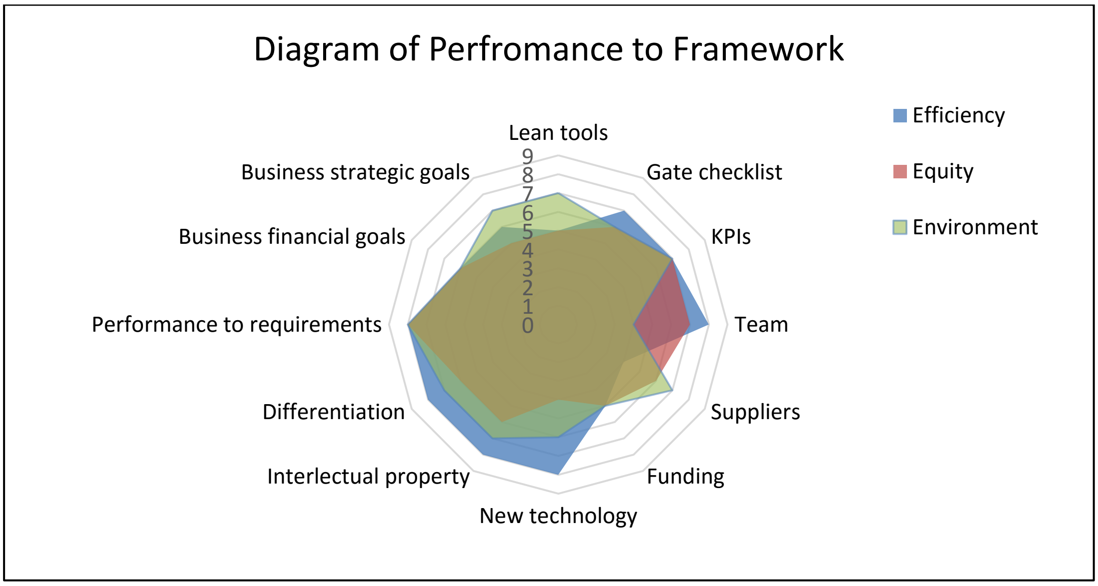

Figure 26: Diagram of Project Performance - nodes view

In the next set of diagrams a portfolio of projects is displayed in three views (Figure 27 to Figure 29). These views are built up from the previous example however it is not possible to keep the same structure of the diagram and continue to present the information without the view being cluttered. In these views the framework and/or sustainability factors are the outer edges of the spider diagram with the project scores mapped inside. The first diagram is performance to sustainability factors, the second performance to framework nodes, the third a combined view (the lines are individual projects). Of these views the simplest is the combined view, Figure 29. To build the combined view the three sustainability factor are adjusted to represent 4 areas like the framework has. This is achieved by multiplying the sustainability scores by 0.75 (3/4) to correct the range difference with the framework scores (also well highlighted in the scoring range difference 0-1080 for sustainability and 0-810 for framework). This gives a holistic view of the projects and is the best view for strategic review and decision making. The other two views are useful to consider sustainability and the framework performance separately. It is worth nothing these three charts are more visually pleasing if the project score areas are overlaid, as in Figure 25, but in this example there are too many projects for the overlaid view to remain clear.

The diagrams may be used to identify individual projects for exemplary performance or improvements. For example, project B has a low performance on the sustainability factors of *efficiency* and *equity* which could be linked to its poor performance on technology. Whereas project D has an overall strong level of performance. In the diagrams presented the *environmental* performance looks to be an area for improvement and this may be driven through the weaker areas in the framework nodes, such as *technology* (for example with alternative technologies) and *process* (for example by increased use of design for sustainability techniques). A more detailed example of a review through the data analysis is given in, Appendix 6.

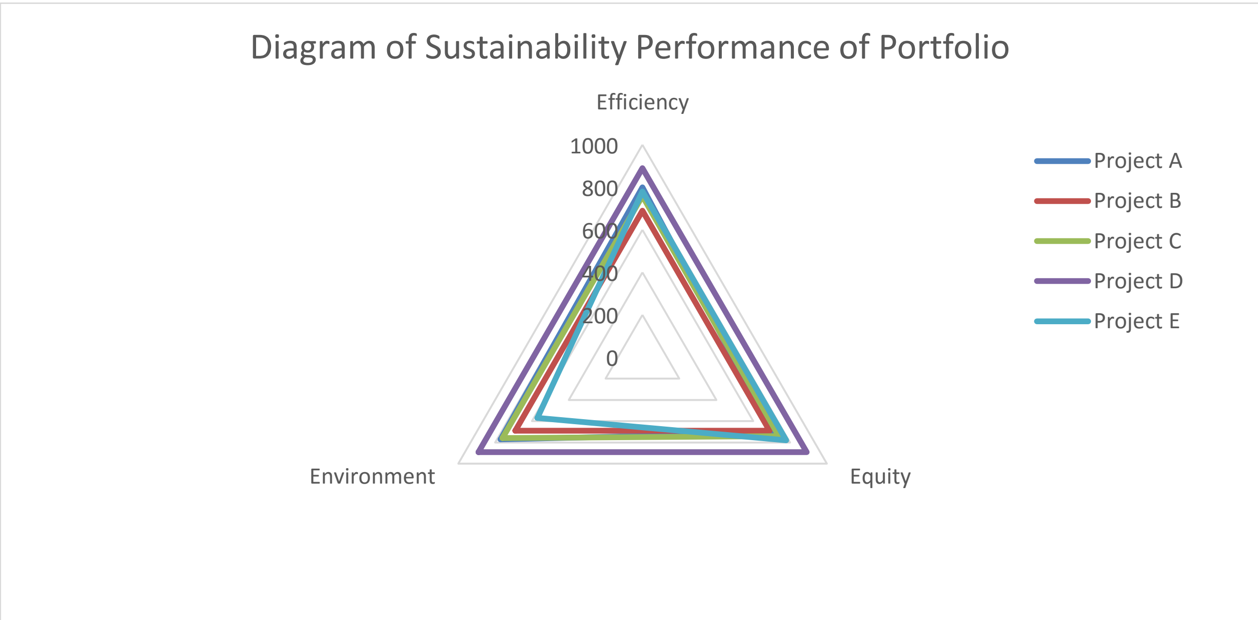

Figure 27: Diagram of portfolio performance to sustainability factors

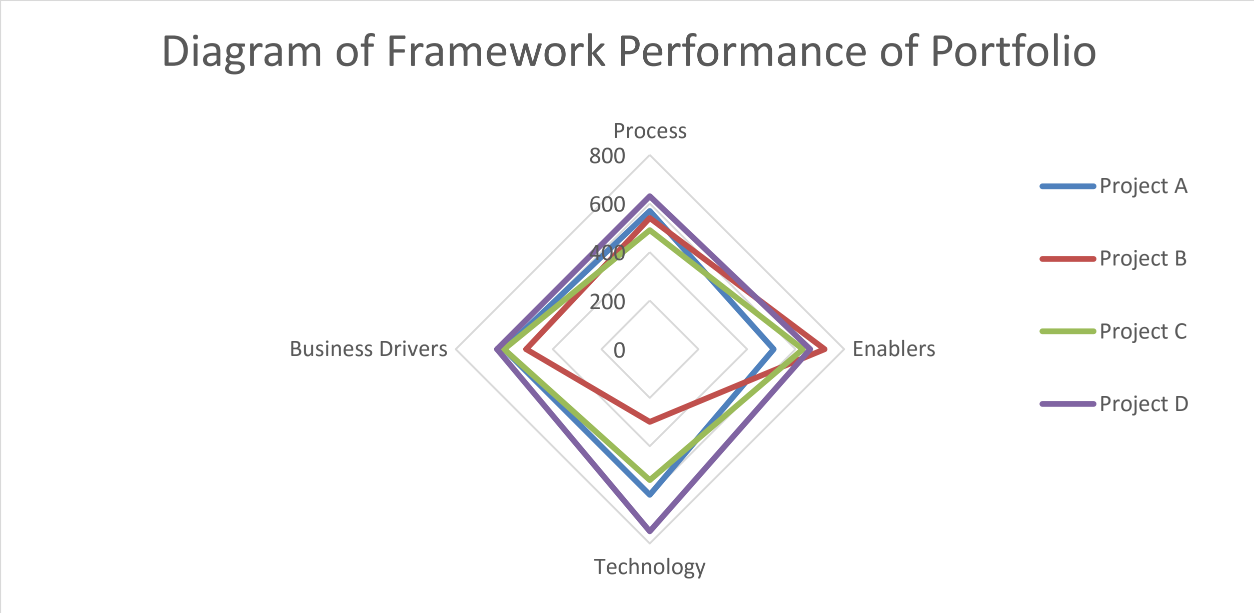

Figure 28: Diagram of portfolio performance to framework nodes

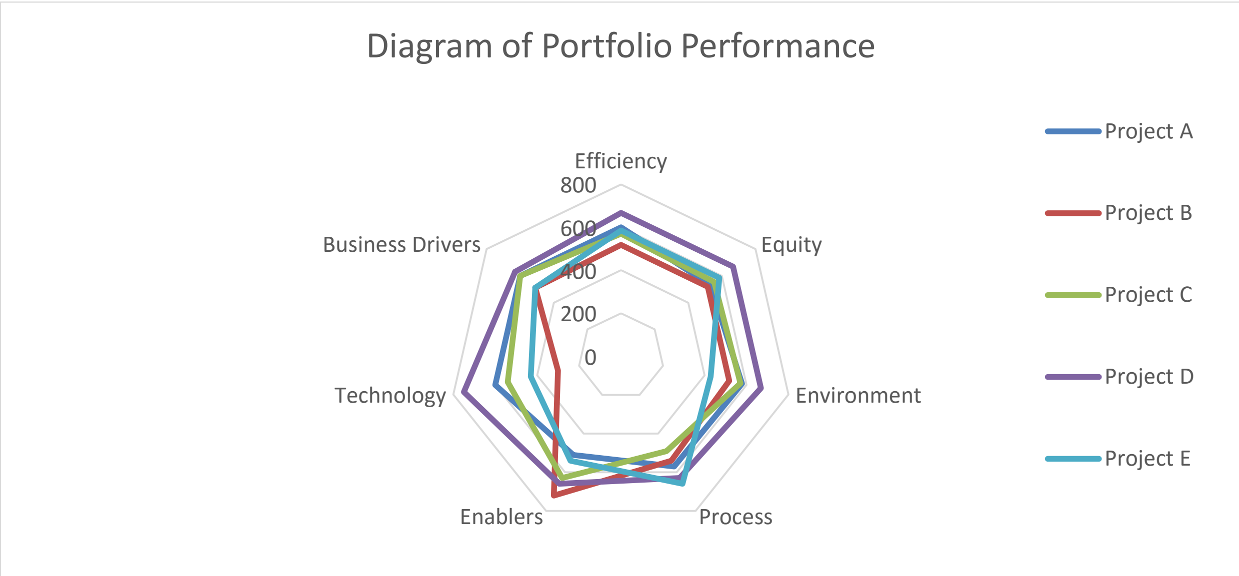

Figure 29: Diagram of Combined Portfolio Performance

5.2.3 Sensitivity Assessment

To understand the workings of the assessment matrix a deeper analysis can be performed by using a sensitivity assessment. There are a variety of methods available such as one at a time, regression, variance or Monte Carlo. An initial review is conducted with a one at a time manner to investigate if a fuller sensitivity analysis using regression, variance or Monte Carlo analysis was required. It is a fast method to conduct and will identify if further work is necessary. A one at a time method does have a drawback that the effect of other parameter change is not analysed, but in this case all parameters are subject to the same assessment range and the same basic relationship to the weighting factor. The basis of the assessment comes from the example in Appendix 6 and it is where further details of the results are shown. The assessment started with varying a score by 1. Project A is first adjusted in lean tools for the environment assessment by 1 both positively and negatively. The result is a change of 1 point which equals a 10 point change due to the weighting factor. In this respect the matrix has a sensitivity of 1:10, or 1:w (where w is the weighting factor) on an individual mark in the matrix.

To consider the sensitivity further the horizontal line of results for the *Environment* assessment are increased by +1. This results in the sustain index increases by 120 points for all projects as there are 12 assessments made. In a similar manner the framework nodes all increase by 30 points as three assessments are changed per node. The result shows a direct proportionality to the assessment change, just as seen on an individual assessment. This confirms a result of sensitivity of 1:w (where w is the weighting factor).

Next in the analysis was to vary a column of results, the *Gate check list* is chosen in the *Process* node. The adjustment made is again one at a time by an increase of 1 point. The results for the *Process* node are increased proportionally upwards. Scores increase by 30 points (three assessments), for example on project A from 570 to 600 and on project B from 540 to 570. The result is a 4% to 6% change from the original assessment on of the *Process* node. The percentage change is dependent on the original assessment result.

Lastly to consider is a change to the weighting in which a regression technique is used. A variation was made to the weighting factor from 10 to 15, to 20 then 25 on the *Environment* line. The results showed again direct proportionality horizontally on the *Environment* line with the same relationship of 1:w. The impact on the framework scores is different, the results are not proportionally moved. Scores from Project A on *Process* moved from 570 to 666 to 763 to 860, a change of 96 points each time. Scores for Project B on *Process* moved from 540 to 632 to 724 to 816 a change of 92 points. And scores for Project C on *Process* moved from 490 to 573 to 656 to 739 a movement of 83. The change is of the same proportion in increase, 17% of the original value (17% of 490 is 83). The results for another area of the framework, *Technology*, move differently, this time 16% of the original value. The reason for this is down to the variation contained within the matrix. The result is well visualised in the diagram below, Figure 30, the environment score moves increasingly outwards while the other results move in a fixed manner outwards except efficiency and equity which remain unchanged:

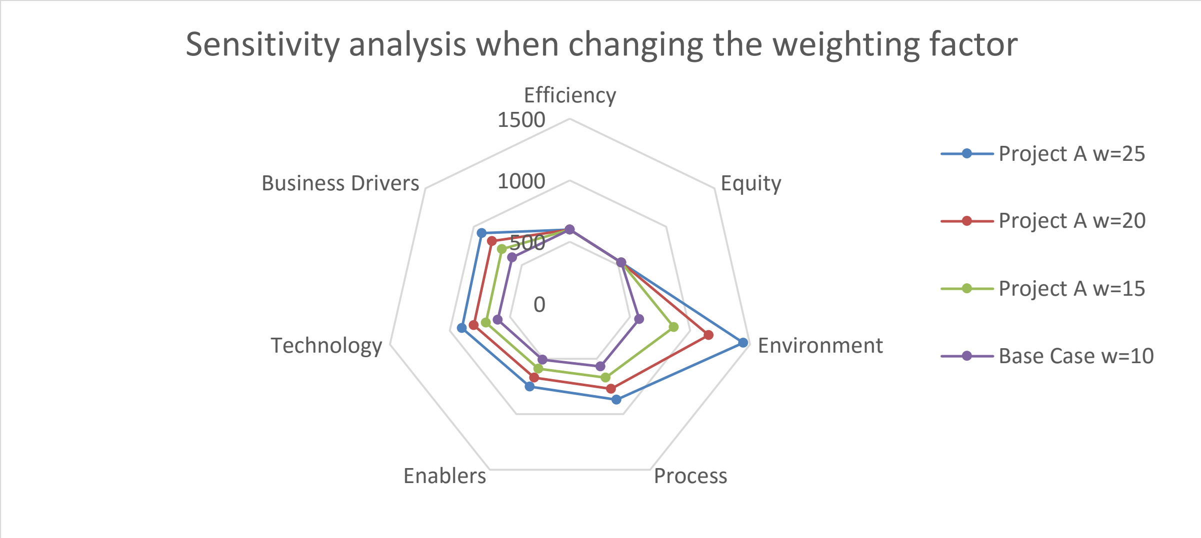

Figure 30: Graph of varying the weighting factor on environment for project A

From the one at a time analysis and basic regression work on the weighting, the matrix sensitivity is identified as 1:*w* that is a direct relationship to the weighting factor. In this respect it was decided to not go further to a multiple point assessment such as a Monte Carlo analysis as the main relationship (1:*w*) is known.

5.3 Development and Application of New Technologies in the Industrial Gases Industry

While developing the sustainable product development method an area of activity in technology was identified. The aim of the technology node in the framework is to support and introduce new technologies appropriate to a company through its product development process. This was identified as being a need for the industrial gas sector due to the limited changes in technology and late adoption of technology changes. In order to explore this area in the methodology it was decided to run a number of trials and investigate if the concept works.

A specific work element in *New Technologies for the Industrial Gases Industry* was undertaken in which the following is explored:

- Review of new and trending areas of technologies, identifying where benefits are possible and identification of suitable technologies for testing
- Development of a method to approach the application of technologies
- Testing a range of technologies through the methodology developed
- Discussion of the positives and negatives of the technologies in their application along with similarities and dissimilarities to other industries
- Discussion of a technology focus and learnings from the use of a technology focus in product development

- Identification of conclusions and recommendation for future activities

For the first step, use of new technologies in the industrial gas sector was further investigated with a focus on either process technologies (for instance in the supply chain or gas manufacturing) and application based technologies (the use of the gas). The findings were limited in both quantity and market impact. Furthermore most of cases identified were not of highly advanced technologies, the evidence showed reuse of technologies pioneered elsewhere. To transition to a leading position in technology would require a change of strategy. It was decided to identify areas of new technology that could be enhancing for the industry and run test projects applying these technologies.

Research was conducted of published literature into industry segments of high and low technology industries to highlight trends along with current trends of activity. For high technology industries the focus was on automotive, aerospace and defence industries. For low technologies the food and chemical industries were investigated. The research identified the following as areas for consideration (see (Pemberton G. , Develpoment and Application of New Technologies in the Industrial Gas Industry, 2015a)):

- Advanced materials
- Advanced measurement
- Additive layer manufacture
- Electronics
- Sensors
- Communications
- Data handling
- Virtual Reality

Each area was then reviewed against its potential application in the industrial gas industry along with feasible projects the author could conduct. A short list of three technologies were identified for further investigation. These were; additive layer manufacture, virtual reality, electronics/sensing/communications. The area of electronics/sensing/communications is combined as it is envisaged that a product using electronics shall have some form of sensing involved and that communications may be a desirable feature. These technology areas were also chosen for their potential to be pioneering in application to the industrial gas industry.

With the three areas identified a methodology as to how to apply the technology was considered. This identified options such as expert interviews, surveys and case studies. Each of these were then explored for their benefits and drawbacks. A summary is made here, further details are in

Development and Application of New Technologies in the Industrial Gases Industry (Pemberton G. , Develpoment and Application of New Technologies in the Industrial Gas Industry, 2015a). Interviews of experts in the industry was seen to have validity in providing a set of opinions from the industry. Using a semi-structured interview would enable a method to ask open questions and gather quantitative data (Brinkmann, 2014) (Taylor, Bogdan, & DeVault, 2015). A closed fixed response interview would not be suitable as it would not give opportunity to explore the subject matter. The method relies on the questions being detailed enough to draw conclusions (Dudovskiy, 2016) (Valenzuela & Shrivastava, 2002), given the high level of uncertainty in the subject matter this would not be suitable. Interviews provide an option to gather detailed insight and opportunity to clarify responses (Taylor, Bogdan, & DeVault, 2015) (Dudovskiy, 2016), both benefits are valuable in looking at how new technologies could be adopted. A drawback in conducting interviews is often the time required to organise, conduct and determine the results (Dudovskiy, 2016). A potential problem with interview is that they may collect areas of bias (Valenzuela & Shrivastava, 2002) (Fowler, 2013). For example, a bias towards continuing with the historical norm or an over optimism that the technology could radically change the industry. In the research required, there is a further drawback that interviews would not answer the question of, in reality, what would be found if the technology was applied.

Surveys are a strong method of choice when the expected outcome is numerical descriptions (Fowler, 2013). A survey enables quantitative analysis of opinions (Fowler, 2013), which would be insightful for the research required. Surveys have a benefit of being able to minimise or identify bias through data analysis (Trochim, , 2002). However the response rate is often low which may cause problems, in terms of reliability, if the sample size is limited (Chetty, 1996). For this work, the research involves unknown technology for the industry. Therefore a survey would be influenced heavily by opinions (as there is little practical experience of the technology) and the sample size is likely to be small (small group of relevant respondents). In this view it is unlikely a survey would fulfil the requirement of understanding the details of new technology application. A surveys of other industries where the chosen new technologies have been applied could give indications of how to approach the work in industrial gases. Such work would provide robust data as the sample size can be larger and experiences concrete. However such an approach would not address the more pertinent question of if the technology can work in industrial gases. The results from other industries may not be valid for the industrial gas sector due to the applicability of the technology.

Case studies are a suitable method to apply when little is known on the subject and the sample size is small (Eisenhardt & Graebner, 2007) (Chetty, 1996), which is the case with new technologies in industrial gases. A strength of case studies is the ability to record behaviours and details not seen by quantitative analysis (Chetty, 1996) (Eisenhardt & Graebner, 2007). In this aspect case studies allow a deeper analysis than an interview can provide. However case studies are often a one off review and can lack the robustness of surveys and interviews. To address the validity of case studies, repetition of the study can be conducted (Cook & Campbell, 1976) (Chetty, 1996). A major downside of the case study approach is the lack of quantitative data produced, this results in comparison of cases studies being difficult, as well as a lack of data for decision making. In this work case studies would provide a test-bed scenario for new technology applications reducing perceived risk in adoption. Case studies appear to provide the highest level of insight into the application of new technologies and be flexible enough to capture where benefits and challenges are observed. From this view case studies are the chosen option.

An approach was identified of using a set of three case studies with differing technology applications (Pemberton G. , Develpoment and Application of New Technologies in the Industrial Gas Industry, 2015a). The reasoning for this is that replication of the general concept (of new technology) can be considered as well as the specific technology. In this approach a multiple data point analysis is built considering several perspectives. These are seen as areas of strength for a rigorous case study approach (Chetty, 1996). While the sample set (of three) is relatively small, which could lead to miss interpretations (Stake, 1995), this is a manageable size within the scope of the work. A weakness is that the method proposed does not address is the question of if the individual technologies themselves are replicable in application to the same level of benefit. This would require a set of cross case studies (Geering, 2006) which was identified as further work not possible within the scope of time available.

To compare the case studies a standardised format to report the work was developed along with a standardised set of hypotheses. This follows best practices in constructing a case study (Stake, 1995) (Yin, 2013). The idea of this approach is that there would be specific areas for comparison between each case study. It was observed that the case study format could mirror that of a learning loop. In doing so this would give a structure and comparable format. The learning loop followed is that of Observe, Plan, Do, Check and Adjust loop (OPDCA) (Rother, 2010). The *observations* are understanding the current application of the technology. The *plan* is in understanding how can the technology be applied. The *do* is in conducting the application. The *check* is comparing the results with the expectations and success criteria. The *adjust* stage is covered by the learning from the application. Following an OPDCA loop (Rother, 2010) enables a decision on the applicability of a technology node for industrial gases.

The structure for the case studies uses the following four main questions:

- Can the technology be applied to the industrial gas business?
- Are benefits seen in the application and are these benefits similar to those seen in other industries?
- What is the likely uptake in industrial gases?
- What are the specific challenges experienced and anticipated, and are these similar to other industries?

These questions form the basis of the comparisons between case studies. The four questions identify whether the technology application is likely to be successful, if that success is in line with the initial intention and what was learnt from the application. Building on the questions and using the OPDCA loop a structure was derived in which to conduct and report the case studies, as detailed below:

- Introduction to the technology
- Introduction of the subject area for application
- Project and gap identification
- Expected benefits
- Application example, Observations and Results
- Discussion
- Conclusion
- Recommendations

In the following sections each of the three case studies are generalised with a summary of their results given. A fuller report of the case studies may be viewed in Appendix 9 and the *New Technologies for Industrial Gases report* (Pemberton G. , 2015a). The summaries are then taken into a discussion and conclusions made on the findings of the investigation, see section 5.7.

5.4 Case Study 1: Additive Layer Manufacture

In this case study application of an additive layer manufacturing process is applied to the development of a gas cylinder valve guard. Observations on this technology determine that while the process has been used for many years, since the 1980s, it is only recently that it is being adopted (Bird, 2012). A main aspect of the recent rise in use is from material improvements along with the ability to deliver products rapidly without the need for tooling (Miners, 2013) (Berman, 2012). Drawbacks are identified in the material properties, surface finish and scalability. With these properties the process is ideal for prototyping and small scale manufacture (in particular if the design intent is highly customisable).

The chosen application is the design of a cylinder valve guard, Figure 31 shows a typical product. The current design process is outlined in Figure 32, typically taking 11 to 17 months. The process has no feedback loops and takes a high risk strategy of committing to tooling with limited performance knowledge. As the product is structural it must conform to strict standards (ISO 11117 (International Standards Organisation, 2012)), the risk of failure using such an approach is high. Issues have been seen in meeting the expected standard often owing to using best estimates of performance with limited calculations. The shortcomings in the design process are also apparent with the wide range of typical project timescales (a variation of 6 months for a 1.5 year process). It was observed that the process is often conducted at the end of a cylinder valve development process, which results in a significant time pressure for those involved in the development of the guard. In these cases the process is undertaken with a focus to have a product launched as quickly as possible. It appears errors occur and leads to delays.

Figure 31: Typical valve guards

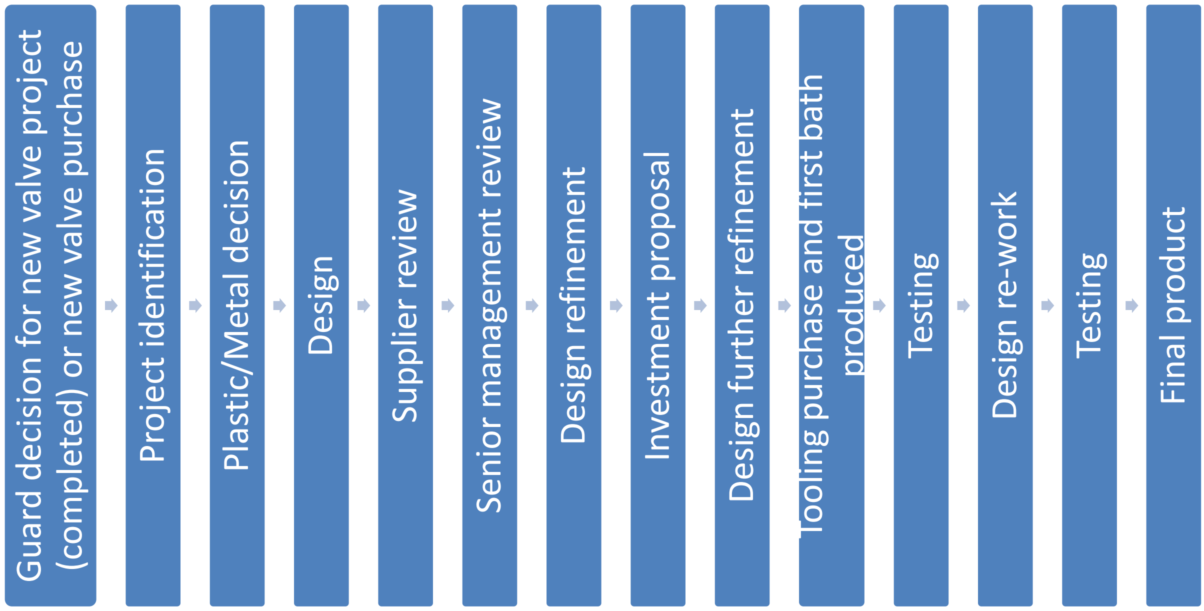

Figure 32: Typical valve guard development process

The opportunity for improvement by applying an additive layer manufacturing process is that the time to complete the project could be substantially reduced along with the costs for re-work.

Before the technology is applied a best practise for the process applied to take advantage of the technology. A revised process is shown in Figure 33.

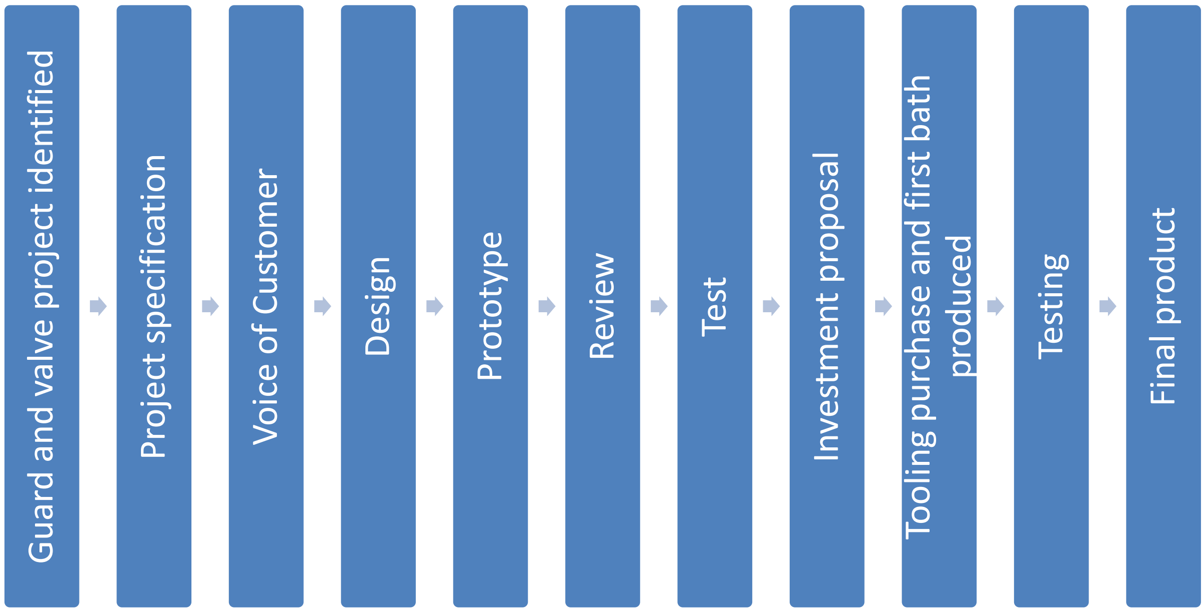

Figure 33: New process for cylinder valve guard development

In comparison to Figure 32, overall, there are three fewer process steps, even though three new process steps have been added. The additional steps add feedback loops to the process. The overall estimated time for the new process is 7 to 8 months, a reduction of between 36% and 53%, but also importantly a much lower spread of expected time from 6 months to 1 month (due to not expecting to re-work tools at the end of the development).

The process was followed for a new guard development, starting with ten concepts and selecting a single option for prototyping. This design was refined for review and further refined in the test stage. Customer focus groups and a survey of users were used to gather information. When the investment proposal was made a design was presented that had received customer feedback (which was used to guide the design), had a computationally simulated pass to all required tests (through the use of finite element analysis), had been partially tested (to validate the model) and was on time. A decision was made to progress the investment for tooling with feedback that the risks in making the decision had been reduced. The final product passed ISO 11117 (International Standards Organisation, 2012) tests first time, and the project was completed on time and in budget. The initial customers all gave positive feedback on style and ergonomics. Overall the programme took 7 months. Further reductions in timescales can now be achieved with repetition as some of the methods used had to be developed during this exercise (for example the design process and the finite element model).

5.4.1 Summary of Case Study 1: Additive Layer Manufacture

Considering the initial goals for the project it can be considered as a successful application of new technology to the industrial gas industry. The proposed standard questions of the technology case studies, the findings are shown in Table 4.

Question	**Findings**	**Drawbacks**	**Further work**
Can the technology be applied to the industrial gas business?	The case study shows the technology can be applied to an industrial gas product.	Improvements in material options, material properties and surface finish are desired and would extend a potential buyer's view (e.g. in gas equipment)	The work did not investigate if the technology can be applied for production parts.
Are benefits seen in the application and are these benefits similar to those seen in other industries?	Yes the technology delivered richer design reviews, an improved product, reduced timing and reduced overall costs. These are all typical benefits.	The cost of technology meant expenditure in the design phase was much higher than in previous similar projects. The prototypes were seen as being virtually real products by senior managers which lead to expectations of very short lead times.	It would be interesting to see if the magnitude of the benefit is similar to experiences in other industries.

What is the likely uptake?	Highly likely, the technology enabled a much easier approval to advance the product.	A barrier to uptake may be the cost of parts.	Replicate the process.
What are the specific challenges experienced and anticipated, and are these similar to other industries?	Material properties were an area of challenge, along with surface finish. These are similar to challenges faced in other industries.	The material properties resulted in an incomplete validation. The surface finish meant that post manufacture processing were required.	It is likely that continued work with material and manufacturing processing will result in improved qualities.

Table 4: Table of findings for additive layer manufacturing application

In addition to the findings presented in Table 4 the work built a new process for the development of cylinder valve guards. The process integrated the technology and by doing so tangible benefits are found, such as in time and costs. Whilst the product itself was innovative and led to a registration of the design rights and a patent application on a lifting mechanism, it is the process that enables the innovation. It is thought that this is the first time additive layer manufacture has been integrated into the design process for an industrial gases product.

As identified in Table 4, there is some further work that can now be conducted. A key element of this is to repeat the application and prove that the process is consistently delivering similar or improved results. Continuous improvement of the process is also expected in areas such as market feedback as it is likely that, with experience, the process could be streamlined. It is also expected that developments in additive layer technology in terms of material properties and finish shall provide incremental improvements to the process in costs and time. The finite element model developed was validated in part; this can now be fully validated from the testing of real products.

Considering the results it would now be of interest to investigate if the magnitude of the benefits and challenges experienced in this project are similar to other applications of additive layer manufacturing in industrial gases through repeat applications in other products.

5.5 Case Study 2: Virtual Reality

Virtual reality is a technology that enables a computational graphical representation of objects/environments in as realistic a manner as possible for a user. The technology essentially provides a user experience without a physical model. Techniques, methods and applications have been possible for many years, however recently applications have become increasing popular (Vafadar M. , 2013).

Immersive virtual reality is the richest form of the technology. In this approach the user is only able to see the virtual world, their movements or actions cause real time reactions in the virtual world (Watts, Swann, & Pearson). Immersive virtual reality has been applied by the following industries; military, automotive, aerospace, medical, and entertainment (Abulrub & Shende, 2012). In these sectors virtual reality has been used to provide the benefits identified below (Abulrub, Yin, & Williams, 2012), (Choi & Cheung, 2008), (De Sa & Zachmann, 1999), (Deisigner, Brening, Rosler, Ruckert, & Hofleman, 2000), (Vafadar M. , 2013) (Watts, Swann, & Pearson):

- **Efficiency of design reviews:** the information presented is processed by the review team rapidly and agreements tend to be found quickly the resulting benefit is seen in reduced costs and time
- **Depth of discussion promoted:** due to the richer environment users see more details in the design and its context, this results in many project specific benefits but generally improved designs and reductions in time and cost
- **Insight to product quality:** due to the richer environment potential quality issues are easier to identify and the other quality aspects of the product (such as manufacture and assembly) are well presented through virtual reality. The resulting benefit is lower rejects and customer complaints.
- **Early application of downstream opinion:** the technology enables design review to include its application environment. This can be used to consider activities such as training and maintenance. It is highly beneficial in design reviews to use a cross functional team, for example including members from the supply chain. Design reviews including the application environment and use of a cross functional team shall promote discussions on the whole product life cycle. This should lead to design iterations that have considered downstream activities in more detail than traditional design methods.

However, virtual reality is not commonplace in industries. There are barriers to using virtual reality in costs (from hardware, software, training and the area required) and in building the models (requires specialist skills) (Fernandes, Raja, & Eyre, 2003). Additionally, the time to implement the process can be quite lengthy as it requires new skills and time to perfect those skills (Abulrub, Yin, & Williams, 2012). A further challenge to the technology is that there is no consensus as to the best process to conduct the work (Watts, Swann, & Pearson). These challenges have resulted in a slow adoption of the technology, in particular outside of companies with significantly large research and development budgets. *Watts et al* state the technology to be in a "pre-paradigmatic" stage (Watts, Swann, & Pearson).

The use of virtual reality within the industrial gas sector has been very limited. Only one instance was identified of using a virtual reality system. This was a study into the efficiency of an industrial furnace using an Oxygen-Fuel burner. *Freitag & Urness* explore the visualisation of burner temperature profiles in a CAVE (Automatic Virtual Environment) system (Freitag & Urness, 2002). They found efficiency benefits in reviewing the data and that rich information was derived from the data.

The only other work found with consideration of visualisation techniques in the industrial gas sector is a three dimensional model for air flow in human airways. This work builds a computational fluid flow model in three dimensions which is used to indicate visually areas of high and low flow (Fodil, et al.). It was concluded that there is limited literature relevant to this technology from the industrial gas sector.

5.5.1 Application of Virtual Reality

Virtual reality is the projection of a fictional view such that it realistically can be viewed by the user in the environment with a real product. An application for the technology was found in design and build of industrial gas plants in China. The concept of the overall project was to design a standard gas cylinder filling plant with add on modules that could be replicated across China as part of an expansion plan. The project team was struggling to agree the best routes forward with the design, in particular with the layout. Additionally, the feedback on forecasted costs showed they were too high. In fact more than double that of expected local build costs.

A programme was identified in which virtual reality could be used in the design of a standard gas cylinder plant and enable a lower cost design to be explored. Virtual reality presents itself as an ideal tool for this work as a *right first time* approach is essential in this project to not replicate mistakes. Confidence in the design is important in this project due to the replication. Virtual reality can help achieve a consensus and ensure the design is reviewed thoroughly. Additionally, as a significantly lower cost design is sought, it is likely the design may challenge certain normalities. Virtual reality provides a mechanism by which ideas can be tested quickly and with limited costs (no physical models are required). Virtual reality is therefore highly applicable to the project identified.

A methodology for the project was then derived shown in Figure 34, which resulted in the following areas of work:

- **Skills** – as the work is being conducted as a trial the required skills should be found externally. Therefore a supply partner would be required, who could provide the necessary skills. Options were considered using a resourcing specialist or a design consultancy company. The latter route was taken as it did not require investment in computational software and hardware.
- **Equipment and Technique** – as the work would be a trial there was no opportunity to invest in the necessary virtual reality system. The University of Warwick was identified as an ideal partner who had the necessary equipment, skills to assist in conducting the design reviews and had worked previously with the identified design consultancy company, who could provide the main body of the work.
- **Funding** – in order to reduce the monetary risk exposed in the project, grant funding was sought. As the skills partner was an SME they were able to obtain a CATAPULT grant (Catapult, 2013). This reduces the risk of the project funding running out which was a concern as the required work hours could only be estimated at the start due to this being a first application necessitating an amount of learning as the project was executed.

In addition to the above, a road map was developed showing how to advance the project in a step-wise manner. The purpose of this was to develop a set of achievable technical goals. The road map was developed in conjunction with experts at the University of Warwick (Williams, Attridge, & Abulrub, 2013). The map was built to bridge from a known starting point to the end achievement of a fully immersive and realistic design review. The work is split into five phases, four of which need to be completed to achieve the aim, a fifth stage was also identified in which a photorealistic model could be adapted live during the design review. The last stage was reserved to be achieved with a second application of the technology in order to reduce the scope tackled in the first application; this improved the certainty of delivering the project on time. The road map is presented in Figure 34.

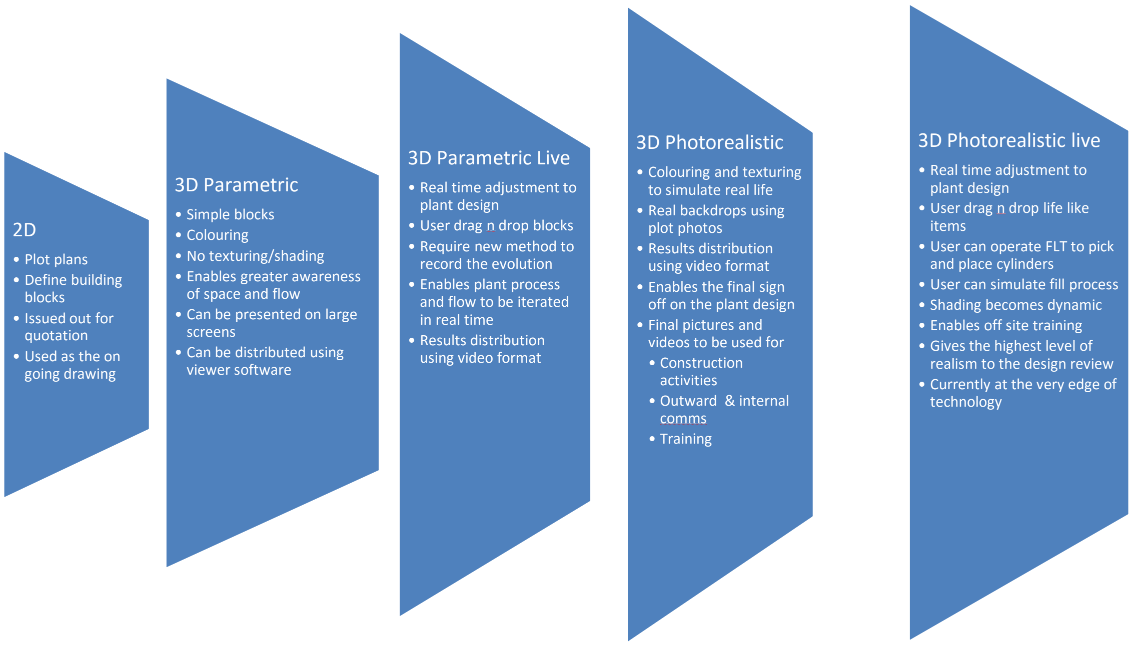

Figure 34: Virtual Reality Road Map for Industrial Gas Plants

A design work shop was held to create a lower cost plant using value engineering methods. This work identified, a more radical design with a single basic plant from which five options could be added to expand its capacity and/or capability. In the basic design two concepts of filling layouts were identified which were to be tested in the design review for preference. These options were covered by a total of seven layout plans which were developed first in two dimensional CAD. The proposed design reduced costs by 45% through a value engineering event, which was an excellent achievement. Details of the development activities are given in Appendix 9, Case Study 2: Virtual Reality.

Development of three dimensional models and the design review structure was worked on with expertise from the University of Warwick (Williams, Attridge, & Abulrub, 2013). A two day design review strategy was developed, in which the first day would use a team, who had been working on the development. This would act as a test run and identify any issues or necessary improvements of the model and method. The second day would involve a broad team from the decision makers on the plant design to the operational team of such plants. A technical bias was made to the second team to give some sensitivity to any problems with the technology

The feedback from the first review (with the development team) focused on a number of technical challenges such as the speed of guided walks and some wrong cylinder colours used. A number of plant layout improvements were identified for discussion at the second day of review. Capturing the changes was found to be more complex in the virtual environment. Whilst some could be done live in a three dimensional environment it was not possible to do this with a live photorealistic model. An option identified was to use A1 sized print outs of the two dimensional designs which could be placed on a wall and used to capture any necessary changes through sketches on the plan view. There was then an opportunity, during breaks, to perform minor updates to the photorealistic model.

The second design review was then conducted and it was observed that the participants interacted with the environment very quickly and made comments on very specific details. Discussions were raised freely and often contained a rounded view of all aspects from construction, to operation to maintenance. The two dimensional printouts and use of a scribe worked exceptionally well; the ideas were well captured and any conflicts of ideas were visualised on the layouts (with different colours). There was a high number of necessary changes requested, seventeen in total including some critical safety issues. One major issue was that the path assigned for delivery trucks passed too close to a frequently used door. The resolution of the issue resulted in a near complete change in the layout. Additionally twenty five improvement ideas were seen and fifteen future considerations highlighted.

The feedback from the event was highly positive and is summarised below:

- All participants found the review resulted in an improved assessment of plant design (compared to 2D designs)
- All participants found the review gave a significant insights and that virtual reality identified necessary changes that would not have been found until the plant was in operation
- All participants recognised that virtual reality could provide significant time and cost savings
- The review identified several significant safety issues that previous plot plan reviews had not identified
- Participants who had no experience of virtual reality could quickly become assimilated to the environment
- Participants found the structure of the review gave a good balance of structure and areas of flexibility

5.5.2 Summary of Case Study 2: Virtual Reality

A suitable application of virtual reality technology was identified in the design of gas plants for China. A structured approach was developed to bridge the gap between current practices and that of the virtual world by taking a series of specific steps (Figure 34). Each step set an achievable goal that built up towards a design review in an immersive virtual reality environment. In following the approach a design review was conducted that resulted in avoiding design faults, reaching a clear consensus on the design and achieving confidence in the design. The effect was a saving in avoided time and costs, through early identification of mistakes and improvements to the design.

The participants of the design review adapted to the process with ease and discussions were focused on what was working well in the design and what needed to be changed. Contributions from the participants were highly relevant and valid. The overall view was that the technology had enabled a number of decisions to be made and a number of issues to be rectified much faster than could be achieved with the current method of work (using two dimensional CAD). The reason these decisions could be made faster is that the users were better informed about the design at the moment of making a choice. In the virtual world much of the required information surrounds the decision makers allowing them to act in a more informed manner.

The ability for first time users (in particular those not from an engineering background) to adapt to and participate in the technology was better than expected. This may be due to the structure of the approach, the realism of the images or simply the technology which would be an interesting area to investigate further.

The development of the technology for application to industrial gases did provide a number of challenges in the skills and hardware which had to be resolved to complete the work. The main challenge was in the development of the virtual reality model, balancing detailed CAD geometries and sufficient numbers of components with the stability and speed of the virtual reality model.

In summary it was found that virtual reality is an emerging technology with many application possibilities. It has delivered improvements in the design review process, in particular, in achieving decisions. This resulted in avoiding costs and time in downstream work and re-work. The overall conclusions can be summarised in the table of four questions below;

Question	Findings	Drawbacks	Further work
Can the technology be applied to the industrial gas business?	Yes. A model has been built of an industrial gases plant which has been through a design review process	CAD data was needed to be generated. The modelling and integration to virtual reality is not seamless.	Look for a second application in which more benefits can be achieved and steps can be taken towards the 3D parametric live stage identified.
Are benefits seen in the application and are these benefits similar to those seen in other industries?	Yes. Speed in decision making, richness of information and reducing costs (in this case particularly avoiding costs) are all typical benefits.	Quantifying these benefits is not simple and may not be directly achieved in the business results.	Look for continued improvement goals.
What is the likely uptake?	Quite high	The cost of the development may restrict re-application	Internal promotion of the application may assist in the uptake
What are the specific challenges experienced and anticipated, and are these similar to other industries?	The size of the model and reliability. These are similar concerns to other industries	Speed and time are the main roadblocks which need continual works.	The major challenge was the instability and speed to complete. This is similar to others using large CAD models

Figure 35: Table of conclusions for Virtual Reality

5.6 Case Study 3: Electronics and Wireless Communications

In this last case study, technologies associated with electronics and wireless communications shall be applied to an industrial gases product. The associated technology in this case study is potentially quite broad. There are many methods and techniques, which can be applied and have been applied in other industries. There has also been some application of electronics in the industrial gas sector, particularly in recent years. One area in particular is that of medical gas cylinders. Linde and Air Liquide both have softly launched a medical oxygen cylinder with a digital gauge. In these products the user benefits from a calculated time left before the cylinder is empty as opposed to a pressure indication on a mechanical gauge. There is another product, named Genie® from Linde being used in a number of applications (from welding to balloon gas), that also has an electronic gauge, again displaying the time left before empty. The technical details of these products are shown in the full case study information in Appendix 9, Case Study 3: Electronics and Wireless Communications.

A number of key issues are identified in the offerings by Linde and Air Liquide. Firstly, the cost of the package is greatly increased. Secondly, the accuracy of the information in all cases is not significantly greater than that of a mechanical gauge. It is the format of the information that has been improved (time in hours and minutes as opposed to pressure in bar). In all cases, wireless communications are not offered as standard and it is unclear if any of the highlighted products actually work with a wireless communications system. In all of the above applications, the technologies applied are generally off-the-shelf use of sensors and displays.

A review of the product provider and end user needs was created to identify gaps in the current products and areas for innovation. This resulted in the list of requirements below:

- Accurate measurement of content (for compressible gases)
- Low power consumption circuits
- Maintenance intervals to be long, greater than 2 years
- Display screens to be used cautiously
- Data protection to be designed in
- Ease of use
- Low cost
- Useable in the external environment as well as internal

The main issues presented with current technologies are high costs, high power consumption in circuits and low accuracy of the measurement. This is largely dictated by the incumbent measurement technology of pressure sensing. In order to achieve step changes the sensing technology should be re-considered. The other identified areas of need in the list above can be grouped together in two other areas of work. First of all, there are the electronics which shall determine the remaining costs, the display and data protection. A second area is in the design, which affects the ease of use and use in external and internal environments.

One application area considered is with a medical product, there are clear consumer benefits in showing the time left of a cylinder (which would be possible through calculations) but there are barriers to entry in compliance testing and the time to complete such tests. A simpler route would be in the industrial sectors, the largest of which is in metals fabrication. This would also present a challenging market from a cost and product acceptance stand point. It was also noted that if successful it should be easier to replicate the technology to other sectors than with a medical gases product.

The requirement for the sensor development was then outlined. A process was followed of researching technologies, identifying their suitability to industrial gas products and then testing promising technologies. A fundamental strategy was to address the fact that pressure measurement has an inherent inaccuracy as a measure of content with gases (owing to compressibility), unless accurate measurement was also made of gas temperature and volume. With this as a starting point investigations were conducted in mass measurement and density. Mass would be a challenging option owing to the small increments in mass change that would be required to be measured compared to the mass of the cylinder. For instance a typical user flow rate could result in a measurement of 30 grams/minute on a package weight of 100 Kg. This would obviously require a highly accurate and wide range sensor. Density provides an alternative route and a number of technical options were possible. One method of density measurement is through comparing the natural frequency of a quartz resonator in the gas with one in ambient conditions. This would provide a measurement of frequency shift which can be converted to mass (providing volume is known). Quartz measurement products have been developed for gas applications, such as monitoring the presence of sulphur hexafluoride in gas insulated switchgear (Trafag, 2015). A development project was then conducted to apply a quartz measurement method to a gas cylinder; this resulted in a patented technology (USA Patent No. US20130306650. , 2013). The benefits from this technology are the accuracy, low power consumption and cost. The technical details are summarised against a standard pressure transmitter are shown in Appendix 9. What is achieved is a step change in sensing technology. The quartz system is low cost, low power and highly accurate.

Whilst the sensor development was being conducted, an electronics package was developed. The features of this were created through four steps

- Consideration and identification of features in current knowledge base
- Idea generation using a forward thinking team
- Survey of users on ideas
- Idea generation using a customer focused team

These steps were taken to balance expressed customer needs along with innovative ideas. It lead to the following features to be identified for inclusion:

Feature	Concept
Content	Display pressure and or time left
Low content alarm	Flashing light and audible would be desirable
Predicted time before empty	Learning algorithm using non-ideal gas laws and actual flow measurements to give time in hrs/mins or greater than specific numbers
Flow	Accurate flow measurement calculated by change in density over time. Options to identify significant changes in flow and inform user.
Usage data	Present user consumption patterns and give improved visibility of information
Wireless transmission of information	Use of latest Bluetooth technology to provide low power option of transmitting information to smart phone app
Re-order product at point of use	Use of data and smart phone app that could automate the re-order process
Leak detection	Use of flow measurement could identify flow when no flow is expected (leaks)
Fault indication	Use of a warning graphic to show different faults

Table 5: Table of features

A target cost for the product was devised using a reverse profit and loss methodology. The sales price was used as a driver to determine the budget cost for the electronics package. The sales price was tested through a market survey against the features above in a conjoint analysis.

From these requirements two prototypes were developed to test aspects of the concepts. In particular, how much information to display on the cylinder and how much information could be available on a mobile application. These were tested in six focus groups which determined a favourable mid ground between the products and found all the concepts to be highly desirable.

The electronics development was relatively straightforward requiring the necessary board development to take a sensed reading, conduct calculations then transmit wirelessly the information to a remote display. A learning and adaptive calculation of content based on density changes was developed using a variety of application scenarios. This led to a patent application on the calculation process.

The wireless communications feature was developed following a review of communication options. This was conducted through a rating exercise on the features of cost and power consumption (two key drivers identified earlier) along with other strengths and weaknesses. The results of this review are presented in the full case study report in Appendix 9. Bluetooth 4.0 offered the lowest cost and lowest power consumption but also had wider technical features, particularly in two way communication and connection distance.

A mobile application was developed which had a number of challenging areas. Firstly, as this was new ground, it was important to understand and provide features which the customers would benefit from. Secondly, the technology chosen in Bluetooth 4.0 was in its infancy and would therefore could be likely to have some technical issues to overcome. The application was developed using a story board approach which was then tested both technically and with customers as a concept. The first concept was deliberately built with a number of features in, these could then be reduced based on customer feedback. Through focus groups three key areas of the application were identified, the cylinder information itself, customer account information and, lastly, technical support. The final mobile application was based on these areas and a partner was used to develop the application. There were a number of programming challenges which the partner overcame, such as how to handle tens to hundreds of cylinders in the application, and how to quickly connect to individual cylinders. The resulting mobile application was completed with features such as; an overview of all cylinders in a location, individual information of a cylinder and its use, re-ordering in a three step system at the point of use, and support information. The details of the mobile application are shown in Appendix 9.

The use of the customer focus groups led to a final design of electronics package and mobile application. These are shown in Appendix 9.

The result of the development was a product with which customers interacted more enthusiastically. This is likely to be due to the increase in contact time of the customer with the product compared to standard offerings. The product enabled the customer to have access to an increased amount of data about their gas and its use. The usefulness of the data and improvements are still to be fully realised. This requires a longer term survey of the customer use of the data and the data itself. The technology enhancements and benefits could not have been as well achieved without the breakthrough sensor developed. The unique characteristics of high accuracy, low power and low cost enabled an electronics product for a conservative, tough environment that is highly price sensitive.

5.6.1 Summary of Case Study 3: Electronics and Wireless Communications

It was identified that a key growth area for many products has been to equip products with electronic features to gather increased amounts of data on performance that can be used to give the customer more information, from which, improved decisions can be made. It has been seen that electronic sensing and display technologies have been applied to the industrial gases industry but with limited success in the gas cylinder market. A project was identified, in which, a compelling cylinder product has been developed. In this project the failings of other electronic cylinders was addressed (the product life, cost and accuracy). The reasoning why these areas required improvement was found to be largely due to the sensing system. A specific development programme was followed for a new sensor while the electronics system was developed separately along with wireless communications.

The sensor developed breaks new ground in many areas and has further possibilities. The cost, accuracy and durability are all in-line with the expectations set out. This means that a highly applicable sensor has been developed. The technology can be considered for developments of flow sensing, plant monitoring, and gas detection.

There is clearly much more that can be done with an electronic enabled cylinder. There are replications into a wide range of gas variants, applications and sectors (medical, food, high purity). There is wider use of the technology in supply chain management such as customer demand planning and inventory control. There are additional features that can be enabled, in particular with additional sensors. For example, a g-force sensor could identify the cylinder movements (loading, unloading and customer handling) and any safety incidents (cylinder falls).

A summary of the findings towards the original set of questions asked of the technology development are detailed below in Table 21.

Question	Findings	Drawbacks	Further work
Can the technology be applied to the industrial gas business?	Yes. Electronics was shown to be applicable and deliver a feature rich product	The complexity of the product is increased	Continue to develop in the field knowledge on use and application
Are benefits seen in the application and are these benefits similar to those seen in other industries?	Yes. Customers engage with the features and product. The data generated opens new options	There is an impact in product costs but this is similar to other industries	Quantification of the supply chain benefits
What is the likely uptake?	Positive from the focus groups.	The product will appeal to early adopters for others it may take time to be convinced	Monitor the introduction of the product
What are the specific challenges experienced and anticipated, and are these similar to other industries?	Some technical difficulties with the product which is inline with other electronic products.	Mechanical systems are still more reliable.	Develop extended life testing and robustness of software like other industries do

Table 6: Summary of benefits for electronics and communications

5.7 New Technology Summary

In the development of a new methodology for sustainable product development a node of technology focus is proposed as part of the framework method. The node provides a focus on technology to form boundary conditions for product development and to introduce new technologies. It was proposed to test the concept and see if new technologies could be introduced into industrial gas developments and therefore identify if a technology strategy can work for this industry.

An approach to such a test was considered determining a set of case studies to be the most suitable approach. As the approach and technologies would be new, the validity of using surveys and interviews was questioned. Case studies offer a method to gain real world experience, while replication of case studies gives insight to the extended use of the techniques applied.

Three case studies are used to investigate three separate new technology applications in the industrial gas sector. They follow a structured approach to develop a product with the technology. The same method of consideration and process are taken with each technology choice so that comparisons can be made. The case studies have been presented in sections 0, 5.5, and 5.6

In each application a success story is seen in introducing a new technology to the industry. The applications are technically advanced in comparison to the current products. In each case study the technology enables a pioneering new product and/or process. It can be concluded that each of these products improve the competitive offering for the seller. While all the activities had technical challenges in the application of the technology this was to be expected and the challenges were overcome.

The generic set of four questions on benefits are detailed in each case study with a brief description of the findings, drawbacks and future work. In all cases there were clear beneficial findings towards each of the questions. Furthermore, the typical benefits of the technology seen in other industries do replicate themselves in the industrial gas sector. This means that it can be expected that other new technologies can be suitably applied to the industrial gas sector. That breaks a barrier of resistance, in the belief that the industrial gas industry is a more basic and process led industry that would not benefit from advanced and new technologies.

There are three main themes of benefit seen in all of the applications, namely;

- Improved development time
- Reduced overall costs for the project and/or product
- Improved product/process features

These benefits are similar to other industrial applications of the technologies explored. All three case studies identify improvements in time, cost and the product itself. In the case studies presented these benefits were highly significant. For instance the development time by using additive layer manufacturing was reduced from between 11 and 17 months to between 7 and 8 months. The improvement is not just in the total time but also in the expected variance in time. It was also identified this could be improved upon further as the finite element modelling used improves and the material properties in additive layer manufacturing improves to enable production. There are potentially 6 to 8 weeks of tooling manufacturing that could be removed from the total time if appropriate production methods of additive layer manufacturing are developed. In the virtual reality case study significant costs were avoided by identifying safety issues. If the plant had been built (or started to be built) as originally designed it would have had to been re-worked. This could have had a significant cost impact on a highly cost sensitive project. It would also have delayed the start-up and ultimately the payback of the plant. As the design was to be replicated there was a risk that the design faults could have been replicated if multiple builds had started in similar time frames. The electronics and communications case study highlights the improvements to a product that can be enabled by technologies. There were a number of new and improved features to the product, such as time remaining, re-ordering, leak testing and stock management. The technology enables these features to be possible resulting in a product which is of higher added value to the customer.

The drawbacks of the technology applications had similarities to other applications of the technology. For instance, in all three cases they required more cost and time in the initial phases of work. The result is a more focused application and implementation phase, but it is recognised that increasing initial costs and time has challenges in business justifications.

Each of the case studies suffered challenges during their development. A number of these challenges were technical in nature and a result of applying the technology to a new industrial sector. Such issues are difficult to plan for, but improved communication and the creation of a risk register could have helped to achieve an earlier view of the challenges. Many of the challenges faced were quite typical for the technologies explored. For instance, the electronics project had a number of software iterations, the virtual reality project had issues of instability in the model and the additive layer manufacture project had issues with material properties.

The likely uptake of the technology is yet to be fully quantified, but the work here shows there is positive support from the business and technical communities to continue further work and use new technologies. Improved confidence in the method shall be possible following further application of technologies.

There were a number of cases where specific benefits, challenges and drawbacks were seen due to the application in the industrial gas sector. For example, in additive layer manufacturing the testing requires a low temperature structural integrity test. This is highly challenging for the technology and unlikely to be encountered often in other industries. The virtual reality project had specific benefits in being able to move layouts but also challenges in representing the storage areas full of cylinders. The electronics project had a number of specific challenges in finding a suitable high accuracy sensing technology and a low cost package which had to be robust and long lasting. While these are not entirely unique to the industrial gas sector the combination of high accuracy, low cost and low power consumption is extremely important for the industrial gas industry.

In conducting the case studies, it was learnt how to manage projects involving new technologies. Across all three case studies the learning can be summarised in three points:

- Application of new technology is not as simple as other development projects. Many more barriers are seen both technically and non-technically.
- Planning and understanding risks is key in the successful delivery of the work.
- Communication is always vital, but on new technologies people are more sceptical of success and it requires increased levels of communication to improve belief in the technology

The approach in all of the projects has been to follow learning loops, which help to cover the three areas above. However, since the projects have now been concluded it shall be possible to take specific strategies to address these points. For instance, for new technology projects a risk management tool could be developed and required as part of the project documentation. Similarly additional communication points and methods of communication could be developed and required as part of the project management.

An important next step with all of the case studies is to continue with further application of the technologies developed. In the case studies it was identified that replication would continue to bring benefits in the chosen application. Additionally, replication of the technology into other applications was identified to be beneficial too. As discussed in the choice of methodology, having one application may not be sufficient evidence that the technology shall always replicate with similar benefits. It has been shown that new technologies can be successfully applied to the industrial gas sector and that there are similarities in the benefits and challenges seen in other industries.

Whilst re-application is clearly a beneficial next step, it is not a highly strategic option. The technologies chosen here were the result of consideration of high technology industries using a theory of applying technologies others saw as important to the industrial gas sector. As identified in the sustainable development model (Pemberton G. , 2015a) the new technology node should be driven from a technology road map. Therefore it is important to complete further activity in the technology node once a road map is built.

With a technology road map, strategic introduction of new technology can take place. A strategy of continuously introducing new technologies shall continue to improve both products and processes. Replication of the technologies shall also introduce further benefits in both process/products and creating new ideas. The strategy covered here is to identify and deploy new technologies that have had benefits in other industries and that had not been used in the industrial gas industry (or at least not extensively). Longer term the industry should also look to create and pioneer its own new technologies. While this is a higher risk strategy it also offers a higher degree of competitive advantage.

The full application of the sustainable development process can now be conducted. The development process followed in the case studies largely followed the principles of the sustainable development framework but they did not use the assessment method as these were one off specific tests. In the next section of work the full model can be followed. This shall enable additional focus to sustainable product features, how the overall project is being managed, and review of its benefits.

An observation that can now be considered is, since the technology approach has worked in the industrial gas industry could the approach work in other lagging industries? It would be reasonable to expect that as the general benefits of the new technologies appear to be transferable similar benefits could be replicated elsewhere.

6 Implementing the methodology, results and findings

In the previous chapters it has been shown that products in the industrial gas sector can be more sustainable and technology benefits can be realised. However this does not mean the product is automatically a success. It was found that without the whole organisation's support and desire to release a new product to market it will not be successful. A transition to an integrated sustainable development methodology is needed. From the literature similar issues were observed in the adoption of sustainable product development methods (Byggeth, Broman, & Karl-Henrik, 2007) (Howarth & Hadfield, A sustainable product design model, 2006). A new sustainable product development method has been developed using a framework and an assessment method. To take the learning cycle round to the beginning, an implementation of the new methodology is required along with observation of the implementation.

Following the implementation section a review can then be conducted on the results and findings of the development process undertaken. This covers identified learning and benefits found through the implementation programme.

6.1 A Framework and Assessment Method for Sustainable Product Development Part 3: Implementation

The goal for this work element is not to simply to implement the methodology. As identified in the development activities (Pemberton G. , 2014c) the method of implementation can greatly affect success. Presented here is the development of a method for implementation and then a case study of the implementation.

6.1.1 Development of a method for Implementation

The work started by considering change and transformational change in product development processes. An approach was considered through a literature search. There are sources for best practice in transformational change management (Kotter, 1996) (Jick, 1990) (Garvin, 2000) (Jackson, 2006). Although these are not documented in application to research and development, the generic approach is deemed suitable to use as part of a structured approach. Change in research and development is acknowledged to require a different approach to other areas. This is due to change being a day to day operation in research and development. Therefore to achieve and embed a transformational change a structured approach sympathetic to the requirements of research and development is needed. Works, such as that by *Farris* and *Ellis* in 1990, considered major changes in research and development. They identify that management support (at all levels) and a good reason to change are base requirements for successful change (Farris & Ellis, 1990). *Hoskisson* and *Johnson* considered strategic change in research and development and found positives and negatives. They found it is essential for leadership to reduce the scope of activities and intensity to ensure an improvement in efficiency, without this failures were observed (Hoskisson & Johnson, 1992). *Paulsen et al* take the aspect of leadership further and find that it is key to have a charismatic leader during major change to build good team spirit, trust and support, encourage creativity and not discourage failure. (Paulsen, Maldonado, Callan, & Ayoko, 2009).

The investigations identify a gap in knowledge of best practices for transformational change in research and development processes. An approach to investigate this gap was considered with a route chosen of using expert interviews conducted in a standardised method such that the information provided was not purely qualitative and could be compared.

The purpose of the interviews would be to investigate how practitioners had conducted change in research and development teams. Two key areas from the literature that required further investigation were methods to manage change in research and development and how to manage the human aspects of change. These two key areas were identified through the observation that personnel in research and development teams experience change on daily basis and are constantly exposed to uncertainty (Farris & Ellis, 1990) (Paulsen, Maldonado, Callan, & Ayoko, 2009). This is different to other areas of a business where change management processes have been developed. In order to investigate further these two areas five specific sets of questions were identified. They are:

- What is the typical scope of change,
- What are the trends in processes for change?
- What process change methods are used?
- What human aspects of change need to be considered?

These questions investigate the dimensions and boundary conditions of change, how the change was decided and how the change was managed. To develop these a set of twenty seven questions were built covering each segment in detail. The questions were derived from a literature search conducted and critique of previous surveys (Pemberton G. , A Framework and Assessment Method for Sustainable Product Development Part 3: Implementation, 2015b). Each question would aim to gather quantifiable and comparable data along with more open explanations. The questions are presented in the table below, Table 7.

No.	Area	Question
Q01	Scope	Have you changed your innovation process recently?
Q02	Scope	How long have you been using your current process for NPD
Q03	Scope	How many people are directly involved in the NPD team
Q04	Scope	What is the split of the team technical R&D/other functions
Q05	Scope	Do you use portfolio management as part of the decision making process in NPD
Q06	Scope	How many project are typically running
Q07	Scope	What is the value to the business?
Q08	Trends	Is there an increasing application of advanced techniques such as modelling, RPT, VR
Q09	Trends	Is there an increasing application of methodologies such as the lean tool set and sustainable development
Q10	Trends	Is there more effort spent in the disruptive field of innovation than in recent past.
Q11	Trends	Is there an increase in the use of collaborative tools internally and externally within NPD
Q12	NPD Change	How are changes to your NPD system managed?
Q13	NPD Change	Are there differences to making changes within R&D to other types of changes and therefore is the change management system applied suitable?
Q14	NPD Change	Is the success of changes in NPD measured? If so how.
Q15	NPD Change	Have changes to your own NPD process been successful
Q16	NPD Change	What was the most significant barrier to changes in NPD?
Q17	NPD Change	Does a focus on disruptive innovations aid or create a barrier to changes in NPD
Q18	NPD Change	Is the working environment (layout/facilities) an element to consider during changes to NPD? Can environmental change encourage changes in culture.
Q19	NPD Change	Have the changes made in NPD systems evolved the culture within the NPD team?
Q20	NPD Change	How long does it take for changes to become embedded?
Q21	NPD Change	If you could make one change to the way changes were made what would it be?
Q22	NPD Personnel	Is the team within NPD generally stable, is there a significant turnover in staff (what is the strategy).
Q23	NPD Personnel	How would you describe the characteristics of the team?
Q24	NPD Personnel	Do these characteristics aide to assist or resist change
Q25	NPD Personnel	Do you find the cultural characteristics within the NPD teams reflective of the rest of the company or does it differ?
Q26	NPD Personnel	Is there an impact of generation C (connected generation) personnel within NPD team
Q27	NPD Personnel	How is the career planning of team members within NPD handled

Table 7: Interview questions on change in R&D

The interviewees were chosen from organisations who had made transformational change in a research and development department. Of particular interest were industries seen as best in class for product development such as defence, automotive and aerospace or close to the sector of interest such as the power industry and the chemical industry. Five interviews were conducted with respondents from automotive, aerospace, and the chemical industry each representing a different company. Each interview was conducted on a one to one basis. A number of the interviewees did not want their responses to be published in relation to the company, so the data has been anonymised. A set of highlights are presented firstly below, which are the direct information from the interviewees. With the interviews collated review of the information provides a set of finding which are discussed below, from which a set of conclusion are made. The full interview results are available in Appendix 7.

The highlights from the interviews is discussed for each of the main sections of the questions (Scope, Trends, NPD change and NPD personnel). In terms of scope all respondents had been through or just started a major change in their product development processes within the last eight years. All bar one respondent had been using the new process for between 2 and 8 years. In one response after two years the interviewee felt the process was not yet embedded. The team sizes varied across the respondents, the span of R&D groups was from 30 to 80 people. But how this was split up varied with two respondents using small teams (less than 10 people) to work on specific areas. The others did not detail how the team was structured, but gave an indication in subsequent questions that they were also using small teams for projects. In three cases the team was a mix of engineers and other skills coming from functions such as marketing, finance and sales. In all cases, engineers were the dominant group. In one case the team was purely engineers, with the other required inputs for a project (such as cost benefit analysis) coming from a product manager. In four of the responses portfolio management was identified as being either part of product development process or used for product planning. All respondents showed a desire to be using portfolio management regularly, two respondents expressed portfolio management was an important and regularly applied approach. The number of projects being conducted by the teams varied significantly from 3 to 70, however the higher quantities were smaller projects. In terms of large project the teams were working on between 3 and 5. It was clear that the value of these projects were significant for the companies involved.

In consideration of the trends for product development several interesting finding can been detailed. Three of the respondents use extensive computational assessments in their product development process. Two did not, and saw limited benefit in the technology for their industry. In the use of lean, three of the respondents are applying lean techniques extensively. The fourth stated they had limited application potential. All respondents agreed there is pressure to develop more disruptive products. Two respondents had specific strategies and methodologies to apply. While all the respondents were using some form of sharing tool locally, only a few could be used with external suppliers or partners.

Changing the product development process varied across the respondents. One applied limited management methods in the change process. Others treated the change like a project, and in two cases the change was conducted by a project team (members from outside of research of development). Methods for continuous change were not identified in this interview.

There were no common methods for performance rating. While it was recognised a theme of time based indications were being used as part of a performance reporting approach. A highlight was a "20%" reduction in product development cycle time being found. In all cases the respondents had seen benefits from the change that was conducted, in one case a "300%" return was found. Barriers to changing the process were highlighted to be due the board (two respondents) or due to the incumbent resources. One found technical difficulties with their sharing system. Four respondents highlighted a trend to be looking for more disruptive innovations. One respondent found disruptive projects to be creating barriers within the product development process. A respondent stated a separate team was used for disruptive work, which effectively removed barriers. Interestingly three respondents stated that disruptive innovations help to develop change in the product development process.

Two respondents had changed the working environment as part of the process change, a third recognised benefits from environment change in helping a cultural change. One respondent had recently moved buildings and the team was happy with what was there. The final respondent made no change to the work environment but were considering a change.

Three of the respondents found that changes in process had helped make changes in culture. The other two respondents stated they had not observed a significant change in culture.

The time for change to become implemented varied between the respondents from one to three years. If they had their time again, three of respondents stated they would have spent more time with the board/senior management to gain more support for when situations need to be addressed. One respondent would have engaged the team earlier in the process for their ideas, and one stated they would not change how they did it.

The next set of questions covered research and development staff from a development and retention view point. Four respondents reported that the team was generally of an older average age and had many years of experience, this resulted in a stable team who were used to varying projects to work on. In the main it appears that the work force in research and development is fairly stable. All respondents were complimentary about the skills of their teams and stated they knew the general characteristics of the team, three indicated a passion for their job was key. A high level of knowledge was indicated by three respondents as important, one of which also identified that this could lead to conflicts. Only one respondent had used a recognised tool for managing team characteristics (Belbin). The majority of the respondents recognised that culture within the R&D team differed to the rest of the company, identifying characteristics of increased creativity, openness and calmness. None of the respondents had very young team members from the so called connected generation, but no major concerns or need for adaptation to younger team members were raised. And finally the majority of the respondents said there was little to no career planning for people in R&D, one respondent was actively managing careers with yearly and longer term planning. The full details of each response is given in Appendix 7: Interviews Conducted with Product Development Experts, noting the respondents have been made anonymous.

From the findings of the interviews the following conclusions are drawn:

- Senior management support was necessary to both implement change and ensure the interacting areas work with the new processes
- Changes to research and development processes were often a strategic decision and expected to deliver significant step changes in performance
- Changes to research and development processes had been undertaken to significantly increase competitiveness
- Assessments were made so that a current and future state could be identified and communicated
- Disruptive innovations were sought, but recognised they could be difficult to identify and manage
- Disruptive innovations were sought and sometimes managed using a separate process
- Portfolio management was often a goal of changes but took time to implement
- There was a lack of change management process when product development processes were changed. This was different to other changes managed in the organisations
- Barriers to change were varied and found in the immediate teams involved in product development, the interfacing organisations and the senior management
- There was a desire to provide an environment change to those working within product development as part of the process changes

- Barriers to change were not well discussed. (These shall be explored in the implementation section of this work). But the greatest likelihood of failure was meeting an unforeseen barrier when conducting the change

Additionally, the research found a number of best practices in product development processes that are outlined in the list below:

- Portfolio management had been brought in as part of recent changes
- Stage-Gate® models were an identified best practice
- Advanced techniques and lean tools were a trend and seen as best practice in product development
- Small teams were often used and found to be highly effective
- Integrated development models were well used
- The teams involved in product development tended to be more multifunctional than the rest of the organisation
- Collaborative tools were seen as an essential part of the process

6.1.2 Process for Implementation

Using the research presented in the previous section a method for transformational change is developed to use the strengths of key published methods. Change management is a well-documented area of literature with key methods described by *Kotter*, *Jick*, *Jackson* and *Garvin* (Kotter, 1996) (Jick, 1990) (Jackson, 2006) (Garvin, 2000) (Reason & Reason, 1997). In a transformational plan the aspect of creating a need to change is reduced as there is already an identification from senior management that a change is needed. Therefore a more logical starting point is to follow *Jick's* model for change management in analysing and creating a gap analysis (Jick, 1990). *Jackson's* model is then followed to define the problem and design a strategy. Practically this is completed through an assessment for change and customising the framework (Jackson, 2006). As with all the techniques, the mid-section of the change is about planning and obtaining senior management approval. The later stages follow the GE process for change and look for continued improvement (Garvin, 2000). This can be brought together in a seven step plan for implementation, as presented below and in Figure 36.

1) Assess the current status and need for change – this identifies the current status, the need for change and gaps presented to reach the future state (vision) in line with the sustainable product development framework
2) Tailor the framework – in this step preparations to fit the methodology to the company can be identified and undertaken

3) Develop a change plan – this is to be conducted by the affected team using an X-matrix approach. Importantly a leader should be proposed at this step

4) Obtain senior management approval – in this step the team presents the plan to a steering committee who formally appoints the leader and agrees the plan

5) Conduct the process change – carry out the plan and adjust as necessary and report back to the timing plan

6) Assess the effectiveness of the change – use key metrics in the X-matrix and timing plan to asses achievements

7) Identify improvements – continuously look for improvements and take actions. Two loops of review should be conducted

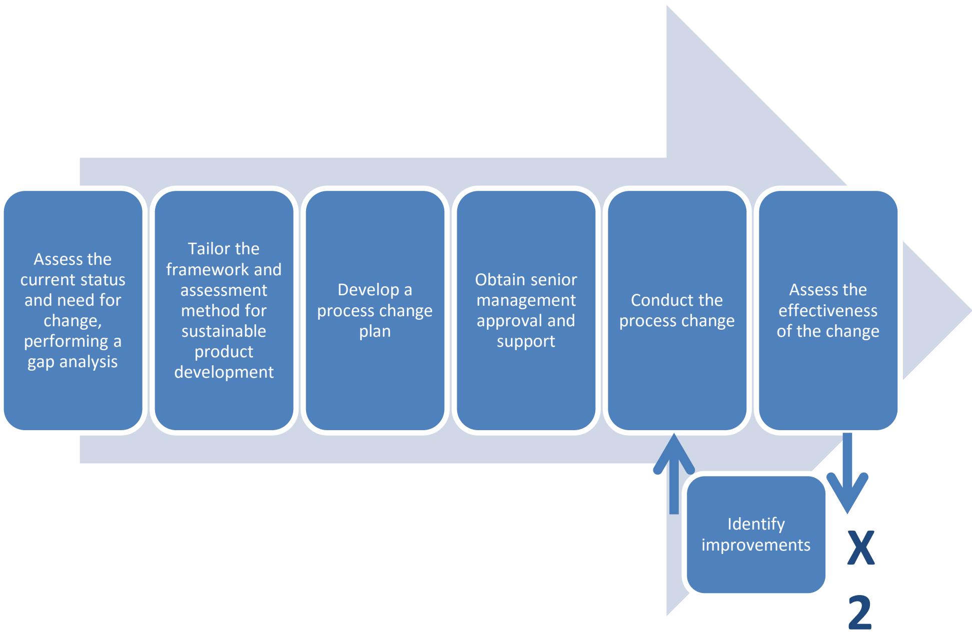

Figure 36: Implementation process

The first step is an assessment of the current process and gap identification towards best practices. An assessment sheet was built to consider the nodes of the framework and the current performance in sustainability. The assessment sheet is shown in Appendix 8. It enables gaps to be identified in each node towards best practices. Plans can then be drawn up as to how to achieve the best practices and consideration is to be given to the tailoring of the framework and assessment process. As part of the plan the barriers for implementation should be identified. This creates an execution strategy for the change.

The next step in the process is to review the areas for tailoring and take decisions on specific areas to fit current company policy and culture. The areas for tailoring are identified in the guideline (see

Appendix 8), the major areas being; the Stage-Gate® process and requirements, financial assessment, sustainability goals, and developing the interfaces with other areas of the company. Each of the areas for tailoring should have a clear strategy and this is then translated into practical activity. For example, in the Stage-Gate® process and requirements, if a company has identified it is necessary to improve its quality performance then an additional gate can be used at a production stage to emphasise quality control. Whist it is not the aim here to develop rules on everything to tailor in the methodology (as that is a highly company specific requirement), it is identified that a standard methodology could be produced to assist in tailoring along with using standard tools.

Once the areas of tailoring are detailed there is a clear gap analysis created and an identification of the finish stage. What is then needed is a plan of how to bridge the gap. Without careful planning it is likely that the implementation will not run as smoothly as it could and there will be more opportunities for the change to fail or not fully achieve the initial goal (O'Connor, 2014). A best practice for a change plan is the X-matrix which develops stretch targets into a series of actions (Jackson, 2006). The actions can be managed using a Gannt chart, to show the timing, connectivity and criticality of task items (Wilson J. M., 2003). Once a change plan is created, it should then be reviewed and approved by a steering committee consisting of senior management. It is important that senior management are well informed of the change and know the areas where they will be required to provide support and assistance.

The next step is to obtain approval and support from the senior management team for the work outlined to be conducted. At this stage a leader is required to conduct the change. The leader must be supported by the research and development team, be charismatic and interact well with the whole organisation (Farris & Ellis, 1990). The leader should be appointed by the senior management team to show their support.

In the implementation of the plan, the human aspects of the change are important to identify and manage. Whilst the research and development teams deal with change on a daily basis they need to see the benefit of a change before they are supportive (Farris & Ellis, 1990). In the change process a method to engage the passion of the team should be sought. This was seen to enable a more successful implementation (Pemberton G. , 2015b). Those responsible for implementing the change should be constantly conscious of the human factors and tailor communications accordingly (Pemberton G. , 2015b).

It is inevitable that certain product development projects will be partially completed and converted into the new process as the change is implemented. These should be treated as transitional projects and while they provide useful cases to establish the process, care should be taken in using them for performance indication. It may be difficult to realise all the benefits of the new process owing to underlying issues from the old process. It also provides an amnesty opportunity for the team.

Once a number of projects have been completed they can be reviewed to the new process and against the key performance indicators identified. These are recommended to be; time between gates, adherence to the launch plan, the budget and market feedback. Alongside this information, feedback from the team conducting the projects should be conducted and also feedback from those not directly involved but affected by the project. If possible market perception of the products produced by the new process in comparison to other recent developments should be gathered. This gives an external view on if the change has made a difference. Once such information is gathered it should be critically evaluated by representatives of those conducting the change, practitioners of the change and those indirectly affected. Identification of learning and areas for improvement are to be completed along with a plan to implement. This work should be presented to the stakeholders for approval. This then completes the learning loop identified in Figure 36. The review and improve stages identified are seen as a critical section for the longevity of the process. Two loops of review and improve are recommended with the second review focusing on ensuring the initial improvements are completed and that long term changes are planned for action. This was developed to stop relapse to the old process (Garvin, 2000).

6.1.3 Case Study: Gas Control Equipment

A case study was conducted to assess the applicability of the implementation method and the benefits of the framework and assessment method for sustainable product development. A case study was used as it is a strong method to capture real world experiences (Gomm, Hammersley, & Foster, 2000). Use of surveys or interviews would only provide circumstantial evidence of expert opinion (Brinkmann, 2014). While replication of case studies would provide further depth there was not the opportunity to conduct this at another company in the industrial gas industry during the time scale of this work.

The case study subject matter is Gas Control Equipment (GCE) a multi-national gas equipment manufacturer. The company had recently changed their Chief Executive Officer and created a new position of Director of Innovation, which was taken by the author. The strategic goals of the company were changed towards a time based competence and an aim to double the size of the company every five years. With such a background it provided a good opportunity for an implementation study. The implementation method developed was followed using the seven step plan of assess the status and need, tailor the framework, develop a plan, approve the plan, conduct the change, assess the effectiveness, identify improvement and plan actions. The system and tools identified in the previous section are to be used in this implementation and detailed over the following sections.

6.1.3.1 Step 1 Assess the current status and need for change

The initial evaluation of the company showed a low level of product development maturity, see Appendix 10: Initial Assessment of GCE. The reason is the recent history of the company; over the past 15 years mergers and acquisitions were its primary focus. Little product development occurred as resources concentrated on centralising production and supply chain efficiency. The acquired development teams were not absorbed but disbanded. Prior to that period a number of key products were developed and GCE is still a market leader in these products (for example medical combination cylinder valves). In the mergers period the teams associated with product development were disassembled, only leaving a team in the Czech Republic. This team was focused on reducing the range of products and incremental upgrades on existing products. During the recent global recession the external environment led to a sharp downturn in the gas equipment industry and subsequently growth has been slow.

A gap analysis is then conducted using the standard tool developed and is shown in Appendix 11: Gap Analysis for GCE to Implement Sustainable Development Methodology. This gives further details on why the gap is present and how to address the gap.

As part of the gap analysis a team assessment was also conducted using a one to one interview to assess skills, motivations, and capabilities. The assessment showed that the team had limited knowledge of advanced engineering techniques and did not have the capabilities to work with such tools. Actions were identified in both training and increasing the skill set through new resources.

6.1.3.2 Step 2 Tailor the framework

The framework methodology and assessment method were tailored for application to GCE by using the gap analysis tool and standard areas for tailoring. This identified the following requirements:

- A new Stage-Gate® process was required with additional focus on quality – the use of a pre-launch production review gate was recommended as a result of recent technical launch issues
- A method for project reporting and portfolio analysis was required to be built
- A method for financial project assessment was required
- The project documentation needed to be totally changed involving twenty nine new documents
- A service level agreement was made with each interfacing area of the company with research and development

- Sustainability targets were required to be set – this would be completed once the an initial review of findings was conducted

6.1.3.3 Step 3 Develop a change plan

With a low maturity level in product development identified, strategies were required to rapidly increase the capability to develop products while not over stretching the team. It was identified that new team members would assist to address the skills shortages. A two-stage implementation plan was created. The first stage would bring the company up-to-speed with best practices in product development, the second would provide a sustainable process. The approach was identified as being suitable from observing how the team reacted to other changes and how the team was currently performing. There was no experience of large step changes, the team was accustomed to smaller changes. The focus of their work was on customer requested product customisations. Longer term development programmes struggled to be technically developed and released into production. There was evidence that a number of previous changes in process failed to be implemented, the team had reverted back to old methods. Using a two-stage process had a number of benefits; the new direction appears easier to achieve as it comes in two-stages, which softens the change and increases the likelihood of adoption compared to a single stage. Two stages provide more opportunity for feedback to monitor the adoption and take appropriate actions. The two-stage concept was strategised with senior managers and actions identified through a brainstorming event. The results are as follows:

The first stage of the plan involved the following steps:

- Splitting the existing team to focus on customisation of products and new product developments separately
- Creating a new team in a different environment (UK) to work on more disruptive developments
- Training the team in lean techniques
- Increasing the cross communication mechanisms including a collaborative documentation tool
- Implementing a customised Stage-Gate® method

The second stage of the plan included:

- Training on environmental tools
- Training on design for X methods
- Identifying current and future strategic supplier partnerships
- Developing a technology road map

- Conducting voice of customer activities on all projects
- Completing market analysis to identify future trends
- Implementing the sustainable assessment method
- Conducting portfolio review sessions

The plans were documented in an X-matrix and Gannt charts developed for the individual actions.

6.1.3.4 Step 4: Obtain senior management approval

The plan was taken to the board of directors for approval with the recommendation that the Director of Innovation takes the role as the leader for the change. The plan was approved and supported by all on the board of directors.

6.1.3.5 Step 6 Conduct the process change

The first stage was completed over a six month period, with a stabilisation period of three months used before a further six months were taken to implement the second stage of the plan. While the time plan was felt to be aggressive, consistent monitoring gave opportunities to slow the process if necessary or to take additional actions.

6.1.3.6 Step 7 Assess the implementation and review

The results of the implementation are assessed in this section both in terms of success for the method and the company. The scores were made by the author using the assessment sheet. This route was followed so that there would be a consistency in the scoring, although the risk of bias and subjectivity is present. Such issues should be visible in the data analysis. The assessment scores (initial and after scores) are summarised in the table below (Table 8), some key information is as follows. The initial assessment involved twelve projects of which five projects were incremental in nature, three partnered, two family extensions, and two next generation. The average initial scores were all below half the possible maximum with a variance ranging from 190 points to 335 points. The sustainability indices scored efficiency 336, equity 323 and environment 307. This indicates that there was room for improvement in both scores and the variability in the results. In contrast the after assessment involved twenty one projects of which nine were incremental, five partnered, six next generation and one breakthrough. The average scores after implementation were nearly all above half the possible maximum scores, with variances ranging from 376 points to 420 points. The sustainability indices scored efficiency 420, equity 414, and environment 404. This shows a marked improvement in both results and variance. The additional information of types and quantity of projects also indicates an improved portfolio. The quantity of projects increased but interestingly the share of incremental projects remained the same at 42%. This indicates the efficiency of the team has increased but there may be room to improve the balance of project types. For comparison purposes the averages (mean, mode and median) of the projects before and after have been displayed on one spider diagram, see Figure 37. All three averages are shown in order to see if there commonality between results. In this view it is clear that a strong improvement has been made overall as all views of the average are improved from the before picture. The mean and median tend to follow a similar proportional improvement where the mode lags this improvement in the after results. This is somewhat understandable as the modal view also highlights the results are highly frequent and perhaps this is not the most informative average to consider.

GCE	Efficiency	Equity	Environment	Process	Enablers	Technology	Business Drivers
Mean Before	336	323	307	221	336	319	374
Median Before	330	300	263	190	335	300	370
Mode Before	375	240	240	180	210	280	360
Mean After	420	414	404	432	376	420	454
Median After	428	428	398	450	390	450	480
Mode After	300	300	300	480	450	300	360

Table 8: Table of results before and after implementation

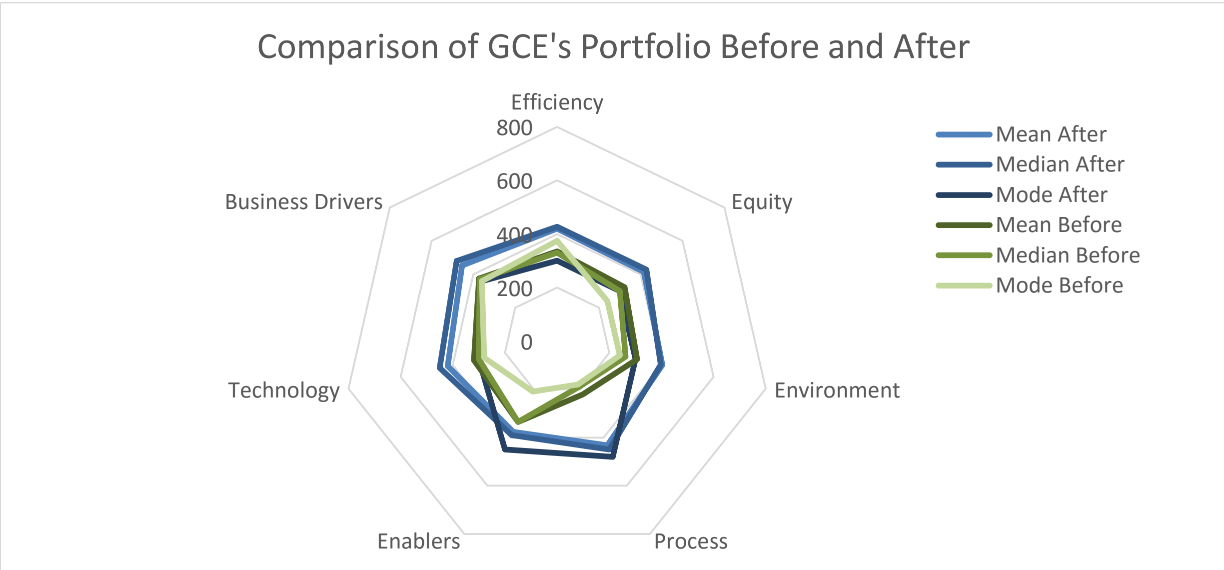

Figure 37: Comparison of GCE's Portfolio Before and After

The results of the assessments have been summarised as follows:

- The sustainability indices increased from initially scoring efficiency: 404 equity: 366 environment: 326; to efficiency: 560 equity: 552 and environment: 538. A 50% improvement and a balancing of performance
- The portfolio impact changed from €10 million to €50 million over one year
- The average time for product development reduced from 24 months to 12 months
- A team in the UK of four people was set up to focus on breakthrough and disruptive developments
- Review of the product development portfolio and the Stage-Gate® process led to 50% of projects being stopped
- 29 standard documents and tools were introduced in adopting the methodology
- The number of initial issues with the product reduced
- In the first year of implementation 15 products were released in comparison to 3 in the year before

From the results it is clear that the activities have been successful in delivering improvements. In terms of efficiency the product development process became more effective in producing products over a reduced time period. Equity aspects were improved; the supplier base was developed in technical abilities and increased volumes. The largest gain was in the company's business value gained through product development. The area of least improvement was in environmental performance. There was an increase in projects involving the environmental use of gases (such as gases for energy) and reduced material consumption was a theme on a number of projects. However, there were not significant improvements made in life cycle benefits (such as recycling or in-use upgrades). Continued application of the design for X tools and stronger use of life cycle analysis should address this improvement opportunity. In this view the work has resulted in typical engineering improvements. It means the system needs to place more emphasis on environmental factors.

In considering the performance to the framework the most significant change is seen in process. This has moved from a mean value of 220 points to 432 points and is the largest shift of performance. This indicates that the methodology has had the most effect on process or that the starting point from GCE was particularly weak regarding process.

A significant improvement in GCE's competitiveness is observed from the results of this process change. Further work in monitoring the case study for a longer period of time and completing other case studies would add depth and robustness to the work conducted and data collected. Following a short period after the implementation, it is expected to continue to monitor the company involved in the case study. This will continue to develop the knowledge on both the methodology created and the implementation of the methodology.

A weakness in the results is that the assessment was completed by a one person. The reasoning was for consistency and to test how the system works in practice. Whilst this gives confidence that the directional change in the assessment is broadly correct, the quantified assessment values can be questioned. As only one person was involved the results carry a level of subjectivity which could bias the results. In future applications it is recommended to use a group of people involved in the projects to conduct the assessment.

6.2 Discussions on the sustainable product development methodology

The investigation and development of a new sustainable product development methodology and assessment method has now been completed. A process has been followed in the identification of a requirement and approach, development of a methodology, testing new areas and then implementation. It is now possible to reflect on the approach, the results, and the findings and to consider further work that could be conducted. In this section insights into these three areas shall be explored. What has worked well, areas for improvement and activities which could have been avoided are presented in the next sections.

6.2.1 Discussion on the Approach to the work

The work plan to develop a new methodology identified in chapter 3 had a step-wise approach to build on each section of investigation. The concept was to use learning loops, like those used by *Deming* and *Boyd* to lead up to an overall methodology (Deming, 1952) (Richard, 2004). This approach has resulted in a successful conclusion, in that a methodology was developed (the framework, consisting of a guideline, assessment method and implementation process, see chapter 5). There has been benefits delivered on the journey (see the new technology area, section 5.3 and the implementation, see section 6.1).

In taking this approach the methodology had constant feedback, which has led to a tailored result for the industrial gas sector. While the step-wise approach breaks down challenges into more manageable activities it does follow an incremental path. A faster result may have been achieved by not using feedback loops or considering how to tailor the process. Without feedback or tailoring it is likely that an improved methodology would still be delivered, but it is unlikely to be as robust.

The approach promoted a set of distinct tasks, which in the case of the trial for improved sustainability and the new technology study were quite isolated activities to the main development. The extension in the life of a gas cylinder (chapter 4) sits as an almost individual piece of work. Similarly the exploration into the application of new technologies (section 5.3) works as a stand-alone activity too. There are benefits of this approach in that each area of activity is individually justifiable and has been worked through to ensure it achieves the intended goals. In this view the *do* or *act* element of a learning cycle is completed and therefore the next set of work has the opportunity to *observe* and *orient* from the findings (Deming, 1952) (Richard, 2004). But in taking this approach it questions if the results will be as valid when combined with the whole methodology. This is hopefully addressed by testing on the implementation activity. It could be argued that taking all the ideas and testing in one go is a more effective route. Another alternative would be to develop and test several different methodologies. In both options it may be more difficult to identify what is and what is not working well in comparison to the approach used. As it was expected the methodology developed would cover new areas then it was important to see what was working and not working well.

Research was undertaken to define sustainability, what is sustainable development and sustainable product development methods. The work identified a preferred definition of sustainability using the terms efficiency, equity and environment. Promising methods to sustainable development were highlighted such as the five capitals approach and various frameworks and guidelines. An area to address with these was over complexity and this has driven decisions in the new product development process. For example the five capitals model could have been used in the new methodology but it was felt this may have added complexity and have some difficulties in defining exact areas of performance to each capital. It was observed that the five capitals model may need some adaptation and has more challenges to work with than other product development methods. These challenges are associated to the social capital and human capital aspects particularly. This indicates the system may be better utilised in organisational level decision making.

Past activities in sustainable development were observed to be over environmentally focused (Maxwell & van der Vorst, 2010) (Kaebernick, Kara, & Sun, 2003) and/or over complex (Hallstedt, 2008) (Byggeth, Broman, & Karl-Henrik, 2007) . As a result the methods had limited application (Choi, Nies, & Ramani, 2008) (Hoffman, 2007).

There has been a few areas where local information on a limited environmental benefit has been observed. It raises a question of if there is still an improved balance of environmental performance to implementation success that can be achieved. Is a successful implementation likely to have a reduced environmental performance?

Advancements in product development processes were considered with best practice methods identified (Cooper, Edgett, & Klienschmidt, 2004) (Macintyre, 2010). Trends in product development approaches were observed such as disruptive innovation (Linton & Walsh, 2004) and portfolio management (Wheelwright & Clark, 2011) (Morris & Pinto, Project program & portfolio maangement, 2007). However, these methods on their own do not deliver on sustainable prodcuts. Collectively they exhibit an emphasis on efficiency.

The approach considered the development of an overarching new methodology as opposed to focused improvements in specific areas to form best practices. This approach was used as it had been observed in literature that individual improvement tools failed to achieve the full benefits of the tool. Often this was due to limitations in adoption and integrating with other company practices. The approach leads to the development of a framework, guideline, assessment method and an implementation method. These tools provide a robust system that addresses the gaps in the literature and the needs of stakeholders, managers and practitioners.

As the work developed additional focus on the implementation of the methodology was needed. Implementation was taken both as a separate work item and as an integral part of methodology development. A learning from the failures of others is that, having a desirable system will dramatically increase the success of implementation.

In the approach taken the individual test areas were highly manageable but some presented extreme step changes for the interacting areas both in business operations and processes. It was observed that the interfacing elements of the business saw familiarity within the total process. This may not be true in the replication of implementation, therefore consideration should be given as to how to manage a large step change. In the completion of this work it is felt that the approach to implementation has worked well and can handle the step change. The main area for improvement is in the replication activities, which can be conducted as further work.

6.2.2 Findings in the development of a new sustainable product development methodology

The work presented has had a number of positive contributions. Highly beneficial products have been developed though the work elements conducted, these being:

- Ultra high pressure gas pack
- Gas saving integrated cylinder valve
- Ergonomic valve guard
- A standard gas cylinder filling plant design
- Electronic cylinder with wireless communications

Each of these products has had technical success in their own right. The new gas packages (ultra-high pressure pack, gas saving valve, ergonomic valve guard and electronic cylinder) had significantly positive customer feedback and are in a launch phase. In the cases of the ultra high pressure gas pack and gas saving integrated valve, these products suffered from insufficiencies in the development process and remain challenging to launch. In the case of the electronic cylinder the launch is slowed owing to commercial decisions, financing restrictions and manpower restrictions. The technical development of the products listed above are alone noteworthy achievements. Importantly customers saw benefits from these products. The indication is the products have potential to be business successes.

The methodology development work explored a technology node. New technologies were tested in an industrial gases arena and showed many similar benefits to other industry applications. As identified in section 5.3 it was proposed that new technologies will have similar characteristics of performance in the industrial gas industry as observed elsewhere. Furthermore, it was expected that improved products would be developed. The case studies delivered concrete evidence that replication of technology benefits is possible within the industrial gas sector. The products developed from the process are pioneering for the industry.

In the work plan, activities were broken down into a set of work elements and handed out. Each activity was well identified and actions were taken to explore and fulfil gaps. For instance in improving the life of a gas cylinder, it was identified that models by *Shahani et al*, *Zafer & Luecke*, *Reynolds*, *Xia* and others did not work for the high pressure or non-ideal situations under investigation (Shahani, Esmali, Aryaei, Mohammadi, & Nahar, 2011) (Zafer & Luecke, 2008) (Reynolds & Kays, 1958) (Xia, Smith, & Yadigaroglu, 1993). Improved models for predicting gas cylinder behaviour (in filling and use) were required. Appropriate models were subsequently developed and applied. These models enabled simulations to be conducted, exploring design boundaries and form targets to be achieved. Without the models, the end results would certainly not have been as beneficial nor as innovative.

In the development of the new methodology it was identified that the system had to have a simple identification of performance and where actions may need to be taken (Pemberton G. , 2014c). This led to the development of a sustain index, which presents a simple solution for assessment and decision making.

Research was conducted into a best practice for transformational change in research and development. This was completed with two approaches, a literature review and a set of expert interviews. Areas of commonality and differences were identified along with further areas for investigation (such as the human aspects of change in research and development teams). The knowledge gathered was used to develop a seven step plan for transformational change in research and development.

An implementation of the methodology, using the seven step plan, is carried out to learn from an application and review the benefits and areas for development. A case study with GCE is presented. The transformational change method is applied and is successful in being used to manage change. The product development process significantly improves and more sustainable products are developed. Overall there were many positive outcomes, but the environmental performance lagged other areas.

In implementation, a main activity involved tailoring the process. The case study developed twenty nine new standard documents. While this seems a significant quantity it was necessary due to a lack of documents. In order to not alienate the team in these changes the whole team was involved in the change which helped to achieve confidence that the new system is an improvement.

There are some areas where engineering models could have been further explored. For instance, it was recognised that there was a gap in modelling mathematically a real gas regulator for design purposes (Pemberton G. , 2014a). This model was not developed and an empirical method was followed instead. The decision was based largely on the time required for the development of the model, which did not fit with the time required to complete the activity.

Each product development presented had some unique challenges. These can be generalised as challenges in external influences and technical difficulties (which are expected in development work) (Pemberton G. , 2014c) (Pemberton G. , 2015a). Systematic issues in the processes followed were not found (Pemberton G. , 2015a) (Pemberton G. , 2015b). The indication is that while further preventative measures could be taken in the challenge areas, the overall process is producing positive results.

The methodology presented may be worthwhile exploring outside of the industrial gas industry. There may be some specific industry/company policy requirements for consideration before exploring replication. Although there is nothing in the methodology that would specifically not apply to other industries, it is noted that some learning and refinement may be required to improve the implementation in other sectors.

6.3 Further work and development of the methodology and techniques

Improvements to the methodology are likely be identified from continued review of the first adopter. It is recognised that with subsequent implementations a continuous improvement approach could be followed so that learning is identified and taken into the methodology.

The main area for further work is the continued use of the methodology (Pemberton G. , 2015b). The methodology has been tested but still requires time to be embedded and to determine fully its success. This could take a year or more, although early indications are that substantial improvements have been achieved, noting that a cultural shift to sustainability could take significantly longer. It is necessary for the implementation to be continuously evaluated and identify learning from the barriers presented.

Another areas for further work is in the assessment method and the scale named the *sustain index*. This can be further developed from the application presented by continued use of the assessment method. That will bring insight into values and ranges of values of the sustain index (Pemberton G. , 2015b). Monitoring the values over a number of projects and on a comparative basis will start to enable a deeper understanding of the scale and numerical values used in measurement. A scale could be developed from expanded applications, but for the scale to be transferable it would require development with a range of companies. It is recommended to seek suitable participants to develop a scale for the sustain index.

An important aspect of this work will be to consider how the assessments are conducted. The case study provided used a single person to determine the ratings. This promoted consistency but perhaps at the expense of subjectivity. In is recommended that in further work a group is used for the assessments as this is likely to improve decisions making associated to individual scores and also provide feedback on the scoring method itself. This is essential to improve the guidance for scoring or even if a new approach to scoring is required.

An additional area for development that could now be considered is connecting the performance in sustain index to company performance. This could be achieved through a study of financial performance with sustain index performance and observing linkages. From this an indicator of performance could be recommended. The result would enable a clear link of sustainable product development to company performance. This would build a business case for the application of the methodology.

There is further work required on the dynamic modelling of a real gas regulator (Pemberton G. , 2014a). This activity has started with Rouen University as it requires a high level of mathematical knowledge and a computational method to be produced. A work plan has been created to introduce the real effects of a gas in a step-wise manner and verify each step. The first step, introducing compressibility, has been explored and a base model built and tested. Verification of the model is in progress. The next steps are to introduce the Joule-Thompson affect and additional gas properties (with regards their gas to liquid transition points and mixture properties). It is expected that this work shall have a contribution to knowledge and enable more advanced methods for gas regulator design.

The introduction of the technology node was tested and the activities presented. Clear benefits were seen and similarities could be drawn to other industries' application of such technologies. The work in this area can be continued. One implementation was finalised in this report and repetition of such work should be continued (Pemberton G. , 2015a).

The application of a technology road map and its alignment to the industry is an area where further work would provide refinements. For instance, through consideration of the current technology used by competitors and the requirements of governing standards, the route to adopt a new technology could be significantly influenced. For example, producing a production gas valve by additive layer manufacture is a large step-change in current technology. Competitors could react in a highly resistive manner, likely reactions would be lobbying customers and approval bodies that the technology is unproven. The governing standards (for example ISO 10297) are designed to cover the incumbent manufacturing process (forging and machining). Additional requirements for fatigue testing and impact testing could be considered necessary. Further work in a best practice for technology road mapping for sustainable development is recommended.

The sustainable product development methodology presented has been driven towards the industrial gas industry. However it is generic enough to be applied elsewhere (Pemberton G. , 2015b). In order to confirm this application it is recommended in other industries. Additionally, this would test that benefits found in the methodology are not industry specific.

In the product developments presented, they had a tendency to increase initial costs and time in the design phase (Pemberton G. , 2015a). A good example is with the application of virtual reality, the cost to conduct the work was much greater than the traditional method, but it was evident in the issues identified and design decisions made costs and time were saved. It will always be a challenge to justify additional costs to business leaders. A method to assess a justification could be built. A method could be developed to estimate the total costs of the new approach against the current methods. This could be tested and supported by a set of case studies which would give consistent and clear justification of the method.

Replication of the technologies in further projects is a clear area for further work that shall continue to provide benefits. Only one such repetition has been conducted so far, that is with the use of virtual reality in gas cylinder plant design. The process has been applied to a new plant development in Europe. Particular focus has been on using the system to optimise cylinder movements. Simulation was made of a variety of layouts and investigating the time taken to move cylinders through the production steps. Similarly, operator activities have been reviewed to optimise the handling time. A focus on the safety aspects of the plant was also part of the work. The virtual reality system can be used to conduct a safety review. The feedback from the team involved was that virtual reality was enabling ideas to be reviewed quicker and clearer than could be achieved through traditional methods.

In the work presented a number of potential publications are possible. The technical developments, would be a good opportunity for publication like using virtual reality design reviews for an industrial gas plant. It may also be possible to publish the core findings in the methodology developed. It is appropriate now to develop the potential publications:

- A review into sustainable product development methods and best practices for product development
- A new method to conduct transformational change in research and development
- A new methodology for sustainable product development and assessment

There are further areas for publication. A particular opportunity is in the development of a real gas model for dynamic gas regulator prediction, a publication would be highly suitable to pursue. The development of a scale for the sustain index may also lead to a publication. The work identified in technology road maps could also lead to a publication on best practices for technology roadmaps in sustainable product development.

7 Conclusions and Recommendations

In the work presented a journey has been taken in which sustainability and product development have been brought together to produce a sustainable product development method and assessment method for the industrial gas industry. In this chapter the learning and achievements are presented. Specific achievements in innovation and contribution to knowledge are highlighted in separate sections. In concluding the development, a number of new areas of work have been identified, which are covered in a recommendations section. Areas of further work from the activities conducted are detailed in section 6.3.

At the beginning of the work it was believed that a sustainable product development methodology could address a number of product development problems experienced in the industrial gas industry. An investigation into the industry identified a general use of low technologies and limited new products. There was an awareness of sustainability and the industry recognises it has a role to play in sustainability. It was found that there were very few innovative products, research and development was underfunded and most of the developments had been focused on incremental improvements. In this background a step-change was to be developed. The methodology developed was presented and addresses these areas. The methodology achieves this by interlinking and balancing emphasis of the efficiency, equity and environmental aspects. Not only does this work on a triple bottom line perspective but these aspects are interlinked to the product development process itself and the performance management of the portfolio of projects conducted. For the application, an improved impact from the projects is also targeted.

A first investigation of a more sustainable product was conducted by improving the useable life of a gas cylinder. Two key methods were identified in this work either, to increase the content or to minimise the losses. For both methods a technical development was identified and completed. The results of these developments are significant increases in the life of the product with the customer. An increase of life of at least 30% is achieved through content. An increase of life of between 11% and 142% (depending on customer use cycle) is achieved through an adaptive low loss gas regulating valve. Sustainability is improved in all three aspects:

- Environmental impact of the product was reduced from raw material consumption and through to supply chain reductions.
- Equity elements of the product improved. The customer had improved value from the product, safety was improved through reduced manual handling and the producer benefitted from a lower number of required assets.

- Efficiency of the product improved from various aspects, the consumer probably seeing the largest benefit through greater than 30% increases in the useable life. The supply chain of the product also becomes more efficient requiring fewer vehicles in the fleet and fewer deliveries to service a customer.

The improved life products were well received by customers and technically broke new ground in the industry. However, both products struggled to be implemented due to a variety of downstream issues. It was identified from this that the product development process itself needed to be revised in order to address deficiencies in product development.

The investigation identified that significant benefits were possible from improving sustainability at a product level, and that the sector may be ready for a change. Further investigations identified that industrial gases has desires to be sustainable but is falling short of achieving any such goals.

In order to address this it was identified that a new sustainable product development process would be required. An approach to the work was designed following a process of conducting research to identify gaps, address the learnings from the steps taken then address the areas with the next step. Five significant steps were then conducted in the development work in; perform a trial, conduct research, conduct a development, test new areas conduct a trial(s). The steps form the submissions which are highlighted below (note Figure 13 gives additional details of the expected achievements):

- Trial a case for sustainability: Improving the life of a gas cylinder
- Review published knowledge: Sustainable product development part 1: Literature review
- Create a new methodology: Sustainable product development part 2: Development
- Test new areas of the methodology: Development and Application of New Technologies in the Industrial Gas Industry
- Application and refinement of the model: Sustainable product development part 3: Implementation

In the literature review of sustainable development gaps in knowledge and best practices for sustainable product development were identified. The review considered best practices and methods and focused in on new product development, sustainable product development and portfolio management. The investigations found a number of best practices in product development that are not applied in sustainable development, in particular using a Stage-Gate® model along with an integrated product development team. The work then identified that while there has been a number of studies on sustainable product development, there is evidence of an over focus on environmental performance leading to over complex systems. Due to this adoption of sustainable product development processes may be restricted. Similarly, it was found that portfolio management was not often conducted in research and development but it is an ideal sector to be using the approach. Additionally, disruptive innovations were found to be an area for consideration as they can be highly sustainable. There are few clear methods to manage such projects.

In the development of a new methodology investigations were undertaken to determine a new approach. From the literature it was apparent that there was a need for an overarching system, a method to determine performance and to give instruction to practitioners. These are the needs of stakeholders, managers and those conducting the development. It was found none of the published sustainable product development methodologies addressed all three needs.

A framework approach was then developed for the overarching system. The framework merges best practices in product development to sustainability. The framework uses a process definition to create boundaries on the frame. Part of the framework process is a focus on new technology. This part of the framework is aimed at ensuring that products continue to be developed and adopt new technologies. Sustainability factors are centralised in the framework and are key to the performance measurement. The frame work is innovative in its combination of product development best practices, a technology focus area and sustainability. The framework is developed with implementation in mind enabling specific sections to be customised to company needs.

In support of the framework a guideline for practitioners is produced. This provides instructions for the process but also the areas for tailoring the framework to a specific company.

An assessment method was developed to address the need for quantitative performance analysis towards sustainability. A simple rating matrix was developed for assessment. This provides comparative assessments to be made in the key areas of the product development process. The assessment method achieves a link between performance in product development aspects with sustainability. The assessment method quantifies results so that areas for balancing and improvement can be easily identified. This indicates in which areas of the framework additional focus is required. The assessment model develops a concept of a sustain index based on the calculation matrix. The assessment method can be considered visually through spider diagrams and the matrix assessment at both a product and portfolio level. These are new techniques in product development practices.

The methodology uses portfolio management and delivers a key supporting tool in the assessment method and sustain index. While the assessment process has opportunities for development with further data and analysis of the sustain index, it should lead to clear decision making for both products and the portfolio.

The new technology section in the framework was tested in the environment of industrial gas through a set of case studies. An approach was developed, using three case studies to implement new technologies into an industrial gas product/process. Each case study tests the technology in terms of its relevance and success. The technologies are chosen from key trends in high technology sectors. The aim was to compare the similarities in benefits, drawbacks and identity specifics to the application in industrial gas sector. It was found that a strategy of applying new technologies significantly improves development time/overall costs and the product/process features. The case studies provide pioneering projects, which have many replication and development opportunities.

A method for implementation was identified as a need, developed and tested. Research into best practices for implementation was conducted in two stages; a literature search and then a set of expert interviews. The interviews gathered knowledge of transformational change to research and development teams. From the information found, an approach to implementation was developed. This created a seven step plan. The process was then tested along with the whole methodology successfully. The company used as a case study achieved a turnaround in its product developments. The results are that the new methodology for sustainable product development is successfully implemented and producing products with a stronger performance in efficiency, equity and the environment terms. Replication of similar results remains an outstanding question of the methodology presented. Only one case study has been performed, further case studies would be required to provide evidence that this was not a one off case.

A development has been presented, in which a concept of sustainable product development for the industrial gas industry is explored. The journey has resulted in a number of innovative products and processes. With the new technology exploration a number of pioneering works have been presented. New knowledge has been created in sustainable product development methods, through a new framework and assessment method, and in the implementation of the process. Success has been delivered through the implementation of the method which addresses the original hypothesis that benefits can be found using sustainable development in the industrial gas sector.

7.1 Identified areas of Innovation

The main innovation is attributed to the framework and assessment method developed. As seen in the trial of a more sustainable product (improving the life of a gas cylinder) new methods of product development in industrial gases were required. The research conducted on methodologies found current sustainable product development methods were not well adopted due to complexity and an over focus on environmental benefits particularly within the product. It was identified that best practices in product development were not well associated to sustainable product development techniques. An innovation in this work is the development of a system that integrates best practices in product development with sustainable product development methods. The framework presented is transforming a model of integrated product development to a framework, addressing a weakness in technology focus and centralising sustainability as the core function in the framework.

The next major innovation is the performance management of the framework with an easy to use assessment process. Previously observed methods are cumbersome and difficult. This enables performance review at a product and portfolio level to be evaluated. The assessment method introduces a novel key performance indicator, the sustain index. This factor can now be developed into a scaled assessment, but also for cross industry assessments. The sustain index is a new qualitative step that is the result of exploring the integrated approach to product development, along with sustainability. A guideline approach is additionally supplied for the framework. While not highly innovative, it is novel in bringing together the best practices of product development into a guideline.

In the development of the methodology a number of test cases were conducted. These led to product innovations such as the two position cylinder regulator. This is a further benefit of the process developed in that it promotes product innovation by highlighting gaps in performance and challenging the teams to develop products to fill the gaps.

A few examples of the product innovations are as follows.

- A high pressure and high flow regulator which is unique in its performance. It is inventive in enabling the seat design to be combined with an in-line spring. Additionally the material choice enables a highly compact and highly stable regulator.
- The two position gas saving integrated cylinder valve is highly novel in its mechanism using a rotating CAM design to pre-set to spring positions. It is inventive in providing benefits by adapting to gas use profiles. The result is in an extension to the life of a gas cylinder. The system and mechanism have a patent application pending.
- The use of additive layer manufacture was novel in its application to a cylinder valve guard development project. It was inventive in the combined use of additive layer manufacture with finite element analysis to significantly reduce development time. The design process resulted in a highly innovative design with a lifting mechanism, rolling ergonomics and a distinctive design. These aspects have been protected through design rights and a patent application for the lifting feature.
- The application of virtual reality was novel in its use with a gas cylinder filling plant. There was innovation in the process followed with the roadmap generated. A similar step-wise

process had not been used previously in virtual reality, this enabled a series of achievable steps. Another innovation highlighted by creating the roadmap, was a live system for adjustments during the design review. This is an area that can be further explored now the models have been developed. Another inventive step was in the design review process itself, in the use of two dimensional methods to capture the actions and changes within an immersive design review. The design review process developed could form a publication of best practices for application of virtual reality to low technology industries.

- The electronics development was novel in the use of communications in a cylinder product with a mobile device. While electronics had been seen on cylinders before they had not had working communications, others had not developed an application for a mobile device which enhanced the user experience of the gas cylinder. There were a number of inventions in the electronics such as the predictive calculation for cylinder life, and the ability to check for leaks in downstream systems.
- The quartz sensor development enables a breakthrough in technology. With the sensor and the electronics package design it was possible to achieve the required characteristics of low current consumption, high accuracy and low product cost. The quartz system led to a specific calculation method for cylinder life which has a patent pending.

7.2 Contributions to knowledge and further areas of research

The work elements conducted have contributed to new areas of knowledge, in particular in modelling of gas behaviours. Two key areas were in the modelling of gas cylinder filling and calculation of gas loss, the gas cylinder filling model is the first time a predictive thermodynamics model for cryogenic gas cylinder filling has been built. The model enabled investigations of filling gas cylinders at a higher pressure than that conducted today, providing knowledge on design specifications such as maximum process pressure and temperatures. The model also enabled investigation of alternative filling methods such as by controlling temperatures. This identified that a standard filling system can be used to deliver higher temperature fills by controlling a sub-ambient temperature on the cylinder walls.

The calculation method for gas cylinder life was the first time a complete model had been created for gas loses including surge and flow variation. The model provided knowledge of key design parameters through the evaluation of sensitivity to differing input factors. This enabled a specification to be made for optimised surge and flow variation. This led to the idea of a two position cylinder valve to give optimal settings depending on user profile.

New knowledge in implementing transformational change to research and development has been found. Through the results of a literature search (combining best practice in change management with insight to research and development) and a set of interviews, a seven step process for transformational change was developed. This knowledge was applied and found to provide a suitable structure to manage change in research and development processes.

There are two main further areas in which new knowledge may be created. The first identified was in the dynamic modelling of a real gas regulator. The published literature on predictive models are not accurate above 200 barg and were not suitable for the development investigated, at 450 barg. While a step-wise approach was used (due to time constraints) for a gas regulator development, it did identify potential problems with that model that, iterations could have reduced. There is scope for a contribution to knowledge in building a dynamic gas regulator model, including the real gas behaviours of compressibility and Joule-Thompson effects. Such a model could dramatically change the design process and typical designs of gas regulators.

The second main area for new knowledge creation is in the sustain index. The factor has been introduced with the development of the assessment method. However, the factor calculated is currently only useable in a comparable format with other projects. With further research, it should be possible to build a scale of values, which may provide insight on externally comparable system. As such the sustain index could provide a benchmark of a product development and a company's development portfolio. There is further potential to develop the calculation method with further research.

As discussed in the section on further work (6.3) it is recommended to develop a number of the work elements conducted into publications. These are to be centred around the core of the development, that is the sustainable product development methodology. The identified publications are:

- A review into sustainable product development methods and best practices for product development
- A new method to conduct transformational change in research and development
- A new methodology for sustainable product development and assessment

With further work additional publications could be achieved, identified as:

- A real gas model for dynamic analysis of a gas regulator
- Managing human aspects of change in research and development
- The development of a scalar sustain index for sustainable product development assessment

- Technology roadmaps best practices for sustainable product development
- Idea generation for sustainable product development
- Managing disruptive innovation in a sustainable product development portfolio
- Use of industrial design in the industrial gas sector

It would be pragmatic to limit the efforts of future work for the methodology. This would enable an emphasis on publications in; the development of a scalar sustain index, technology roadmaps and idea generation for sustainable product development.

7.3 Recommendations following the development of a new methodology for sustainable product development process

Within the exploration of sustainable product development many additional activities were identified. Each of the main submissions has their own set of recommended actions. In this section the main areas of recommended work are identified and explored. Additionally, areas of new questioning and research can now be highlighted.

Further improvements to the methodology were recommended throughout the report. The further work identified is discussed in section 6.3. In new activities, exploration of specific areas of the methodology could be conducted. For instance, in the *enablers* node of the framework, the funding methods for research and development activities could be explored. It was discussed that a best practice would be to fund projects gate by gate. Such a funding model is novel and could be explored through comparative tests to a more common approach such as yearly budgeting. In the process node Stage-Gate® was a recommendation, but exploration of Stage-Gate® to sustainable product development has not been explicitly tested. In the further work a continuous improvement approach was identified for sustainable product development. However, to achieve a further step-change in process improvement a more fundamental approach is required. This could be achieved by taking elements of the new process and conducting further research to derive new approaches. The two examples highlighted (in funding methods and application of Stage-Gate®) could be used for such work. Research and development at this stage is recommended so that step-wise improvements are sought through reconsideration of best practices within the framework nodes.

In the methodology development the five capitals approach was identified as having potential for incorporation in the model. This could now be further explored, areas of interest are the use of the five capitals method in the framework and integration of the five capitals approach for portfolio management.

The impact of the methodology within the industry should be considered along with its longevity as a best in class process. It is now possible to consider this and monitor the impact of application in terms of competitive advantage and reaction of competitors. It is recommended that a monitoring mechanism is considered to be developed to review the performance of the methodology. With such a monitoring system, implementation external to the industrial gas industry may also be reviewed. It is recommended in the further work to test implementations of the methodology in other industries.

An area of impact to pay attention to is environmental performance. In the implementation conducted, environmental performance was the weakest area of improvement. The approach undertaken to develop the methodology paid attention to not over focus on environmental aspects. It can now be recommended to consider how environmental performance can be encouraged through the methodology.

To develop further knowledge on the methodology, replication is essential in order that observations and a further results can be collected to have the required evidence for development work.

As identified in the further work section, continued activities with Rouen University are required to build a real gas dynamic model of gas regulators. It is expected that this work shall have a contribution to knowledge and enable more advanced methods for gas regulator design. Such a model may have application outside of gas regulators, it could be developed to investigate quick acting valves. It is recommended that not only is the further work conducted on real gas model developments but opportunities to exploit the further the work considered.

Models of cylinder filling and cylinder life have been presented in the work on extending the life of a gas cylinder. These models were used to predict different scenarios to enable decisions on the packaging and equipment. These views were taken in isolation on two different products. The models have brought insight into how to balance end pressure and fill temperature with package size and ambient conditions. In the increase of a gas cylinder's life, it was considered as to how to balance gas surge with stability to extend the useable amount of gas delivered. The models could now be used in a more holistic view of packaging. Such as, how can the package and equipment be optimised from a filling and user standpoint? Additionally, a supply chain view could be included that gives input on inventory and transportation aspects.

The models developed for cylinder filling and cylinder life prediction may also be further exploited. The models could be developed to include supply chain interests. For example in cylinder filling a model could be developed to represent the production activities of a plant. This could be used to predict the best operation sequences and optimise labour allocations. In cylinder life predictions the model could be used to understand different supply chain models, especially replenishment strategies. It is recommended that further consideration is given to the supply chain impact of the models developed and appropriate activities identified. It is likely that these could form individual areas of study, which may be appropriate for partnering activities.

A new question that can be asked from the development of the sustain index is: how should the index's value be put into context? As identified in the report, the index is appropriate to reference within the portfolio of products being considered. In that context, the sustain index is directly comparable to other projects. Additional questions can now be proposed for further investigation, such as, how to balance the portfolio using the values and what range of values should be aimed at? It is recommended that not only is further development of a sustain index scale conducted but also investigation in the application of the index in decision making criteria.

As the work developed, human aspects of both the methodology and the change became increasingly important as the process moved from theory to a practical implementation. It was identified as further work that the human aspects off change in research and development could be investigated. A particular area of interest would be team dynamics. While it was identified that a positive team approach to implementation greatly assists the transition, methods to manage this were not covered in depth. It is recommended that further studies in the human aspects associated to the methodology are considered. A psychological view could be appropriate to consider especially in the techniques for conducting research (such as the use of observed tasks which is more popular in psychology than scientific research).

Another area of work that can now be further explored is disruptive innovations. During the process disruptive innovation became an increasingly interesting area of work to consider. It was considered in the methodology and resulted in a step out process. Disruptive innovations could now be explored further as an individual work element such as the approach with new technologies. They could be investigated as an additional node to the framework. It is recommended that a strategy to investigate an improved inclusion of disruptive innovations within a portfolio of product developments is considered. However it is recognised examples of disruptive innovation do not occur frequently, this needs to be considered in the planning of such work.

Idea generation was not included in the initial aims of the methodology development. The reasoning was to not distract from the required focus on improving sustainable product development and processes. Now that the methodology has been developed, idea generation can be considered. A number of tools and practices for idea generation are well known and have brought benefits to users.

However, in the concept of sustainable development there is likely to be scope to develop methods for idea generation. The question that could now be considered is, are further improvements to sustainability possible through idea generation methods?

Industrial design activities were conducted within the technology case studies with good success. The designs produced were highly novel and well aligned to customer needs. It was found in the focus groups that customers appreciated the design work. Application of industrial design to in industrial gas products is identified as an area that could be considered for further research. It is recommended here that a strategy and approach is developed to explore the benefits of using industrial design.

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Appendix 1: Assessment of approaches to a new methodology for product development

Assessment of approaches to a new methodology for product development.

	Framework	**Guideline**	**Process map**
Definition	A definition of the boundaries in which to conduct activities in	A set steering descriptions or questions that give direction and recommendations of what to do	A description of activities and the timing of activities
Strengths	Defines strategy and a macro-structure, the why aspects. Able to use for portfolio management Strong approach for transformational change	Focus on how to do activities	Focus on what and when to conduct activities
Weakness	Does not describe the timing of activities or what to do in specific circumstances	Open to interpretation and can lack specific information provision. It may lack explanation of the timing of activities	Does not describe how to conduct activities or give context to the work. Works well on an individual project perspective.
Comments on sustainability	Strong method to describe the overall concept and guiding boundaries	Has been used as method to improve practice in environmental activities	Strong from an efficiency perspective and timing
Gaps towards sustainability	A framework can clearly describe boundaries in which the aspects of sustainability can be described but it will not cover the details of how, what and when.	Guidelines have struggled to be well implemented as they can be over complex and miss not describing the overall need. The published examples focused too much on environmental aspects. The guideline needs to provide an integrated view.	Process maps are highly efficient, but do not focus well environmental and equity aspects. Additional mechanisms are needed to describe the rest of the requirements for sustainability.
Key literature	(Bhuiyan, 2011) (Choi, Nies, & Ramani, 2008) (Hallstedt, 2008) (van Weenen, 1995)	(Byggeth, Broman, & Karl-Henrik, 2007) (Hansen, 1999) (Siebenhuner & Arnold, 2007)	(Liker, 2004) (Baumann, Booms, & Bragd, 2002) (Kaebernick, Kara, & Sun, 2003)

Table 9: Review of methods to product development systems

Appendix 2: Table of development methodology goals and the lean approach

Table of development methodology goals and the lean approach

	Goals	Appropriate tools	Appropriate measures
Customers	• Solves a problem • Meets/exceeds market performance • Produced in a sustainable manner • End of product life contributes to something else • The company is ran in a fair way and can be trusted	• Cause and effect • Voice of Customer • Benchmarking • SWOT & PEST • Life cycle analysis • Design for X tools • Design for environment • Design for energy efficiency • Design for recycling and reuse • Design for dematerialisation • Design for disassembly • Design for sustainability • Auditing tools • Customer survey	• Compliance to customer requirements • Comparative competitive product assessment • Life cycle and environmental impact • Measures of emission impact • Embodied energy calculations • End of life and waste analysis • Calculation of sustain index • Performance factors on end of life recyclability/reuse
Stakeholders	• Continued life and growth of the company • Company contributes to local society • Model company behaviour • Long term goals	• Roadmapping • Calculation tool kits • Mapping (process and communication) • Any of the design tools mentioned above	• Financial measures Net present value, internal rate of return, payback and profitability index • Expenditure/time allocation to community focused work • Corporate governance compliance • Long range plan compliance
Legislation	• Focus on environmental impact reductions • Safety and security performance	• Design for Environment • Design for zero toxics • Design for compliance • Material sustainability index • Failure mode and effect analysis • Audit	• Environmental impact analysis • Failure rate analysis • Compliance to legislation rating • Time allocation for legislative work

Table 10: Table of goals connected to lean tools and measures

Appendix 3: Table of actions and expectations from a new product development methodology

Table of actions and expected outcomes in the implementation of a new product development methodology to the Industrial Gas Sector.

Factor	**Actions**	**Expected impact of actions**	**Measures**
Benefit of methodology	Introduce success stories from other industries and discuss time lag of industrial gas sector. Quantify a baseline of current performance and ensure factors can be measure comparably in new method. Qualify the impact in non-measurable terms Set a timescale to see benefits	Drive a compelling case that can deliver measureable results Set an achievable expectation	Performance factors: Development time Cost of development Resource Environmental rating Equity rating Efficiency rating
Why is a change required	Highlight technology/quality/performance changes that have occurred in other industries in comparison to the conservative nature of the industrial gas industry. Use information on importance of sustainability highlighted by major players and how little achievement has been made. Prepare improvement timescale. Prepare case of doing nothing.	Clarify why current path is not sustainable and offer a timeframe as to when this can be addressed	Environmental rating Equity rating Efficiency rating
What are the areas for improvement	Benchmark current performance to industrial gas industry and to automotive sector	A focused approach to bring the benefits quickly	Adherence to time plan Environmental rating Equity rating Efficiency rating
How is the process to be implemented	Detail an implementation plan in bite size pieces Plan and hold upfront meetings with senior management before starting work.	Minimise potential failures in implementation	Clarity of understanding by team members Adherence to time plan
What is the process for continuous improvement	Continue to monitor and benchmark performance factors. Promote idea generation. Review performance and planning regularly.	Improvement over time of key performance factors	Environmental rating Equity rating Efficiency rating
What are the expected barriers	Understand the drivers of key personnel and departments. Identify potential barriers. Take measures to tackle restrictions upfront. Look outside of organisation for barriers and solutions.	Minimise the effect of barriers on the project.	Adherence to time plan

Table 11: Table of actions and expectations from a new product development methodology

Appendix 4: Guideline to the Sustainable Product Development Framework

Guideline to the Sustainable Product Development Framework

In the following sections a guideline is outlined into how to work with the framework presented in Figure 23.

Business Drivers

A key building block in a product development process is the business drivers. This node in the framework contains the requirements for an organisation in terms of profitability, competition, legislation, technologies, trends, environment and socio-demographics. Clearly the customer requirements are also essential for a business to understand. Two tools which are well known practices in industry for setting and understanding business drivers are SWOT (Strengths, Weaknesses, Opportunities and Threats) and PEST (Political, Economic, Social and Technology). It is recommended both these tools are used in order to create a set of statements on the business drivers using the following sections;

- Company core competence
- Growth strategy
- Competitive strategy
- Business strategies
- Legislative movements

From the statements an overall company statement is built. Then, for each specific project, the work on the business drivers' statement should be re-visited and tailored accordingly. This would enable some flexibility in setting the business drivers for projects which may challenge the current business model. An example would be a company which states its core competence in manufacturing and expansion through highly customised production would find challenges in progressing a project that involved high volume assembly. Enabling an option to review the business drivers would give senior management the opportunity to not only review the project with the current business frame but also with a frame of view that the current ways could be challenged.

A further important element in deriving the business drivers is to set some business goals that explain what the project could do for the business. Naturally, such goals will be financially biased and should certainly highlight the sales potential, the profit and payback, after all the business needs these to continue to survive. However, other goals such as contribution to the company's environmental performance or improvements in the working conditions should be contained in order to maintain focus on the three areas of sustainability.

In summary for the business area node the following should contain:

- Business statement(s) (in-line with the strategy statements)
- Goals/Targets

Enablers

The Enablers node is concerned with the organisational way in which product development is enabled and ideas have the means to advance through the cycle of development. It is concerned with the following key areas; Strategy, Tools and Organisation.

Strategy

Setting a company strategy is an obvious task but one seldom well undertaken. Within the enablers node it is seen as a significant area a company needs to provide information up. The strategy work undertaken should deliver the overall company strategy, any divisional strategy and any individual/stakeholder strategy that may cause an influence on the project in hand. There are a number of tools available to describe a company's strategy. There is a wealth of methods and graphical ways to display a strategy. Whichever method is used it is important that the following factors are covered; leadership position, market introduction and technology.

It is important for this element that the model has clear descriptions to identify the approach to; development, launch, post launch support and end of life activities.

Tools

The use of lean tools within the development process was highlighted by the literature as a best practise to improve the speed, quality and cost of development. A number of lean tools were identified as suitable for new product development. This information along with identification of the stage in the process where the key tools are most applicable are tabulated below. This table should be used by practitioners as a basis to review and choose appropriate lean tools for product development. It is acknowledged that the list is not exhaustive, as it is intended to give room for companies/practitioners to develop their preferences.

Gate	Lean Tools
Concept	Quality Function Deployment Road mapping 6 Hats ASIT/TRIZ SWOT/PEST Brainstorm Discovery driven planning
Prototype	EcoDesign Design for X Life Cycle Analysis Morphological approach SWOT/PEST Brainstorm Failure mode analysis
Development	EcoDesign Design for X Life Cycle Analysis Quality function deployment Value stream mapping Just in Time Six S Relationship mapping Mistake proofing Kanban Failure mode analysis
Launch	Life Cycle Analysis Value stream mapping Just in Time Six S SWOT/PEST Failure mode analysis Mistake proofing One piece flow Point of use storage Load levelling Kanban

Table 12: Lean tools for use in a new product development cycle

Organisation

The organisation section of enablers recognises the importance of the individuals and team working on a project. The organisation section needs to provide methods of motivation and tools to enable the organisation to react to the project and deliver it as well as possible. A key part of organisational structure in the integrated model is enabling cross-overs and changes in reporting lines. For instance in the integrated model support from all areas of the organisation is required. This may require seconding personnel from different areas, such as marketing or sales, to work full time on the project.

Decisions are therefore needed to be taken on how their reporting lines change and more importantly how motivating factors change. An example would be taking a sales personnel into a full time role on a development project. They would now not have the normal motivational structure and this needs to be replaced in order to maintain the best output of both the individual and the team.

The organisation area is also concerned with suppliers. Within the organisation there should be personnel assigned to work with the key suppliers. These key suppliers are to be regularly reviewed and perhaps development plans established. Further support with the supplier may be necessary in order to deliver a project. In such cases techniques like seconding personnel into the supplier may be required. Similar to the above example of a sales person seconding a team member into a supplier will present managerial challenges.

A further area of organisation activities is the overall management of projects. Decisions shall be required such as the approach to project management and if projects are to be managed centrally or at an individual level. These decisions can impact the flow of funds and allocation of resources.

Process

The process node of the framework is concerned with the way projects are moved from idea to reality. Process looks at the choice of projects, the actual steps within the development and where and when the development is to be completed.

A best practice identified for the product development process was Stage-Gate®. The method uses a set of gate meetings to advance a project from idea to launch. While the process is not prescriptive in the number of gates, nor in the exact requirements of a go/stop/recycle, it does make a recommendation of a 5 gate process and gives a guideline on the expected review criteria for gate meetings (Cooper R. G., 2008). As identified in the literature search this process works well with the integrated approach to product development and it is the recommended process here in the process node. The process is well described by the process map below.

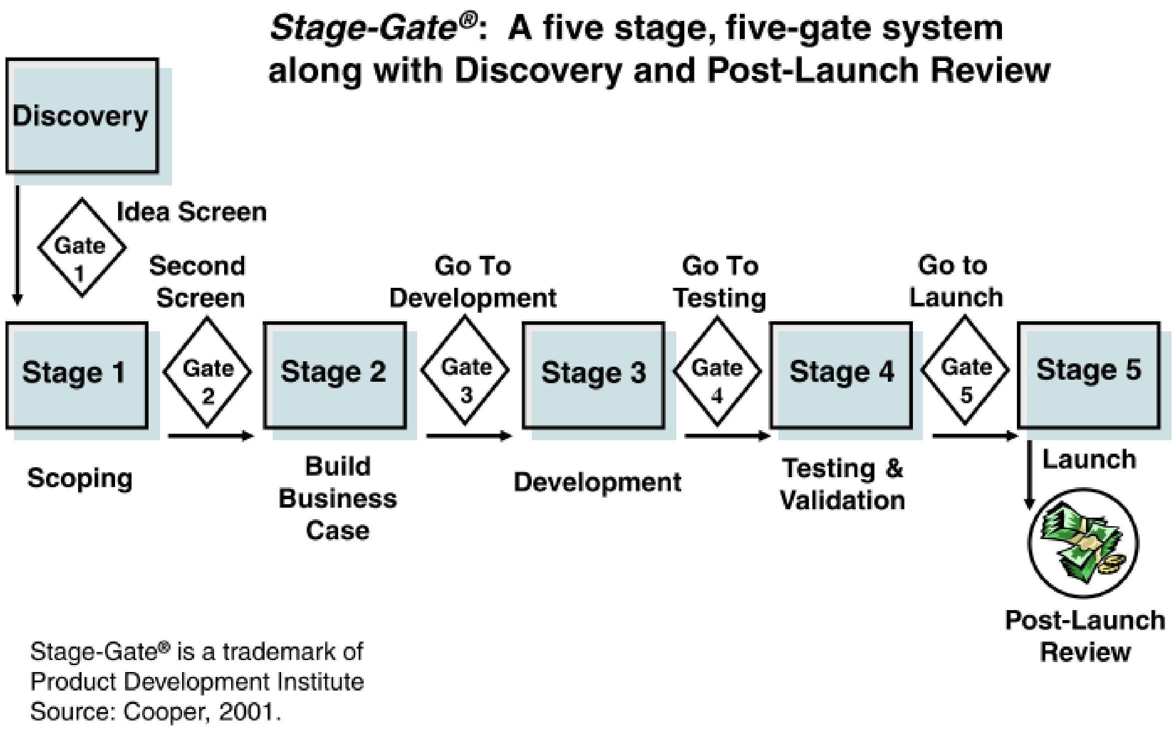

Figure 0-1: Typical Stage-Gate® process (Cooper R. G., 2008)

In light of discussions made on sustainability in the product development process it is clearly important to integrate sustainability. Therefore as part of the gate meetings sustainability shall be a key area to review. It is recommended that at gate meetings a review is conducted of the results of the sustainable assessment method. Utilising the literature search (Pemberton G. , 2014b) (Pemberton G. , 2014c) further recommendations can be made to the content of the gate meetings. These are detailed below in Table 13.

Gate	Requirements from responsible parties				
	R&D	**Business**	**Marketing**	**Supply Chain**	**Production**
Gate 1 (Idea)	Technical assessment Laboratory testing Sustainability target setting	Strategy Sustainability target setting	Competitor analysis Customer view Sustainability target setting	Sustainability target setting Supply chain ideas	Sustainability target setting
Gate 2 (Build business case)	Material options Environmental impact End of life concepts	Financial targets Organisation impact	Competitor analysis Customer view	Supply chain concepts	Manufacturing review
Gate 3 (Development)	Sustainability review within technical review Cradle to grave proposal	Financial details	Market survey Market identification and information	Supply chain fit and options	Manufacturing options
Gate 4 (Testing and Validation)	Requirements of trail to measure sustainability elements	Financial details Organisation changes and challenges	Trial targets and required information gathering	Requirements of trial	Requirements of trial manufacturing
Gate 5 (Launch)	Technical review Results of sustainability metrics	Final P&L and financial metrics Review of business proposal	Customer feedback Results of market analysis	Results of trial supply	Results of trial manufacturing

Table 13: Table of gate review requirements

Technology

The node for technology considers not only the base line technologies being worked on, but also the technologies that support that work. This stretches from IT infrastructure, to modelling methods, machine tools, experimental activities, and technology that may help a product part way through its life cycle, to end of life recycling methods. A short, medium and long term plan of technology should be established in line with the business strategies. This must also identify skill gaps to feed into the enablers node. It is recommended that road-mapping is used as the tool to pull together a technology strategy, examples of the process are well described in literature (Linton & Walsh, 2004), (Phaal, Farrukh, & Probert, 2004), (Rinne, 2004).

The technology element is also where differentiation on a technical basis is considered. Activities in this node include benchmarking and reporting on technologies developed by competitors, suppliers and outside of the field industries.

The technology node also covers the intellectual property activities of the organisation. This is recommended to include a strategic map of the organisations specific field, a strategy to organisations approach and regular patent and paper reviews.

Lastly, technology is a node of investigation in which the team and stakeholder should be continuously thinking internally and externally how best to exploit technology in product development. One tool that can be great assistance to such an assessment is the use of technology maps. As presented by *Phaal et al,* road maps are a means to support long term strategic goals by aligning technological steps to the market opportunities (Phaal, Farrukh, & Probert, 2004). There are eight main types of roadmaps with varying focus from product planning, to strategy and knowledge development. A general graphical overview is presented in Figure 0-2. The concept is a mark-up of technological steps towards a future technology state (which may or may not be known) and then to align these to product developments and market responses, see Figure 0-2.

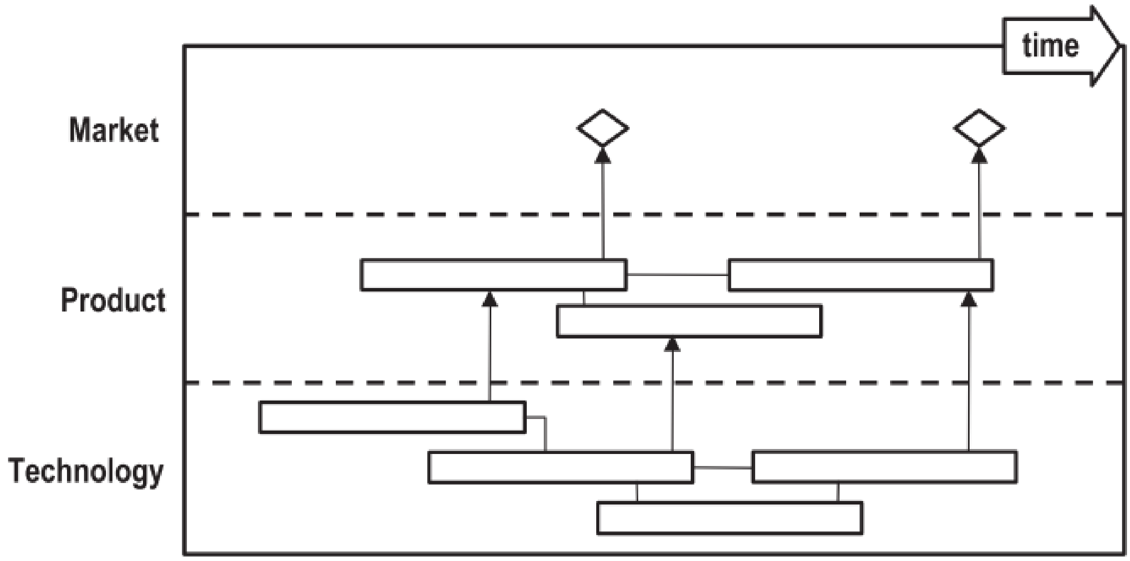

Figure 0-2: Schematic of a technology road map (Phaal, Farruh, & Probert, 2004)

Sustainability at the heart of the framework

The elements of sustainability are at the heart of presented framework. This is both a visual assistance to ensure focus on balancing environment, efficiency and equity: and also highlighting that the actual work conducted must focus equally on environment, efficiency and equity equally. Assessment of sustainability by the assessment method may be made at an individual project level. This would focus the steering committee to take note of individual projects contribution towards sustainability. It is then recommended that the results are collated for all projects to give an overall portfolio view. The assessment method is the subject of a separate section. This framework enables practitioners to focus on the development while working within a boundary that drives sustainability.

Appendix 5: Rating guidance for assessment method

Guidance sheet for ratings in the assessment method.

Sustainable Assessment Method Tool For Conducting the Assessment

Name & Date ____________________ **Project** ____________________ **Company** ____________________

Process										
		1	2	3	4	5	6	7	8	9
Lean Tools	**Efficiency**	1 No effect on efficiency	2	3	4	5 Application of tools inline with desired efficiency gain	6	7	8	9 Significant benefits above targeted benefit in efficiency
	Equity	1 No improvement in equity terms from lean tools	2	3	0.1	5 Some improvements in equity terms due to lean tools	6	7	8	9 Significant above targeted benefits due to application of lean tools
	Environment	1 No identifiable benefit in environment terms from application of lean tools	2	3	4	5 Some measureable environmental benefits due to lean tools	6	7	8	9 Significant environmental benefits achieved through lean tools
Stage Gate Process	**Efficiency**	1 No effect on efficiency	2	3	4	5 Stage gate process followed and delivering project at expectation	6	7	8	9 Stage gate embedded as a process and project delivering more than expected
	Equity	1 No improvement in equity terms from stage-gate process	2	3	4	5 Some improvements in equity terms due to stage-gate	6	7	8	9 Significant above targeted benefits due to stage-gate process
	Environment	1 No identifiable benefit in environment terms from stage-gate	2	3	4	5 Some measureable environmental benefits due to stage-gate	6	7	8	9 Significant environmental benefits achieved through stage-gate
Key Performance Indicators	**Efficiency**	1 No application of KPIs and no regular performance review	2	3	4	5 KPIs regularly reported and actions taken against KPIS	6	7	8	9 KPIs continuously assessed and actions undertaken to improve and maintain performance
	Equity	1 No improvement in equity terms from application of KPIs	2	3	4	5 KPIs consider more than single project and company	6	7	8	9 KPIs report on holistic areas and affects of project
	Environment	1 No identifiable environment benefit from application of KPIs nor any specific environmental KPIs	2	3	4	5 Measureable environmental KPIs in place	6	7	8	9 Environmental KPIs formed as part of project strategy and reporting on company/supplier/customer performance

Enablers										
Team										
	Efficiency	1 Team disjointed and not communicating to all interested parties	2	3	4	5 Multifunctional team with part time representation commitment	6	7	8	9 Multifunctional team seconded to project with high communication levels and tools
	Equity	1 Limited to no diversity	2	3	4	5 Diverse team that respects other team members	6	7	8	9 Diverse and inclusive team actively working to sharing roles
	Environment	1 Team has little to no focus on environmental concern	2	3	4	5 Team works in a suitable environment	6	7	8	9 Team working a forward thinking environment and actively looks for ways to improve the local environment
Supplier										
	Efficiency	1 Suppliers not engaged for efficiency gains	2	3	4	5 Supplier is engaged and has targeted efficiency improvements	6	7	8	9 Supplier is integrated and consciously improving their efficiency.
	Equity	1 Supplier is not valued	2	3	4	5 Supplier is valued actively involved with project in both technical and sales elements	6	7	8	9 Supplier is promoting ideas and integrated in development process and resourcing
	Environment	1 Supplier is bringing no environmental benefits	2	3	4	5 Supplier is environmentally conscious and meeting set environmental targets	6	7	8	9 Supplier is proactively finding ways to improve environmental aspects of the project
Funding										
	Efficiency	1 Funding is creating a delay in the project	2	3	4	5 Funding is well identified along with a clear budget	6	7	8	9 Funding methods is providing efficiency improvements
	Equity	1 No equity benefit seen in funding	2	3	4	5 Funding enables a fair distribution and workload	6	7	8	9 Funding is derived with all involved parties
	Environment	1 The funding of the project does not consider the environment	2	3	4	5 The project funding is such that immediate environmental benefits are achieved	6	7	8	9 The funding enables long term environmental benefits and ensure offsetting the development environmental impact

Technology

New Technology										
	Efficiency	1 Technologies bring little efficiency benefit to project	2	3	4	5 Funding enables efficiency in product and/or development programme	6	7	8	9 New technologies strategically deployed for efficiency purposes
	Equity	1 Technologies bring little equity benefit to project	2	3	4	5 Technologies enable benefits in equity terms	6	7	8	9 Technologies strategically deployed for equity benefits
	Environment	1 Technologies bring little environment improvements	2	3	4	5 Technologies bring immediate environment benefits	6	7	8	9 Strategic application of technologies for environmental benefits
Intellectual Property										
	Efficiency	1 Technologies have no efficiency protection	2	3	4	5 Technologies have design right / patented protection towards efficiency benefits	6	7	8	9 New technologies have a patent family and trade secrets protecting efficiency protection globally
	Equity	1 Technologies are protected such that equitable benefits are restricted	2	3	4	5 Technologies have rights that limit equitable benefits	6	7	8	9 Technologies are transferable to all beneficial parties
	Environment	1 Technologies are protected such that they limit potential environmental benefits	2	3	4	5 Technologies are protected such that they drive benefits in environmental benefits	6	7	8	9 Technologies are protected such that they drive a step change in environmental benefits
Differentiation										
	Efficiency	1 Technologies do not deliver product differentiation	2	3	4	5 Technologies off a differentiated product	6	7	8	9 Technologies enable a range of differentiated products that are highly beneficial
	Equity	1 Technologies bring no equity benefits through differentiation	2	3	4	5 Technologies bring some equity benefits through differentiation	6	7	8	9 Technologies bring significant equity benefits through differentiation
	Environment	1 Technologies offer no differentiation in environmental benefits	2	3	4	5 Technologies offer some differentiation in environmental benefits	6	7	8	9 Technologies offer highly differentiated environmental benefits

Business Drivers										
Requirements										
	Efficiency	1 Business requirements require no efficiency improvement	2	3	4	5 Business requirements require efficiency improvement	6	7	8	9 Business requirements require step change in efficiency improvement
	Equity	1 Business requirements have no equity benefits	2	3	4	5 Business requirements identify equity benefits	6	7	8	9 Business requirements identify step change in equity benefits
	Environment	1 Business requirements identify no environmental benefits	2	3	4	5 Business requirements strong environmental benefits	6	7	8	9 Business requirements step change environmental benefits
Financial Goals										
	Efficiency	1 Financial goals have no impact from efficiency	2	3	4	5 Financial goals strong impact from efficiency	6	7	8	9 Financial goals require step changes in efficiency
	Equity	1 Financial goals do not consider equity benefits	2	3	4	5 Financial goals drive equity benefits in whole supply chain	6	7	8	9 Financial goals depend on step changes in equity benefits in whole supply chain
	Environment	1 Financial goals do not consider environmental benefits	2	3	4	5 Financial goals are underpinned with environmental benefits	6	7	8	9 Financial goals are built to deliver step wise improvements in environmental benefits
Strategic Goals										
	Efficiency	1 Strategic Goals are not set around efficiency performance	2	3	4	5 Strategic Goals are set on improved efficiency performance	6	7	8	9 Strategic Goals are set on step wise efficiency performance improvements
	Equity	1 Strategic Goals are not set around equity performance	2	3	4	5 Strategic Goals are set on improved equity performance	6	7	8	9 Strategic Goals are set on step wise equity performance improvements
	Environment	1 Strategic Goals are not set around environmental performance	2	3	4	5 Strategic Goals are set on improved environmental performance	6	7	8	9 Strategic Goals are set on step wise environmental performance improvements

Appendix 6: Sustainable Product Development Assessment Method

Example of application
To illustrate the methodology an existing portfolio of projects is considered. The overall dimensions are summarised in the table below

	Project A	Project B	Project C	Project D	Project E
Classification	Breakthrough	Incremental	Partnered	Breakthrough	Incremental
Status	Prototype	Concept	Development	Prototype	Implementati on
Time to completion	15 months	3 months	7 months	18 months	1 month
NPV	£ 150,000	£ 30,000	£ 300,000	£ 100,000	£ 15,000
IRR	15%	12%	10%	20%	12%
Payback	24 months	3 months	36 months	18 months	2 months
Resource allocation	3	0.3	4	3	0.5
Budget required to next stage	£ 10,000	£ 1,000	£ 7,000	£ 15,000	£ 5,000
Risk	Medium	Low	High	High	Medium

Table 14: Summary of projects

Firstly, consideration of the framework shall be applied to each project, then the assessment made. The assessment is made using the guideline, and in this example a single individual has made the assessment using an appropriate score on the scale in the guideline and in comparison with the other projects. For example in the case of Project D it is a breakthrough project with new technology that is technically more of an advancement than the other projects has clear intellectual property and is a significant differentiator. The results applied while somewhat arbitrary as this is an example have been selected to represent the project dimensions outlined above. The summary results are shown below, Table 15, with the individual assessments at the end of this chapter. The results are best considered through the spider diagrams presented in Figure 3-1 to Figure 3-5. The first of the spider diagrams (Figures 3-1 and 3-2) show the results of an individual project, project A is taken as an example. These views show how the project performance to the framework looks in terms of the sustainability definitions. The two views show the framework firstly in its nodes (3-1) and secondly in its detailed areas of assessment (3-2). The first view is the simplest to work with it clearly shows how sustainability performance relates to the framework and from this the areas of strength and for improvement can be identified. The next spider diagrams (3-3 to 3-5) consider the whole portfolio of projects. Figure 3-3 displays the performance of the portfolio in respect to sustainability. Each of the projects have had their scores drawn round in the sustainability factors. In Figure 3-4 the portfolio performance is shown in terms of the framework with each project score to the nodes displayed. Figure 3-5 shows the framework and sustainability factors combined with each project score shown individually, in order to combine the scores the sustainability results are factored by 0.75 of the their original result to compensate the ranges (810/1080 = 0.75).

Summary	Efficiency	Equity	Environment	Process	Enablers	Technology	Business Drivers
Project A	800	710	770	570	510	600	600
Project B	690	690	690	540	720	300	510
Project C	760	740	760	490	630	540	600
Project D	890	890	890	630	660	750	630
Project E	780	780	570	660	540	430	510

Table 15: Summary of results of weighted scoring

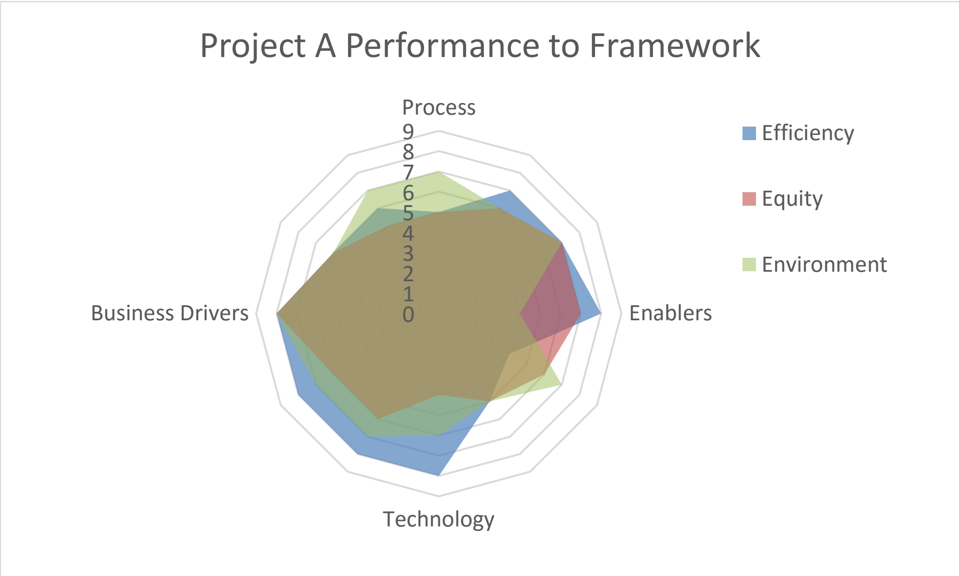

Figure 5-1: Project A performance to Framework

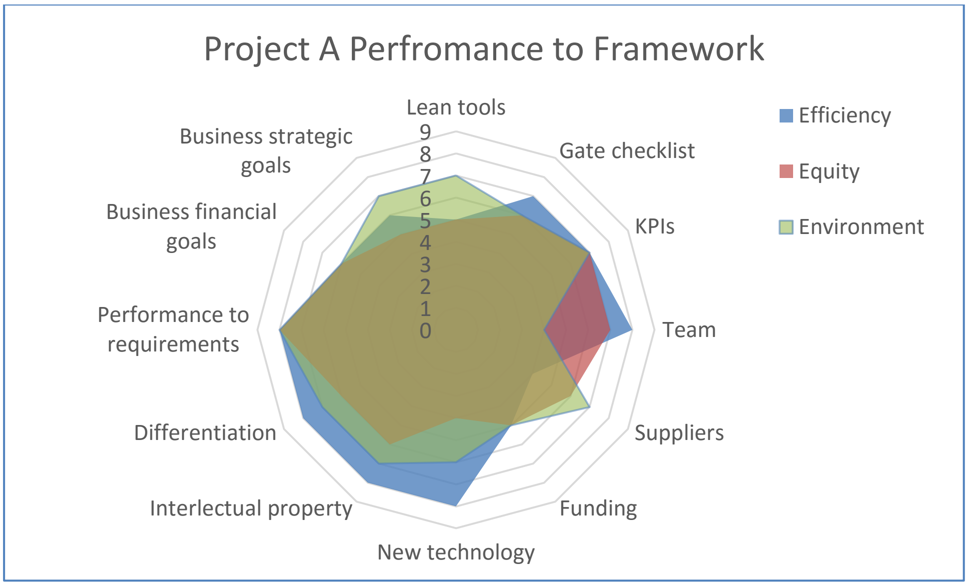

Figure 5-2: Project A Performance to Framework

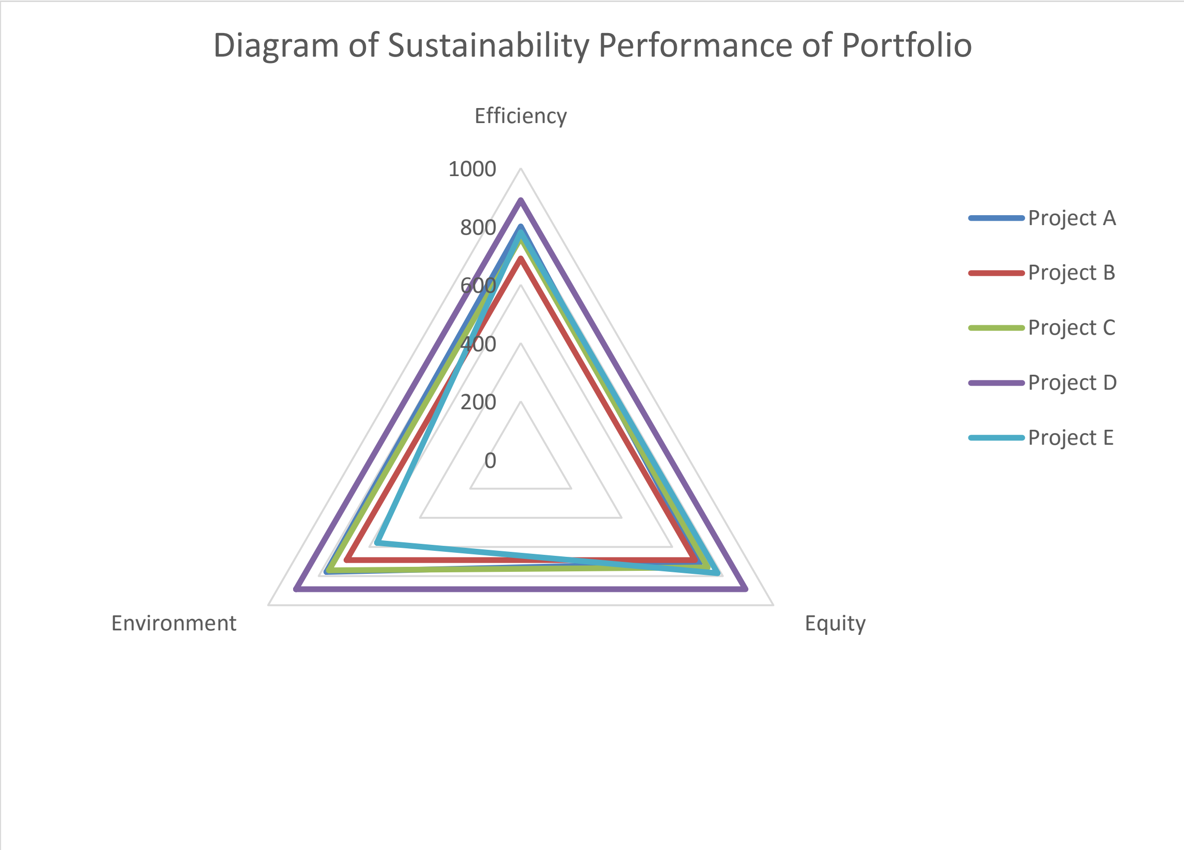

Figure 5-3: Diagram of Sustainability Performance of Portfolio

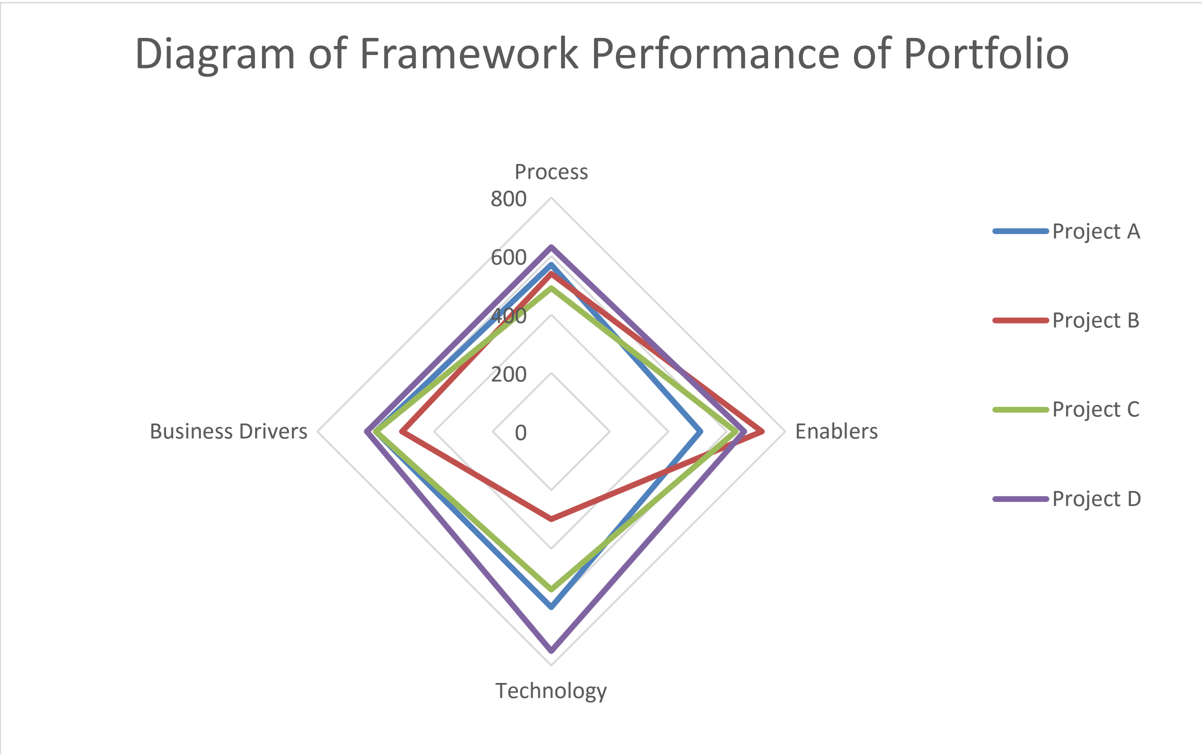

Figure 5-4: Diagram of Framework Performance of Portfolio

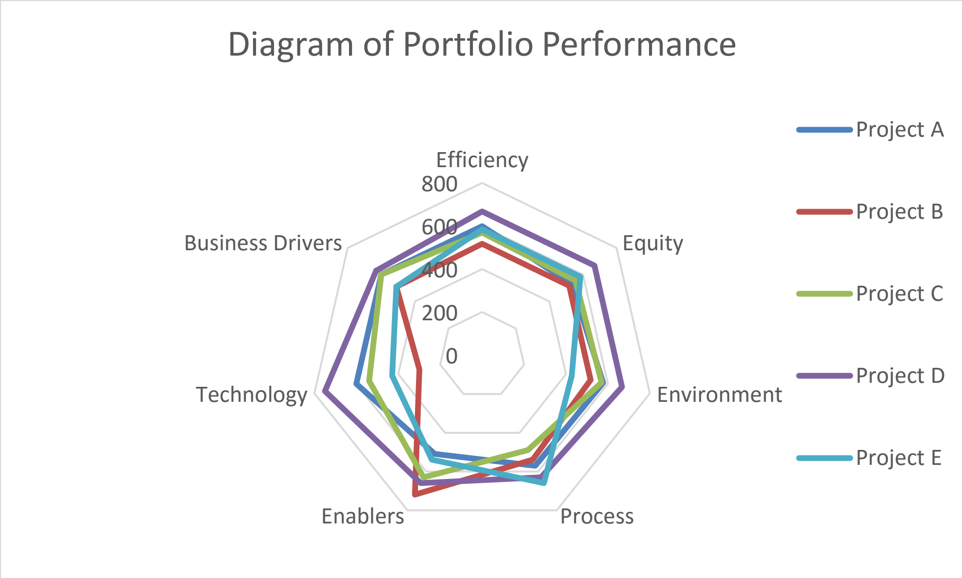

Figure 5-5: Diagram of Portfolio Performance

Discussion of the example

The example presented is now considered in terms of its strengths and weaknesses. A wide spread of final figures is seen in the summary table (Table 15) ranging from 570 to 890 for sustainability and 430 to 750 for performance to the framework. Maximal scores available are 1080 for sustainability and 810 for compliance to the framework. The results indicate the portfolio has a wide spread of performance over categories and is certainly not optimal in any area. However there is strong individual performance of projects in specific areas, as seen by some of the high scores achieved. There is scope to improve the overall portfolio performance and that of the individual projects.

Consider the sustainability performance as shown in **Error! Reference source not found.**3-3; it ighlights that the overall performance is strongest for efficiency and weakest for environment. Environmental performance also has the widest spread of results (shown well on the spider diagram) which indicates this area of performance requires improved stability. Of the projects considered project D has the best overall performance with project B the worst overall performance.

Looking at the assessment to the framework, the strongest performance is in enablers whilst the weakest in technology. Technology also has the highest variance in the results shown well in Figure 3-4 and 3-5, the technology performance is the least consistent of all factors. For individual projects the performance mirrors that of the sustainability, project D has the best performance with project B the worst. In particular for project B, the score in technology and business drivers is comparatively low.

Combining the view of framework and sustainability, Figure 3-5, shows the performance in sustainability is notably more stable than the framework. The combined view also highlights the performance of project B being quite inconsistent with a very strong enablers score and poor technology score. Project D in this view is clearly the best performing projects across all factors.

Using the data some decisions can be guided. In sustainability performance more effort is required in environmental performance. Consider enablers, in which performance in environmental aspects is low. This could be addressed through increased use of design for the environment, design for end of life and life cycle analysis. If these are not completed for the projects then they should be done so with priority.

The performance in technology is also comparatively weak. Consideration of the technology strategy and how it is being achieved should be considered at this point. Is the strategy too challenging? Looking at the data points, the differentiation performance is consistently the best area of performance. Additional focus on new technologies and intellectual performance would improve the technology performance.

A further question that should also be considered is whether the project is right to continue with? Project B looks questionable. It has poor performance on overall sustainability and specifically business drivers, technology and application of lean tools. The team working on project B should be informed of the result and in particular to consider how the project could be improved. The next gate review would be critical for the project. The project is at a concept stage and thus limited amount of resourcing has been expended. It would be better to take a decision to stop the project at this stage than to carry on. The risk is that as it is at concept stage, is not enough information has been found on the project. There might be something which drastically changes the performance of the project.

Results of individual project assessment

Project A

		Process			Enablers			Technology			Business Drivers			
	Weighting factor	Lean tools	Gate checklist	KPIs	Team	Suppliers	Funding	New technology	Interlectual property	Differentiation	Performance to requirements	Business financial goals	Business strategic goals	SUSTAIN INDEX
Efficiency	10	5	7	7	8	4	5	8	8	8	8	6	6	800
Equity	10	5	6	7	7	6	5	4	6	6	8	6	5	710
Environment	10	7	6	7	4	7	5	6	7	7	8	6	7	770
Total weight		170	190	210	190	170	150	180	210	210	240	180	180	

Process		Enablers		Technology		Business Drivers	
Process	570	Enablers	510	Technology	600	Business Drivers	600

Project B

		Process			Enablers			Technology			Business Drivers			
	Weighting factor	Lean tools	Gate checklist	KPIs	Team	Suppliers	Funding	New technology	Interlectual property	Differentiation	Performance to requirements	Business financial goals	Business strategic goals	SUSTAIN INDEX
Efficiency	10	3	6	9	8	8	8	4	2	4	7	5	5	690
Equity	10	3	6	9	8	8	8	4	2	4	7	5	5	690
Environment	10	3	6	9	8	8	8	4	2	4	7	5	5	690
Total weight		90	180	270	240	240	240	120	60	120	210	150	150	

Process		Enablers		Technology		Business Drivers	
Process	540	Enablers	720	Technology	300	Business Drivers	510

Project C

		Process			Enablers			Technology			Business Drivers			
	Weighting factor	Lean tools	Gate checklist	KPIs	Team	Suppliers	Funding	New technology	Interlectual property	Differentiation	Performance to requirements	Business financial goals	Business strategic goals	SUSTAIN INDEX
Efficiency	10	6	7	4	6	7	8	7	5	6	7	7	6	760
Equity	10	4	7	4	6	7	8	7	5	6	7	7	6	740
Environment	10	6	7	4	6	7	8	7	5	6	7	7	6	760
Total weight		160	210	120	180	210	240	210	150	180	210	210	180	

Process		Enablers		Technology		Business Drivers	
Process	490	Enablers	630	Technology	540	Business Drivers	600

Project D

		Process			Enablers			Technology			Business Drivers			
	Weighting factor	Lean tools	Gate checklist	KPIs	Team	Suppliers	Funding	New technology	Interlectual property	Differentiation	Performance to requirements	Business financial goals	Business strategic goals	SUSTAIN INDEX
Efficiency	10	7	7	7	7	7	8	9	8	8	6	7	8	890
Equity	10	7	7	7	7	7	8	9	8	8	6	7	8	890
Environment	10	7	7	7	7	7	8	9	8	8	6	7	8	890
Total weight		210	210	210	210	210	240	270	240	240	180	210	240	

Process		Enablers		Technology		Business Drivers	
Process	630	Enablers	660	Technology	750	Business Drivers	630

Project E

		Process			Enablers			Technology			Business Drivers			
	Weighting factor	Lean tools	Gate checklist	KPIs	Team	Suppliers	Funding	New technology	Interlectual property	Differentiation	Performance to requirements	Business financial goals	Business strategic goals	SUSTAIN INDEX
Efficiency	10	5	8	9	7	6	8	5	5	6	8	6	6	790
Equity	10	5	8	9	7	6	8	5	5	6	8	6	5	780
Environment	10	5	8	9	4	4	4	3	5	3	4	4	4	570
Total weight		150	240	270	180	160	200	130	150	150	200	160	150	

Process		Enablers		Technology		Business Drivers	
Process	660	Enablers	540	Technology	430	Business Drivers	510

Results of Sensitivity Assessment

Base Case

Base Case

	Efficiency	Equity	Environment	Process	Enablers	Technology	Business Drivers	Totals
Project A	800	710	770	570	510	600	600	4560
Project B	690	690	690	540	720	300	510	4140
Project C	760	740	760	490	630	540	600	4520
Project D	890	890	890	630	621	750	630	5301
Project E	780	780	570	660	540	430	510	4270
Totals	3920	3810	3680	2890	3021	2620	2850	

Increase scores on environment line by one point

Increase score on environment by 1 point

	Efficiency	Equity	Environment	Process	Enablers	Technology	Business Drivers	Totals
Project A	800	710	890	600	540	630	630	4800
Project B	690	690	810	570	750	330	540	4380
Project C	760	740	880	520	660	570	630	4760
Project D	890	890	990	660	690	780	640	5540
Project E	780	780	690	690	570	460	540	4510
Totals	3920	3810	4260	3040	3210	2770	2980	

Decrease scores on environment line by one point

Decrease score on environment by one point

	Efficiency	Equity	Environment	Process	Enablers	Technology	Business Drivers	Totals
Project A	800	710	650	540	480	570	570	4320
Project B	690	690	570	510	690	270	480	3900
Project C	760	740	640	460	600	510	570	4280
Project D	890	890	770	600	630	720	600	5100
Project E	780	780	450	630	510	400	480	4030
Totals	3920	3810	3080	2740	2910	2470	2700	

Increase score on process by one point for all projects

Increase score on process node by one point

	Efficiency	Equity	Environment	Process	Enablers	Technology	Business Drivers	Totals
Project A	800	710	770	600	510	600	600	4590
Project B	690	690	690	570	720	300	510	4170
Project C	760	740	760	520	630	540	600	4550
Project D	890	890	890	660	621	750	630	5331
Project E	780	780	570	690	540	430	510	4300
Totals	3920	3810	3680	3040	3021	2620	2850	

Increase score on technology by one point for all projects

Increase score on technology node by one point

	Efficiency	Equity	Environment	Process	Enablers	Technology	Business Drivers	Totals
Project A	830	740	800	570	510	690	600	4740
Project B	720	720	720	540	720	390	510	4320
Project C	790	770	790	490	630	630	600	4700
Project D	920	920	920	630	660	840	630	5520
Project E	810	810	600	660	540	520	510	4450
Totals	4070	3960	3830	2890	3060	3070	2850	

Increase weighting from 10 to 15 on environment

Change environment weighting from 10 to 15 on all projects

	Efficiency	Equity	Environment	Process	Enablers	Technology	Business Drivers	Totals
Project A	800	710	1155	670	590	700	705	5330
Project B	690	690	1035	630	840	350	595	4830
Project C	760	740	1140	575	735	630	700	5280
Project D	890	890	1335	735	770	875	735	6230
Project E	780	780	855	770	600	485	570	4840
Totals	3920	3810	5520	3380	3535	3040	3305	

Increase weighting from 10 to 20 on environment

Change environment weighting from 10 to 20 on all projects

	Efficiency	Equity	Environment	Process	Enablers	Technology	Business Drivers	Totals
Project A	800	710	1540	770	670	800	810	6100
Project B	690	690	345	720	960	400	680	4485
Project C	760	740	380	660	840	720	800	4900
Project D	890	890	445	840	880	1000	840	5785
Project E	780	780	285	880	660	540	630	4555
Totals	3920	3810	2995	3870	4010	3460	3760	

Increase weighting from 10 to 25 on environment

Change environment weighting from 10 to 25 on all projects

	Efficiency	Equity	Environment	Process	Enablers	Technology	Business Drivers	Totals
Project A	800	710	1925	870	750	900	915	6870
Project B	690	690	345	810	1080	450	765	4830
Project C	760	740	380	745	945	810	900	5280
Project D	890	890	445	945	990	1125	945	6230
Project E	780	780	285	990	720	595	690	4840
Totals	3920	3810	3380	4360	4485	3880	4215	

Appendix 7: Interviews Conducted with Product Development Experts

Innovation Survey							
			Response				
Question No.	Category	Question	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5
Q01	Scope	Have you changed your innovation process recently?	Yes from a development organisation to a true R&D organisation. Which means adding pure research.	Yes set up a European businesses and R&D department.	Yes why brought in	Yes just started the process.	Five years ago we made a major change to how we conduct product development.
Q02	Scope	How long have you been using your current process for NPD	Innovation in its own right not embedded yet it's been in process 2 yrs.	Running for 8 years	2 years	The process that is to be replaced has been in place something like 10 years.	Five years. I'm not sure how long the previous process was in place for.
Q03	Scope	How many people are directly involved in the NPD team	55 people in total	80 (start base was 4 people)	6 in the team and indirectly 12 more research side had support from a main research group. This was a small business arm within the company. Sales and Product managers accounted for 30 people.	In my direct team which is a specific area of R&D there are 10. There are five similar teams working in different areas.	In the whole company, many, I think 300 plus. The team of engineers on this type of product is 32. I guess out the whole company is probably 80% engineering.
Q04	Scope	What is the split of the team technical R&D/other functions	Pure technical. The innovations team is placed to a product management who then find the business case/product to place the innovation	Yes, it was insisted that the team included a marketing group of 4 people. Made interesting discussions on market analysis, which was a source of conflict.	Team had been formed from the acquisition. Originally technical people, but very business focused as had worked in small business. NB think they know mkt better than sales. Multi hat wearing was common.	Out of the 10, 7 are engineers, 1 marketing, 1 business development, 1 project manager.	On a project we get a mixed team. Each project is assigned a marketing person, sales representative, production, purchasing, quality etc. That's all worked out per project.
Q05	Scope	Do you use portfolio management as part of the decision making process in NPD	Yes but not part of the innovation process in product planning. Looking more for gaps in innovation.	Yes an essential part of the process. Used a 6 criteria fit for assessment with a 1-10 rating assessment used. The requests for additional funding would be identified to improve the weakest points. It was a struggle to get the assessments done "getting a feel" was a challenge. Ended up training significant amount of people through a screening process then had to present a presentation for funding. Also conducted role plays with "expert" interviews. Funding presentations were Dragon's Den style. Driven comfort zone decisions.	Yes - was part of the change. Simple system semi formalised in an excel sheet with StageGate(R) process. But no rigour in decision.	We have a good feel for the projects so it's not a specific part of the process, but we are aware that we choose a balance of projects and prioritise returns.	Yes, there is a long term plan for product portfolio which then feeds into the development plan. Then everything is reviewed by steering committee every quarter and resource adjusted depending on progress.

Q06	Scope	How many project are typically running	25	70 (5 were large projects))	Amnesty held on 50 projects. Many were stopped. Now 30 is more common.	About 3 to 5.	It's something like 30 projects. 5 major new products then a lot of smaller upgrades and improvements.
Q07	Scope	What is the value to the business?	Targets are set in value of return and costs are looked at per project. Cost of development plus benefit per part produced is considered.	Used NPV with risk adjusted NPV for stage gate. Risk adjustment was about 40 m Euro from a spend of 16m Euro. But post project review found 1/4 justification of results	Not clear in value. But measured in product volumes - aim was 2000 units more of the product.	The projects are valued at about €0.5m to €3m each.	Oh the return for the work, multi millions.
Q08	Trends	Is there an increasing application of advanced techniques such as modelling, RPT, VR	Europe yes, Japan no. Which is frustrating.	In chemicals yes in advanced polymer science modelling. No VR.	Not in this industry. See some opportunities, but historical reasons. Still a dirty practical industry which you don't need huge technical competence to get going. Still very evolutionary.	We use engineering simulation tools right from the start. There is a lot of virtual assessment of the product before making a prototype.	Yes and increasingly so, virtual reality is being applied more and more. That really helps gets everybody's ideas together.
Q09	Trends	Is there an increasing application of methodologies such as the lean tool set and sustainable development	In centralisation yes, for idea gathering in particular plus introducing management of ideas. Moving towards globalised systems	Not really. Use of FMEA was sort of done. Tolerances was the important review section.	Not well used. Applied for the gates in time during NPD.	Environmentally we are always looking for the best materials and manufacturing methods. It's not exactly prioritised but the engineers think about it. Same with lean we try and apply some tools.	The development projects always have environmental targets. They tend to follow a strategy of sustainability. I wouldn't say it's perfect but sustainability is defiantly thought about. Lean on the other hand is just something we do, it's been about for a long time.
Q10	Trends	Is there more effort spent in the disruptive field of innovation than in recent past.	Yes as sales are reduced and sales features have changed from car based to electronics based.	Analysed that competitors were scrambling over smaller and smaller niches. This was at odds with the strategy to produce on a large scale. Therefore the strategy turns to 8 chemical areas to develop new business areas. So most of it was this was a change.	Spending about 10-15% on real new products rest was in product support and customisation. Then separated team for customisation and product development. Had to change the ways of working and working times.	Yeah the board is asking for that. It's a bit hard to say we will run x amount of disruptive projects but we try and identify them.	Do you mean game changers (interviewer clarified yes)? Yes we have a set of projects looking at next technologies and how to be disruptive. It's almost a separate team.
Q11	Trends	Is there an increase in the use of collaborative tools internally and externally within NPD	SharePoint yes. Plus centralisation of ideas with an internal tool. These tools would not be used externally.	Shared the process with all the teams. Training above enabled a common vocab. Shared data bases, video etc. all used. But it was crucial to get people in the same room. Care was in multicultural teams used a crossover of position to ensure there was no misunderstandings .	Spreadsheets were there as some collaborative tools. Cross functional monthly weekly meetings really helped for prioritisation. Applying more rigor in their request process.	We do a lot of partnered development so we have a file sharing platform and a sharing conferencing system. Still it's good to do face to face meetings which is ok with the local partners.	Yes we have a product development platform which holds all the information on the project. But this is not shared externally. That has to go through a document referral system.

Q12	NPD Change	How are changes to your NPD system managed?	Part of the change was a resourcing requirement to move to Europe and set a team in Europe. A position was created to look after the change process to a research organisation.	Kotler's 12 steps to change. Focus on conversion of by-standers. Therefore 70% training.	Change was managed by a project. Classic approach issue (scope) - waste - eliminate - implement. Started with board. NB even went back to defining what a project is (stepping out of the norm to do something different - had to dedicate several project days). Very systemised and planned. Very much about aligning. Explaining people were doing their best but in a wrong direction.	Its more introducing new things to do at the moment rather changing what we do. I guess if we did a big change again we would use our management of change system.	All change goes through our changes system. Quite time intensive but it's strict and makes sure everything is validated off line before its implemented.
Q13	NPD Change	Are there differences to making changes within R&D to other types of changes and therefore is the change management system applied suitable?	Yes as other functions have different focus. E.g. change to production would go through many more reviews completely different process	Change management systems are suitable but need to conduct a skills and gap analysis. For example is it worth training the PhDs to do discounted cash flow analysis. Largest change was moving to multifunctional teams with 80% technical.	No should be the same and used the same process for change in other areas of the business	Not sure really, for us we all just get on-board change.	No we just manage change in the same way, its time intensive but it works.
Q14	NPD Change	Is the success of changes in NPD measured? If so how.	No. Ideas are measured. But not particularly as targets. No KPI is applied.	Key measure was risk adjusted contribution margin.	I was measured at a target level of 2 releases per year.	We didn't exactly measure the effects of the change. But we are defiantly making better products now and much faster.	Yes the major change we did reduced the lead time by 20%. It was all done to speed up development.
Q15	NPD Change	Have changes to your own NPD process been successful	Yes, creating more ideas now	Yeah in terms of delivering a 300% return. Difficulty was stealing the thunder of the commercial team.	Appears to have been successful. Meeting target.	Defiantly it's a much more creative approach now. That's helping the sales team offer differentiated products in the market.	Yes we have one of the best product development processes in the industry and it's helped us continue to grow.
Q16	NPD Change	What was the most significant barrier to changes in NPD?	Resource changes and finding new talent. There is a fixed allocation of resoucre which has to be balanced with the development requirement.	Power was the major barrier. Needed the CEO to clear up a few areas of conflict.	CEO and board was the largest barrier and resistor to change. Said the right things to start with, but struggled to support with poor behaviour.	I think there was still a bit of the old guard approach. Took a bit of time to convince everyone.	There were problems in the details like how to transfer documents into the new document system. Lots of details.
Q17	NPD Change	Does a focus on disruptive innovations aid or create a barrier to changes in NPD	Yes these are generating barriers e.g. no confidence in quality higher risk.	It was aiding to make changes as was avoiding clash with current market areas	Focusing on substituting products does help to make the change.	Interesting question, I think we have to always be thinking about the next big thing in the industry. So I guess it helps drive product development.	It's sort of a separate team and process for game changers so it's not really effecting other work.

Q18	NPD Change	Is the working environment (layout/facilities) an element to consider during changes to NPD? Can environmental change encourage changes in culture.	No change, still using silos. Looking into change mainly due to split of resourcing (only 5% in innovation).	Yes - there was a new location. Deliberately not alone and mixed up teams. Placed marketing team in the centre.	Purely work process changes. Wasn't like the team were lacking means. Yes environmental change can help change culture. Seen that in the way the team developed from past. Often really helps to re-set the working culture.	We didn't significantly change the area, I think the office area is pretty attractive anyhow. As it's quite a creative place I think the development team can get on and not feel out of place. Other locations are a bit different, I guess this one is the nicest.	We changed the layout of the office, loads of new kit. It looks great and I guess that has helped the atmosphere.
Q19	NPD Change	Have the changes made in NPD systems evolved the culture within the NPD team?	Globally no. The teams have flexed into innovation then development.	Yes it helped. The training course was the nucleus of change.	Yes it changed their culture that then spread out to whole of the business area. And was fundamental to be changing the business.	Yes some of the old guard are now much more integrated with the team.	Not significantly we have a better focus.
Q20	NPD Change	How long does it take for changes to become embedded?	Cost will drive the time - if it is needed in 6 months it's a priority, if not its low priority.	2.5 yrs.	Can't say they were ever embedded. A number were company culture.	I would say it took us over a year to be really working well.	The system was implemented over a year then we took about 6 months validating the process.
Q21	NPD Change	If you could make one change to the way changes were made what would it be?	Would reconsider the funding element. Too politically dependant on the development. Reduces the freedom on the research. Funding is only there for relatively certain projects.	Would go back to the board and find a way for them to believe the strategic criteria in their heart. It was there in the mind, and they were told what it was. An approach could be used so that they would develop the criteria.	Frankly nothing was brilliant. I would have secured availability of one of the directors who had a dual hat more as it resulted. But the largest implementation challenge was in production. I would have tried to avoid changes in the board. Or spending more time with CEO and changing his way of work.	We should have had all the team together in the first brainstorming. We got everyone together later, but earlier would have helped.	Nothing major really, there was a lot of planning so it was quite smooth.
Q22	NPD Personnel	Is the team within NPD generally stable, is there a significant turnover in staff (what is the strategy).	Defiantly not, its set project by project and changes during the project.	As projects went into production, discussion were held on what technology goes with the project and this also included personnel. Became a transition ground for people wanting to move in the organisation.	All stable lifeforms. There was a problem in driving the changes through. They were less susceptible to change. And I would have liked to bring in outside talent.	Pretty stable we've introduced a few new people.	There is changes in the management but a lot of the engineers have been in the same position for quite a few years.
Q23	NPD Personnel	How would you describe the characteristics of the team?	Yes they are available. And they are KEEN.	Used Belbin. One of the reasons why training worked.	Very professional team, bit of arrogance, knew they were experts and set in their way. Passionate in the products. Frustrated in priority changes and knee jerk "fictitious" changes. Quite prickly can be argumentative.	Creative, intelligent. Good bunch.	Efficient, certainly they do a lot to get these projects done.

Q24	NPD Personnel	Do these characteristics aide to assist or resist change	Yes the keenness really helps the motivation.	Could clearly see when didn't complete the Belbin roles there were many more issues.	Initially resistive. But if can tap into the passion it can really aide it. Getting them to understand that the change in business was tough going.	I guess assisting, they'll point out if it does not make sense.	I don't think resistive. When we decide to change we know what to do and get on with it.
Q25	NPD Personnel	Do you find the cultural characteristics within the NPD teams reflective of the rest of the company or does it differ?	In the European staff yes.	No had much higher levels of satisfaction. Different culture very relaxed and participative.	Differs but find some similar characters.	Yes it is quite reflective, lots of creativity.	I think so they are diligent, and work with the process and documentation well. I guess more challenging, in they ask more questions.
Q26	NPD Personnel	Is there an impact of generation C (connected generation) personnel within NPD team	A lot of research is bought in and the suppliers have more of the Generation Cs. So don't see the affect yet.	Diversity is essential. Chemists look for a chemical solution but often the mechanical engineers fix was simpler and cheaper. The difference will be that it takes several years to understand what is happening, this will be a challenge with Gen C to keep them occupied while they develop the understanding. Failure rate is 50%.	Can't envisage it. Won't have a huge influence on the ways of working. Don't think it will be a fundamental change to others in the teams. The type of research teams won't attract many of the gen C characteristics because it is more detailed research. Would possibly affect. But Gen Cs in sales org would be very different e.g. relationship building is poor in Gen C.	We have a few recent graduates, if that's what you mean? They are a bit different, but we have paired them up with the more experience guys.	The team hasn't had new starters for some time, they have been going into other areas of the business to gather experience.
Q27	NPD Personnel	How is the career planning of team members within NPD handled	Don't do career planning as ad-hoc team so it's not in this process. But no difference within the company. Same measurement systems.	Training was different but otherwise the same process. No system for planning in place.	Nil. People had moved in and out to product mgmt. and to business mgmt. but in distant past. Missed opportunity to not screen new talent, but care required to place them in the team. Should have encouraged the tech expertise sharing within the company. A view on career enhancement would have been good including recognition for expertise. There was limited recognition with the white collar workers when they do something special.	Much like everyone else.	Just like everyone in the company, they have a 1 year plan. Then the senior team are looking 5 years out and working out who has potential.

Appendix 8: Sustainable Product Development Methodology Implementation Assessment sheet

Assessment sheet for current product development processes

Node	Best Practices	Assessment
Process	Stage-Gate® Lean tools Standard documentation Standard processes and checklists Key performance identifiers used	
Enablers	Multifunctional team Integrated activities with suppliers Funding assigned per project and per stage Portfolio reviews conducted	
Technology	Advanced engineering techniques employed Technology road map used Intellectual property strategy defined Intellectual property landscapes used Technology differentiation to competitors (in product and process)	
Business Drivers	Strategic goals for business performance set and development projects aligned Performance to strategic goals measured Clear financial goals set for project performance Financial assessments made for product performance with sensitivity analysis	
Sustainability	Environmental goals set for product development Actions taken to promote fairness in employment and the entire supply chain Efficiency goals set for the organisation and continuous improvement conducted	

Appendix 9 Case Studies

In the following sections a fuller report of the case studies is presented.

Case Study 1: Additive Layer Manufacturing

In this case study application of an additive layer manufacturing process is applied to the development of a cylinder valve guard. Observations on this technology determine that the while the process has been used for many years, since the 1980s, it is only recently that it is being adopted (Bird, 2012). A main aspect of the recent surge in use is the ability to deliver products rapidly without the need for tooling. Drawbacks are identified in the material properties, surface finish and scalability. With these properties the process is ideal for prototyping and small scale manufacture (in particular if the design intent is highly customisable).

The chosen application is the design of a cylinder valve guard, Figure 6 shows a typical product. The current design process is outlined in Figure 7, typically taking 11 to 17 months. The process has no feedback loops and takes a high risk strategy of committing to tooling with limited performance knowledge. As the product is structural it must conform to strict standards (ISO 11117 (International Standards Organisation, 2012)) so the risk of failure is high. Issues meeting the expected standard are often owing to making best estimates of performance with limited calculations. The failures in process are apparent, consider the wide range of typical project timescales (6 months). It was also observed that the process is often conducted at the end of the cylinder valve development process which adds significant time pressure to those involved in the development of the guard. In these cases the process is undertaken in order to have a product launched as quickly as possible.

Figure 6: A typical cylinder valve guard

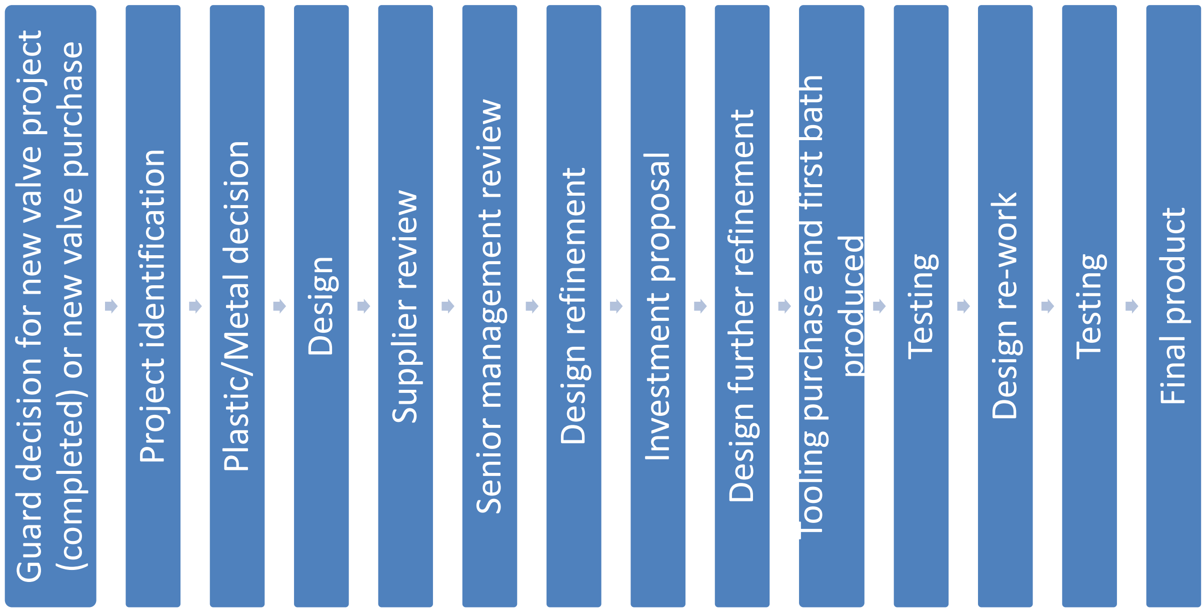

Figure 7: Cylinder valve guard development process

The opportunities for improvement are in the time to execute the project, the use of feedback loops to improve design with customer feedback, and the optimisation of performance and cost. The expected benefits are very much in-line with benefits seen in other applications of additive layer manufacturing (Gibson, Rosen, & Stucker, 2015). The one area not expected from this project but is quite typically explored in additive layer studies, is customisation of the design to specific needs. The reason this technical benefit is not explored is mainly due to the application, gas cylinders users expect products to be same each time they use them. Currently there is not a market for customised products, additionally products are used by many different end users over its life (often 10 years). Although it would be interesting to investigate the potential opportunities in customisation it was deemed to be introducing a variable to the process that could affect the goals of the project. Furthermore, it was not expected to use the additive layer process to produce production parts as the material properties are not good enough (as a structural plastic), and the process costs would be too high.

The design process was then evaluated and ideas brainstormed into the required steps for a process using additive layer manufacturing. In this review opportunities for time reduction were identified in either removing process steps, reducing the time of the step or using an alternative process instead. A new process was created and is shown in Figure 7. In comparison to Figure 8, overall there are three fewer process steps, even though there have been three new process steps added. The new processes added are project specification, voice of customer and prototype. These steps provide feedback opportunities and check points to the process. The intention is that clearer goals are identified and achievement of the goal is monitored. The removed steps from the original process involve, less design time down-stream, planned re-work and upfront material decision. These activities are either not necessary (downstream design work and rework), or become part of another process (material decision is now in the project specification, design and prototype stages). The overall estimated time for the new process is 7 to 8 months, a reduction of between 36% and 53%, but also importantly a lower spread of expected time (due to not re-setting tools at the end of the development).

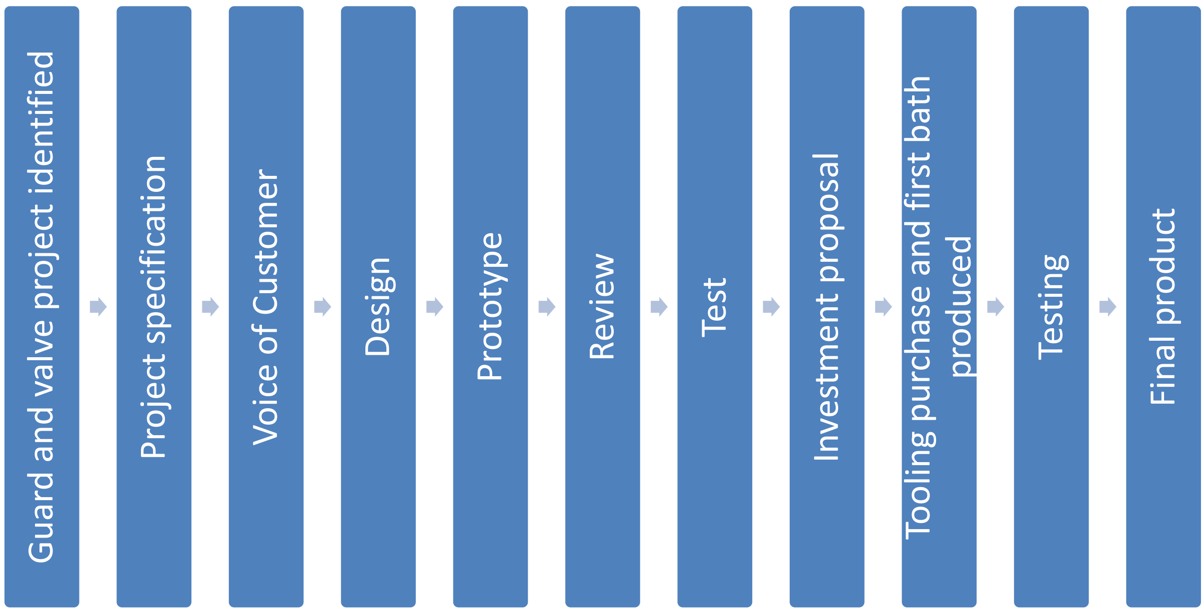

Figure 8: New process for cylinder valve guard development

The project was undertook setting an initially wide specification for the product which identified the end customer (and their application) along with key parameters (such as cylinder size and valve). With the main boundaries in place a voice of customer exercise was conducted using a survey and building a mood board. This information was then presented to an industrial designer who was tasked with creating a number of concept drawings. Ten concepts were produced and following review of the concepts one was chosen to manufacture by selective laser sintering (SLS) of plastic. The chosen concept was based upon a short survey of the research and development, main users and decision makers. The concept was highly different to known designs are in the market place and proposed a radical system of using two fasteners to join the two half's of the product together. Currently upwards of four fasteners are used with six being commonplace.

The prototype was built and used to gather further feedback on from customers and internal teams such as marketing, supply chain and operators. In the review session it was noted that the physical prototype enabled a greater detail of review than using three dimensional representations. The following areas were particularly discussed:

- Size of apertures
- Ergonomic aspects of egress and handling
- Assembly procedures
- Maintenance
- Tolerances and fit
- General properties such as weight, colour and overall dimensions
- Effect of colour in the design and branding
- Cost and areas of the design that impact cost of manufacture (for example split lines)

The additive layer model did have some drawbacks in its surface finish, colouration and loss of some design details. These drawbacks were expected, and are the general technical challenges additive layer manufacturers are trying to address. The feedback gathered was highly important and used to create a final concept. For instance the access to the fill valve was increased to address concerns of ergonomics, maintenance and safety. At this stage the design was also developed for performance using a finite element model to replicate the tests in ISO 11117 (International Standards Organisation, 2012). Following the design updates a test set of twenty guards were produced. These would provide a representative product to test with. Twelve were used in customer testing and six in physical testing. The customer testing focused on the ergonomics and visual appeal. Along with customer testing supplier engagement was conducted too, using the parts for discussions on manufacturing. The physical tests conducted were in line with ISO 11117 (International Standards Organisation, 2012) and completed using high frame rate video capture. The video capture enabled a comparison to the finite element work conducted in order to validate the model using an appropriate.

The feedback gathered highlights a number of benefits from using this process, these are summarised below:

- The assembly of the radical concept (using only two bolts) worked but some further design for assembly would enable an improved assembly time
- Plastic injection moulders had concerns of shrinkage which some additional ribs would solve
- Minor draft angle improvements would improve release from the mould
- The material properties of the rapid prototype models was far below that of the actual design intent material (a UTS of 35 N/mm2 was found as opposed to 60 N/mm2)
- The impact behaviour followed the finite element model in the initial stages of impact but subsequent deflections were following a buckling behaviour due to the significantly lower material properties
- Customers loved the aesthetics of the design but questioned if it was tough enough
- The importance to the customer of certain features was underestimated, such as product colour coding

From this feedback steps were taken to produce a final design with identified design improvements conducted and the finite element analysis model validated as far as possible and updated. Other activities in supply chain, procurement and other shared serviced were completed. Also in order to hold a gate meeting (following the Stage-Gate® model (Cooper R. G., 2008)) a clarity in process and attire was instructed. Though testing and had positive modelling result to show compliance to standards. The product had been designed for manufacture and assembly. The finite element model was not fully validated due to the material properties of the rapid prototypes not being representative of real material, the rapid prototype properties were used in the model to enable a good degree of validation. The time to complete the project was estimated with a low uncertainty, mainly reliant on the tooling although the manufacturer of this was now well informed and was well prepared. Furthermore the costs to complete the project (tooling, initial batch production, type testing) were well known as were the final product costs. Without using the rapid prototyping techniques this information could not be wholly found. The steering committee approved the project towards production.

The end product passed its ISO 1117 (International Standards Organisation, 2012) tests first time, and the project ran to time and costs. The initial customers all gave positive feedback on style and ergonomics. Overall the programme took 7 months, which indicates lower timescales can be achieved with repetition as in this work many of the methods had to be developed during the execution (for example the design process and the finite element model).

Summary of Case Study 1: Additive Layer Manufacture

Considering the initial goals for the project it can be considered as a successful application of new technology to the industrial gas sector. Review of the proposed questions of the technology and the findings is shown in Table 16.

Question	Findings	Drawbacks	Further work
Can the technology be applied to the industrial gas business?	The case study shows the technology can be applied successfully to the industrial gas industry	Improvements in material options, material properties and surface finish are desired and would extend a potential buyers view (e.g. in gas equipment)	The work did not investigate if the technology can be applied for production parts.
Are benefits seen in the application and are these benefits similar to those seen in other industries?	Yes the technology delivered, richer design reviews, an improved product, reduced timing and reduced overall costs. These are all typical benefits.	The cost of technology meant expenditure in the design phase was much higher than in previous similar projects. The prototypes were seen as being virtually real products by senior managers which lead to expectations of very short lead times.	It would be interesting to see if the magnitude of the benefit is similar to experiences in other industries.
What is the likely uptake?	Highly likely, the technology enabled a much easier approval to advance the product.	A barrier to uptake may be the cost of parts.	Replicate the process.

What are the specific challenges experienced and anticipated, and are these similar to other industries?	Material properties were an area of challenge, along with surface finish. These are similar challenges faced in other industries.	The material properties resulted in an incomplete validation. The surface finish meant that post manufacture process were required increasing costs.	It is likely that continued work with material and manufacturing process will result in improved qualities.

Table 16: Table of findings for additive layer manufacturing application

In addition to the findings presented in Table 16 the work developed a new process for development of cylinder valve guards. The process integrated the technology and it is using this that tangible benefits are found, such as in time. While the product itself was innovative and lead to a registration of the design rights and a patent application on a lifting mechanism, it is the process that enables the innovation. Additionally it is thought that this is the first time additive layer manufacture has been integrated into the design process for an industrial gases product. Although the process is not highly innovative, as it is similar to other industry applications of the technology, it is novel and has provided the opportunity to be innovative.

As identified in Table 16, there is some further work that can now be conducted. A key element of this is to repeat the application and prove that the process is consistently delivering similar or improved results. Continuous improvement of the process is also expected in areas such as market feedback, it is likely that with experience the process could be streamlined. It is also expected that developments in the technology, in material properties and finish shall provide incremental improvements to the process in costs and time. The finite element model developed was validated partly, this can now be fully validated from the testing of real products.

Considering the results it would now be of interest to investigate if the magnitude of the benefits and challenges experienced in this project are similar to other applications and with repeat application in the industrial gas sector.

Case Study 2: Virtual Reality

Virtual reality is a technology that enables a computational graphical representation of objects/environments in as realistic a manner as possible for a user. The technology essentially provides a user experience without a physical model. The application of the method is provided in many forms, from computer games to headsets to 3D projections. Techniques, methods and applications have been possible for many years, however recently applications have become increasing popular (Vafadar M. , 2013).

Immersive virtual reality is the richest form of the technology, in this approach the user is only able to see the virtual world, and their movements or actions cause real time interactions with the virtual world (Watts, Swann, & Pearson). Such systems are well described by Figure 9. In this arrangement a central computer takes graphical inputs and user inputs and produces (at a minimum) a graphical output updated to the feedback gathered. Virtual reality has been applied by many sectors. Regular and key uses are in the following industries; military, automotive, aerospace, medical, and entertainment (Abulrub & Shende, 2012). In these sectors virtual reality has been successfully applied to provide the following benefits; overall time reduction to complete the project, richness of design reviews and overall cost reduction to conduct the process.

However, virtual reality is not commonplace in other industries. There are barriers to using virtual reality such as costs (from hardware, software, training and the area required) and in building the models (requires specialist skills) (Fernandes, Raja, & Eyre, 2003). Additionally, the time to implement the process can be quite lengthy as it requires new skills and time to perfect those skills (Abulrub, Yin, & Williams, 2012). A further challenge to the technology is that there is no consensus as to the best process to conduct the work (Watts, Swann, & Pearson). These challenges have resulted in a slow adoption of the technology, in particular outside of companies with significantly large budgets. *Watts et al* state the technology to be in a "pre-paradigmatic" stage (Watts, Swann, & Pearson).

The use of virtual reality within the industrial gas sector has been very limited. Only one instance was identified of using a virtual reality system. This was a study into the efficiency of an industrial furnace using an Oxygen-Fuel burner. *Freitag & Urness* explore the visualisation of burner temperature profiles in a CAVE (Automatic Virtual Environment) system (Freitag & Urness, 2002). They find efficiency benefits in reviewing the data and that there is rich information available from the data. Another work in the industry shows more advanced engineering activities such as modelling the air flow in human airways (Fodil, et al.). It was concluded on there is limited literature relevant to this work from the industrial gas sector.

Many technical challenges are identified in literature. *Vafadar*, *Bowman and McMahan* expand their work to identify human aspects that could present challenges to adoption and use (Vafadar M. , 2013) (Bowman & McMahan). First time users are identified to react strongly to the technology which may bias their opinion of the object/environment to be assessed. Less practical aspects from a design and development view are also identified, such as concepts in law and inventory.

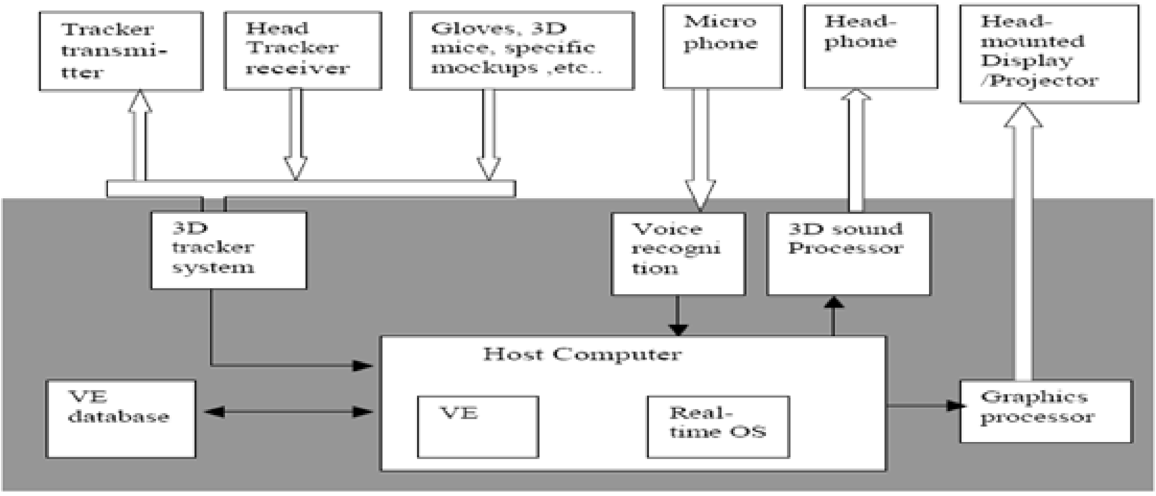

Figure 9: Overview of typical component that make a virtual reality system (Vafadar M. , 2013)

The benefits of virtual reality are well identified in the literature (Abulrub, Yin, & Williams, 2012), (Choi & Cheung, 2008), (De Sa & Zachmann, 1999), (Deisigner, Brening, Rosler, Ruckert, & Hofleman, 2000), (Vafadar M. , 2013) (Watts, Swann, & Pearson), they can be collated into the following main areas:

- **Efficiency of design reviews:** as the information presented is processed by the review team faster and agreements tend to be found quickly the resulting benefit is seen in reduced costs and time
- **Depth of discussion promoted:** due to the richer environment users see more details in the design and its context, this results in many project specific benefits but generally improved designs and reductions in time and cost
- **Quality of product:** due to the richer environment potential quality issues are easier to identify and the over quality aspects of the product (such as manufacture and assembly) are well presented through virtual reality. The resulting benefit is lower rejects and customer complaints.
- **Early application of downstream opinion:** as it is typical to review the product its application environment then consideration is stimulated to activities such as training and maintenance. It is highly beneficial in design reviews to use a cross functional team, for example including members from the supply chain, this then promotes discussions on the whole product life cycle. This should lead to design iterations that have considered downstream activities in more detail than traditional design methods.

The method of application of virtual reality was explored. It had been identified in the literature that defence, aerospace and automotive are key regular users of virtual reality for engineering design reviews (Abulrub, Yin, & Williams, 2012). The users were typical of the identified industries (large corporations holding large budgets highly focused up on research, development and technologies) that can enable improved product developments. Consideration was given to the other end of the scale in small to medium sized enterprises (SME's). The concept was that adoption outside of the large companies is necessary for the technology to become more common place and adopted by other industries (Abulrub, Yin, & Williams, 2012). Therefore small to medium sized enterprises would provide a highly challenging area. However the agility, niche skills and ability to find competitive advantage for SME's would enable potential success factors towards the general application of the technology. With literature researched three key strategies were identified for application of virtual reality:

- **Partner with a University or company who has the relevant equipment:** The investment in the required hardware and space required is unlikely to be justified.
- **Find a grant funding route for the initial project:** The initial project shall involve a high risk in the amount of design time and set up time required, the result could be that costs spiral out of control quickly.
- **Partner for skills using an SME:** An advantage of SME's is their niche skill sets, it is likely with Virtual Reality that this skill does not exist in the current team. As opposed to contracting in the resource it is recommended to train internal resource.

Skills remains a key element for project execution and longevity. Failure to secure the right skill set on the project is likely to result in a poor execution or failure to complete the project due to the highly technical requirements in the modelling. The equipment requirements are more likely to be affordable for a large company but it may not follow the company strategy or present too large a risk. Partnering is a lower risk proposal, for example an experienced partner is more likely to be able to rapidly solve issues with the equipment that could result in long delays owing to repairs being a specialist activity. Large companies may see a high risk in the design time involved being difficult to estimate and control. A grant funding route is an idea method to reduce the exposure of such risks and would be one of the reasons why such funding's would be attractive. Failure to secure a funding route could result in the project being limited in scope, for example the realism of the environment may be reduced to minimise uncertainty in the amount of design time required.

Application of Virtual Reality to the Industrial Gas Industry

Considering that there is very little application of this technology within the industrial gas industry the expected benefits should be in-line with those identified for other industries. That is

- **Efficiency in design reviews** – while the design reviews may lose some efficiency due to the inexperience of the users it shall provide an environment where decisions are encouraged.
- **Depth of discussion promoted** – similarly as above, while it is expected that the discussions could expand due to being unfamiliar with the environment it is expected that the technology shall encourage discussion
- **Improved quality of product** – it is expected that potential quality problems are identified and in particular a greater emphasis on ergonomics and product use shall result from the technology application
- **Discussion of downstream activities in the design stage** – As a cross functional team is used it is anticipated that during the design reviews discussion of activities such as operation and maintenance shall be covered and these are likely to provide design refinements.

An application for the technology was investigated with the most suitable found in the design and building of industrial gas plants in China. The concept of the overall project was to design a standard gas cylinder filling plant with add on modules for non-standard activities that could be replicated across China as part of an expansion business plan. The project had been running for some time with initial concepts of the design created. The project team was struggling to agree the best routes forward with the design, in particular with the layout. Additionally, the feedback on forecasted costs was that they were too high. In fact more than double that of local building costs. A programme was identified in which virtual reality could be used in the design of a standard gas cylinder plant and enable a lower cost design to be explored. Virtual reality presents itself as an ideal tool for this work as a *right first time* approach is essential in this case as to not replicate mistakes, therefore confidence in the design can be improved by achieving a consensus and ensuring the design is thoroughly reviewed. Additionally as a significantly lower cost design is sought, it is likely the design may challenge certain design normalities. Virtual reality provides a mechanism that ideas can be tested in a low cost approach (that is without building anything physical).

A methodology for the project was then derived using the findings from the investigations made. This resulted in the following strategies and activities:

- **Skills** – as the work is being conducted as a trial the required skills would need to be found externally. Therefore a supplying partner would be required who could provide the necessary skills. Options were considered of using a resourcing specialist or a consultancy company. The latter route was taken as it did not require investment in computational software and hardware.
- **Equipment and Technique** – as the work would be a trial there was no opportunity to invest in the necessary equipment. The University of Warwick was identified as an ideal partner who had the necessary equipment, skills to assist in the conducting the design reviews and had worked previously with the identified consultancy company who could provide the main body of design work.
- **Funding** – in order to further reduce the monetary risk exposed in the project, a grant funding was sought. As the skills partner was an SME they were able to successfully obtain a CATPULT grant. This reduces the risk of the project funding running out which was a concern as the required work hours could only be estimated due to this being a first application which would necessitate an amount of learning as the project was executed.

In addition to the above, a road map was developed showing how to advance the project in a step-wise manner. The purpose of this was to develop a set of achievable technical goals to achieve. The road map was developed in conjunction with experts at the University of Warwick (Williams, Attridge, & Abulrub, 2013). The map was built to bridge from a known starting point to the end achievement of a fully immersive and realistic design review. The work is split into five phases, four of which need to be completed to achieve the aim, a fifth stage was also identified in which a photorealistic model can be adopted live. This would mean that changes to design could be conducted during the design review, such as moving building in a drag and drop process. This last stage was identified as being best reserved to achieve with a second application of the technology in order to reduce the scope tackled in the first application which would improve the certainty of delivering the project on time. The road map is presented in Figure 10.

The process starts with a two dimensional drawing stage, which the team knew the technology for and was regularly using for design reviews. This is then built into a three dimensional parametric model, which would require the creation of a library of parts, some simple structures such as blocks for buildings but also more specialist equipment such as tanks, cylinders and valves. This would achieve a three dimensional computational model which can be converted and configured for virtual reality using several software packages. At this stage the model can be tested and refined for use with virtual reality. The stage also includes development of the design review including walk-though routes and specific areas of the model for review. These are built in at this stage so that performance tests can be completed on the software and hardware in a live environment before the model is finalised. Once a working model has been developed the last stage can be conducted which is to make the model photorealistic. This includes development of the textures, lighting and the external environment such that the model feels as real as possible. The model should be suitable for design reviews with guided tours as well as other activities such as training and process optimisation. The last stage in the process (which is not conducted as mentioned previously) would then be to then adjust the model during the design review. An identified target would be the movement of buildings along with replicating the process such as moving a forklift truck with a pallet of cylinders on it. Such options would provide a near to real experience of the plant and enable changes which could be tested far faster than in real life. For instance a cylinder store could be moved from one side of the plant to other then the process re-ran and reviewed for improvements. Such changes on an operational plant design would be extremely challenging to conduct, but highly beneficial.

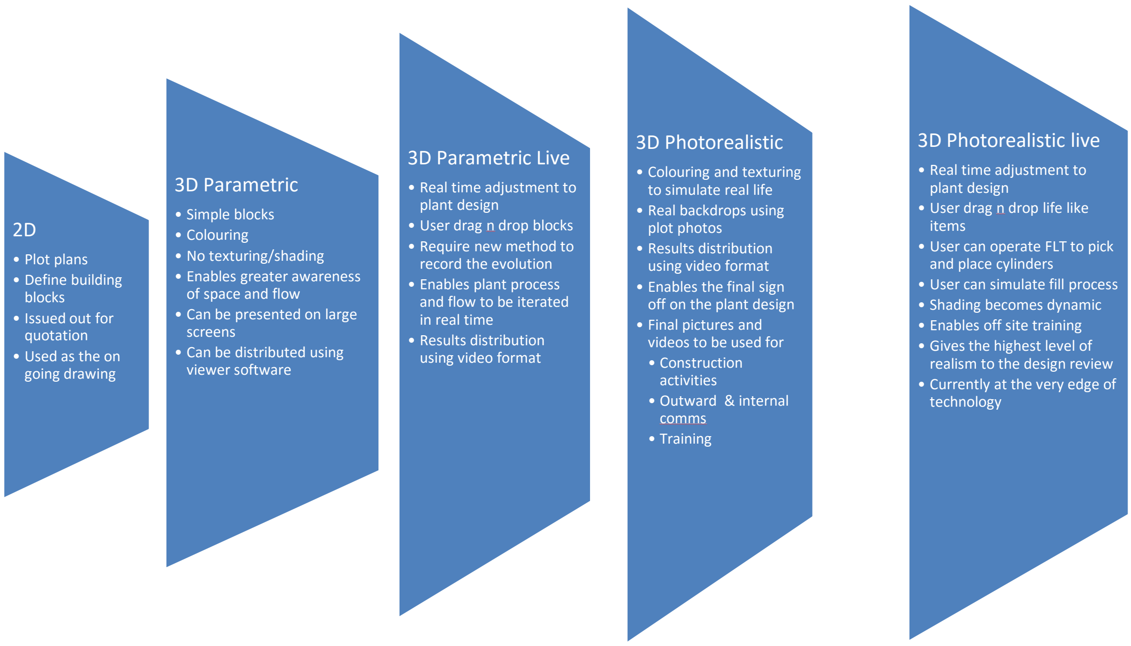

Figure 10: Virtual Reality Road Map for Industrial Gas Plants

The process was then followed using an SME partner for the design work and the University of Warwick for the virtual reality equipment and translation of the CAD into virtual reality. The redesign work to create a lower cost plant was conducted through a value engineering event. This work identified a more radical design with a single basic plant from which five options could added to expanded its capacity and/or capability. In the basic design two concepts of filling layouts were identified, which were to be tested in the design review for preference. These options were covered by a total of seven layout plans which were developed in two dimensional CAD. The proposed design reduced costs by 45% through a value engineering event, which was an excellent achievement.

With the two dimensional phase complete the development of the three dimensional CAD progressed. This focused on a library of parts, some of which were gathered from suppliers and other were developed. It was identified in the CAD collected from suppliers that some of the files contained more details than necessary for the design reviews. This included detailed internal geometries and components (for instance seals). A risk associated to this would be that the end file would contain too much detail and stretch the computing power of the virtual reality equipment resulting in slow transitions or instability.

Once a three dimensional model was complete for one of the layouts, a transfer to virtual reality and development to the 3D parametric live stage was conducted. The model conversions were successfully completed requiring only minor correction. The first tests of the model in the virtual reality environment proved to be more challenging. The model was unstable and, when running, transitions were very slow. In these circumstances the system would be useable for a design review and would not advance to live manipulation nor photorealism. The problem was analysed and identified to be associated with the complexity in the CAD geometry. The CAD geometry of a number of components was re-worked and reduced and a cycle test and rework conducted until the model was not only functioning smoothly but could be adjusted in the virtual environment too.

With a functioning model created, the design review requirements were built; this includes a general overview of the design, walking the production flow path, then a set of specific areas of the plant to review. Expected areas of change were additionally identified and tested, such as moving storage locations. This completed the 3D parametric live stage.

The last work step was then conducted to give the virtual environment realism. Specific software was required to complete this activity. The partnering option used enabled this task to be well conducted as both the University of Warwick and SME had experiences of the same software tool. The photo realism therefore developed quickly. One particular area of attention was the surrounding environment. Pictures of prospective sites in China were requested from which the general environment of neighbours' buildings, road networks and even a sky was created. Once re-tested in the virtual environment the model continued to work well.

During the development of the three dimensional models the design review structure was worked upon with expertise from the University of Warwick (Williams, Attridge, & Abulrub, 2013). A two day strategy was developed, in which the first day would be spent by a team, who had been working on the development. This would act as a test run and identify any issues or necessary improvements. The second day would involve a broad team from the decision makers on the plant design to the operational team of such plants. A technical bias was made to the second team to give some sensitivity to any problems with the technology. For any subsequent applications of the technology this first project had to be well received. There was a risk that if the technology did not work it would be seen as unreliable and not ready for commercial application. The design review process itself would follow the steps outlined below:

- Technology familiarisation (example of another model show in the virtual environment)
- Explanation of the designs to be reviewed, aims and objectives of the review and order of presentation
- Design 1 review
- Design 2 review
- Break
- Design 3 review
- Design 4 review
- Break
- Design 5 review
- Design 6 review
- Break
- Design 7 review
- Recap on all designs and any other specific requirements
- Summary discussion & feedback

The feedback from the first review (with the development team) focused on a number of changes in the speed of guided walks and some technical errors, such as wrong cylinder colours in wrong storage locations. In the first review a number of design improvements were identified for discussion at the second day of review. However, capturing the changes seemed to be more complex, whilst some could be done live in the three dimensional environment without the photorealism, it was felt this would reduce the impact of the photorealistic model. An option identified was to use A1 sized print outs of the two dimensional designs which could be placed on a wall and used to capture any necessary changes. It was identified that a scribe should be allocated to this activity to ensure no loss in ideas. There was then an opportunity, during breaks, to update the model.

The second design review was then conducted. The introduction and assimilation with the environment worked very well, although it did raise the expectations of realism in the model about to be presented. In the design review it was seen that the participants interacted with the environment very quickly and made comments on very specific details quickly. The discussions were raised very freely and often contained a rounded view of all aspects from construction, to operation to maintenance. The two dimensional printouts and scribe worked exceptionally well, the ideas were well captured and conflicts of ideas was visualised on the layouts. There was a high number of necessary changes requested, seventeen in total including some critical safety issues. The major issue was that the path assigned for delivery trucks passed too close to a frequently used door. The resolution of the issue resulted in a near complete change in layout. Additionally twenty five improvement ideas were seen and fifth teen future considerations highlighted.

The feedback from the event was highly positive and is summarised below:

- All participants found the review resulted in an improved assessment
- All participants found the review gave a significant outcome and identified necessary changes that would not have been found until the plant was in operation
- All participants recognised that this methodology could provide significant time and cost savings
- The review identified several significant safety issues that previous reviews had not identified
- Participants who had no experience of virtual reality could quickly become assimilated to the environment
- Participants found the structure of the review gave a good balance of structure and areas for flexibility

Summary of Case Study 2: Virtual Reality

A structured approach was developed in which a suitable application of virtual reality technology could be conducted. The approach bridged the gap between current practices and that of the virtual world by taking a series of specific steps. Each step set an achievable goal that built up towards a design review in an immersive environment. In following the approach a design review was conducted that resulted in avoiding design faults, reaching a clear consensus on the design and having confidence in the design. The effect is a saving in time and costs that while is not directly seen in the project has been avoided.

The participants of the design review adapted to the process with ease and discussions were focused on what was working well in the design and what needed to be changed. Contributions from the participants were highly relevant and valid. The overall view was that the technology had enabled a number of decisions to be made and a number of issues to be rectified much faster than could be achieved in the current method of work. The reason these decisions could be made faster is that the users were more informed about the requirements at the moment of making a choice. In the virtual world much of the required information is surrounding the decision makers therefore they act in a more informed manner.

The ability for first time users in particular to adapt and participate to the technology was better than expectations. This may be due to the structure of the approach, which would be an interesting area to investigate further.

The development of the technology for application to the industrial gas industry did provide a number of challenges in the skills and hardware required to complete the work. The main challenge was in the development of the model, balancing keeping detailed CAD geometries and sufficient numbers of components with the stability and speed of the model.

In summary it is found that Virtual Reality is an emerging technology with many application possibilities. It has delivered improvements in the design review process in particular in achieving decisions. This resulted in avoiding costs and time in downstream work and re-work. The overall conclusions can be summarised in the table below;

Question	Findings	Drawbacks	Further work
Can the technology be applied to the industrial gas business?	Yes. A model has been built of an industrial gases plant which has been through a design review process	CAD data was needed to be generated. The modelling and integration to virtual reality is not seamless.	Look for a second application in which more benefits can be achieved and steps can be taken towards the 3D parametric live stage identified.
Are benefits seen in the application and are these benefits similar to those seen in other industries?	Yes. Speed in decision making, richness of information and reducing costs (in this case particularly avoiding costs) are all typical benefits.	Quantifying these benefits is not simple and may not be directly achieved in the business results.	Look for a continued improvement goals.
What is the likely uptake?	Quite high	The cost of the development may restrict re-application	Internal promotion of the application may assist in the uptake
What are the specific challenges experienced and anticipated, and are these similar to other industries?	The size of the model and reliability. These are similar concerns to other industries	Speed and time are the main roadblocks which need continual works,	The major challenge was the instability and speed to complete. This is similar to others using large CAD models

Figure 11: Table of conclusions for Virtual Reality

Case Study 3: Electronics and Wireless Communications

In this last case study, technologies associated to electronics and wireless communications shall be applied to an industrial gases product. The associated technology in this case study is potentially quite broad. There are many methods and techniques which can be applied and that have been applied in other industries. There has also been some application of electronics in the industrial gas sector, particularly in recent years. One area in particular that has seen application is that of medical gas cylinders. Linde and Air Liquide both have softly launched a medical oxygen cylinder with a digital gauge. These products have a benefit above mechanical pressure gauges to the user in showing the time left before empty. There is another product, named Genie® from Linde being used in a number of applications (from welding to balloon gas) which also contains an electronic gauge again showing the time left before empty. The technical details of these products is shown below:

	Linde LVE	**Linde Genie**	**Air Liquide TAKEO**
Sensing technology	Resistivity measurement of the deflection of a needle on a mechanical pressure gauge. External temperature sensor. Position sensor on flow selector. Claimed magnetic induction sensor	Pressure sensor wheatstone bridge using I2C protocol	Pressure sensor wheatstone bridge using I2C protocol
User interface technology	Back lit custom LCD screen Two button operation	Back lit dot matrix LCD screen with custom graphics Single operation button	Dot matrix LCD screen with custom graphics Two button operation
Communication technology	None	Option for NFC or RFID but not yet completed	Option for NFC or RFID but not yet completed
Power technology	Lithium ion battery	Nickel Cadmium battery	Nickel Cadmium battery
Battery life est.	1 year	6 months to 1 year	6 months
Intellectual property rights	Patent application for position sensor	None But patent associated for cylinder manufacture	EP 1421305 FR 2793297 FR 2901874
Unique Features	Time to run calculation using content and current flow rate	Simplicity	Low cost
Positives	Temperature compensated pressure provides a more accurate system Ability to calculate for selected flow rate Computational power is high	Simplistic application of electronics using off the shelf technologies in a bespoke package	First mover in electronics packages Possible to retro fit

Negatives	Possibly over electronics focus	Unlikely to survive the industrial environment Accuracy of system is poor	Very basic electronics Poor battery life Inaccurate calculations
Launch information	Not formally launched, being trialled in southern Europe (started 2012)	Launched in UK 2013 with very limited penetration.	Geographical restricted launch in France and Southern Europe (started 2011). A re-brand was conducted in 2014.
Electronics contribution to overall package costs	30% approximate	20% approximate	18% approximate

Table 17: Technical overview of electronic products in the gas industry

The table highlights a number of key factors, firstly the cost of the package is greatly increased. This may be higher than the customer valuation of the benefits and not lead to increased market share. Secondly the accuracy of the information in all cases is not significantly more accurate than that shown by a mechanical gauge. Whilst it is in an improved format (time in hours and minutes as opposed to pressure in bar) the base measurement is of the same accuracy. The Linde LVE does offer an improved accuracy through its adaptation of the time remaining to current flow rate and potential for temperature compensation. There remains large errors in the LVE system such as, the time left varying significantly as the flow selector is moved and that the temperature measurement is ambient conditions. Furthermore to accurately know the volume of gas the temperature should be taken in of the gas as opposed to external conditions. None of the products measure gas temperature or attempt to compensate for this inaccuracy. In all cases wireless communications are not offered as standard and it is unclear if any of the highlighted products actually work with a wireless communications system. In all of the above applications, the technologies applied are generally off-the-shelf.

Considering the above discussion and information from Table 16 a set of needs can be created which also identify gaps in the above products and areas for innovation:

- Accurate measurement of content
- Low power consumption circuits
- Maintenance intervals to be long, greater than 2 years
- Display screens to be used cautiously
- Data protection to be designed in
- Ease of use
- Low cost
- Useable in the external environment as well as internal

In order to achieve step changes in power consumption, accuracy and maintenance the sensing technology should be re-considered. These areas of need can be partly considered as interconnected as with the current offerings they are largely affected by the sensing technology employed. The most obvious method to sense the content of a cylinder is to use a pressure sensor and this is what all the three products do. While the Linde LVE is a resistive measurement based on a mechanical pressure sensor displacement the others are direct pressure sensed technologies. In order to address the three issues, consideration of alternative technologies should be given.

The other identified areas can also be grouped together in two other areas of work, the electronics itself which shall determine the cost, the display and data protection. A second area is in the design, which affects the ease of use and use in external and internal environment.

An application area was then considered in regards to the current products. Whist a medical product would have obvious consumer benefits there are barriers to entry in the required compliance testing and time to complete such tests. A simpler route would be in the industrial sectors, the largest of which is in metals fabrication. This would also present a challenging market from a cost and product acceptance stand point. It was also noted that if successful it should be easier to replicate to other sectors than with medical gases product.

To give the best focus on the sensing element it was tackled as separate task with a different team to the electronics board development. This would enable the rest of the development to continue without waiting for a sensor which may or may not be developed. There is a drawback in this approach as it could result in the design of the board having some compromises, in order that both a standard pressure sensor and other sensing technology can be connected. However it does result in the project completion not being dependant on finding a new technology.

The requirements for the sensor development were then outlined and a process of researching other technologies and testing application to gases was conducted. A fundamental strategy was to address the fact that pressure measurement had inherent inaccuracy with gases if the gas temperature and volume were not accurately known. With this as a start point investigations were conducted in mass measurement and density. Mass would be challenging due the small increments in mass change that would need to be measured compared to the mass of the cylinder. For instance a typical user flow rate could result in a measurement of 30 grams/minute on a package weight of nearly 100 Kg. This would obviously require a highly accurate sensor. Density provides an alternative route and a number of technical options were possible. One such method is measuring the natural frequency of a quartz resonator in the gas. This would provide a measurement of frequency which can be converted to mass (volume is known) and from there the consumption time can be calculated. Products have been developed for gas applications, such as monitoring the presence of sulphur hexafluoride in gas insulated switchgear (Trafag, 2015). A development was then conducted to apply a quartz measurement to a gas cylinder, this resulted in a patented technology (USA Patent No. US20130306650. , 2013). The benefits from this technology are the accuracy, low power consumption and cost. The technical details are summarised against a standard pressure transmitter in the table below:

Feature	Standard pressure transmitter	Quartz sensor
Pressure range	Specific to design and scaling of output 0-50 barg many readily available sensors 0-400 barg easily sourced 0-1000 barg difficult to source 0->1000 barg specific engineered products	No scaling or changes required for range changes. Refinement can be achieved in interpretation board. 0-1000 barg tested solution 0->1000 barg not tested but theoretically possible
Accuracy	10% for low cost ranges 5% typical 1% high end <1% special products	3% standard <1% achieved with higher manufacturing tolerance quartz's adding €10 to component costs
Drift	1 to 5% typical except special products Additional 0.5 to 3% per 1 degC of temp change	3% typical 0.1% temperature influence
Supply	3 to 10 Vdc typical	3.3 Vdc
Consumption	8 to 20 mA typical	0.08 mA
Sample rate	0.5 to 2 kHz typical	Up to 10 kHz
Sensing response	0-5V, 0-10V or 4-20 mA 0r I^2C	Frequency 30 to 40 kHz
Weight	50 to 150 g typical	5 g
Cost	€60 to €1000	< ½ cost of a pressure sensor

Table 18: Quartz sensor compared to pressure sensor

Whilst the sensor development was conducted an electronics package was developed. The features of which were created through four steps

- Consideration and identification of features in current knowledge base
- Idea generation using a forward thinking team
- Survey of users on ideas
- Idea generation using a customer focused team

These were taken to balance expressed customer needs along with innovate ideas. It lead to the following features to be identified for inclusion:

Feature	Concept
Content	Display pressure and or time left
Low content alarm	Flashing light and audible would be desirable
Predicted time before empty	Learning algorithm using non-ideal gas laws and actual flow measurements to give time in hrs/mins or greater than specific numbers
Flow	Accurate flow measurement calculated by change in density over time. Options to identify significant changes in flow and inform user.
Usage data	Present user consumption patterns and give improved visibility of information
Wireless transmission of information	Use of latest Bluetooth technology to provide low power option of transmitting information to smart phone app
Re-order product at point of use	Use of data and smart phone app that could automate re-order process
Leak detection	Use of flow measurement could identify flow (leaks) when no flow is expected
Fault indication	Use of a warning graphic in different way to show different faults

Table 19: Table of features

A target cost for the product was devised using a reverse profit and loss methodology. The sales price was used as a driver to determine the budget cost for the electronics package. The sales price was tested through a market survey against the features above in a conjoint analysis.

From these requirements two prototypes were developed to test out aspects of the concepts in particular how much information to display on the cylinder and how much information could be available on a mobile application. These were tested in six focus groups which determined a favourable mid ground between the products and found all the concepts to be highly desirable.

The electronics development was relatively straightforward requiring the necessary board development to take a sensed reading, conduct calculations then transmit the information to a display and wirelessly. A learning and adaptive calculation of content based on density changes was developed using a variety of application scenarios. This lead to a patent application on the calculation process.

The wireless communications feature was developed following a review of communication options. The results of this review are presented below, in Table 20, it focuses on the two key drivers of cost and power consumption. Additional technical features are then taken into account from the strengths and weaknesses review. From the data, Bluetooth 4.0 and near field communications (NFC) had the lowest results in cost and power consumption. Of these two technologies Bluetooth 4.0 offers wider technical features, particularly in two way communication and connection distance. While NFC is the simpler of the two technologies to integrate and work with. As part of the concept is handling customer orders it meant that Bluetooth 4.0 was the most suitable of the solutions to forward with.

Communications Technology	Cost (hardware) (scaled 1-5 lowest to highest)	Power consumption (scaled 1-5 lowest to highest)	Strengths	Weaknesses
WiFi	5	5	High data capacity and variety of files Ability to link to many devices	Data protection can be poor
Zigby	4	5	Ease in ability to network same devices	Requires high level of customisation
Bluetooth	2	4	Ease in connection and standardisation	Battery consumption can be very poor
Bluetooth 4.0	3	2	Changeable header transmissions	New technology, relatively few compatible devices
Near Field Communication (NFC)	4	1	Easily programmed	Low level of data capacity, distance of connection and data protection

Table 20: Review of communications technologies

The mobile application development had a number of challenging areas. Firstly as this was very new ground it was important to understand and provide features which the customers would benefit from. Secondly the technology chosen in Bluetooth 4.0 was in its infancy and would therefore be likely to have some technical issues to overcome. The application was developed using a story board approach which was then tested both technically and with customers as a concept. The first concept was deliberately built with a number of features which could then be reduced based on customer feedback. Three key sections to the application were identified in the cylinder information itself, customer account information and lastly technical support.

The feedback led to a final design of electronics package and mobile application. These are shown in Figure 12, Figure 13, Figure 14 and Figure 15. The product was launched too much accolade at a large trade show.

Figure 12: Variety of views of electronic enabled product

Figure 13: Front view of electronic enabled product

Figure 14: Product in user environment

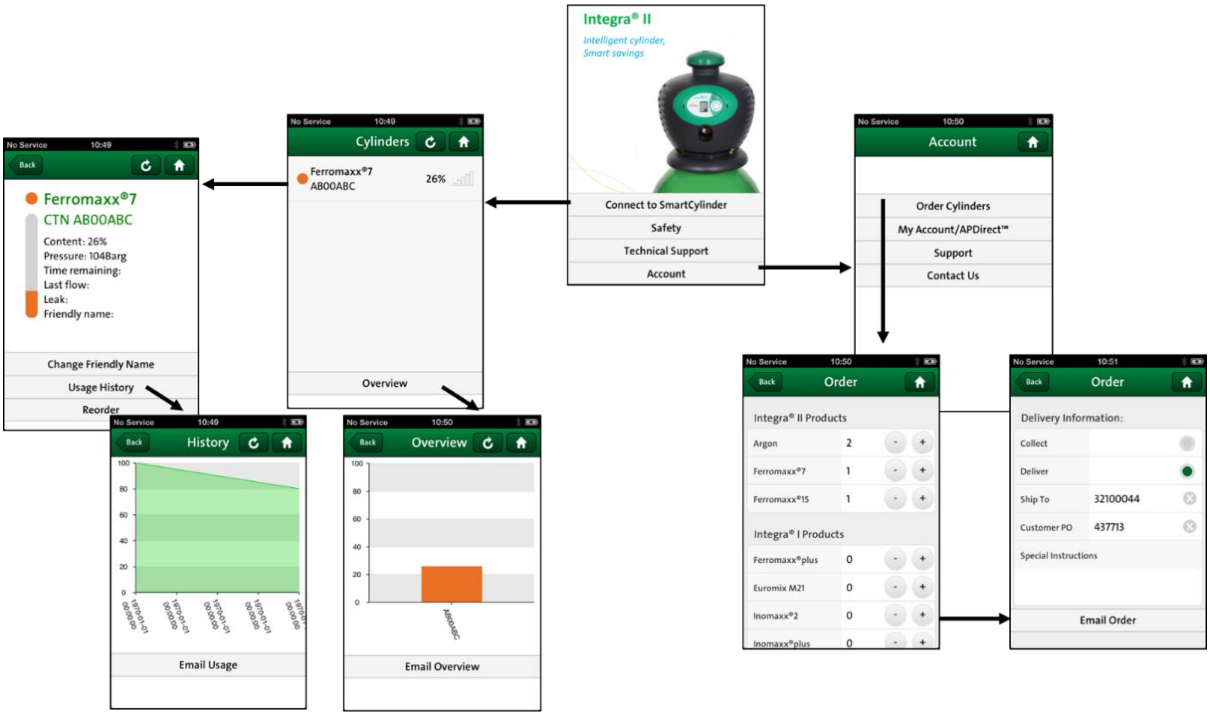

Figure 15: Storyboard of mobile application

The results of the development was a product which customers interacted more with and enthused about. This is likely to be due to the increase in contact time of the customer with the product compared to standard offerings. The product enabled the customer to have access to an increased amount of data much like many other electronic enabled products. The usefulness and improvement delivered thereof are still to be realised. This requires a longer term survey of the customer use of the data and the data itself. These technology enhancements and benefits could not have been as well achieved without the breakthrough sensor developed. The unique characteristics of high accuracy, low power and low cost made it ideal for a conservative, tough environment that is highly price sensitive.

Summary of Case Study 3: Electronics and Wireless Communications

It was identified that a key growth sector for many products has been to equip products with electronic features to gather increased amounts of data on performance which can be used to give the user more information from which they can make decisions based on better information. It has been seen that electronic sensing and display technology has been applied in the industrial gas industry but with limited success on end products in the cylinder market. A project was identified in which a cylinder product could be developed. In this project a number of failing areas of recent attempts are to be addressed. These are in the life, cost and accuracy of the product. The reasoning why these areas need improvement was found to be largely due to the sensing system used. A specific development programme was followed for the sensor while the electronics system was developed separately along with wireless communications.

The sensor developed breaks new ground in many areas and has many possibilities. The cost, accuracy and durability are all in-line with the expectations set out. This means that a highly applicable sensor has been developed that should enable more products. For example the sensor could be developed for flow sensing, plant monitoring, and gas detection.

There is clearly much more that can be done with such electronic enabled cylinders. There are the obvious replications into a wide range of gas variants, applications and sectors. There is wider use of the technology in supply chain management such as customer demand planning and inventory control. There is certainly additional features that can be enabled too in particular with additional sensors.

A summary of the findings towards the original set of questions asked of the technology development are detailed below in Table 21.

Question	**Findings**	**Drawbacks**	**Further work**
Can the technology be applied to the industrial gas business?	Yes. Electronics was shown to be applicable and deliver a feature rich product	The complexity of the product is increased	Continue to develop in the field knowledge on use and application
Are benefits seen in the application and are these benefits similar to those seen in other industries?	Yes. Customers engage with the features and product. The data generated opens new options	There is an impact in product costs but this is similar to other industries	Quantification of the supply chain benefits
What is the likely uptake?	Positive from the focus groups.	The product will appeal to early adopters for others it may take time to be convinced	Monitor the introduction of the product
What are the specific challenges experienced and anticipated, and are these similar to other industries?	Some technical difficulties with the product which is inline with other electronic products.	Mechanical systems are still more reliable.	Develop extended life testing and robustness of software like other industries do

Table 21: Summary of benefits for electronics and communications

Appendix 10: Initial Assessment of GCE

The assessment tool developed has been completed for the case study at GCE. The details are shown in the table below:

Node	Best Practices	Assessment
Process	Stage and gate Lean tools Standard documentation Standard processes and checklists Key performance identifiers used	Limited application Not used Some Used No & difficult to measure
Enablers	Multifunctional team Integrated activities with suppliers Funding assigned per project and per stage Portfolio reviews conducted	No. Silo approach No. Silo approach Not clearly No
Technology	Advanced engineering techniques employed Technology road map used Intellectual property strategy defined Intellectual property landscapes used Technology differentiation to competitors (in product and process)	Very limited No No No No
Business Drivers	Strategic goals for business performance set and development projects aligned Performance to strategic goals measured Clear financial goals set for project performance Financial assessments made for product performance with sensitivity analysis	Goals for business are clear but poor alignment Not measured No No
Sustainability	Environmental goals set for product development Actions taken to promote fairness in employment and the entire supply chain Efficiency goals set for the organisation and continuous improvement conducted	No No No

Table 22: Initial assessment of GCE's product development process

Appendix 11: Gap Analysis for GCE to Implement Sustainable Development Methodology

Sustainable Product Development and Assessment Gap Analysis						
Area	**Gap analysis**					
	Current	**Current issues**	**Future**	**Gap**	**Factors why**	**Actions**
Strategy	Develop custom solutions and lower cost products	Competitors are quicker to develop custom solutions. Competitors, particular from China, are lower cost but are of lower quality. Feedback from the organisation was that development take too long and often failure to meet the customer requirements.	Time based competiveness with compelling products. A continuous development of the product range. Finding and developing products for new markets and new technologies for GCE.	Increase speed of development. Increase customer focus. Introduce sustainable development practices. Work with new technologies. Work in new markets.	There is no urgency in the development process as the systems for development are highly fragmented, there is little communication or linkage to the market. The gas equipment market has been infiltrated by low cost and quality products which during the recession customers moved towards. Custom solutions are desired due to the increasing specialism of European markets. Local competitors have more agility to react to custom solutions as they have less focus on trying to minimise variation, unlike GCE who as a multi-market manufacture tries to consolidate designs.	Develop and communicate a new vision along with the future strategy Communicate why there is a gap and the plan. Change the strategy statements where necessary. Develop sustainable goals.
Culture	Work on what has been instructed only. Cautious approach and low level of confidence. Fear of responsibility	Responsibility not for issues is avoided leading to poor resolution of errors. No proactivity leading to errors being passed down supply chain. Change is met with many barriers.	Proactive approach to work. Innovation occurring frequently, ideas harnessed, explored and developed rapidly. Change is constant. Failure is learning.	Large cultural shift. Responsibility being taken by all. High level of customer focus. Continuous improvement to be common place. Change in management techniques.	Continued slow down in sales in largest business area and a number of significant quality issues creating a fear of failure. Production focused on output and machine utilisation, while quantities decrease. Autocratic management style in the factory. Company structure built barriers which created silo behaviours.	Train and develop at all levels. Set and sustain new behaviours for managers. Review core values and re-communicate. Change performance indicators. Change structure.

Sustainable Product Development and Assessment Gap Analysis

GCE Security in action

Area	Gap analysis					
	Current	Current issues	Future	Gap	Factors why	Actions
People	Pre-dominant base of people in Czech Republic associated to production, with little movement or external experience. Many small sales offices. Generally mixed age range but technical staff lacked mid career staff. Little to no contingency planning. Limited development plans. Limited experience in roles.	Low skill set in technical areas Over resource in some areas and under resource in other areas. Low ability to create future plans.	Knowledge based company. High level of interdisciplinary understanding. All people engaged in personal development. Talent is encouraged to grow. High level of technical competence.	Technical skills. Development planning. Ability and encouragement to change roles. Increased interactions between Czech Republic and rest of organisation.	Company was grown in past 15 years through acquisition and centralisation of production to Czech Republic. Left sales teams disconnected from production. Czech facility location is in a small isolated town. Low talent pool. Attracting talent requires people to travel.	Coaching and training to be conducted by manager. Introduce a technical ladder to drive growth in technical skills. Employee new hires of a higher skill set into technical teams. Employee technical personnel outside of Czech in locations with larger talent pool. Train people in roles especially product management.
Structure	Traditional structure of sales, planning, purchasing, machining, assembly, quality, R&D, marketing. Sales departments set up as individual companies purchasing from a production company. R&D is responsible for custom requests, quality resolutions, production resolutions and new product development.	Silos exists in all areas, cross communication is poor. R&D struggled to focus on new product developments. Constant fire fighting exhibits.	New product development set up as a specific team. Custom solutions set up as a specific team. Integrated approach to development projects. Integrated improvement activities.	Cross functional working. Break down of silos.	Company was grown in past 15 years through acquisition and centralisation of production to Czech Republic. No focus on alternative methods of structuring. Limited focus on new product development.	Splitting R&D team appropriately. Appoint representatives from other teams to development projects. Increase cross communication mechanisms. Increase visibility of development projects and custom developments.

Sustainable Product Development and Assessment Gap Analysis

Area	Gap analysis					
	Current	Current issues	Future	Gap	Factors why	Actions
Processes	A new process for product development had been introduced in 2013. The process involves a seven step system with 3 toll gates.	There is no visibility as to where a project is in the process. Documentation is poor and not to the requirements of the process. The process is not well adhered to. There is no mechanism to enforce use of the process. The process has many discrepancies to best practices. No guide on how to follow process	Integrated stage-gate® model. Cross functional steering committee. Clear gate definitions. Process steps are standardised. Visibility and planning of current and future status. Products not reflecting start point of process.	Change in development process. Complete implementation and monitoring of process. Stage-gate® model to follow best practices. Methods and tools to conduct standard work.	No focus on the new product development process. Poor level of knowledge on best practices for product development. Significant scope changes as market information appears in later stages of project.	Develop custom stage-gate® process. Address process issues. Develop project control and tracking system. Develop system for portfolio review. Develop standard work documents. Train team on new process.
Resources	Manpower is 32 designers, and 2 managers. Laboratory facilities are setup as a third party to conduct tests. Prototyping completed outside factory.	No prototyping facility. Items have to be outsourced or put into the production schedule. Adds time to every design iteration. Managers unable to closely manage team. Laboratory conducts tests but with no interpretation.	Small tight teams. Prototyping to be on demand. Testing to be completed with intelligence to enable fast learning loops.	Change the ratio of team to management. Create system for agile teams for projects. Laboratory to become a partner as opposed pure test centre. Move to internalise more prototyping.	Prototyping machines were moved to production and so called "short track" production route. No management of structure of teams. Laboratory acting as a silo.	Build a prototyping facility. Change the structure of the team. Work with the laboratory to create a partnership.

Sustainable Product Development and Assessment Gap Analysis

GCE Security in action

Area	Gap analysis					
	Current	**Current issues**	**Future**	**Gap**	**Factors why**	**Actions**
Environment	Czech office is noisy and cramped. The company performance is not strong enough and not meeting targets. Competitors are growing. Price competition is strong. Key customer loosing market share.	Mistakes made due to inability to concentrate. External communication by phone is avoided due to noise and no meeting room. Drives communication by email (takes longer and reduces sense or urgency and importance). Low level of free thinking Low moral	Creative, fast paced, environment Competitor unable to keep pace and fall behind in features. Leading in all markets. Openness and agile.	A different office environment needs to be created. The projects worked on need to change to be far more innovative. The culture of the team needs to change.	No to little investment in facilities. The production manager saw the R&D area as low priority for any improvement. The team was grown to cope with increased demand without structural change. It is impossible to be creative and thorough in a disruptive environment.	Re-develop the Czech office. Re-introduce prototype capability to Czech. Build a new facility outside of Czech for R&D with laboratory and prototyping capability. Choose project with more feature differentiation.
Technology	3D CAD available, used by 30% of team. 2D CAD dominant drawing method. On site production is standard machining systems. Material base is brass. Off site machining of higher accuracy and other materials. Many software tools and databases used for product creation	Low level of CAD data. Slow speed to create drawings. Errors made in drawings. Legacy of old drawings. 75% of item number creation is waste.	Configurable 3D CAD. Use of advanced engineering techniques. High use of a rapid manufacturing methods. Strategic application of new technologies (first mover).	Moving from 2D to 3D. Introducing new technologies. Introducing new capabilities.	No focus on technology development. Industrial gases is a low technology area. The level of technology used is not unusual. Item creation systems were step wise built up with little control and direction.	Create a technology roadmap. Investigate integrated software solutions. Training on 3D CAD. Set drawing standards and methodology. Set up a drawing conversion team. Partner for advanced engineering. Partner for rapid manufacture.

Appendix 12: Sustainability Index Assessment at GCE

As part of the methodology the sustainability index assessment was deployed and used as part of the portfolio reviews. The index was used to make decisions on the projects and portfolio to apply more focus in underperforming areas. The assessment has been made by the same individual, which maintains a consistent response to the rating method. This approach was also chosen as it is the first implementation so the experience of the rating may recommend changes to the system during implementation. It is simpler to manage if a single person completes the rating. However it is an individual's view and therefore could be subjective to a bias. This feedback gathered during formal review meetings (held bi-weekly) and informal discussions.

The initial assessment is shown in Figure 12-1 and Table 23. In this view it can be seen that the framework showed poor performance in process and enablers. There was a number of projects that had a strong technology contribution. Interestingly from a business drivers perspective the projects looked quite favourable. The main indicators with underlying issues are process and enablers. The activities in the adopting the methodology are likely to tackle the weaknesses in process as the methodology requires a specific process to be followed. The adoption will also need to consider what areas need change with regards to enablers in order to improve this area of the framework. In the sustainability factors it can be seen that the projects are not well balanced. In efficiency there are a couple of projects that are performing well (projects G and H) but overall there is room for improvement. In equity the same situation is seen: a small number of projects are running with a strong performance but generally there is opportunity for improvement. In environment a similar situation is seen, however there is a wider gap between the strong performers and other projects.

As the adoption of the methodology progressed it was expected that all projects would benefit particularly in process and efficiency. However some projects had to be transitioned mid development to the new method, rather than starting anew. These typically suffered in efficiency as seen in projects J and T in Figure 12-2. Many of these projects suffered technical failures which resulted in rework. This was mainly due to the wider questions being asked of the project from the new process. But also that technical and commercial questions were being asked earlier in the process which brought out several failures generally with customers testing prototypes.

Twelve months following the initial assessment, the portfolio looks quite different. At this point in the transformation teams, are working to the process but skills are not fully improved and sustainability targets are not set. The after assessment is shown in Figure 12-2 and Table 24, along with a comparison view of the average results before and after in Figure 12-3. It is clear in the framework factors that process performance has significantly improved, as have technology and enablers. The business drivers also appear more balanced. The enablers node remains the area where there is most variability in the projects both before and after. This area requires more detailed assessment to determine the causes and appropriate actions taken. In the after picture there are more projects in the portfolio the projects and the scores are more balanced. In the sustainability factors, a significant improvement in the scores is achieved and that all three areas are scoring with improved consistency across the project range. The environmental performance remains as the worst performing area in both average scores and range of results across projects.

To continue to improve the sustainability scores it is observed that setting company sustainability targets is a crucial element. The targets would be best set about a specific strategy for the company. This will drive decisions and actions towards sustainability.

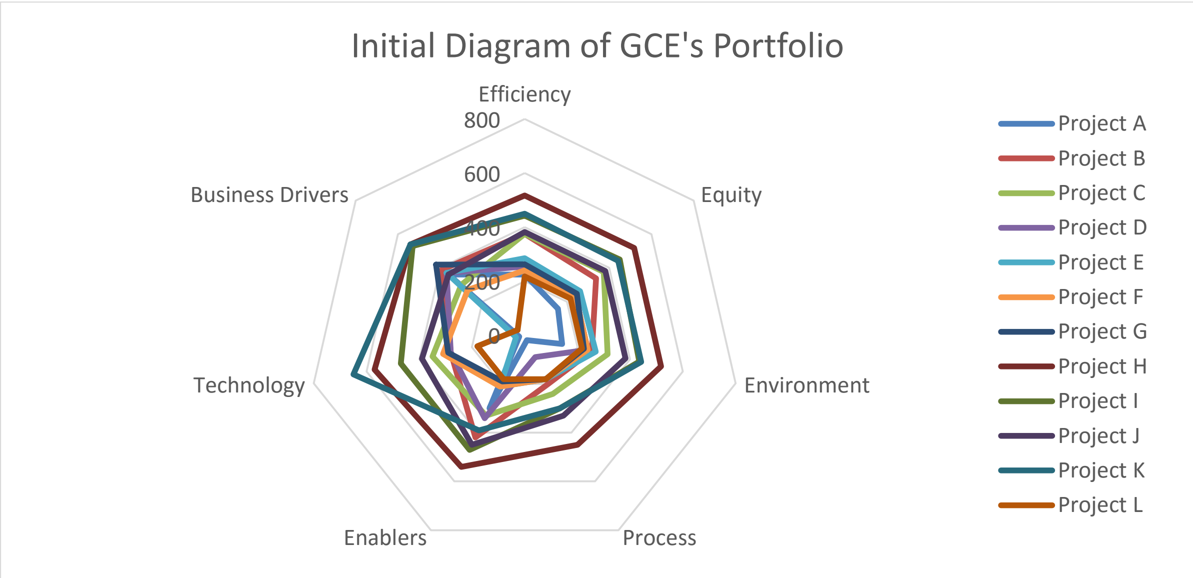

Figure 12-1: Initial Diagram of GCE's Portfolio

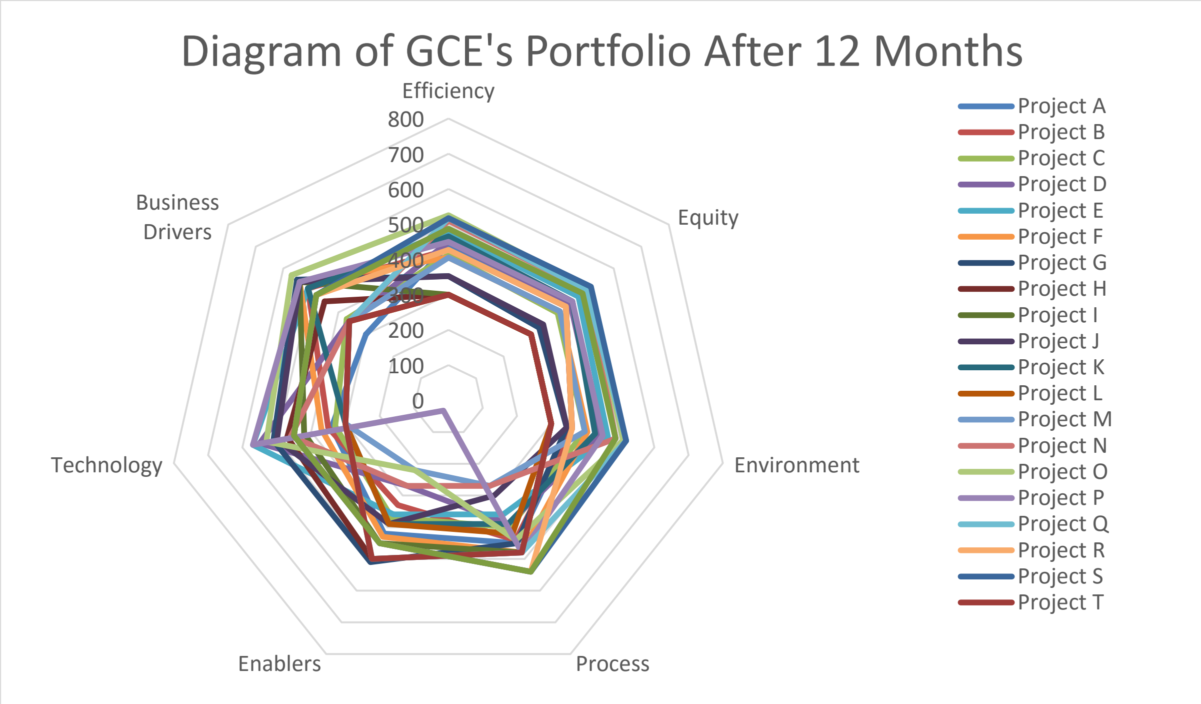

Figure 12-2: Diagram of GCE's Portfolio After 12 Months

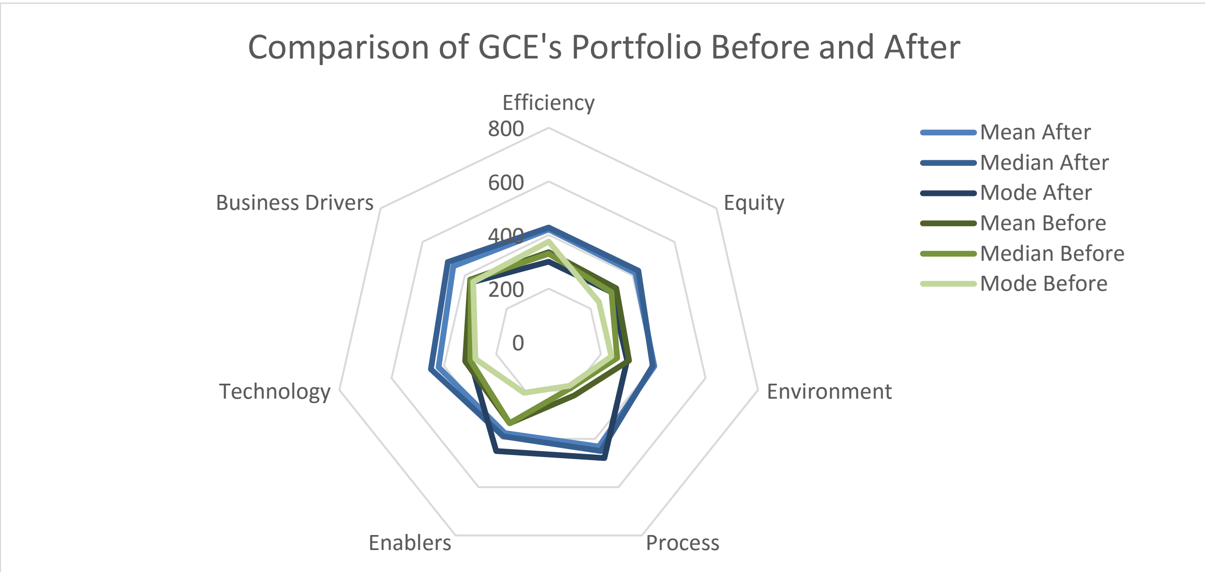

Figure 12-3: Comparison of GCE's Portfolio Before and After

	Efficiency	Equity	Environment	Process	Enablers	Technology	Business Drivers
Project A	225	157.5	142.5	20	300	20	360
Project B	375	337.5	255	200	420	280	390
Project C	375	375	315	240	330	350	300
Project D	255	240	240	90	340	280	370
Project E	285	262.5	270	180	210	33	370
Project F	240	240	240	180	210	310	270
Project G	262.5	247.5	225	180	190	290	420
Project H	517.5	517.5	517.5	450	540	570	540
Project I	442.5	450	435	300	470	470	530
Project J	382.5	382.5	382.5	330	450	390	360
Project K	450	442.5	442.5	300	390	650	540
Project L	217.5	217.5	217.5	180	180	180	33

Table 23: Table of results before implementation

	Efficiency	Equity	Environment	Process	Enablers	Technology	Business Drivers
Project A	590	570	480	450	420	340	300
Project B	570	570	480	440	330	350	510
Project C	550	530	530	400	370	330	370
Project D	600	590	590	390	270	550	360
Project E	640	630	620	360	360	570	510
Project F	540	540	540	480	430	370	540
Project G	470	440	459	450	510	510	550
Project H	400	400	400	480	500	470	450
Project I	400	400	400	480	450	420	540
Project J	470	460	460	300	390	500	540
Project K	620	600	570	390	390	300	510
Project L	400	400	400	420	390	300	360
Project M	540	540	530	270	220	300	360
Project N	680	670	650	270	270	460	360
Project O	700	680	680	440	220	530	570
Project P	600	600	600	480	33	570	540
Project Q	690	670	690	480	500	300	360
Project R	570	570	480	540	450	450	480
Project S	690	690	690	540	450	450	480
Project T	400	400	400	480	500	300	360
Project U	650	650	650	540	450	450	480

Table 24: Table of results after implementation