DEVELOPMENT OF A COMPUTATIONAL FLUID DYNAMICS ASSISTED SUSTAINABLE NEW PRODUCT DEVELOPMENT METHODOLOGY FOR FLOW HANDLING EQUIPMENT INDUSTRY

CHINO CAVEN UZOKA

U1253676

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ABSTRACT

This study presents an assessment of the current state of Computational Fluid Dynamics (CFD) adoption in fluid flow handling equipment industry and demonstrates its utility in the New Product Development (NPD) process through the development of a novel sustainable CFD-assisted NPD methodology. In the flow handling equipment industry, the need for a CFD-optimised methodology in the management of NPD activities is prioritized by the modern global inclination towards increased sustainability practices coupled with the emerging digital industrial revolution. Most fossil-fuelled and green energy sources rely on the control of fluid flow for various purposes such as in valve and piping networks, heat exchangers and wind turbines among others. While fluid flow in either of these systems can be analysed using conventional numerical calculations and experimental methods, CFD as a nascent technology in the digital era, provides a virtual digital environment for simulating, analysing and predicting flow behaviour thereby inspiring sustainable rapid design and development of new flow handling solutions.

Despite these recent advancements, some firms in the flow handling equipment industry experience varied challenges in adopting CFD technology and optimizing its integration to the overall NPD process. In the body of literature, mentions of CFD-optimized NPD methodologies are grossly limited. Where feats achieved using CFD are presented, they are mostly recorded as isolated cases during design but seldom as part of a systemic methodology with capacity to influence the entire NPD process itself. The question as to whether the flow handling equipment industry is ready for such a systemic integration of CFD technology is one that this research develops to assess the current practice with a view to developing a systemic methodology in its place.

Following a pragmatic inquiry, a mixed methods approach was adopted for the research beginning with a qualitative investigation of six flow handling equipment industry firms in West Yorkshire. Six key respondents from Small, Medium and Large Enterprises in the Valve and Fan industry were each interviewed following preliminary questionnaire sessions. The key findings from the study revealed that '*cultural perception*', and '*accessibility*' were key factors that influenced the adoption of CFD technology alongside the original constructs of '*perceived ease of use*' and '*perceived usefulness*' highlighted in the standard Technology Acceptance Model (TAM). As a response to the perceived difficulty in adoption of CFD technology, most of the firms outsourced CFD related work or decided not to use the technology at all. Methodically, most of the firms did not appear to be very structured in their approach to NPD but mostly applied

modified adaptations of traditional staged NPD processes that were not originally designed specifically for flow handling equipment product development processes.

Consequently, a novel CFD-assisted NPD methodology was developed utilizing Systems Engineering principles to provide the industry with a structure for accelerating CFD integration for NPD process in order to stimulate organisational growth and improve sustainable product quality practice within dynamic product lifecycles. Following the development of the new methodology, a pilot test was initiated as the second part of the mixed methods approach, to test the efficacy of the newly developed methodology. A novel hybrid valve design was realised from the pilot test, featuring both linear and equal percentage valve flow characteristics. Other notable novelties from this study include; a new CFD-optimised Technology Acceptance Model to aid in future assessments of CFD-specific technology adoption in flow handling equipment industry, a novel systems engineering process engine for procedural and lifecycle navigation during new product development, and a novel prescriptive product development plan for the novel hybrid valve design.

In recommending future work, the author believes more attempts to integrate CFD technology into the NPD process would improve the prospects for faster, cost effective and high quality new product development in the flow handling equipment industry. The new CFD-optimised technology acceptance model can also provide a guide for assessing future trends in CFD technology adoption specifically when used in line with periodic advancements in computing technology or as global sustainability requirements influence organisational practice within the flow handling equipment industry. Technologically, the author recommends development of user-friendly CFD software as well as cost effective commercial CFD codes to accelerate widespread CFD adoption.

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DEDICATION

To my Parents: Engr. and Barr. (Mrs) C.S. Uzoka and the entire Uzoka Family.

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LIST OF ABBREVIATIONS

Abbreviations	Terms
B&ES	Building and Engineering Services Association
BIM	Building and Information Modelling
BVAA	British Valve and Actuator Industry
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CFD	Computational Fluid Dynamics
ConOps	Concept of Operations
CRM	Customer Relations Management
DOD	Department of Defense
DCF	Dynamic Capabilities Framework
FETA	Federation of Environmental Trade Associations
FEA	Finite Element Analysis
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes Effects and Criticality Analysis
GST	General Systems Theory
HPC	High Performance Computing
HVAC	Heating, Ventilation and Air conditioning
ISO	International Standards Organization
NPD	New Product Development
PLC	Product Life Cycle
SEP	Systems Engineering Process
SME	Small Medium Enterprises
SPC	Statistical Process Control
SWOT	Strengths Weaknesses Opportunities and Threats
TAM	Technology Acceptance Model
TRIZ	Theory of Inventive Problem Solving (Translated from Russian)
TQM	Total Quality Management
QFD	Quality Function Deployment
VOC	Voice of the Customer

CHAPTER 1: INTRODUCTION

This chapter presents an overview of the building blocks to a fascinating research, drawing focus to the dynamics and emerging trends in the flow handling equipment industry, particularly in the area of New Product Development (NPD) and Computational Fluid Dynamics (CFD). An outline of the study's aim, justification, scope and structure of the research is also presented.

1.1. BACKGROUND

In a 21st century world of widespread demand for high quality products and the requisite use of technology as a tool to expedite the process, theoretical and practical norms in the field of engineering innovation undergo continuous refinements often emerging from a combination of engineering and management practices (Hefley & Murphy, 2008; Xiong, Liu, Liu, Zhu, & Shen, 2012). According to Stark (2015), specific entities that are developed from the exploitation of available resources to fulfil a particular need or group of needs are referred to as Products.

Globally, a wide a variety of products exist, often obtainable in various geometric and material formations with each essentially fulfilling one need or the other at various capacities. Historic trends have shown that groups of people with similar interests often collaborate to manage the process of product development for commercial or non-commercial reasons (Hilton & Gibbons, 2002; Landes, Mokyr, & Baumol, 2010). The groups interested in the development of products for commercial purpose are classified in this study as Enterprises. For an enterprise, the main goal of new product development is to ensure that ideas are transformed into meaningful products that perform their functions efficiently and are able to yield profit while reasonably conserving available resources (Greve, 2007; Landes et al., 2010; Stark, 2015).

The term 'Flow Handling Equipment industry' as applied throughout this study, is used to describe a set of commercial enterprises and instituted authorities dedicated to the production and regulation of fluid flow handling equipment solutions ranging from mechanical valves, pumps and pipes to fan systems, turbo chargers and others (Versteeg & Malalasekera, 2007).

In a number of industry sectors committed to fluid flow handling, there exists an emergent interwoven conflict between the societal pressure on engineering enterprises to improve sustainability habits and the growing demand for high quality products (Alblas, Peters, & Wortmann, 2014; McDonald et al., 2011). A number of old traditional techniques for meeting high quality products in the industry are unable to keep up with the dynamic nature of constantly evolving reforms in local legislation towards sustainability targets (Smink, Hekkert, & Negro, 2015). For instance, an automobile firm may undertake multiple manufacturing and vehicular field tests at their testing facility to develop a highly powered engine. Testing related activities may generate gas emissions that contribute to an increase in the company's carbon footprint (Sullivan, Burnham, & Wang, 2010). The company may then require an assessment of environmental pollution from manufacturing activities to ensure they keep within permissible emission limits (Hefny & Ooka, 2009), or seek alternative forms of energy for production related activities (Yuan & Dornfeld, 2009). Similarly, the kind of products that are successfully designed for low emissions in operation, require extensive tests to optimize the emission capabilities of the product (Younglove, Scora, & Barth, 2005). With digital simulation technology, such as the type used in computerized fluid flow handling, the process and product characteristics of such products can be predicted and design-managed computationally. Another example is a severe service control valve, typically designed to manage flow of substances that exhibit extreme physical or chemical properties such as cryogenic materials (Wang, Sun, & Song, 2015), high pressure or temperature fluid, as well as corrosive or particle containing elements that cannot be controlled with conventional valve types (Asim, Charlton, & Mishra, 2017). If the design is not of suitable quality, such valve would pose a risk to the environment in which they operate; producing fugitive emissions (Hassim, Hurme, Amyotte, & Khan, 2012). To provide the best quality, severe service control valve designers may then choose to carry out multiple practical field tests to prevent leakages in the final product. Such tests increase cost of experimentation and risk release of harmful substances into the environment especially in the event of an experimental safety failure. Again, computerized digital simulations can be used to predict flow patterns and system behaviour thereby reducing the number of physical tests required to validate product designs (Anderson, Tannehill, & Pletcher, 2016). The business of creating sustainable products sustainably therefore requires innovative methods to optimize resources and maximize the potential of the flow handling equipment firm to meet desired outcomes.

Some challenges exist in sourcing innovative methods for optimizing product development activities. According to Karjala (2012), businesses are becoming more protective of their inventions and this decreases the rate of new additions to traditional knowledge thereby reducing publicly available information that firms can utilize to remain competitive. Some firms have responded to this situation by creating and managing their own product development tools and techniques, which they secure to gain competitive advantage, while others rely on the old traditionally available methods (Sommer, Hedegaard, Dukovska-Popovska, & Steger-Jensen, 2015). The implication of this situation for the flow handling equipment production industry is that, as more firms protect proprietary strategies for creating sustainable products sustainably, there would be less sustainable strategies available as open or traditional knowledge. It then becomes expedient for the firms to either create their own new processes specifically designed to help develop high quality products sustainably, or purchase premium solutions externally. To survive, the average enterprise must therefore remain innovative. In order to be innovative, it is important to understand the forces at work in enterprises of different sizes.

1.2. ENTERPRISES

An Enterprise is usually classified according to their staff capacity and fiscal assets. There are varying classification standards used by different international regulatory bodies. According to the official European Commission Enterprise classification (European Commision, 2003; Kamal & Flanagan, 2014; Lukács, 2005), a Small Enterprise is identified as a business organization responsible for employees ranging between >10 to <49 and have a financial turnover capacity ranging between 10,000,000 - 50,000,000 Euros. Medium enterprises are responsible for employees ranging between 50 -250 and an annual turnover of 49 - 50 million euros, while Large firms employ over 250 employees and turn over above 50 million Euros. A tabular classification is detailed in Table 1.

Similarly, the British government in the Companies Act of 2006, sections 382 and 465, define a Small Enterprise as a company with staff figures ranging between 0-49 and a turnover of <£6.5million. A medium enterprise has staff figures ranging between 50-249 employees with no more than £25.9 million turnover. A large enterprise would exceed the limits of the SMEs with a range of 250 or more employees and a turnover above £25.9 million (BEIS, 2018; Henry, 2013; Shaw, 2011).

Table 1 Enterprise Classification according to European Commission (Lukács, 2005)

Enterprise Size	No of Employees	Turnover (€)
Micro	Below 10	Below 2 million
Small	10 – 49	10 – 49 million
Medium	50 - 250	50 million & higher
Large	250 and Above	Above 50 million

Statistically SMEs appear to thrive in major economies. In 2018, the British National Statistics figures (BEIS, 2018), reveal that SMEs account for about 99.3% of businesses in the private sector of the United Kingdom. 99.9% of UK businesses that started in 2018 are SMEs and 60% of all private sector employment are in SMEs with a combined annual turnover of £2 trillion pounds. The construction sector leads in population figures, representing a fifth of all SMEs in the UK. 14% of SMEs are engaged in professional scientific and technical activities, while a third of UK SMEs are distributed across the Construction, Manufacturing, Professional scientific and technical sectors of the industry (BEIS, 2018; Rhodes, 2018).

The above figures indicate substantial SME activity in the Science and Engineering sectors. Though the fluid flow handling equipment industry consists of several sectors that provide a vast range of services to many industry sectors in several economies, some examples of the fluid flow handling equipment-serviced sectors highlighted above for SME substantial activity include: Construction sector: environmental services, building ventilation and pollution, valve and piping, waste management, metallurgy, mineral and chemical processing. Some services in the manufacturing sector include: aeronautics, automotive, valve and fans. In the professional scientific sector, services include: food processing, pharmaceuticals and biomedical solutions. While in the energy sector: oil and gas, hydro and heat exchanger systems, wind power and solar energy storage as well as in many other sectors where services are supplied by enterprises in the fluid flow handling equipment industry (Anderson et al., 2016; Blocken, 2014; Eesa, 2009; Hefny & Ooka, 2009; Li & Nielsen, 2011; Morris et al., 2016; Spalart & Venkatakrishnan, 2016; Tu, Yeoh, & Liu, 2018; Yadav & Bhagoria, 2013).

On the other hand, there are approximately 8000 Large companies which make up about 0.1% of UK businesses. However they account for 48% turnover and about 40% of employment figures (Rhodes, 2018). This implies that the other 99.9% of the businesses are either micro enterprises or SMEs. Given the present situation, all of these firms require special techniques to compete even as integral parts of the supply chain. As reasonably-priced revolutionary technology, internet connectivity and online monetary transactions become more widespread, SMEs in the various sectors have been observed to approach wider markets as either potential partners in a supply-chain relationship or as stand alone end-user oriented enterprises but without much intention to become physically larger themselves (Eppinger & Unger, 2011; Jamieson et al., 2012).

1.3. THE RELATIONSHIP BETWEEN SMALL MEDIUM & LARGE ENTERPRISES

Before large enterprises became widespread around the world, Small Medium Enterprises (SMEs) were seen to dominate various aspects of economic civilizations (Landes et al., 2010). The Small Medium Enterprise in modern times is still considered the driving force of contemporary economy (BEIS, 2018; Ghobadian & Gallear, 1996; Henry, 2013). However, their roles seem to have transformed over time.

While SMEs were previously seen as basic business models, they now essentially achieve their business aims by becoming partakers in ensuring their larger counterparts acheive theirs (Shaw, 2011; Wiendahl & Lutz, 2002). Occasionally, Larger firms find certain aspects of their business expensive to fund consistently, due to the fact that the limited usage of certain channels defeat the need to manage it internally (Nieto & Santamaría, 2010). These kind of situations inspire SMEs in the flow Handling Equipment industry to focus on growing their specialised competencies where demand for their services to perform as part of a collaboration is consistent. In a 2012 study involving telephone interviews with 506 SMEs and 49 indepth interviews, 77% of SMEs identified as being part of a supply chain with their larger counterparts (Jamieson et al., 2012). This may suggest that the SMEs choose to remain as SMEs in a strategic effort to avoid the capital intensive requirements of running an end-user retail oriented business that incures high procurement, overhead and marketing costs more commonly borne by Large firms. However, according to Chan & Chung (2002), SME firms no longer compete on the basis of cheap labour but on the strength of their technological capabilities, delivery time and technical know how.

On the other hand, while Large enterprises in the supply chain may have access to larger capital requirements, they are not immune to the challenges of competition with industry rivals. Considering the overall influence SMEs exhibit in the European economy, a collaboration between Large and Small firms in a supply chain can boost the performance of both. This is essentially true as increases in SME productivity would by extension, translate into improved capacity for large firms in the supply chain of the manufacturing industry to consistently develop high quality new products (Lakemond et al., 2006).

Structurally, according to Wayne (2010), large firms appear to run a structure-focused business while SMEs do not appear to be as completely structure-focused. These differences act as a strength in collaboration as structural flexibility is essential for projects where resources are limited and structural rigidity is essential for managing large projects (Harper, 2015). Notwithstanding the above fact that rigidly structured processes may seem inappropriate for situations where business environment factors are typically dynamic, some structure is essential for effective management and responsibility which in turn, enhance control of the business approach and circumvent inefficient and unstable practices (Eldridge & Crombie, 2013; Lam, 2011).

Apart from SMEs acting simply as occasional subcontractors in the supply chain of larger firms, both large and small competing firms seem to more frequently forge alliances for competition often referred to as 'coopetition', in order to boost their collective competitive advantage and dominance in the market (Kraus, Meier, Niemand, Bouncken, & Ritala, 2018). The possible motivation for firms entering into an alliance for the purpose of coopetition may differ based on size related characteristics of the firms involved (Chiambaretto, Bengtsson, Fernandez, & Näsholm, 2019). However, Wu (2014) notes that firms of different sizes can engage in alliances with several other partners such as educational and research institutions. As collaboratiing firms often have different interests, uncertainty may develop. When uncertainty exists in this case, it could lead to unfinished projects due to low productivity; rejection of projects due to lack of optimized time usage and poor quality due to substandard quality reassurance processes (Laursen & Andersen, 2016). By focusing on the prospects ahead rather than the problems inherent, firms may be able to forge ahead and develop innovative products through effective planning (Yang, Burns, & Backhouse, 2004).

It would therefore be a drawback to the entire industry if SMEs are not given as much attention as Large firms in the supply chain when assessing their need for a robust planned process to shorten time of delivery, increase productivity (value for money) and enhance efficiency internally, the absence of which can cause problems for the Large firm (parent firm) and vice versa.

1.4. THE PROSPECTS FOR NEW PRODUCT DEVELOPMENT IN THE FLOW HANDLING EQUIPMENT INDUSTRY

For centuries, New Product development practices in the flow handling equipment industry have emerged in various forms and complexities. Over the past few decades, NPD activity has become an industrial norm in essentially many vital aspects of planned enterprise development models (Barkley, 2008; Brown & Eisenhardt, 1995). Major Evolutionary trends in NPD within the flow handling Equipment related industry show innovative technological advancements from handheld calculators to high performance computers for performing mathematical design calculations (Cipolla-Ficarra, 2011). Handheld wired telephones have also evolved to wireless internet for communication and easy access to information (Bhattacharyya, Deprettere, Leupers, & Takala, 2018). In flow handling equipment design, advancements have also led to increase in product complexity such as in the development of long distance pipelines for transporting fluid materials (Asim & Mishra, 2016) and development of severe service control valves facilitating the rate of fluid flow used in energy systems (Asim et al., 2017). Indubitably, the flow handling equipment industry benefits from multiple global inventions in different sectors, which have continued exposing successive generations to new products, and as such, new prospects for innovative flow handling product development. Most Flow Handling equipment producers in the supply chain develop their products and services for firms in industries such as Aeronautics, Automotive, Petro-chemical, Oil and Gas, Energy, Military, Health as well as for domestic uses (Davidson, 2003; Dvorak, 2006; Goto, 2016).

While interesting feats have been achieved in the emergence of new products from the flow handling equipment industry, it is imperative to note that the entirety of the idea of new product development is not to focus solely on the fabrication or design of a new product. In actual fact, it intends to encompass that and a lot more, it comprises of the link between multifaceted methods involved in identifying, managing and controlling the entire process from the conception of the idea to as far as after launch and the end of the product's working life (Trotta, 2010). The ability of the product and the producing firm to achieve these aims and maximize value are mostly determined by factors such as Quality, Time and Cost (Crawford & Di Benedetto, 2015).

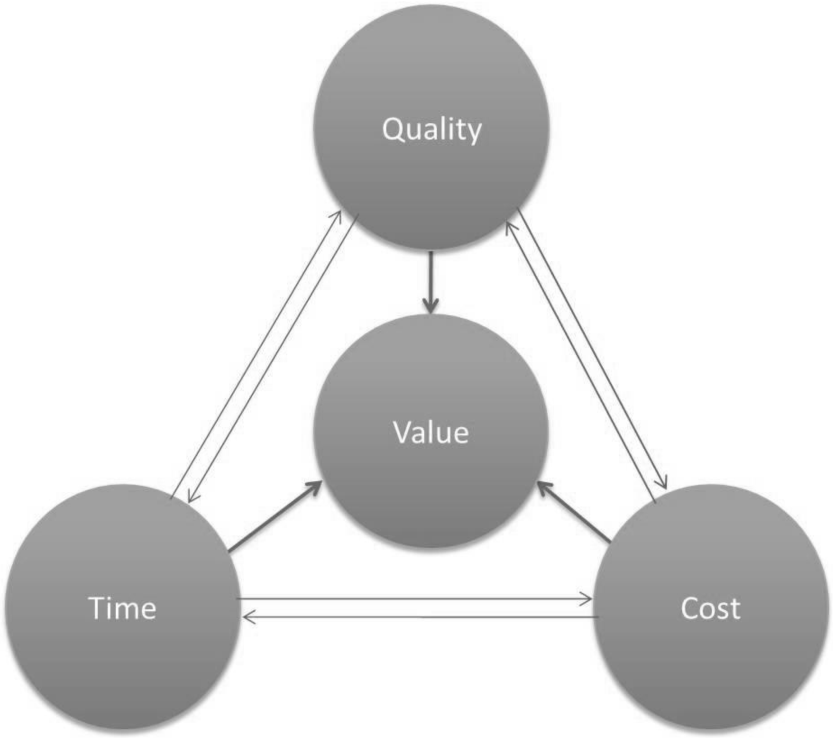


Figure 1 The determining factors of New Product Development (Crawford & Di Benedetto, 2015).

Referring to the illustration in figure 1, the three principles are interdependently linked. Therefore, actions taken to achieve one principle would affect the progress of the others. The aim of an NPD process would typically be to establish an equilibrium between these factors to build value.

Ideally, most enterprises endeavour to attain competitive advantage over industry rivals but are not likely to accomplish this if the processes they use are not carefully planned to take into account, various factors that could affect the new product's success. Eisend, Evanschitzky, and Gilliland (2016) affirm that a proactive new product development planning culture can influence product performance. Consequently, improved product performance improves organisational growth and influences industrial growth by encouraging healthy market competition and ultimately, yielding economic growth. Conversely, the resulting output of a poorly planned or mismanaged NPD process would most likely not yield the expected outcomes (De Coster & Bateman, 2012).

The major challenge for Flow Handling equipment production firms since robustly planned NPD processes became mainstream practice, is keeping up with the fast-paced evolution in customer demand for the next industry sensation and developing products that meet stricter sustainability requirements (Bhamra & Lofthouse, 2016; Genç & Di Benedetto, 2018; Goto, 2016; Powell, 2017). Consequently, NPD models have to be constantly revised and adjusted to keep up to date with industrial changes. Those unable to stay ahead of the competition are faced with a risk of exiting the market prematurely (Porter, 2004). This implies that evolving competition metrics have to be taken into consideration when adopting or applying NPD models.

To help with the achievement of strategic product development goals, an array of partnerships and alliances exist with opportunities for collaboration in the flow handling equipment industry. For example, In the United Kingdom alone, over 190 companies that build and design valves and actuators are registered with the British Valve and Actuator Association (BVAA). This sector accounts for over £1 billion in sales each year (BVAA, 2015). Furthermore, over 1000 UK firms are members of the Building and Engineering Services Association (B&ES, 2015), which is an association concerned specifically with HVAC (Heating, Ventilation and Air conditioning) applications. Over 130 manufacturing and supply firms are registered members of the Heating, Ventilation and Air conditioning Manufacturers Association (HEVAC): the largest member association of the Federation of Environmental Trade Associations (FETA) which focuses on promoting sustainability and Energy efficiency (FETA, 2015).

Ultimately, this research would develop a systematic methodology for planning the entire New Product Development process to ensure relevant ideas and resources are adequately galvanized, interpreted, communicated, managed and executed efficiently, cost effectively and in a timely manner to arrive at a competitive new product.

1.5. COMPUTATIONAL FLUID DYNAMICS AS A TECHNOLOGICAL TOOL FOR NEW PRODUCT DEVELOPMENT IN FLOW HANDLING APPLICATIONS

The major breakthrough technologies in today's engineering new product development practices are often part of Computer Aided Engineering methods such as Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) commonly tagged the digital revolution (Lukač, 2015). In the flow handling equipment industry, an integral part of the technological tools used in the development of flow handling products is Computational Fluid Dynamics (Asim et al., 2017).

Computational Fluid Dynamics (CFD) is the latest phase in the study of Fluid dynamics (Fluid in motion), having evolved from earlier phases of Experimental and Theoretical Fluid dynamics (Anderson et al., 2016; Davidson, 2003; Goto, 2016; Slotnick et al., 2014). CFD has been a beneficiary of technological advancement in digital computing from the middle of the 20th century and its application in diverse areas of fluid handling operations have continued to increase (Anderson et al., 2016). Over the last decade, CFD has made its mark as a vital tool for managing sustainability, saving time, reducing scrap and most importantly improving overall product design in a variety of flow handling applications (Davidson, 2003; Goto, 2016). Consequently, Computational Fluid Dynamics has emerged as the cutting edge technology used for analysing and evaluating whole systems and component part performance with regards to fluid flow (Asim et al., 2017; Goto, 2016; Raynal, Augier, Bazer-Bachi, Haroun, & Pereira da Fonte, 2016).

Among its various functions, CFD is able to reduce cost as well as achieve process optimization and reduction of downtime by providing a credible digital supplement that minimises heavy reliance on physical experiments for product design and development using simulations (Jeong & Seong, 2014; Martinho, Lopes, & da Silva, 2012). While simulated product designs still have to be validated using physical experiments, the number of trials and the requisite cost to perfect the product using the latter is significantly reduced when product design concepts are analysed in a virtual environment (Martinopoulos, Missirlis, Tsilingiridis, Yakinthos, & Kyriakis, 2010; Peksen, Peters, Blum, & Stolten, 2011). CFD is able to simulate and achieve closely related flow results as obtainable in a physical experiment, by solving the equations of motion in discretized elements of a numerical model that detail the characteristics of the flow domain (Goto, 2016).

According to Davidson (2003) and Goto (2016), automation in CFD was introduced with the advent of electronic computers taking advantage of complex numerical calculations. Prior to this development, CFD codes would usually be generated for specific use such as in the production of an aircraft(Spalart & Venkatakrishnan, 2016). In recent times however, sophisticated codes for generic use are developed by software development enterprises targeting users of CFD like institutions, industries and other parastatals with a view to building a business around the use of

CFD technology through sale of CFD code licenses(Bhutta et al., 2012). Likewise, open source CFD exist in today’s fluid flow handling equipment industry, giving developers the freedom to generate integral codes for their intended applications (Jacobsen, Fuhrman, & Fredsøe, 2012). The process for general-purpose CFD application is detailed in the design literature section of this study.

The major challenge within the industry for CFD usage is still highlighted in research as the complexity of understanding the relationships between the different functions of CFD such as mesh quality, solution accuracy and the use of command languages for those intending to develop their own codes, thereby making it seem more inclined towards specialists use (Goto, 2018). Major technological advancements to make CFD more user friendly have led to the development of simplified codes such that all-in-one software packages for pre-processing (such as geometry design and mesh generation) are provided alongside processor solvers and post processing tools(Keshmiri & Andrews, 2015). Besides, the prospects for CFD as a technology present great user benefits, one of such benefits is in reducing the need to make the kind of assumptions that are common using physical experimentation alone (Goto, 2018). As an example, CFD technology offers opportunities for both local and global flow analysis as it is digitally programmed to provide a clear representation of the flow behaviour at each point in the flow. While global flow behaviour can be determined experimentally, local flow behaviour in corners hidden by obstructions cannot be observed in the experiment.

Along with helping firms improve reliability of product design, time to market, and meeting sustainability standards, Davidson (2003) believes the economic contributions made from CFD use are enormous but often go under reported. Davidson (2003) explains this in detail citing an economic case where CFD use yielded a six-fold return on investment and suggested that CFD awareness can be improved if placed in the hands of those who make the strategic business decisions as well as the operators of the products to be designed. Over a decade later, more publications have been released detailing significant case studies that describe CFD applications in practice. Some of these are detailed in the literature section and more can be found in online magazines such as *ANSYS Advantage Magazine* and Scholarly journals such as *International Journal of Computational Fluid Dynamics, Progress in Computational Fluid Dynamics, Advances in Computational Fluid Dynamics* and many more. The potential for development using CFD seems promising, however detailed publications that provide a thorough assessment of management use of CFD as part of a new product development methodology are limited in literature.

The author believes that design prediction, testing and analysis, a major aspect of New Product Development, can benefit tremendously from this new technology if embedded in the New Product Development process of firms in the flow handling equipment production industry.

1.6. THE FUTURE OF COMPUTATIONAL FLUID DYNAMICS IN THE FLOW HANDLING EQUIPMENT INDUSTRY

During the Industrial revolution in the middle of the 18^{th} century, the flow handling industry concentrated on innovative forms of harnessing fossil-fuelled energy, often requiring fluid flow handling techniques (Wrigley, 2013). Energy and transportation had evolved from animal drawn carriages and naturally powered energy sources to steam powered trains and gas turbine-powered generation plants (Chu & Majumdar, 2012). Over the course of time, rising carbon emission levels emanating from fossil-fuelled energy generation, transport and consumption, posed significant risks to the environment and stirred the rise of climate change protection initiatives globally, attempting to curtail activities that cause more damage to the planet (McDonough & Braungart, 2017).

At present, global population figures have more than doubled alongside its associated energy consumption and demand. With an estimated 7 billion world population figure in 2011 and an existing potential to rise to about 9 billion by 2050 then 10.1 billion by 2100 (Lee, 2011), the corresponding demand for energy would reach peak levels (Chu & Majumdar, 2012). If the world continues to rely on fossil fuels for its energy and transportation needs, it would result in higher rates of carbon emissions which have detrimental effects on climate and the environment (Alderson, Cranston, & Hammond, 2012; Zou, Zhao, Zhang, & Xiong, 2016).

While the flow handling equipment industry consists of many product development processes and products powered by fossil-fuelled engines, there has been substantial pressure on energy producers and users alike to seek more sustainable forms of energy for their activities (Nidumolu, Prahalad, & Rangaswami, 2009). The prospects of access to clean and reliable energy has recently been met with optimism due to the emergence of alternative energy sources such as Solar, Wind and Water powered systems (Panwar, Kaushik, & Kothari, 2011). Thus, drawing industrial focus away from fossil-fuelled sources of energy to cleaner and renewable forms. The duty then lies with producers in the flow handling equipment industry to key into these innovative technologies, as most of them require flow optimization techniques that Computational Fluid Dynamics provides.

With continued plans to cut down global carbon emissions (Alderson et al., 2012), it is expected that more firms in the fluid flow handling equipment business would remain relevant as practitioners of sustainable forms of new product development using simulation based techniques for reducing over reliance on practical experimentation(Jeong & Seong, 2014). Examples of CFD prospects gathered from a literary search include: advancements in the aeronautic industry (Spalart & Venkatakrishnan, 2016), verification of air pollutant emissions from vehicular traffic and industrial plants (Hefny & Ooka, 2009), Strategic breakthrough in Cardiovascular medicine (Morris et al., 2016), Solar powered air heaters (Yadav & Bhagoria, 2013), Modelling Fermenting Reactors (Formenti et al., 2014), indoor use in ventilation monitoring and identification of airborne disease spread (Li & Nielsen, 2011). Predicting and monitoring blast waves from Explosions (Hansen, Hinze, Engel, & Davis, 2010), cavitation detection in pumps and pipes (Ding, Visser, Jiang, & Furmanczyk, 2011) and in design of valves for severe service systems (Asim et al., 2017) among many others. Advancements in CFD use have also stimulated improvements in CFD-related technology, an example is in advancements of computing graphics processing units (Vanka, Shinn, & Sahu, 2011). Within the CFD technology itself, some recent innovations have been developed such as a meshless approach to flow modelling though this area is expensive to implement and still in its early stages (Shadloo, Oger, & Le Touzé, 2016). Challenges identified in implementation of the technology for the flow handling equipment industry include: Numerical solution, computing power and physical modelling (Spalart & Venkatakrishnan, 2016).

A horizon scan of CFD use in the fluid flow handling equipment industry over the next 10 years reveal enormous potential for technological growth and implementation, especially with advancements in areas of clean transportation and clean energy generation (Chu & Majumdar, 2012). As Vanka et al. (2011) remarks, the potential for high performance computing with graphic processing units is a major advancement for computational ways of testing product designs. As carbon emissions are gradually phased out before 2050 (Alderson et al., 2012), the potential for CFD development should significantly increase in areas of alternative energy Wind energy (fan), Solar energy, Wave energy, and Health related development particularly in Cardiovascular medicine. Advancements in the CFD technology itself can be envisaged with better-improved computing processing power (Vanka et al., 2011), meshless modelling (Shadloo et al., 2016), and integration of CFD systems into other process technology systems which this research plans to accomplish. There also exists varied potential for design such as in Building Information systems (Volkov, Sedov, & Chelyshkov, 2013), Industry 4.0 (Ang, Goh, & Li, 2016; Pan et al., 2015) and the digital twin (Kraft, 2016; Tuegel, Ingraffea, Eason, & Spottswood, 2011).

1.7. RESEARCH RATIONALE

This research intends to improve new product development practice by extending its ability to support sustainability using 21st century digital technology. The study is brought about by the growing demand for sustainability practices globally. In a few decades, fossil fuelled energy would be phased out due to carbon emissions effect on climate change and the environment while renewable sources of energy would become mainstream (Alderson et al., 2012). The introduction of these alternative renewable sources of energy have incidentally emerged alongside the digital revolution which implies that sooner or later, product developers would be required to key into digital technology to remain active in competition (Al-Khouri, 2013).

In the flow handling equipment industry, the prospects for Computational Fluid Dynamics (CFD) since its inception in the 1950s and 1960s, have grown considerably over the last 3 decades (Anderson et al., 2016; Goto, 2016). Fluid flow analysis using computer simulations are renowned for the reduction of heavy reliance on multiple practical tests as they consume valuable resources in terms of time, cost and quality (Goto, 2016). Utilization of this nascent technology as an analysis tool for new product development in flow handling equipment applications has proven effective in various industries such as the Aeronautics, Oil & Gas, automobile, medical and health sector among others (Versteeg & Malalasekera, 2007). The technology itself has experienced upgrades. One of such improvements has been the development of High Performance Computing (HPC) for simulations with improved storage and processing capabilities performing even higher number of numerical calculations at faster rates(Holmes & Newall, 2016). This trend is expected to experience tremendous growth over the next decade (Slotnick et al., 2014). The plethora of innovative advancements taking place in additive and subtractive manufacturing techniques also create new avenues for manufacturability of complex product designs a number of which are informed by numerical design optimization (Langelaar, 2017; Liu & To, 2017).

Notwithstanding recent developments, firms still appear to use this tool parsimoniously despite repeated plans to boost technological integration in mainstream Engineering design and manufacturing techniques. It has been gathered that many firms do not adopt a robust approach to the application of Computational Fluid Dynamics and the reasons for this is not clearly defined in available literature. Instead, most publications in this area focus extensively on individual isolated events where CFD has been used but do not directly discuss management influence on CFD utilization.

Similarly, there are limited publications on the integration of CFD as part of an adoptable systematic NPD process to enable firms of varying sizes in the fluid flow handling equipment industry put their various ingenious ideas and tools into context. If this can be achieved, obstacles to technology advancements and a clear understanding of the necessary steps required for CFD development would grow at a faster rate and make new product development in flow handling applications more of a purposefully driven process, guaranteeing efficiency in unique and dynamic situations. If firms can then manufacture their products right first time, issues that result in concession, product ban or loss of client trust, would be minimal or negligible.

This research focuses on SMEs and Large enterprises alike. This is because, apart from the amount of investments well-known large companies make in advancing enterprise growth, Small Medium Enterprises (SMEs), essentially those in key supply-chain positions, have also contributed enormously to the growth of the flow handling equipment industry (Colombo, Inzoli, & Mereu, 2012). However, both SMEs and Large companies, face similar challenges with having to meet up with technological demands and tough competition in bringing new products to market sustainably. Technological collaborations are identified as having the potential to bridge the innovation gap between SMEs and Large firms(Nieto & Santamaría, 2010). Consequently, such firms would be expected to possess the necessary tools to thrive and lead technological advancements in the area without much of the difficulties before, during and after the product's useful life (Chan & Chung, 2002).

Studying the dynamics of their internal structure would help define how prepared the firms are for CFD integration. Consequently, an innovatively structured methodology for applying CFD as a technological tool for systematic use in NPD processes is sought as the intended outcome of this research. The resulting benefit of this work is the improvement of small, medium and large enterprise engineering New product development practices within the flow handling equipment industry, using process improvement measures that would promote sustainability through wider application of CFD technology in practice.

1.8. RESEARCH AIMS

The primary aim of this research is:

To build an authentic system that integrates CFD into the operational framework of a new product development process in the flow handling equipment industry.

In order to achieve this aim, the research is split into the three parts that make up the title of the research and the research aim.

- Flow Handling Equipment Industry - Organisation
- New Product Development - Process
- CFD – Design

The following research questions have been developed from the study based on the three areas highlighted above.

1.8.1. RESEARCH QUESTIONS

The Three Research Questions of the study are:

- **RQ 1:** How do firms in flow handling equipment industry organize their resources and processes for New Product Development?

- **RQ 2:** What New Product Development methodologies are preferred by firms in the flow handling equipment industry?

- **RQ 3:** How do firms react to CFD technology during the NPD process?

The answers to these research questions will form the first three objectives of this research. Consequently, these would then form the basis for the accomplishment of the remaining objectives to achieve the main aim of the research.

1.8.2. RESEARCH CONTRIBUTIONS & OBJECTIVES

The full list of the research objectives as detailed below is categorized into three phases based on the intended main contributions to the research.

Main Contribution 1: Develop a novel assessment of Flow Handling Equipment Industry enterprise preparedness for Computational Fluid Dynamics integration into the New Product Development Process.

- **Objective 1:** Outline useful internal and external organisational knowledge resources for New Product Development in flow handling equipment industry enterprise.
- **Objective 2:** Outline NPD methods and tools used in practice by firms in flow handling equipment industry for New Product Development.
- **Objective 3:** Outline the reaction of firms to CFD technology adoption for New Product Development in the Flow Handling Equipment Industry.

Main Contribution 2: Develop a novel methodology to help firms integrate the best tools and methods to their process.

- **Objective 4:** New Methodology should utilize key unique internal and external organisation resources for NPD.
- **Objective 5:** New Methodology should utilize procedures for dynamic product lifecycles.
- **Objective 6:** New Methodology should enable systematic integration of CFD technology as part of the design phase of the NPD process.

Main Contribution 3: Develop a Novel Product using CFD analysis as an integrated technological approach to inform product development.

- **Objective 7:** Product should meet organisational design specifications
- **Objective 8:** Provide documented procedure for Product's development using novel methodology.
- **Objective 9:** Product design should be optimized using CFD technology

The proceeds from these research objectives would establish an up to date assessment and reference point for more organisational and technological development in the future.

1.9. RESEARCH SCOPE

This study was conducted to develop a new methodology for CFD integration into the new product development process. It was compelled by the absence of a detailed CFD integrated methodology for new product development within the flow handling equipment industry in the United Kingdom. The areas of research covered and assessed were based on the three major areas of the research, which include the organisational preparedness of firms, their NPD methods as well as their use of CFD technology in practice.

A comprehensive literature search was initiated and key journals from each section were identified and adequately referenced making up a substantial part of the review. Materials used for literary investigation include Journal articles, books, organisational briefs, as well as governmental and industry publications. All of these references were sourced from multiple scholarly resources such as Science Direct, Summon, Elsevier and Springer. Scholarly articles from top journals were also referenced throughout the research some of which include: *IEEE Engineering journal, Technovation, Journal of Fluid dynamics, Journal of Engineering Education, International Journal of Engineering Manufacture, International Journal of Quality and Reliability management, Journal of Engineering and Management, Systems Engineering etc.*

The findings from literature were evaluated based on the research questions. Typical organisation dynamics were examined to provide valuable insight into the factors inherent in organisational preparedness for product development and decision-making within the flow handling equipment industry. Typical methods for new product development were also examined alongside prospects for CFD advancement within the flow handling equipment industry.

A mixed methods process was applied to the study in two parts. The first is a qualitative approach for data inquiry, and the second is a quantitative simulated experiment for the pilot study stage. A qualitative approach is used for data inquiry in this research, as the intent of the investigation is to obtain possible influencing habits that flow-handling equipment enterprises are likely to exhibit in relation to new product development and CFD usage. A quantitative styled approach is not used during the initial data collection phase until the pilot phase, as the intent of the study is not to obtain a statistical representation of CFD overall use for generalisation but to assess the possible factors that influence organisational preparedness in order to provide a solution in line with a pragmatic philosophy.

The inquiry focused on an exploration of six firms spread across small, medium and large enterprises from both valve and fan industry sectors of the fluid flow handling equipment industry in West Yorkshire, United Kingdom. The selection of 3 Valve and 3 Fan companies as representatives of the flow handling equipment industry for data collection was made due to their product and development process being of a manageable scale within the time frame and scope of this project. The different sizes of the firms involved (2 industry firms per size) were selected to offer an encompassing insight into the peculiarities of the industry and how it affects firms of different performance capacities. The quality of information obtained from the data collection process is strategically capable of influencing the wider industry dynamics as all the participating firms are key performers in the area and keen on improving industrial practices in the region.

A qualitative preliminary survey and a follow up interview approach have been used for each company to obtain as much useful information as possible for triangulation in the assessment stage of the research. Useful theories such as systems theory and technology acceptance model (TAM) were also discussed to assist with the evaluation of the collected data results. NVIVO software was used for coding the results from the data inquiry. The analysis was then carried out using thematic analysis and related theme findings were developed for guidance in the creation of the novel methodology. Suitable systems engineering methods proven to impact high quality product development were assessed and optimized to integrate Computational Fluid Dynamics into industry specific product development lifecycles. This led to the development of a requisite blueprint methodological solution to improve technological design integration to the new product development process.

The quantitative approach of the mixed methods is then applied afterwards through a pilot test of the new methodology using CFD simulated experiments to test the performance of the new product design to ascertain the efficacy of the new methodology in compliance with the aims of the investigation. During the Pilot phase of the research, *ANSYS Fluent wa*s the CFD simulation software used to analyse the design performance characteristics of the product in development.

As the research is focused on CFD integration, the scope of this research restricts the product development to virtual prototyping alone using CFD as a tool to test product performance and does not involve an actual physical product build. Also, FEA analysis was not carried out in this study as it is beyond the scope. The research was completed after the research questions were answered and all the objectives had been met.

1.10. RESEARCH PLAN

Figure 2 illustrates a map of the research plan. It presents the topic of the research and the route taken to arrive at a fulfilment of the research aims. As observable from the flow diagram, the topic is divided into three core areas, based on the objectives of the research: Organisation, Process and Design. These three areas are comprehensively explored in literature in a bid to develop an understanding of the first three objectives of the research and to obtain valuable information to aid in the data inquiry process for meeting the other aims of the research. At the Data collection stage, a pragmatic mixed methods approach is deployed to obtain information in line with the research questions. The new findings from data collection are then analysed and presented as novel findings while a solution-based novel methodology is developed from an assessment of the systems engineering principles. The newly developed methodology is then applied to the development of a novel product through a pilot study. The conclusions from each of the three areas are conclusively evaluated to assess how the objectives and aim of the research have been met, future recommendations are given then the research closes.

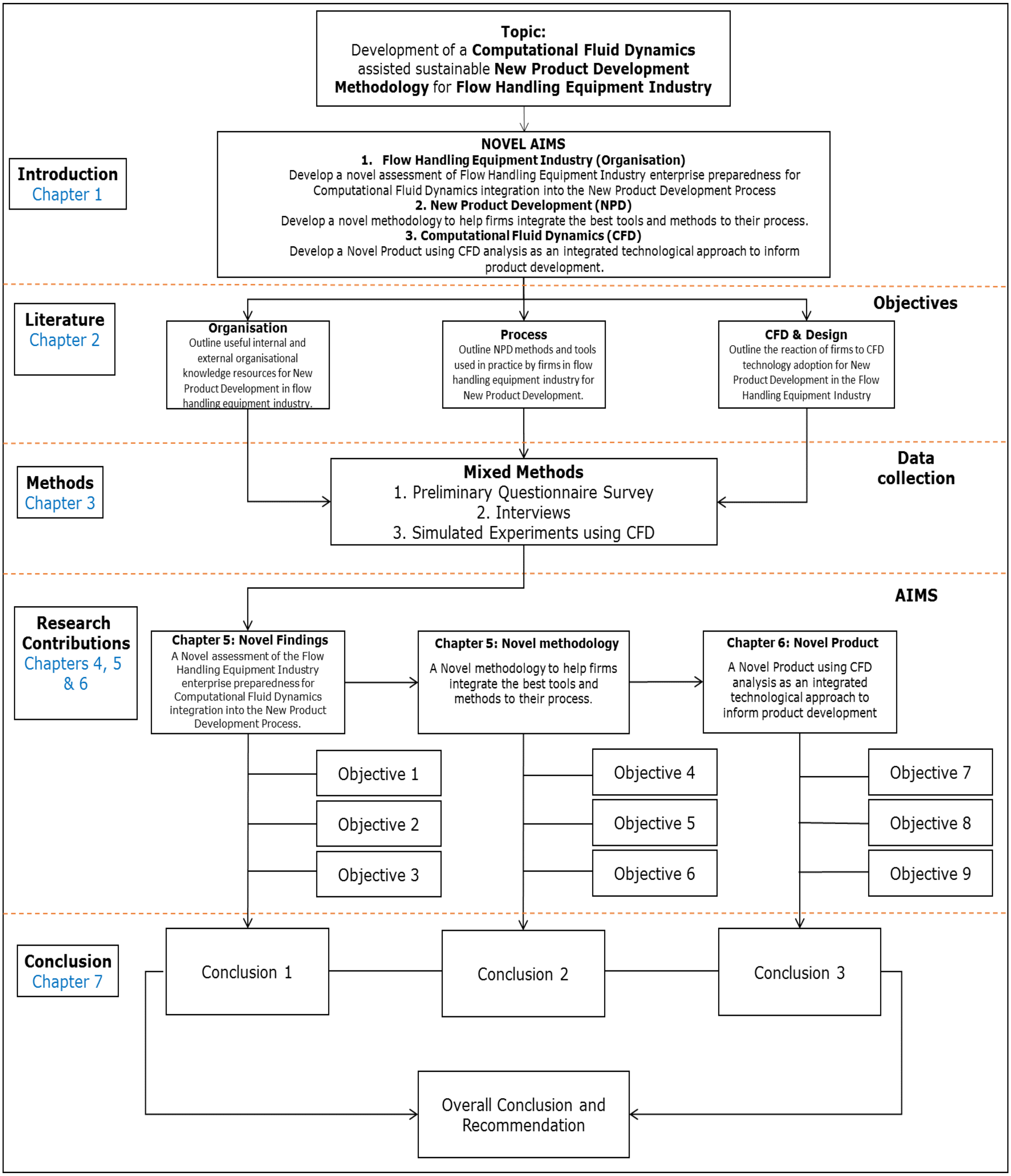


Figure 2 Map of the Research Plan

1.11. OUTLINE OF THESIS

This research consists of seven (7) chapters. The following describes each chapter content:

Chapter 1 presents an introductory overview of the research context; the background of the study is provided highlighting trends in enterprise and CFD technology growth within the fluid flow handling equipment industry. The rationale for scholarly research is also presented alongside the research scope, questions, aim and objectives.

Chapter 2 reviews existing literature in the three major aspects of the research relating to the fluid flow handling equipment industry: organisation, product development processes and CFD design development. It concludes with an assessment of the need for data collection based on the gaps from the research.

Chapter 3 outlines the research methodology used for data collection and subsequent analysis of the research data. It also illustrates the view-lens of the author in assessing the overall research and data collection process. The preliminary survey and interview plans are discussed as well as ethical considerations, limitations and a dissemination plan. This is shortly followed by a section dedicated to useful theories for analysing the results from the data collection process.

Chapter 4 highlights the data preparation of proceeds from the interviews, transcription and analysis process. It then reveals the results of the investigation based on the objectives 1 - 3 of the research and presents a modified technology acceptance model optimised for assessing CFD technology adoption in flow handling equipment industry.

Chapter 5 uses interpretations of the data from preceding chapters to develop a new product development methodology to meet objectives 4 – 6 of the research. Two systems engineering processes are analysed and relevant aspects of their processes that meet the expectations for the new process are utilised for the development of a new methodology. Consequently, a novel systems engine and product lifecycle is developed alongside a list of resource NPD tools that can be utilized in various parts of the process.

Chapter 6 features the deployment of the new methodology as developed in the previous chapter to design and develop a new product to meet objectives 7 – 9 of the research. A novel hybrid valve is then developed and CFD analysis is used to assess its performance.

Chapter 7 concludes the research with a summary of the findings, aims and novelty contributions that have been made. Limitations to the study as well as recommendations and future work are also presented.

CHAPTER 2: LITERATURE REVIEW

In the previous chapter, the dynamics of the flow handling equipment industry and potential for Computational Fluid Dynamics (CFD) use in innovative New Product Development (NPD) were defined. The motivation, aim and scope of the study were also presented. This chapter now examines the available literature in the field to uncover existing work done in the research area. Based on the main contributions of the research aim from chapter 1, this Literature section is divided into three sections termed Organisation, Process and Design as illustrated in figure 3. Each of the sections are focused on exploring one of the three research questions to develop a better understanding of the topic concepts, expose the gaps of the research and ultimately strengthen the inquiry for data collection in subsequent chapters.

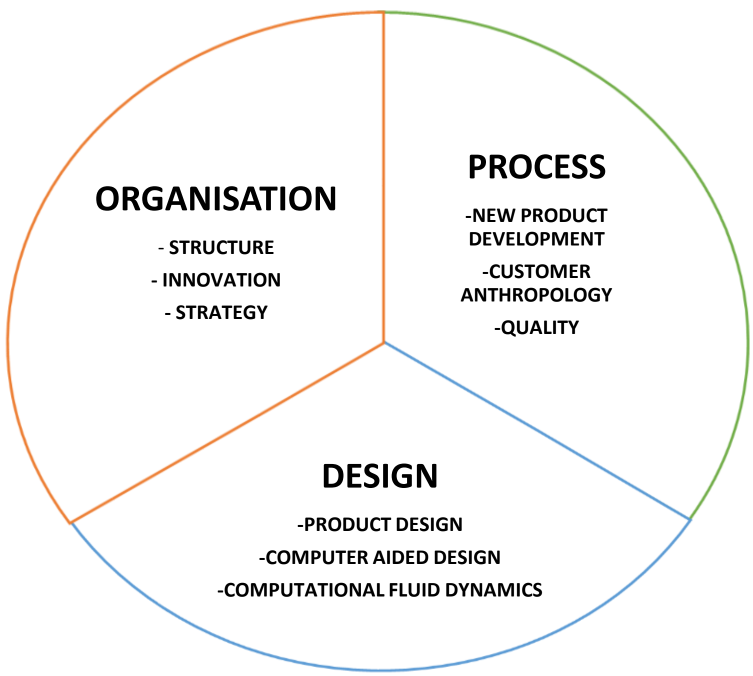


Figure 3 Literature Review Sections

In the first section of this review, trends in **organisation management** are established as it relates to the internal structures, innovative potential and external strategies used by firms in the flow handling equipment industry. The second section highlights relevant advancements in known **process development** methods used to facilitate new product development, understanding customer requirements and quality assurance activities within the flow handling equipment industry. The third and final section of the literature review attempts to discover **design** trends in Flow handling equipment industry alongside prospects for CFD as the latest technological design innovation in flow handling equipment industry.

ORGANISATIONAL DEVELOPMENT

This section reviews literary information in organisation development and relates it to the flow handling equipment industry. It first examines structural organisational factors that affect performance, then draws attention to the way firms build innovation and manage strategic priorities. Key journals referenced in this section include: *Technovation, Procedia-Social Behavioral Sciences, The International Journal of Business in Society, International Journal of Business Globalisation, Business Process Management Journal, Harvard business review, Organization Science, Journal of Small Business and Enterprise Development.* This review helps define the literary perspective on organisational formations and understanding how they relate to internal and external situations in tandem with objective one of the study.

2.1. ORGANIZATIONAL STRUCTURE

Historically, different structures have been considered desirable in line with the priorities of the industrial factors in time. At the time of the inception of CFD computational codes in the 1950s-60s (Anderson, Degrez, Dick, & Grundmann, 2013), Burns and Stalker (1966) highlighted two organizational structure categories, the mechanical and organic structure. The mechanical system is formal and rigid, while the organic system tends to be more informal and flexible. The recommendation of Burns and Stalker (1966) at the time, was for firms to adopt a formal decentralized structure for highly challenging business environments.

Between the 1980's-90s, computerized technology advancements greatly improved the prospects for detailed flow handling solutions (Schmitz, 1999). Choueke and Armstrong (1998) observe the common trend in manufacturing industries during this time, stating that while firms in this period were more motivated to implement the formal mechanical structure as suggested by Burns and Stalker, opportunities still existed for growth using organic structures.

Later on, the initial submission by Burns and Stalker (1966) was challenged by Cosh and Fu (2012) who propose that younger technology-oriented firms have a tendency to exhibit more innovative capabilities in a highly challenging business environment by applying an organic structure system. Cosh and Fu (2012) present an exception to the Burns and Stalker (1966) narrative about the proposed supremacy of the mechanical system, highlighting that mechanical systems are only seen to be successfully used in modern times when new firms are technology-oriented or with older firms that are very much experienced in the field. Therefore, it can be inferred from the above, that firms with less experience and lower rates of technology adoption are more likely to use an organic structure to achieve their aims.

More recently, Johnson, Whittington, Angwin, Regner, and Scholes (2014) claim that five prominent structures are commonly used in both large and small medium enterprises in contemporary practice, they are: Functional, Matrix, Multinational, Multidivisional, and Project Based organizational structures. In most firms, particularly in the flow handling equipment industry, the commonly used structures are the Functional and Matrix systems (Goto, 2016; Meijaard, Brand, & Mosselman, 2005; Rivkin & Siggelkow, 2003; Wayne, 2010). In the Functional structure, the work is divided into departments by specialisation and employees can report to the departmental head. On the other hand, Matrix structured teams simultaneously work in parallel towards a goal, this is common in project-oriented organizations and places where employees report through line/project managers or corporate managers (Johnson et al., 2014; Meijaard et al., 2005; Rivkin & Siggelkow, 2003; Wayne, 2010)

In general, structures are essential to firm performance. The findings of Meijaard et al. (2005), reveal that a firm's organisational structure would have substantial effects on the performance of the organization. However, Wayne (2010) stipulates that while Small Medium Enterprises (SME) possess some form of organisational structure, they are not ardent followers of the system and as such, do not exhibit defined structures compared to their Larger counterparts. This implies that SMEs looking to improve performance would require some structure to improve their performance for future improvement (Eisend et al., 2016).

Rivkin and Siggelkow (2003) believe that the constituents of a typical organisational structure are interconnected as well as inter-reliant. Many firms appear to depend on a variety of influencing factors such as organizational culture, technology, decision making, or other external factors when deciding to adopt an organisational structure system (Eisend et al., 2016). According to Green et al (2008) and Eisend et al. (2016), structure influences culture of a firm and is necessary for better informed decision making..

As previously hinted by Cosh and Fu (2012), technology or other internal and external factors can influence the kind of structure used by firms. For the flow handling equipment industry, structure can be technologically oriented and the measure of importance SMEs attach to having a planned organisation structure that is technology oriented, depends largely on the likelihood of the organisation to meet such requirements financially or otherwise (Lungeanu, Stern, & Zajac, 2016). The implications of this for the flow handling equipment industry is that organisations would make decisions whether to invest in CFD technology based on the affordability of the technology.

2.1.1. ORGANISATIONAL CULTURE

Many scholars have defined organisation culture as a collective expression of ethics, beliefs or the natural practice synonymous with a set of individuals that belong to a specific organisation (Chu, 2003; Deshpande & Webster, 1989; Foster & Taylor, 2016; Hale, 2000; Schein, 2010). Culture can either be formally articulated by management (Colin, 1998; Thompson & McHugh, 2009) or organically through a more natural informal experiential process (Alvesson, 2002; Burnes, 2000). A common response from both narratives reveal that the organisation culture style adopted by firms would differ geographically due to the characteristic norms present where the firm is domiciled.

In the United Kingdom, there is a tendency for SMEs to not exhibit a formal style of organization culture and structure unlike Large companies that are more structured in nature (Adebanjo & Kehoe, 1998; Swift & Lawrence, 2003; Wayne, 2010). This is primarily attributed to the fact that the majority of UK SMEs are owned and run by families (Eisend et al., 2016) and in such cases, family leaders would typically make all the management decisions concerning the business. Members of the management team are also likely to be selected on the basis of family relations and not fundamentally as a function of specific skills that the individuals possess, often leaving little room for experts in-house to make key decisions. Swift and Lawrence (2003) argue in line with this notion, stating that the bulk of UK SMEs do not adopt formal kind of cultures for their work environment and therefore there is bound to be an unstable change of culture each time a new leadership emerges. In most cases of family appointed management, the common approach where certain aspects of the job require specialist knowledge, would then be to subcontract the respective job aspect for external assistance (Yong & Panikkos, 2010).

Inglehart (2018), Carson (1995) and Slater and Narver (1995) posit that cultural patterns may also be reflected on an industry wide level. For instance, in the flow handling equipment industry, the norm prior to the advent of CFD had been for product developers to use empirical and experimental methods for evaluating fluid flow predictions (Goto, 2016). Similarly, visual aids specific to flow handling operations such as diagrams, maps, charts and graphs have been observed to be better understood by technical staff of firms from process industries where flow handling is likely to be a main activity too (Edmonds, 2016). In some cases, the exact culture practiced by organizations in an industry may be difficult to distinctly define due to the characteristic complexity of leadership within the firms (Eisend et al., 2016; Ouchi & Wilkins, 1985). However, some studies in this area have indicated that most firms including SMEs are conscious of their specific organisation culture (Crane, 2017; Parsons et al., 2014). However a salient point to note is that the culture of the firm is most likely influenced internally by the management style of owners and board members at the helm of affairs (Mishra & Kapil, 2017)

From the above, it can be surmised that culture is influenced externally; by social norms of a geographical region and industry, and internally; by structure and decision making leadership (Brooks, 2008; Choueke & Armstrong, 1998; Green et al., 2008; Mishra & Kapil, 2017). The choice in setting up a winning culture then depends on the decision-makers of the firm.

2.1.2. ORGANISATIONAL DECISION MAKING

According to Haskel (1999) and Atkinson and Storey (2016), it is common place to find SMEs that enforce labour through a variety of roles. On the other hand, other research indicate labour utilization is more specialized in large firms (Garicano, 2000). This implies that organization size is likely to influence the degree of specialisation that firms would adopt in carrying out new product development activities.

Practically, a typical decision making system as defined by Rached, Bahroun, and Campagne (2016) is categorized into two:

- **Centralized decision-making:** This refers to decisions that are usually only made by top management. This is likely to occur in a functional structure.
- **Decentralized decision-making:** This deals with the involvement of non-top management staff in aspects of the decision making process. This occurs more often in firms exhibiting a Matrix styled structure.

Management orientation accounts for a majority of strategic decision-making and value systems in most firms (Mishra & Kapil, 2017). Czarnitzki and Kraft (2009) state that firms managed by decision making owners are less likely to invest in research and development and are more likely to develop products that are considerably less innovative. On the other hand, they find that firms led by managers tend to be more innovative and less profit oriented. This finding is chiefly based on the fact that owner-led management is more likely to focus more on the profitability of the business than necessarily improving innovation, while firm managers are less likely to focus entirely on profits and more likely to build on innovation for career achievements and increased reputation (Zahra, 2005). In such situations, the debt incurred from attempts to maximize innovation at the expense of financial cost or vice versa, disciplines management decisions and returns the focus of the firm to the market (Johnsen & McMahon, 2005). Therefore, the management structure significantly influences the decision system used in the firm.

The ability of firms to adopt technological tools within the flow handling equipment industry would depend largely on structural decision-making. Wayne (2010) proposes allocation of additional decision making authorities beyond top management to include team leaders and even production floor staff. The aim of this is to enhance employee co-ordination, responsibility awareness and better collaboration. Also, decision making is fast becoming more automated. A particular example of such in modern era is the effects of Industry 4.0 on how firms carry out various functions (Lee, Kao, & Yang, 2014; Zhou, Liu, & Zhou, 2015). The next section would describe some of the dynamics that influence technology adoption within firms.

2.1.3. ORGANISATIONAL TECHNOLOGY

Organisational technology can simply be defined as the mechanisms or procedures organisations use to achieve their products and services (Harvey, 1968; Sandfort, 2010). Understanding technology and technology use in the flow handling equipment industry is relative to the structural context of each organisation. The importance of establishing the difference in viewpoints of organisational key players based on technology adoption is highlighted by Scarbrough and Corbett (2013) who posit that the perception of technology held by designers, users and managers may differ and can be shaped by the technology itself. There is also an established link between technology and job functions as roles may be assigned in line with how technology is applied within an organisation (Stone, Deadrick, Lukaszewski, & Johnson, 2015).

In a study to understand how firms are positioned to approach technology functions within a bespoke or batch production business, Harvey (1968) drew focus to a connection between organisational technicality and other attributes of organisational structure which include authority levels, manager to personnel ratio, specialization units and program specification. The findings of the research revealed that firms with technical capabilities were likely to exhibit varied structural and cultural patterns depending on the specificity of their technical applications, whether technically-specific or technically-diverse. It was discovered that, while technically-specific firms were likely to exhibit a differentiation culture (product specialisation) in the allocation of work roles, firms that were less technically-specific (i.e. technically diverse firms) displayed a lower propensity to practice a differentiation culture in allocation of work roles because of the dynamic nature of their product development activities. Harvey's research also discovered that firms with moderate structure complexity (i.e neither technically specific nor technically diverse), were seen to exhibit less specialisation in product development but exhibited more specialisation in marketing or administrative positions. Furthermore, in the area of decision-making, technically specific firms were seen to exhibit a tendency to make more routine decisions than innovative decisions. The reverse was the case for technically diverse firms, as the latter tended to be free from restrictions often imposed by structure and this was anticipated to build a flexible environment for innovation. It can be inferred from Harvey's study that while technically specific firms would find it difficult to diversify their application due to the structures in place, technically diverse firms tend to find it difficult to build their structures around varied applications. However, Harvey's research did not comment on how the firms with different technical complexities exhibiting different structures could improve in their practice. Notwithstanding, Phillips (1980) adds that, uncertainty in decision making can be reduced by creating more structure combined variety to accommodate specific and diverse applications and this can be facilitated by technology.

Organisational technology can also be analysed in a social context to ascertain its implications for how organisations are structured. A possible description of ways through which technology can influence structure can be obtained from the social constructivism belief that the function of a product is decided by what customers belief patterns accept it to be and conversely, the design specifications of a product are determined by customer requirements which are interpreted based on the social constructions of the developer (Kroes & Verbeek, 2014). More specifically, DeSanctis and Poole (1994) relate social constructivism theory to the organizational context and believe technologies are developed with embedded structure patterns in mind which social constructivist developers use to influence firms into acting structured in accomplishing tasks that have been designed to be followed structurally. This might explain why new technology-oriented firms seem to exhibit mechanical structures, as observed by Cosh and Fu (2012), due to the predefined necessity to mirror the structural patterns embedded within the technology itself and the possibility that the other firms may rely on embedded structures to function and therefore choose to follow a flexible structure.

Conversely, there are those who believe firms still need to develop their own structures for managing technology independent of what the developers intended. Renowned British sociologist, Anthony Giddens, in his earlier works (Giddens, 1979, 1984) attempts to clarify the standpoint of social implications of design through his structuration theory which describes structure as practical and not external to human action. This therefore implies that the social constructivism belief of a structure embedded in technology cannot be interpreted as a structural characteristic of an organisation and as such, structure is only apparent in the way the users interact with the technology.

Modern schools of thought by Orlikowski (2008) and Mutch (2010) also advance the structuration approach asserting that when a firm has any interaction with technology, the structure exists only in the interaction itself and as such the organisation can set up structures for interaction with the technology but does not imply that a particular structure type is embedded within the technology itself. This, Orlikowski (2008) believes, is because technology can be modified or redesigned, therefore leaving room for personalization which eliminates the structural rigidity of the process. Additionally, if the technology is not used often, then the virtual structure it purportedly possesses, would not be useful.

All of the above indicate that there is some correlation between technology and the social behaviour of firms and that the latter can interpret the function of the technology either dependent or independently of the makers of the technology, depending on the social disposition of the user. Huber (1990) and later Scarbrough and Corbett (2013) shed more light in this regard, stating that firms tend to be influenced by technology when it comes to decision making. This could mean something new for process developers that have problems getting firms to follow structures laid down by management. Perhaps if these structures were embedded in technology they would be more likely to follow them or possibly the presence of technology would create a need for firms to structure their activities around the technology. The significance of this for the flow handling equipment industry is that firms need to decide what kind technology what works in their best interest e.g CFD, and this can be achieved using organisational strategy.

2.2. ORGANISATIONAL STRATEGY

Grant (2009) defines organisation strategy as a derivation of a distinctive and meritorious plan aimed at linking different activities to achieve organisational purposes. Knowledge is a key strategic resource in any enterprise (Ipe, 2003). The capacity of any organisation to generate knowledge and innovate is an essential requirement in strategy creation (Goffin & Mitchell, 2016).

Many firms value strategy as a necessary infrastructure for successfully aligning organisational advancement (Cummings & Worley, 2014; Jones, 2013; Namada, 2018). However, new market challenges can make keeping up strategically, a daunting task especially when adequate strategies have not been developed (Marquis & Raynard, 2015). The performance of a firm is therefore likely to rely on the reliability of their strategies. (Johnson et al., 2014) acknowledge that strategies are essential long-term plans and are better when applied in Business, Corporate and Operational tiers.

For new products to be successful, it is necessary for firms in the flow handling equipment industry to develop strategies that take the innovation capacity of the firm and the market into consideration. The different ways firms approach strategy would be based on the intention of the decision makers and available resources in relation to the market. Strategies as defined by (Johnson et al., 2014) are usually classified as Deliberate or Emergent.

2.2.1. DELIBERATE VS EMERGENT STRATEGIES

Studies have shown a paradigm shift from firms' reliance on deliberate strategy to more emergent forms of strategy. As Bamford and Forrester (2003) indicate, firms were previously inclined to develop deliberate strategies which were pro-active and pre-meditated to facilitate change in organisational practice. Earlier works by Lewin and Cartwright (1952) and Kanter, Stein, and Jick (1992) also highlight prominent use of deliberate strategy during their time. However, Garvin (1993) and (Schein, 2010) argue against the viability of deliberate strategies in the years that followed shortly after, going further to highlight the dynamic nature of recent market conditions and how emergent strategies are more reactive focusing on the adaptation of organisations to changing situations. More recently, both deliberate and emergent strategies are used (Eden & Ackermann, 2013; Mirabeau & Maguire, 2014).

While the above research angles differ in proposition, there are similar views that can be obtained from their respective positions on the issue: There exists a possibility that adopted strategies would be influenced by the predictability of the market. These strategies however have their challenges in application. Mintzberg and Waters (1985) as well as Titus Jr, Covin, and Slevin (2011) propose that 'Deliberate strategies' should be planned with all levels of decision making in the firm for maximum results and that while 'Emergent strategies' might be effective, they still require some form of consistency in the development of the strategy to ensure effectiveness even in a volatile market. Clarke and Fuller (2010) and Bodwell and Chermack (2010) however disclosed that in practice, firms do not always implement either of the strategies perfectly but that it tends to be more of an application of both strategy types used together or other strategies that share similar characteristics with the above stated strategies (Mirabeau & Maguire, 2014).

2.2.2. COMPETITIVE ADVANTAGE

Most firms are often confronted with the daunting task of selecting a target market especially for SMEs as there is a probability most of the competition would be dominated by large companies in the same business (Musso & Francioni, 2014). But Brethauer (2002) believes that small to medium firms entering a market with a new product that is innovative, stand an equal or greater chance of staying ahead of the competition than their larger counterparts. This therefore dispels some of the myths that SMEs cannot compete with large companies. The key point to note is that competitive success would be measured relative to the resources invested in the product's development versus how it meets the market requirements. Therefore, it is important for SMEs in the flow handling equipment industry to build strategies in order to compete favourably, while large firms need to make their strategies more innovative in order to remain relevant in the market. Porter (2008) illustrates a model for five classes of competition now commonly referred to as the Porter's five forces. As displayed in figure 4, they are: Threat to new entry, Power of Suppliers, Competitive Rivalry, Power of buyers and Threat of substitution. These forces tend to control the competition and firms' decision makers can then design their strategies to focus on the opportunities for market entry. However, firms stand a chance of losing competitive advantage when these forces are ignored or cannot be conquered.

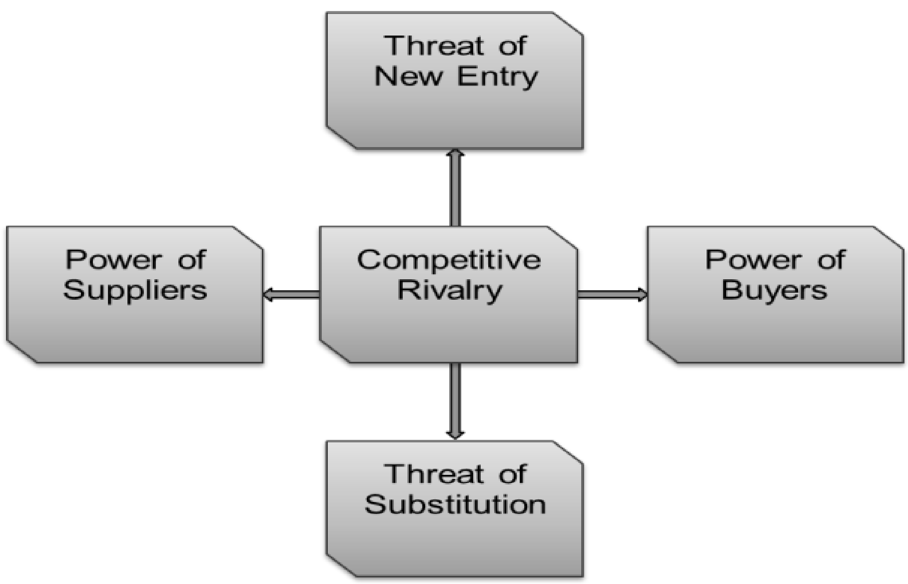


Figure 4. Porters 5 forces of Competition (Porter, 2008)

2.2.3. COMPETITIVE RISK MANAGEMENT

Porter (2004) outlines three generic competitive strategies for managing competition. They are: Cost Leadership, Market Differentiation, and Market Focus. The Cost leadership strategy focuses on building competitive advantage by offering competitively low prices in the market for the product. Differentiation focuses more on developing unique products that make the firm stand out from other generic products, while market focus strategy like the name implies, is focused on targeting a specific market to expand product competitive advantage within the market (Allen & Helms, 2006).

Deciding an appropriate strategy to adopt in risky situations is often a challenge for most firms in the flow handling equipment industry. Smith and Meiksins (1995) state that firms dependence on internal or external factors add to the uncertainty in selecting a strategy to adopt. Annacchino (2011) shares this point of view and also goes further to state that large companies benefit from homogenous market situations to dominate competition by exploiting market factors such as the availability of the product, supply and pricing options. Woodcock, Mosey, and Wood (2000) and Cooper, Edgett, and Kleinschmidt (2004) state that the differentiation system guarantees competitive success. Koo, Koh, and Nam (2004) discovered that traditional firms are likely to apply a differentiation strategy while online software based firms tend to use a market focused strategy.

As highlighted above, the tendency to apply competitive strategies may depend on the priorities of the firm or industry dynamics. According to Wang, Walker, and Redmond (2011) SMEs do not tend to engage in long-term business especially when the decision maker is the owner. This is possibly due to the standpoint that SMEs tend to apply flexible strategies moving and finding new markets with better prospects thereby reducing any risks of SMEs losing substantially in the event of a setback. Conversely, Mortara and Minshall (2011) state that large firms are likely to engage in business for the long term and have to manage the risk of losing out in the event of a set-back especially when they have committed a lot of resources to the investment. This may suggest why large firms tend to invest in deliberate strategies. However, for the flow handling equipment industry, it is imperative that an enterprise approaches strategy with a focus on the internal and external factors that might affect the outcome of the business and the strategy formulation itself. Some widely used structures that exist include SWOT analysis (Strength Weakness, Opportunity and Threat) and PESTEL (Political Economic Social Technological, Environment and Legal) factors (Shilei & Yong, 2009). Numerous other strategic approaches and tools also exist that can be useful. The ability for firms to come up with their own strategy formulation would depend on the firm’s innovative capabilities.

2.3. ORGANIZATIONAL INNOVATION

As Greve (2007) defines it, Innovation is the exploitation of useful intuitions for lucrative purposes. Innovation is often mistaken for Invention. Invention is referred to as a new idea, while Innovation is the development of the idea into an exemplified concept (Ettlie, 2000). Innovation is a key phenomenon in organisational and product development. A great deal of research has been done to uncover new ways of generating innovation and turning these into successful new products while remaining well structured. Faced with the imminent uncertainty in market conditions, SMEs and Large firms in the flow handling equipment industry can still explore and increase the prospects for Innovation inspired new product development (Maslach, 2016; Spalart & Venkatakrishnan, 2016; Squires, 1983). While Burns and Stalker (1966) contend that innovation occurs more often in informally structured firms, Zhang and Tian (2010), indicate that organisational innovation can be sourced both externally and internally, listing Technological innovation and Entrepreneurship as two factors most responsible for enterprise growth. Lungeanu et al. (2016) investigates the reaction of firms to technology during poor innovation performance in relation to their financial slack and pointed out that firms with greater financial slack responded by seeking to diversify and acquire new avenues for technology use to drive change, while those with less financial slack responded by reverting to sticking to familiar technological avenues.

2.3.1. RADICAL AND INCREMENTAL INNOVATION

Two classes of innovation exists, the Radical Innovation that tends to be infrequent but possesses potential for a unique product, and the Incremental innovation which tends to build on already established concepts (Remoreras, 2009; Verganti, 2009). A visual representation of the different classes of innovation is contained in figure 5.

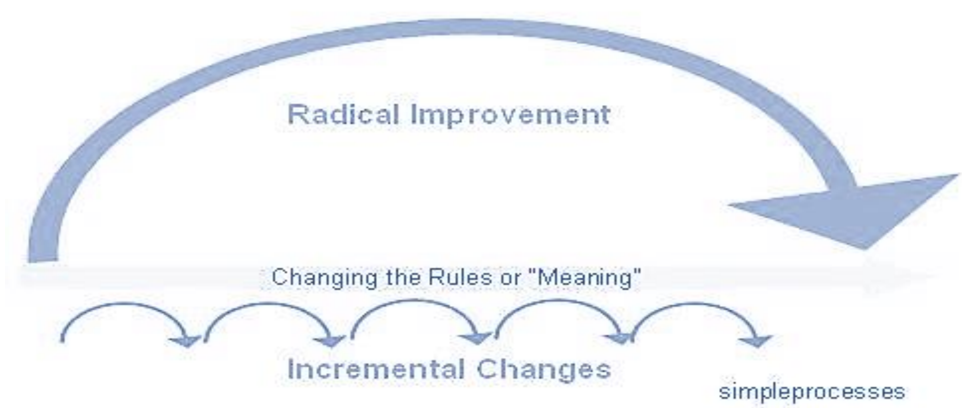


Figure 5. Difference between Radical and Incremental Innovation (Remoreras, 2009).

As firms in the flow handling equipment industry tend to focus on improving their ability to design and manufacture products that meet the customers need, they also need to satisfy appropriate regulatory authorities concerned with their processes in the development of new products, which would usually affect time, cost and quality of delivery (Amable, Ledezma, & Robin, 2016). Innovation is therefore necessary at key stages in the new product development process to manage these constituents and in the same vein, develop a product that meets the customers' needs. Due to the fact that NPD is about new products, Innovation can be seen as a core concept for successful new product development.

It is common to notice a wide range of companies that yield happier customers having processes that can be considered to be innovative (Gad, 2016). In whatever form it is used, either as a marketing plan, a new design or even a strategic agenda, Innovation is a concept that is based on the originality of the application and its ability to be valuable (Bowers & Khorakian, 2014). Audretsch (2001), highlights the fact that small firms are likely to be as innovative as larger firms. However, according to Coad, Segarra, and Teruel (2016), younger firms are likely to be more innovative than older firms. Furthermore, new firms grow in experience by observing the norms in their respective industries and learning how to dominate the market competition (Coviello & Joseph, 2012). Eventually, firms that become accustomed to the mode of operations are bound to encounter growth while firms struggling to meet up might be compelled to prematurely exit the industry market (Atkinson, 2013).

SECTION SUMMARY – ORGANISATION

The organisation development section extracts valuable information on the dynamics of organisational behaviour within the flow handling equipment industry, taking into consideration, structural positioning of different sizes of firms in relation to their inherent culture and decision-making. The likelihood of these firms to focus on technology as well as strategic preparation in the flow handling equipment industry is also taken into account. From this section, it can be observed that at about the time the flow handling equipment industry experienced the introduction of CFD, firms were ideally focused on having rigid systems, however over time more flexible structures developed. Cosh and fu (2012) identified the firms that utilised the former to be those with higher rates of technology use and experience. Among the discoveries extracted from literature: Structure is necessary for better decision-making. Decision makers set the pace for integrating a winning culture. Culture determines how firms react to new technology and structure. Strategies are dependent on the priorities of the firm, and Firms can break into new market with a new product.

PROCESS DEVELOPMENT

This section reviews the literature on new product development (NPD) process-related practices and analyses the ways they are structured. It also provides an insight into trends in customer behaviour and provides a background review on quality techniques in the flow handling equipment industry. Key journals referenced in this section include: *Journal of Industrial Engineering and Management, International Journal of Operations & Production Management. Research-Technology Management, Journal of Engineering Manufacture, Strategic Management Journal, International Journal of Quality & Reliability Management.*

2.4. NEW PRODUCT DEVELOPMENT AND BEST PRACTICES

According to Eppinger and Unger (2011), New product development processes are essentially used to design new products and bring them to market. Its importance as a process is rooted in the market factors and expectations that compel companies to continue developing new products to stay in business. Crawford and Di Benedetto (2015) highlight five basic parts common to each new product development life cycle.

Table 2 Basic New Products process (Crawford & Di Benedetto, 2015)

PHASE	PROCESS
Phase 1:	Opportunity Identification and Selection.
Phase 2:	Concept Generation.
Phase 3:	Concept/Project Evaluation.
Phase 4:	Development.
Phase 5:	Launch.

As displayed in Table 2, the new product usually starts out as an idea most times necessitated by a perceived opportunity. The concept of the product is then generated and evaluated before developing the actual product itself and proceeding to launch. As global sustainability requirements increased in the 1990s, Fox (1993) suggested two extra phases '*After launch Maintenance'* and '*Product discontinuation after its useful life'* for managing product development after the product's launch and ensuring the products are designed to be disposed properly without causing harm to the environment.

2.4.1. NPD PROCESS STRUCTURE FOR FLOW HANDLING EQUIPMENT INDUSTRY

Following emerging trends in product development within the flow handling equipment industry, particularly with the rising demand for sustainability practices, recent research suggests that firms are now required to enhance their adopted NPD structures to meet the demands for quality and sustainability (Nidumolu et al., 2009). While a significant portion of existing processes are considered effective, some firms still find it difficult to relate these methods to their specific applications either internally or externally (Crawford & Di Benedetto, 2015). According to Annacchino (2011), decision making leadership influences commitment and optimism among teams in the new product development process. When analysed by structure, New Product Development processes are usually either stage-oriented or spiral-oriented (Eppinger & Unger, 2011).

2.4.1.1. STAGED PROCESSES:

Staged process are very common especially with the introduction of the stage gate model (Cooper, 2011). This process works in sequential phases or steps that tend to be rigid and are less flexible in managing progression to the next phase at any point during the process. The core of its function is to provide process stability, as iterations are kept to a minimum and product definitions are usually clear. They are likely to be effective when the project specifications are well understood and technology operators are experts at applying these to the process. According to Gmelin and Seuring (2014), this staged process is similar to a waterfall process due to the dependability of the subsequent stage on the just concluded phase. An example of this process is the Stage gate (Cooper, 2011).

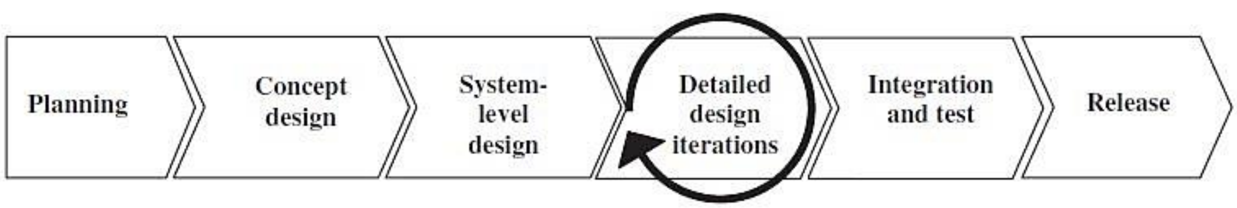


Figure 6 Staged NPD process (Eppinger & Unger, 2011)

The drawbacks to applying this method as with most waterfall systems observed in the staged process in figure 6, is that faults from previous stages discovered later on in the project, would require the process to move backwards across the stages placing a huge constraint on time to completion (Eppinger & Unger, 2011). Eppinger and Unger (2011) also pointed out that firms tend to make the mistake of speculating consistency in customer needs and ignore the possibility of market changes which eventually changes the requirements of the product. The rigidity of the staged process would therefore make it difficult for the firms to keep up to date with dynamic demands. This would be very expensive to fix when things go wrong and is certainly not a convenient method for NPD projects that are likely to have specifications that could change abruptly. Extended development time in one stage would delay the entire process as the next team in sequence depends on output from teams in previous stages of the process (Gmelin & Seuring, 2014; Rainey, 2008; Smith & Reinertsen, 1998). This gives room for complacency, as teams could remain idle before they receive the product in their stage and after their stage is complete. This also implies that teams responsible for each stage are likely only to focus on their part of the production and might not have an idea what the other teams in the process truly require to get the job done.

2.4.1.2. SPIRAL PROCESS:

The Spiral process is applied in conceptual phases similar to the staged process but using a cycle based approach with multiple iterations rather than sequential phases. The core function of this process is its flexibility which provides product developers with timely feedback (Zamenopoulos & Alexiou, 2007). Eppinger and Unger (2011) draw attention to the fact that this method was adopted from a model used commonly by software developers and proved to be effective in reducing expensive rework ensuring the project phases got the desired attention. The process is a network of spiral webs linking each phase of the NPD process in iterative loops to enable the process have some flexibility as shown in figure 7. It is also designed to encourage multiple concurrent teams to work in parallel and simultaneously on a project. An example of this method is Lean/Agile product development (Karlström & Runeson, 2006).

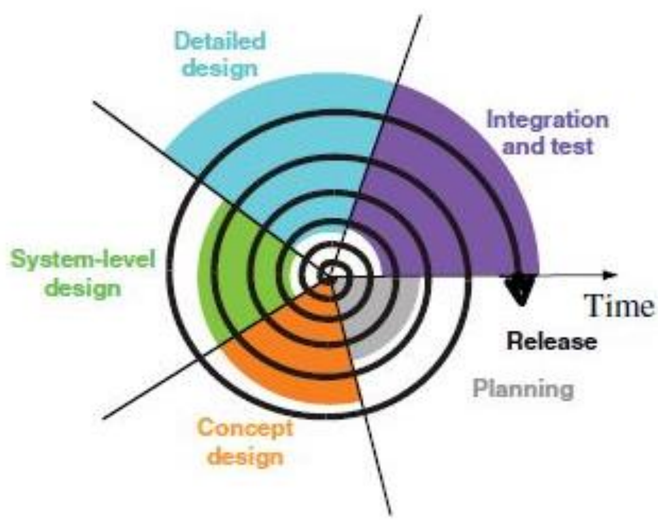


Figure 7 Spiral NPD process (Eppinger & Unger, 2011)

A challenge in implementing this system is bringing iterations down to an easy workable level. Detailed sub-processes would also be difficult to create considering the flexibility of the system.

If the development steps are known and there are limited iteration loops to undergo, this process might not prove effective for such application. In fact it would not be exactly too different from a staged process. Therefore, this style is more applicable to processes that are likely to experience abrupt fluctuations in specifications and market influence.

The difference that exists between the staged and spiral process is that while a stage process structure is likely to support cross-functional teamwork, the spiral NPD process does it with ease. This is because iterations are done in rounds and there would be no extended waiting time as each team would be able to work and interact simultaneously while providing feedback across the phases. In both of the above cases, the process would require a set of phases that are common to both applications. This can be explained in the context of NPD best Practices.

2.4.2. BEST PRACTICES IN NEW PRODUCT DEVELOPMENT SYSTEMS

There is no widely recognised definition of best practices (Druery, McCormack, & Murphy, 2013; Spencer et al., 2013). However, Camp (1989) and Urban (2018) define best practices as methods and techniques that have been proven to accomplish their proposed aim better than their alternatives. Therefore, New Product Development (NPD) best practices can be described as those NPD techniques that have been proven to accomplish development of new products more consistently than other methods.

A number of widely recognized NPD best practices are listed below:

- Stage Gate Process
- Theory of Inventive Problem Solving (TRIZ in Russian)
- Quality Function Deployment (QFD)
- Affinity Diagram
- Mind Map
- Voice of the Customer (VOC)
- Kano model
- Failure Modes and Effects Analysis
- TILMAG
- Knowledge Recycling

2.4.2.1. STAGE GATE

Discovered in 1985 by Dr Robert G. Cooper, Stage Gate quick became a successful method for systematically improving efficiency in NPD applications. The process, as illustrated in Figure 8, is made up of stages each representing a phase of the New Product development process from discovering the potential for a product, scoping, building the business case to product development, testing & validation as well as planning the Launch activity. There are checks after each stage which in this context are referred to as gates (Cooper, 2011). These checks are usually carried out in form of reviews and approval protocols essential for monitoring the product's advancement through the process.

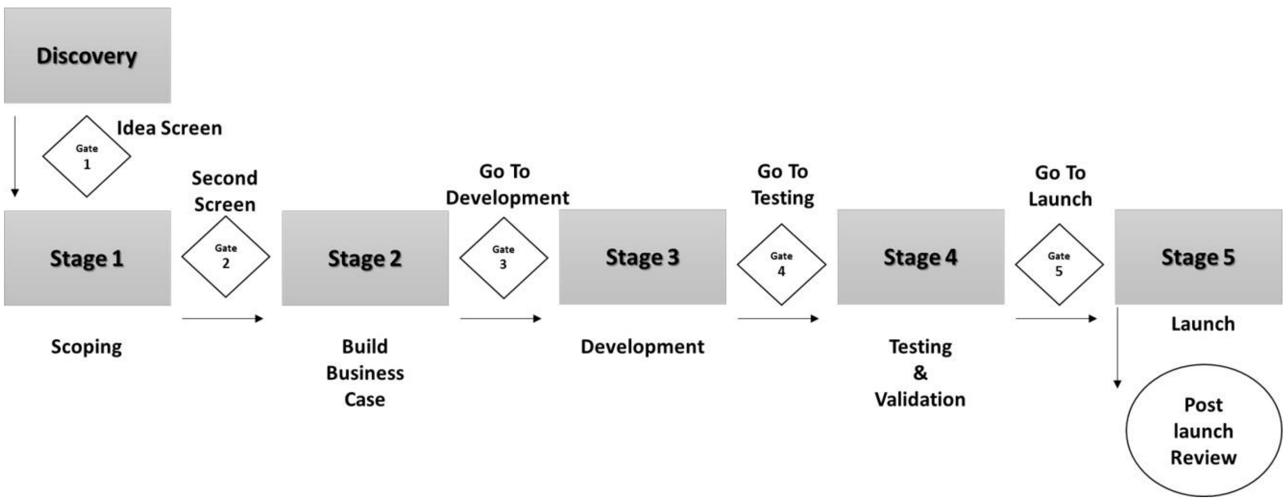


Figure 8 The Stage Gate Process (Cooper 2011)

- **APPLICATION OF STAGE GATE**

Five stages and corresponding gates are prominent in a standard stage gate set up. It starts with the identification of an opportunity for a new idea to become a concept. This idea is then screened and placed into the framework in Stage 1. The potential of the idea is then verified at the stage checks to determine the progression of the product idea. At the stage 2, the idea concept is then used to develop a business case. After clearance to proceed to the next stage, Stage 3, the design and production is carried out. After meeting satisfactory requirements, the product proceeds to Stage 4 where testing is carried out on the product to verify its potential for the market. After clearance to proceed to the final stage, Stage 5, the product is prepared and released to the customers/market. The Post Launch Review is a stage that can then allow the firms analyse their products and evaluate its prospects.

PROSPECTS AND CHALLENGES IN THE STAGE GATE PROCESS

While stage gate is globally recognised by firms in new product development, Joan (2005), states that 69% of successful companies use stage gate or stage oriented processes. Cooper(2011) points out a major challenge of the process is a tendency for implementing firms to compromise the project at the gates. The result is that useful ideas might be scrapped and some bad projects are allowed to continue through to production. This implies that there are no systematic conditions on which to accept progression at the gates. Hutchins and Muller (2012) subscribes to this notion and analyses it a little further, stating that firms often apply Stage gate processes as a forthright approach and expect it to automatically suit their intended application of the principles. However, Hutchins and Muller (2012) recommend assumptions are tested at each stage of the process before stage progression is permitted.

2.4.2.2. TRIZ

The Theory of Inventive Problem Solving, is an English translation of the acronym, TRIZ, with its original title in Russian tagged теория решения изобретательских задач or T*eoriya Resheniya Izobretatelskikh Zadatch* (Sheng & Kok-Soo, 2010). Unlike the Stage Gate process, TRIZ is not a method but a useful tool for resolving design contradictions during the product development process (Terninko, 2018). TRIZ was created by Genrich Altshuller, an engineer resident in the former USSR (Ilevbare, Probert, & Phaal, 2013). It is believed that Genrich had designed an underwater breathing apparatus at age 14, for which he was awarded a patent (Terninko, 2018). In the 1940s, Genrich began collecting thousands of patents while working at a Naval Patent office in USSR (San, 2014). At the time, patent discoveries were made through trial and error tests. However, Genrich Altshuller was more interested in discovering patterns that were synonymous with other patterns in the patents he had collected (Mahto, 2013). Eventually, he was able to detect five distinct patterns that emerged. Linking the patterns together, he found he was able to develop solutions to contradictions and generate inventive solutions (Stratton & Mann, 2003).

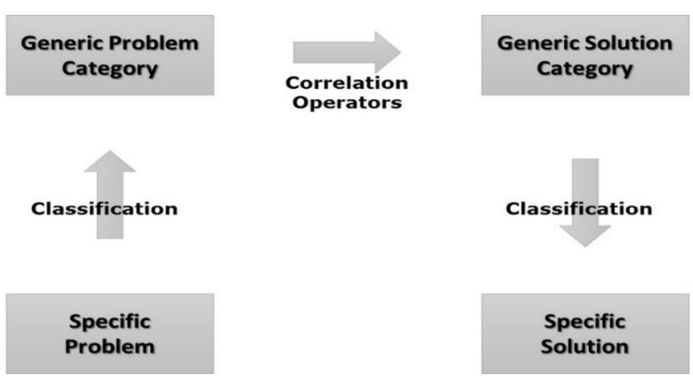


Figure 9 TRIZ Method (Mahto, 2013; Terninko, Zusman, & Zlotin, 1998)

- **APPLICATION OF TRIZ**

TRIZ helps product developers apply generic solutions to new problems (Terninko, 2018). TRIZ is administered using its 40 inventive principles and 39 contradictions (San, 2014). As contained in figure 9, TRIZ examines a specific problem and tries to match it with a similar generic problem category. The developer then attempts to apply the same generic solutions to the generic problems, to the specific problem that prompted the search. TRIZ operates on 5 principles, they are: Contradictions, Resources, Evolutionary trends, Ideality, and Functionality (Vinodh, Kamala, & Jayakrishna, 2014).

- **PROSPECTS AND CHALLENGES IN THE TRIZ PROCESS**

Ilevbare et al. (2013) recommend TRIZ as a useful tool for generation of ideas and collaboration between teams, however the tendency for the system to be extremely complex makes learning and applying it challenging. Though instructions on how to implement TRIZ exist, these are often very complex. Similarly, Rutitsky (2010) highlighted the same issues focusing on the tendency for TRIZ applications to be too generic in a bid for one solution to accommodate a variety of problems and as a result, not specific enough and therefore difficult for firms to select the right solutions it offers. Ilevbare et al. (2013) records that attempts to simplify TRIZ have proved futile as a result of major opposition from Russian TRIZ specialists who fear simplification might reduce its efficacy.

Zlotin et al. (1999). reports that Genric Altshuller, the inventor of TRIZ, once noticed his students had not used TRIZ efficiently due to its complexity. For this reason, the Theory for Creative Personality Development (referred to with the acronym, TRTL, in Russian) was developed. Notwithstanding, application of TRIZ in non-technical situations would still require knowledge of TRIZ in its technical practice. According to (Spreafico & Russo, 2016), TRIZ is still a fundamental best practice NPD technique that is actively applied in a number of processes in the Automotive, Electronics, Energy and Electrical, Engineering Information Technology, Healthcare, Chemical, Textile and Biomedic Industries among others.

2.4.2.3. QUALITY FUNCTION DEPLOYMENT (QFD)

For most firms in the development of new products manufacturing and design, precision is a skill that is necessary when interpreting customer specifications. It is very common to find these firms conducting market surveys to establish customer needs but thereafter, they retire to the factories and workshops to design products that do not match what the customers' need. A major cause of this incidence is that one or more departments responsible for the products might have interpreted the customers' needs based on a wrongly perceived notion of the customer's expectations or where the customer's expectations are clear but design difficulties exist in achieving these specifications. Firms in this category have a tendency for work distribution to be independently structured, i.e where different specialisation departments would have different perceptions of the product concept and how it should be interpreted in design. For example: a marketing employee would be likely to have a different perception of customer's specifications as opposed to an engineering employee.

In order to combat this situation, in 1966, Dr Yoji Akao developed the Quality Function Deployment (QFD) for product development applications, this best practice tool process became increasingly famous for its House of Quality matrix (HOQ)(Terninko, 2018). QFD creates a platform for analysing relationships between customer wants and design specifications as well as measuring the gap between competitors to ascertain what needs to be done to properly interpret customer specifications and respond to competition (Cohen, 1995; Jaiswal, 2012).

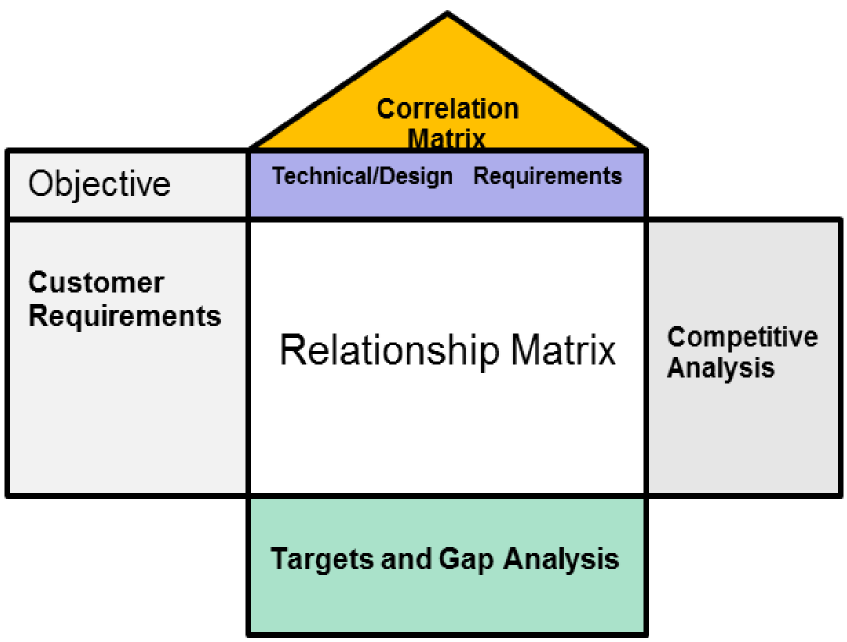


Figure 10 QFD House of Quality Matrix (Rainey, 2008)

- **APPLICATION OF THE QFD PROCESS**

In using the QFD House of Quality matrix as shown in figure 10, the designer first focuses on collecting and recording the customer requirements on the left side of the matrix. Hauser and Clausing (1988) state that customer data can be obtained in two ways: Customer experience and Customer preference. These are then prioritized with a number scale. The next step would be to list the technical design requirements necessary for meeting the stated customer requirements adjacent to the customer requirements on the horizontal adjacent plane of the top of the HOQ matrix. This relationship can then be traced on the matrix using the space in the middle of the HOQ matrix to show relationship. The roof of the HOQ also known as the Correlation Matrix is used to identify conflicts in the design. Where conflicts exist, these should be resolved or the product concept would be terminated. The Targets and Gap Analysis section is used to record the set targets in levels that specify to what extent customer needs can be met with design specifications in the relationship matrix area. Finally, on the right plane, Designers can measure and evaluate their performance alongside competitors' propensity to achieve the connections recorded on the relationship matrix (Rainey, 2008).

- **PROSPECTS AND CHALLENGES IN THE QFD PROCESS**

QFD focuses on improving quality. The design is confirmed to be achievable using the HOQ matrix before the product is produced, thereby preventing scrap and waste, a trait that is unlikely in the Stage gate system, where the prototype is built before being tested and validated. Zairi and Youssef (1995) and Taifa and Desai (2015) commend QFD's utility but show concerns about the complex level of detail required in understanding the true customer need, its generic applicability, and the time required for very large products applications such as vehicle design which might take extremely long periods of time beyond the time scope for the project. Daetz (1989) and Do Nascimento Gambi, Gerolamo, and Carpinetti (2013), recommend integrating QFD gradually as a result of the tendency of QFD to bring about culture change in firms. Furthermore, the success of QFD is dependent on the creativity of its users. Also there have been other forms of QFD such that it serves multiple purposes like production and process planning, as well as design development (Chan and Wu, 2002). Sometimes these are placed in a waterfall arrangement. However, this system is not very popular and is likely to have complications when mistakes are made in multiple tiers of the waterfall style QFD systems, typically those that exhibit dependency of present tasks on multiple tiers that were previously run by different departments were the mistakes occurred. However, Hauser and Clausing (1988) uncover brilliant prospects for development in QFD applications quoting popular global companies to have used them like AT&T, Toyota, Hewlett Packard and Ford.

2.4.3. SOME USEFUL TOOLS IN NPD PRACTICES

2.4.3.1. MINDMAP

The Mindmap process was first created by Tony Buzan as a brainstorming tool in the 1960s (Elhoseiny & Elgammal, 2012). The purpose of the tool is to extend the thought process by linking patterns to create ideas. As Illustrated in figure 11, it is believed that the brain is activated through this process to actively produce more innovative connections through pictorial ideas.

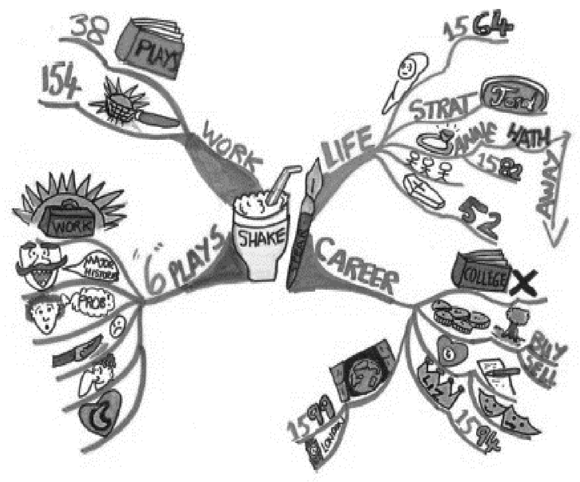


Figure 11 Mind Mapping (Elhoseiny & Elgammal, 2012)

2.4.3.2. AFFINITY DIAGRAM

This is a fantastic brainstorming idea generation tool particularly useful for determining pre-market test customer requirements (Holtzblatt, Wendell, & Wood, 2005). Single-ideas are written on as many tabs as required such as on post it notes. Similar ideas are then grouped topically as shown in figure 12 thereby making it easier for the team involved to get an idea of what the customers want before the actual voice of the customer is sought.

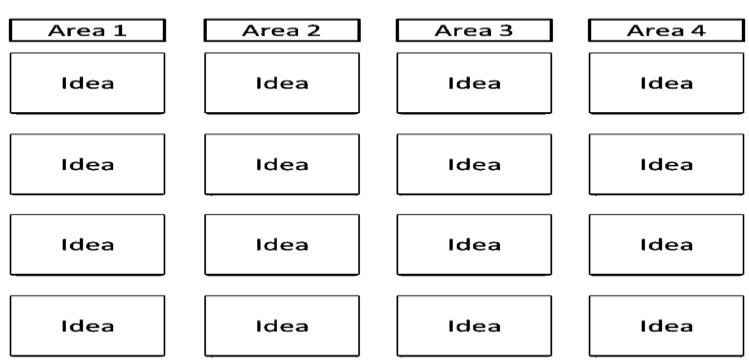


Figure 12 A typical Affinity Diagram Model

2.4.3.3. VOICE OF THE CUSTOMER (VOC)

This system is practically effective in ensuring proper interpretations are made later on in the new product development process (Chang & Taylor, 2016; Griffin & Hauser, 1993). According to Cooper (2011), in order to capture the true customers' need and avoid mis-representation of customer priorities, the "Go to the Gemba" as it is fondly called ('Gemba' in Japanese means "the real place"), is an appropriate way of contacting customers to give a description of the products they want using surveys and interviews.

2.4.3.4. KANO MODEL

First designed by the Japanese scientist Noriaki Kano, the Kano model has become a widely used tool in prioritising customer needs especially after a voice of the customer session has been conducted (Borgianni, 2016; King & Schlicksupp, 1998). It also helps analyse both spoken and unspoken needs of the customer. This can also give the product designers leverage to make product designs based on priority, usually in situations where design limitations make it less possible to fully achieve all the customer needs. As illustrated in figure 13, customer needs are grouped into three categories: dissatisfiers, satisfiers and delighters on the Kano model (Bergman & Klefsjö, 2010). The basic needs (dissatisfiers) reflect the needs of the customers that are compulsory to be met. The Expected needs (Satisfiers) are the desirable needs the customer would like to be met to appreciate the product. While the Excitement needs (delighters) are needs the customer would not usually expect but would be excited if they are met in the product.

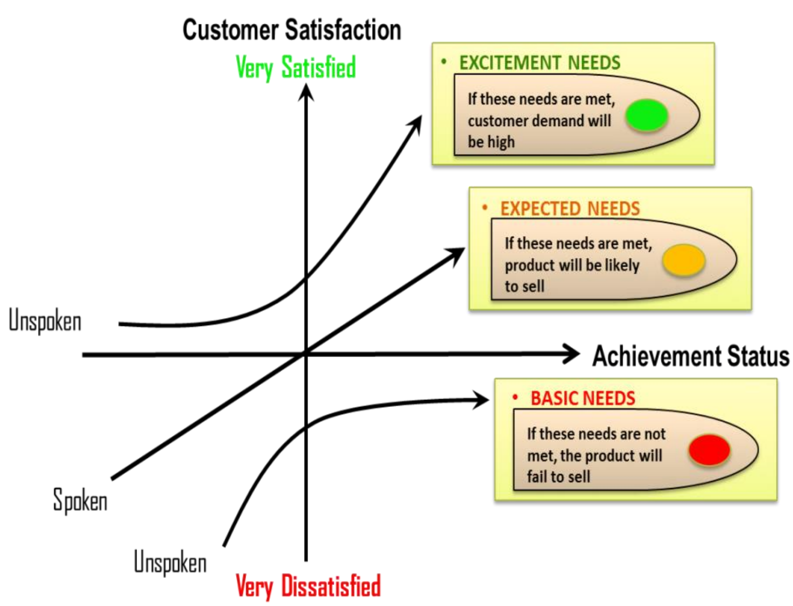


Figure 13 Kano Model (Bergman & Klefsjö, 2010)

2.4.3.5. FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS (FMECA)

The FMECA is a risk assessment tool, typically used to detect parts of a system that are liable to fail (Shafiee & Dinmohammadi, 2014). The end result in new product development is to determine how reliable the system being designed is.

The process is usually carried out on a worksheet table (See figure 14). The component is listed in the first column (on the left), these are the parts of the system under scrutiny and would usually be made up of parts that are susceptible to failure (Herman & Janasak, 2011).

FMECA **Product Name:** ______________________ **Subsystem:**_________________________								
COMPONENT	FAILURE MODE	EFFECT	CAUSE	PROBABILITY (P)	SEVERITY OF FAILURE (S)	DIFFICULTY OF DETECTION (D)	CRITICALITY (C) C = P X S X D	CORRECTIVE ACTION
1. ...								
2. ...								
3. ...								

Figure 14 A sample template for FMECA

The failure modes column displays the modes or situations such components would be most likely to fail, the effects of such failure if/when it happens is recorded in the next column, Cause is recorded to identify what could possibly be responsible for the failure event. Probability (P), Severity (S), Difficulty (D) are determined for each component and the Criticality(C) is then calculated using the formula:

Criticality = $P \times S \times D$.

2.4.3.6. TILMAG

TILMAG is a German acronym for "Transformation of ideal solution elements in an association matrix" This process was created by Dr Helmut Schlicksupp (Johnson & Gibson, 2014). Its main purpose is to assist the user in defining innovative ways of coming up with new ideas that customers would need(Silverstein, Samuel, & DeCarlo, 2013). The purpose is to inspire the user to imagine new frontiers for innovative product development concerning the product idea.

TILMAG	1 Renewable Power	2 Quick Start-Up	3 Large Screen
4 Small Size	Self-winding watch Hybrid Car Battery Battery Free Flashlight Electrochemical Reaction	Portable Radio	Fold out Map Roll-up Mat Projector
3 Large Screen	Solar Panel Microscope	Big Screen TV Scenery Backdrop	X
2 Quick Start-Up	MP3 Player	X	X

Figure 15 An example of TILMAG (Silverstein, Samuel, & DeCarlo, 2013)

First the need has to be defined. The user then uses the matrix chart format to create a convergence of ideas. This is done by entering the customer expectations for the idea in short phrases referred to as Ideal Solution Elements (ISEs). For instance, as seen in the example illustrated in Figure 15 for a laptop design idea, If there are 4 ISEs, only 3 would be written on the top row of the columns leaving the last one out. Afterwards, the user transposes same ISEs to the left column but leaves out the first ISE. The connection can then be entered into the corresponding points on the matrix.

2.4.4. SOME TECHNIQUES IN PRODUCT DEVELOPMENT

2.4.4.1. RESOURCE FORECASTING

Resource forecasting has not received much input from research. As Hird, Mendibil, Duffy, and Whitfield (2015) point out, there appears to be more focus on product related product development than resource related. Yeh, Pai, and Yang (2010) discovered that while well-known NPD processes proved effective, the challenge was in their utilization. Hird et al. (2015) went further to give the following guidelines when planning resource forecasting: Accuracy of method, Consistency, Transparency, Time required. The complexity of this feat, explains the need for software oriented projects. Estimation based approach is usually the norm in Forecast resource planning information.

2.4.4.2. KNOWLEDGE RECYCLING

According to Ferreira (2008), 70% of the time, product cost is determined during the design stage. This explains how important the design stage of any new product development process is. Virtual design remains an integral part of product development in fluid handling solutions. Virtual simulations are often used to speed up the product evaluation process during the physical testing stage. Ferreira (2008) also strongly believes that extraction of past experience information for reuse in future projects is essential, however this is limited by the fact that most software do not possess the capability to extract information that has been embedded in data from previous projects. Therefore Ferreira suggested information preservation and retrieval in order to save costs. This is called Knowledge recycling.

BEST PRACTICE SUMMARY

A review of NPD structures in industry use as well as best practice methods reveal that while most of the NPD processes tend to focus on meeting customer requirements but are not specifically targeted at computational fluid dynamics integration. This may be because, each of the firms in the flow handling equipment industry is focused on different kinds of flow such that for instance, the applicability of flow methods for pipe borne fluid transportation may be different from aerodynamic optimization. However, in each of these sectors, there is still a tendency that processes not designed for industry specific application may not meet customer requirements (Ernst, Kahle, Dubiel, Prabhu, & Subramaniam, 2015). Producers are then faced with the question; What do customers really need? The various arguments in the body of literature concerning customer requirements have prompted industry specific influencers to seek useful strategies for understanding the customer's real need. Some prominent scholars like Juran (1989) have stated that performing firms provide better value for their customers. McQuarrie (2014) also believes that firms with better understanding of their target market customers' need are likely to create better opportunities of maximising the value they offer their customers. For this to be possible, it is important to study the ethnographic constructs of customer perception in the flow handling equipment industry. A promising field for the study of the development of human behaviour over history is anthropology.

2.5. CUSTOMER ANTHROPOLOGY

Anthropology, a study of human behaviour, is an old art that has existed as long as the art of communication itself, however organised systems of managing this phenomena became commonplace in the 18th century (Harris, 2001). At present, this art is still used by scholars to understand the human mind-set, more prominently in social anthropology where cultural norms and practices could effect social perception and interactions(Beattie, 2013).

When social anthropology principles are applied to the study of customer behaviour, a significant amount of detail is required. A number of marketing persons discover that many customers might be unable to articulately describe their needs in ways that the firms can make precise inferences using conventional methods. Therefore, Surveys, focus groups, customer-supplied requirements (in the case of direct company - customer/supplier relationships) or personal perception may not be effective as standalone processes in determining the customers' inherent true need. Understanding the need and an interpretation of the need into a product is equally important. Baxter, Goffin, and Szwejczewski (2014) suggest the Repertory Grid Technique (RGT) for understanding customer hidden needs. However, Dacko, Wang, and Akhtar (2015) reveal that though the RGT is a simple and powerful method for ascertaining customer needs, it does not provide enough link between hidden needs and customer satisfaction. The Kano model as discussed in the previous section tends to identify which needs are likely to satisfy the customer (Borgianni, 2018). Firms therefore need to focus on building the correct information of customer hidden needs and obtain a better understanding of what would satisfy them in order to maximise customer equity. These are elaborated further below.

2.5.1. UNDERSTANDING CUSTOMER BEHAVIOUR

Customer decisions are influenced by some factors when deciding what products to buy. According to a study by Yuan and Demisse (2009); durability, high quality and exceptional design are considered to be the customer needs that guarantee high rates of success while proper pricing and/or brand recognition are expected of products.

Globalisation also seems to be a trend that is becoming a norm in SMEs (Bijaoui, 2017), and while this might increase competition (Ayob & Senik, 2015), customers seem to demand more for bespoke products thereby increasing the amount of work required to satisfy each individual want collectively over a wide area with diverse customer needs (Winch & Bianchi, 2006). As highlighted by Shimp, Samiee, and Madden (1993), some firms tend to outsource their production overseas to countries with low labour requirements. However, this invariably affects other constituents of NPD such as time and most especially quality. Understanding the implications of product origins on customer perception, Usunier Usunier and Cestre (2007) suggest that customers prioritise quality of products on the basis of where they are produced while making purchase decisions. According to Laroche, Papadopoulos, Heslop, and Mourali (2005), where products are designed and produced in multiple global locations, customers tend to overlook the locations as it is difficult to decide what one region was responsible for the products design and production and what quality assurance methods were implemented. As described by Yuan and Demisse (2009), the tendency then would be for customers to focus on the original location of the brand. In answering the question why customers prioritise quality by location; Li, Murray, and Scott (2000) and Chao (1998) found in their research that countries where majority of the firms have excelled at significantly great quality products before, are perceived by customers to be likely to continue producing high quality products. An example of this is described by Chao (1998) where Japanese electronic products sold better than those from Malaysian electronic product markets. This Chao (1998) explained, was a result of the confidence customers have had in quality products from japan and which now serves as an encouragement for continued patronage. In a study, Samiee, Shimp, and Sharma (2005) explain that customer perceptions relative to product origins are based on socioeconomic status, previous international travel experience, foreign linguistic capabilities and gender.

2.5.2. MANAGING CUSTOMER BEHAVIOUR

To effectively manage customer needs, Kassel and Tittmann (2007) propose careful observation of market trends, and other external customer decision influencing factors like cultural change and technology advancement. Kamakura et al. (2005) recommend CRM (Customer Relations Management) methods are used to get feedback from the customers in order to improve satisfaction. Kassel and Tittmann (2007) also propose that firms observe public e-trading services such as amazon and Ebay to study customer responses to products as well as powerful competitors. This promotes better understanding of market trends and improve decision making in firms. More recently, Malthouse, Haenlein, Skiera, Wege, and Zhang (2013) affirm the premise that CRM should be managed effectively to sustain lifetime value for the firm. They also point out the emergence of social media and other technological inventions that have provided new powers to customers over time; enabling them to filter advertising, access competitor product information prices as well as provide feedback on product performance and satisfaction to a global audience. The potential and challenges for this social evolution means that firms would be required to develop customer engagement processes that provide value to both the firm and the product user.

2.5.3. MAXIMIZING CUSTOMER EQUITY

In analysing ways of maximizing benefits from customer interactions, Gupta (2009) believes marketing activities should focus more on reducing cost. Campbell and Frei (2010) share this notion, advising firms to focus on reducing service costs which consequently reduces the charges to the customer and increase profits. Persson (2013) found in a case study of 3 banks, that firms are likely to make sufficient profits by identifying customer related activities that cost high and substituting these for cheaper channels that are just as effective. These alternative channels include telephone, internet, customer self-service hubs. Furthermore, measures to reduce customers can be implemented if the cost required to retain customers surmount the revenue accrued from them. Ultimately, product quality and customer satisfaction should not be compromised in a bid to keep costs low. Parasuraman (2002) refers to the above process as service productivity improvement, adding that the reason for minimizing customer related costs is to increase profits in the long term. The underlying value in understanding and managing customer needs for product development is to provide a product that is likely to meet customer expectations satisfactorily. Futhermore, the capability of a firm to meet all the requirements for transforming customer needs into valuable finished products is determined by their ability to manage quality.

2.5.4. CUSTOMER PERCEPTION AND MARKET COMPETITION IN QUALITY IMPLEMENTATION.

A school of thought exists that Quality management practices would influence better NPD if customers' opinions are sought at some point during the product development process to determine efficiency of the product's quality (Juran, 1989; Pinho, 2008). Slater and Narver (1995) and Diana, Mirela, and Sorin (2017) analyse this further, stating that the level of customer involvement in quality verification often depends on the level of competition. There is a chance that firm focus would be divided in a conflict of interest when customer involvement is perceived to be less important than assessing the competition (Deshpandé, Farley, & Webster, 1993). Based on this assertion, Kordupleski (1993) and Chen, Chen, and Wu (2014) posit that the firms who churn out poor quality products are likely to have disregarded feedback from their customers. However, according to Porter (2004) and Brethauer (2002), competition in NPD mostly exists among firms struggling to add more value to the products they provide to their customers. Consequently, Quality management techniques that consider customer involvement would be beneficial.

2.6. TOTAL QUALITY MANAGEMENT

The term Quality is widely used in various fields of study and there have been many definitions attempting to describe this phenomenon. Among notable scholars in the field, Total Quality pioneers, Deming, Juran and Crosby (Goetsch & Davis, 2014) have tried to simplify its definitions to disambiguate the varied notions. Crosby (1979) defines Quality as full conformance to specifications and overall absence of deficiencies. Juran (1989), another notable scholar in quality analysis, argues against this definition, stating that no product is totally free from defects, and even a product fairly free from deficiencies may not satisfy the customer. Juran (1989) then defines quality from the view of the customer, as a function of meeting customer needs. This Juran believed, is because the absence of defects alone does not prompt the customer to purchase a product. Deming (1986), defines quality based on its reliance on a constant, uniform and foreseeable process for improvement.

In addition to the above definitions, Ishikawa (1985) describe quality in a broader sense. stipulating that quality tends to encompass more than the product and focuses more on the efficiency of the whole of the organizational systems and processes as well as staff and management activities and after the product has been sold. Garvin (1984) believes quality can be value based and efforts could be made to reduce the other constituents of new product development: time and cost in order to maximise quality.

Modern definitions of Quality by notable authors like Oakland (2014) redefine quality in terms of acceleration of change, cost reduction and reputation protection. For Sallis (2014), Quality is what makes the difference between success and failure.

Whether it focuses on the product or service, all the definitions from the of Quality seem to focus on offering a special capability. It can therefore be gathered that quality is relative to its application and would likely mean different things to different departments particularly between marketing and manufacturing employees. These differences in ideology have a tendency to interrupt the success of NPD processes. However, this can be combated by applying an understanding of these views when strategic and managerial decisions are to be made. Alternatively, a good system can channel the strong points of these philosophies to improve the process.

2.6.1. IMPACT OF TQM IMPLEMENTATION ON PERFORMANCE IN THE NPD PROCESS

In recent times, Firms have adopted Total Quality Management (TQM) techniques in managing competition forces (Noe, Hollenbeck, Gerhart, & Wright, 2017). Cummings and Worley (2008) reveal that quality processes influence organisational effectiveness. Ghobadian and Gallear (1996) go further to explain that TQM acts as a facilitator of enterprise advancement and competitive advantage. Though scepticism exists about the propensity for TQM applications to yield significant breakthroughs in the short term (Arawati & Mokhtar, 2000), many scholars believe in the viability of TQM practices in its wider applications (Cummings & Worley, 2008; Goetsch & Davis, 2014; Hendricks & Singhal, 1997). Arawati and Mokhtar (2000) explain that firms involved in manufacturing for industrial applications tend to gain more from the TQM process than firms that manufacture for the end user. Some of the prospects of TQM implementation highlighted by Cummings and Worley (2008) are: Improved technical know-how, Cost optimization, customer satisfaction, and product efficiency.

While applying TQM in the NPD process, Yusof and Aspinwall (2000a) observed that while SMEs are aware of the importance of TQM practices, large firms still have better control of their processes. They also observed that SMEs were more likely to obtain quality certifications such as ISO 9001 but then do not practice these systems effectively. This relates to the findings from earlier part of the literature that technology-oriented SMEs were less likely to practice structured organisational forms.

2.6.3. TOTAL QUALITY MANAGEMENT PRACTICES IN NEW PRODUCT DEVELOPMENT

Different TQM practices are used in the development of new products, Brethauer (2002) suggests prioritizing the activities that promote the product's marketability and completion on time. Some TQM best practices in manufacturing firms are Statistical Process Control (SPC), Lean Six Sigma, Quality Function Deployment (QFD) and Failure Modes and Effects Analysis- FMEA (Krishnan & Parveen, 2013). Although detailed discussion on manufacturing processes is out of the scope of this project considering the fact that this project focuses on firms in the flow handling applications industry, an important method for confirming quality selection, is the Quality Function Deployment (QFD), which has already been discussed previously in this Process development section of the research.

2.6.5. QUALITY STANDARDS IN INDUSTRIAL APPLICATION

There are a number of regulatory systems and organizations responsible for setting quality standards that must be met by manufacturing firms in order to stay in business. A globally recognised body for maintaining standards is the International Standards Organisation (ISO). A majorly accepted standards qualification for manufacturing firms is ISO 9001 (Fonseca, 2015). However, before ISO 9001 became prominent, different quality standards existed such as the DEF STAN 05-21 and DEF STAN 05-24 used in the Ministry of Defence (Bacivarov, 2018). Similarly, UKAEA (United Kingdom Atomic Energy Authority) and LLOYD's standards, were also some of the quality standards widely used in UK and in 1979, a national standard, BS 5750, was created in the UK(Tovey, 2013). Afterwards, other countries tried to integrate their standards into one to encourage cross application in more countries around the world, this led to the formulation of ISO 9000 and eventually, ISO 9001 (Yusof & Aspinwall, 2000a).

2.6.5.1. ISO 9001 IMPLEMENTATION

Presently, the ISO 9001 system is the principal industrial quality requirement for most of the manufacturing firms around the world. Its main aim is to create uniformity in world standards and also for monitoring manufacturing and supplier firms' compliance with these generally accepted standards (Meegan & Taylor, 1997). Main advantages of ISO 9001 implementation include scrap reduction, improved customer satisfaction and reduction in concessions(Tarí, Molina-Azorín, & Heras, 2012). Additionally, compliance with ISO 9001 standards can increase brand recognition through certification (Yusof & Aspinwall, 2000b). Major setbacks that exist in implementation of ISO 9001 include increased cost, process rigidity (McTeer & Dale, 1996; Tarí et al., 2012).

DESIGN DEVELOPMENT

This section details the kind of design activities that take place in the flow handling equipment industry, with a view to establishing trends in CFD technology use. It highlights the sustainability challenges, advancements in Computer Aided Design (CAD) as well as CFD prospects in industry applications and its limitations. Some of the Journals used in literary search include: *Energy Conversion and Management, Journal of Fluids Engineering, International Journal of Fluid Machinery, Renewable and Sustainable Energy Reviews, Computers & Fluids, Journal of Engineering Design, International Journal of Chemical Engineering, Journal of Engineering Education.*

2.7. PRODUCT DESIGN AND SUSTAINABILITY

Tooley (2010) defines 'product design' as a conceptual set of processes that translate customer requirements into visual representations for product development. Pigosso, Zanette, Ometto, and Rozenfeld (2010) define sustainability as the methodical preservation of economic, institutional, societal, and environmental resources. Therefore, a 'sustainable product design' can be described as the conceptual set of methodical processes used in the translation of customer requirements into visual representations for product development while preserving economic, institutional, societal and environmental resources.

Following the industrial revolution in the 1800s, sources of energy that rely on combustion of fossil fuels gradually increased till date (Wrigley, 2013). As a result, some of the products manufactured as well as testing and production processes used by the firms, had over the course of time, become hazardous to the environment triggering a ripple effect in global warming challenges (Held, Theros , & Fane-Hervey, 2013; Taisch, Stahl, & May, 2015). Contemporary firms are now obligated by legislation authorities to be responsible for the impacts of their products and production processes on the environment (McDonough & Braungart, 2017; Vaccaro, Lanari, Marrocchi, & Strappaveccia, 2014). Therefore, designing to meet sustainability standards has become a part of the custom in product development (Asiya & Kazmi, 2012).

As product design focuses majorly on interpretation of specifications using a variety of technical tools and processes (Pahl & Beitz, 2013), product designers are able to control certain factors in the development of product concepts in order to optimize the products ability to meet the specifications. However, huge customer demand on products that are otherwise considered unsustainable to develop or use, put firms in a dilemma to either produce for increased profits, or stay green to protect the environment (Howes, Skea, & Whelan, 2013). To keep the industry in check, Green initiative movements are fast becoming the centre of attention in modern day manufacturing and development activities (Rose, 2014). This implies that companies would have to design sustainable products and at the same time develop them sustainably. In compliance, a number of firms have been seen to contribute to the environment eco-conservation projects either as part of Corporate Social Responsibility (CSR) or in their product development process and policies (Bevilacqua, Ciarapica, & Giacchetta, 2012).

With plans to substantively reduce global carbon emissions before the year 2050 underway (Alderson et al., 2012; Cooper & Hammond, 2018), unsustainable activities that emerge from the fluid flow handling equipment industry operations such as CO_2 carbon emissions. excessive use of energy, non-recyclable waste, oil and toxic chemical spills among others (Hocking, 2016; Ribbens, 2000) have to be significantly brought to a minimum. With global population figures at 7 billion in 2011 and estimated to reach 9 billion by 2050 (Lee, 2011), energy demand is estimated to double accordingly (Chu & Majumdar, 2012). To keep the industry sustainable, major aspects of design have become more complex. Pazhoohesh, Shahmir, and Zhang (2015) utilises Computational fluid dynamics (CFD) alongside Building Information modelling (BIM) to model and analyse indoor conditions in order to optimize the design of HVAC solutions to provide automated thermal comfort relative to the number of occupants in the room in order to reduce energy wastage. This design was especially important as HVAC products are estimated to consume high rates of energy in homes (Pazhoohesh et al., 2015). In construction, Shiftehfar, Golparvar-Fard, Peña-Mora, Karahalios, and Aziz (2010) utilise a framework to visualise green house gas emissions from construction activities by estimating the number of trees required to absorb and neutralise the emissions from construction equipments. In considering sustainability requirements and the energy demand, Abele, Schraml, Beck, Flum, and Eisele (2019) use simulations to model the energetic interactions of machine tool components in order to estimate energy consumption of products early during the design process. This helps the firm to consider the energy demand of the product before deciding whether it is a sustainable enough to forward for manufacture.

The above examples of sustainable approaches to design are largely credited to use of Computer Aided Design techniques. It is believed that Computer Aided Design (CAD) tools can be made more viable with advancements in high performance computing capabilities (Holmes & Newall, 2016). In the fluid flow handling equipment industry, Computational Fluid Dynamics is largely applied to predict flow behaviour. This can be utilised to design products that would act sustainably in operation as well as reduce multiple tests that may increase negative impacts on the environment. A historic analogy of Computer Aided Design and major advancements in Computational fluid dynamics are presented in the sections that follow.

2.8. COMPUTER AIDED DESIGN

Computer aided design can be described as the application of theoretical and practical knowledge of computer skills, to aid the translation of customer needs into products.

Before the discovery of computers and associated systems in technology, Numerical methods were the standard way to evaluate product structures in flow handling equipment design. This would usually consist of a number of mathematical and scientific equations (Anderson et al., 2013). With improvement in technology over time, product design evolved to the use of experimental techniques. These were basically practical set-ups used to test-run built prototypes of the intended product to verify its viability in practice before deciding whether to proceed with massive production and subsequent launch (Goto, 2016). It is mostly done when an element is speculated to have substantial prospects for the product idea but still needs to be clearly defined in order to visualise its success or shortcomings. Eventually, if successful, the production process itself is tested to verify its ability to replicate multiple real products of the design plan. Manufacturing would usually occur afterwards using different human controlled equipment and techniques depending on the complexity of the product. Advancements in technology improved further with the invention of programmable computers in the 19th century. Charles Babbage, an English mathematician in 1822, emerged with the concept of a difference machine (Campbell-Kelly, Aspray, Ensmenger, & Yost, 2013). By 1837, he improved this concept with the Analytical machine which came to be widely acclaimed as the first recognised programmable computer device concept in history (Graham-Cumming, 2010). Though he could not complete the designs during his lifetime (Garwig, 1969), this invention was what led to the development of better computer systems overtime. Eventually modern computers would inspire the use of computer generated product design.

According to Rooney and Steadman (1993), The origins of Computer Aided Design (CAD) can be traced back to the early 1960's, when the revolutionary Sketchpad application was developed by Ivan Sutherland. The sketchpad was able to create graphical illustrations on a computer using strokes from a light pen on the screen. This two dimension graphical representation on the screen was analysable using structural stress calculations.

By 1963, the prospects for a Computer aided Manufacturing (CAM) technology was set to have its big break into the evolution of product development. T.E Johnson had just developed a three dimension version of the sketchpad which enabled the designer view their graphic illustrations from different viewpoints. A numerical milling machine was also designed within the period of the SKETCHPAD, ushering in the early versions of a Computer Aided Manufacturing machine, the machine was capable of machining parts from coded instructions on a tape. Later, an attempt was made to merge the computer aided design methods with the automated manufacturing system by designing the tapes using data from the graphics, but this was only to become practical in the 1980s (Encarnacao, Lindner, & Schlechtendahl, 2012; Rooney & Steadman, 1993). Notwithstanding the late evolution of integrated CAD and CAM systems, firms from successful industries, such as those involved in aeronautics and automobile manufacturing with real needs for robust designs, had inspired the improvements of technological systems considering the interests they have shown in their development since their inception till present day (Otto, 2003). As at the time of this study, there have been many more robust applications of CAD, with high quality 3D definition geometric modelling, simulations, and automated manufacturing (Bianconi, Conti, & Di Angelo, 2006; Reinders, Diehl, & Brezet, 2013).

Otto (2003), describes three types of design; the Original, Adaptive and Variant design. While the original design focuses on originality of concept for a given task, Adaptive designs refer to the adaptation of a known structure to another application, or the modification of a part from an already existing structure to change or improve its function or appearance. Variant designs are focused on modifying the existing geometric or functional parameters of a design to change its appearance usually in order to create a variant of the same product with different dimensional characteristics. Rooney and Steadman (1993) describe four stages common in most design and manufacturing processes : As shown in figure 16.

Figure 16. Structure of the design and manufacturing process (Rooney & Steadman, 1993)

SPECIFICATION: The design process usually commences when a need is identified, defined and various information about the factors necessary for the product to be designed successfully, are collected to provide better understanding of the need.

GENERATION: During the second phase, alternative designs are generated (radical innovation) or existing designs are modified (incremental innovation) to generate a new product.

EVALUATION: The generated designs are tested to see if they meet the criteria/needed, these could then be optimized to increase its potential.

MANUFACTURE: When designs have been successfully evaluated and validated (through simulation or experiment), the design can then be manufactured for subsequent sale.

The loop between the Generation and Evaluation stages illustrated in Figure 16, show a complementary iterative process to evaluate product designs as they are generated. Therefore, if for example; alternative designs have been rejected during its evaluation, the designer can return to the generation stage to generate more designs. Most Engineering Designs are carried out in iterations, this is done in order to ensure mistakes are minimised and to ultimately meet the customers specification (Eppinger & Unger, 2011) . Determining how many iterations would be performed would depend chiefly on the complexity of the project, resources available and the technical specialization of the designers (Ribbens, 2000). Previously completed projects can also be reassessed for testing and the failures compared with current problems (Bennett, 2010). The requirements for Iterative systems are usually relative to the context. Reducing the number of iterations would usually be ideal for most firms, however special consideration must be given to the concepts of Quality, Cost and Time as well as sustainability requirements (Eastman, 2012)

For fluid flow handling equipment design, a number of assessment tools exist to assist designers in meeting the design requirements. These tools include numerical methods, experiments or computational systems (Patankar, 2018). However, the most common tool that is primarily preferred for assessment of designs and Simulation in the industry is Computational Fluid Dynamics (Anderson, 1995; Deitz, 1998; Li & Nielsen, 2011; Morris et al., 2016; Shadloo et al., 2016; Spalart & Venkatakrishnan, 2016; Vanka et al., 2011).

2.9. COMPUTATIONAL FLUID DYNAMICS

Computational Fluid Dynamics (CFD) is a computerized form of fluid dynamics (Wendt, 2009). It deals with the dynamics of fluid flow within and around a given object or phenomena (Deitz, 1998; Shadloo et al., 2016). CFD analysis begins with splitting a body of mass (geometric model) into numerically solvable volumes of grid-patterns (called the mesh), which is designed to fit around the area of flow to be analysed. A range of conditions are then applied to the model, which enables the numerical solver run the fluid dynamics equations across meshed components to determine the fluid flow characteristics within the system (Anderson, 1995; Versteeg & Malalasekera, 2007; Wendt, 2009). This method is used in many industries where flow is analysed and has evolved tremendously over time.

2.9.1. EVOLUTION OF COMPUTATIONAL FLUID DYNAMICS IN INDUSTRY

Prior to the emergence of Computational fluid Dynamics, Theory-oriented and experimental fluid Dynamics, otherwise referred to as the classical approaches to fluid dynamics, have for long been considered the best scientific inventions in the study of fluids, with the former existing for about two centuries (Wendt, 2009). According to Anderson et al. (2013), Computational Fluid Dynamics (CFD) began between the 1950s and 1960s and was brought about by the innovative development of high performance digital computers and accompanying algorithm for representing numerical data. While CFD does not replace theory or experiment in its entirety, the three dimensions of fluid dynamics complement each of their applications as shown in figure 17.

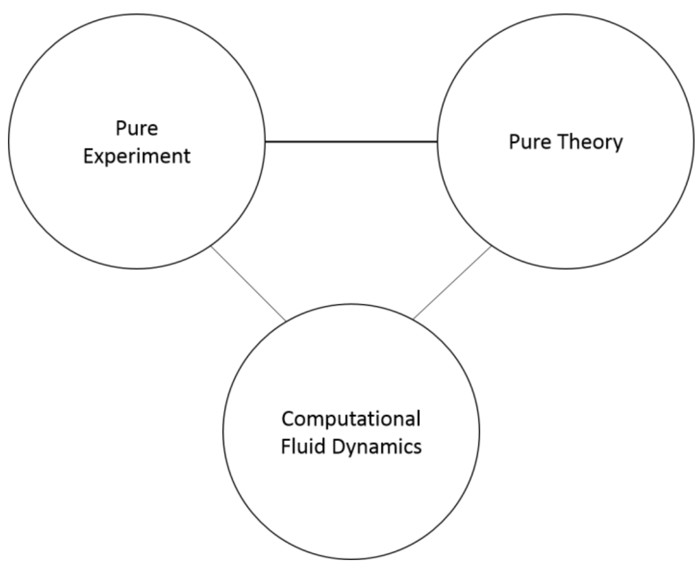


Figure 17. Three dimensions of fluid dynamics (Anderson et al., 2013)

It was not until the 1980s that CFD was seen as having realistic potential with better computer technology (Wendt, 2009). Before then, CFD practiced in the 1970s, was limited by the technological capabilities of the computers at the time that could not exceed solutions beyond two-dimensional flows. By the 1990s, CFD had become fully utilisable in three dimension flow modelling (Anderson et al., 2016).

2.9.2. ROLE OF COMPUTATIONAL FLUID DYNAMICS IN THE DESIGN PROCESS

Fluid related simulations pave the way for more complex 3D designs based on the ability of designers and product planners to test new design concepts virtually using physics based observation and manipulation of design flow phenomena(Tu et al., 2018). CFD uses fluid flow-solving numerical algorithms interpreted into codes that allow users communicate their design problems to the computerised processor and obtain comprehensive results from the solvers. Some popularly established commercial CFD code platforms include, ANSYS CFX and FLUENT, STAR-CD, FlOW-3D, PHOENICS and TASCFLOW (López, Nicholls, Stickland, & Dempster, 2015; Peric & Bertram, 2011; Schluckner, Subotić, Lawlor, & Hochenauer, 2014; Versteeg & Malalasekera, 2007). Others include FloTHERM (Song, Murray, & Sammakia, 2013) and SIMERICS-PUMPLINX (Frosina, Senatore, Buono, & Olivetti, 2014). There are also open source CFD coding platforms such as OPENFOAM(Jacobsen et al., 2012). Computers only understand codes, therefore codes are specifically designed to convert user input into computerized formats or algorithms that the computer would be able to work with. According to Versteeg and Malalasekera (2007), there are three elements of CFD coding, these include; Pre-processor, solver and post processor.

Pre-processor: This process is the beginning of the CFD process. Codes are developed to collect information required by the solver to perform the simulation; Information required would be relative to the expectation of the designer from the system. These include a number of properties such as Geometry specification in the computational domain, Mesh generation, Physiochemical specifications for the phenomena to be modelled, fluid property definition and boundary condition specifications within and around the domain (García, Duque, Boulanger, & Figueroa, 2015). Versteeg and Malalasekera (2007), believe this stage accounts for 50% of the time spent on CFD projects. While Grid/mesh cell size and definition might affect the solver's accuracy, human errors made at any of the core property inputs at this stage, are likely to affect the outcome of the analysis (Desai, Chauhan, Charnia, & Patel, 2011).

Solver: The solver uses numerical algorithms that first synthesize the governing equations of the fluid flow over all the finite control volumes of the domain, it discretises (converts) the integral equations into a system of algebraic equations, these algebraic equations are then solved using iterations, which is due to the complex and non-linear physical nature embedded in the phenomena**.**

Post processor: This code provides the output of the solver to the user in analytic forms that the user can make suitable conclusions from. These are usually presented through visual representations of the simulation results. With advances in graphical design, these analytics have also continued to relatively improve. At the moment, CFD output can be transferred between different code platforms and can be converted into other file extensions for easy sharing and accessibility, including extended use in CAD/CAE.

2.9.3. PROSPECTS OF COMPUTATIONAL FLUID DYNAMICS IN FLUID FLOW HANDLING EQUIPMENT INDUSTRY

The potential for CFD technology growth is enormous. At first, aeronautics was one of the major industries where CFD was applied in the design of aerofoil shapes for optimised lift and other streamlined designs (Spalart & Venkatakrishnan, 2016). As the prospects for technological advancement in the field increased, more applications beyond the Aeronautic industry were added to the range of CFD best practice. Typical applications of present day CFD extend from Aeronautics engineering to a wide range of industrial flow analysis applications; some of which include hydrology, turbo machinery, chemical engineering, architecture and building, structural design, marine engineering, environmental engineering and blood flow simulations in biomedical engineering among others (Ding et al., 2011; Hefny & Ooka, 2009; Morris et al., 2016; Slotnick et al., 2014; Versteeg & Malalasekera, 2007; Yadav & Bhagoria, 2013). According to Versteeg and Malalasekera (2007) this also meant that CFD processes had to become more complex in order to accommodate other fields. Due to the technical complexity involved in carrying out CFD simulations during the early years of its inception, CFD was mostly reserved for people with high levels of scientific knowledge from fluid flow backgrounds such as PhD students and scientific researchers (Broderick & Chen, 2001). These technical experts would run the simulations for verification and validation purposes often with specialist knowledge and append a CFD report to enable the firms' designers understand what simulations have been conducted and the implications of their findings (Deitz, 1996; Schmitz, 1999).

However, as Dvorak (2006) and Broderick & Chen (2001) reveal, designers are beginning to run their own simulations themselves rather than contact specialists to do it for them following major strides in hardware capabilities and CFD code development. This could mean CFD packages have become more user friendly, or that firms are beginning to exhibit more confidence in their own technical capabilities or both. As Deitz (1996) emphasized earlier, software developers have emerged with new codes to make CFD operation more user friendly. Increased demand for high quality and user-friendly CFD software packages require high performance computing capabilities which can impact costs significantly. Vanka et al. (2011) highlight significant improvements in computational speeds with five fluid flow algorithms over a 3 year period using Graphics Processing Unit (GPU) on a single CPU.

Notwithstanding the full scale advantages that CFD offers, major challenges in independently understanding CFD's full application still exist, therefore, compelling these firms to seek help in using CFD related software, either through training programs or hiring specialists (Dvorak, 2006). The major challenge then, seems to be that the sources for such assistance seems limited or expensive (Dvorak, 2006). This limitation is understandable, as these purportedly user friendly software packages are relatively new and still require users to have some background knowledge of the CFD concept as well as what they intend to achieve from the CFD simulation to maximise its potential. Even so, Versteeg and Malalasekera (2007) adduce from research that CFD reduces the overall cost of design and production. Another problem Dvorak (2006) noted was that the firms apply CFD too late in their design process, this is often a result of the firms tendency to still prefer actual experimental tests to computer simulated tests which they believe would invariably need to be validated by experiment. However, in concrete terms, Dvorak (2006) believes they need not validate all the tests, as it would be very expensive to run experiments on multiple prototypes when CFD could narrow it down to one or fewer prototypes that would have been considered from the results of CFD simulation for validation tests. Doing this also saves valuable design time. Therefore, it can be obtained from these assertions, that the ideal time to implement CFD is earlier in the design process in order to determine best design patterns prior to experimental testing.

The varied uses of CFD in analysis and prediction of fluid flow properties within systems have been chronicled to save firms the hassle of conducting multiple practical test rig/wind tunnel experiments, which could be very expensive (Spalart & Venkatakrishnan, 2016). It also saves firms valuable time as it reduces the possibility of potentially bad designs having to be built into physical models for testing before they are eventually scrapped (Dhotre, Nere, Vedantam, & Tabib, 2013). Goto (2017) expresses confidence in the future of CFD and recommends concurrent design innovation and manufacturing technology grow hand in hand in order to reap maximum benefit of each technology. Other advantages of CFD include but are not limited to; its ability to simulate conditions that are not easily implementable experimentally, such as in hazardous applications or in practically unachievable scales, it also gives room for further modifications and is easily transferrable due to its digital composition (Deitz, 1996; Dvorak, 2006; Goto, 2016; Spalart & Venkatakrishnan, 2016; Versteeg & Malalasekera, 2007).

Through modern advancements in additive and subtractive manufacturing processes such as 3D printing and CNC machining respectively, complex designs arising from numerical flow optimization can be manufactured easily. Also, automated grid generators that conform to the geometry and optimise the fineness of the grid/mesh are still being developed for future use in CFD as present technology is unable to achieve robust codes that would automatically generate accurate meshes (Liseikin, 2017; Tomac & Eller, 2011). Similarly, Meshless interfaces are also currently being developed for future adoption in CFD practice (Shadloo et al., 2016). Shadloo et al (2016) mention a meshless approach in CFD which has taken them about 2 decades to materialise and call it the Smoothed Particle Hydrodynamics (SPH). Still in development, the prospects for CFD seems to have dramatically increased with this method. The SPH method does not use any grids and works by replacing the mesh with a number of particles that can carry hydrodynamic properties such as mass and velocity. One major challenge with this method is the large computational cost, which is unachievable with limited hardware. Notwithstanding, Users have a wide range of choices concerning the selection of certain physical or chemical parameters that relate to the actual design conditions intended for the simulation. In many pre-processor code CFD platforms therefore, it can be anticipated, that great potential exists in building systems that would maximise user-generated input at least till codes have been developed for accurate automation. At the time of this research, the area of maximising assisted user-generated inputs has not yet been maximised.

2.9.4. CASES OF COMPUTATIONAL FLUID DYNAMICS USE IN FLOW HANDLING EQUIPMENT INDUSTRY

Indeed, the prospects of CFD appear promising, however, practical applications of CFD in the New Product Development (NPD) process does not seem to have gathered much spotlight in literature. The timeline trend in new discoveries of CFD use as seen in this research, show that it is only recently that people have begun to try using CFD in new ways and in new areas.

2.9.4.1. VALVE AND PUMPS INDUSTRY

Before CFD became an industrial norm, valve and pump production firms were expected to build and test product design prototypes experimentally in order to determine flow capacity and detect issues leading to cavitation (Iannetti, Stickland, & Dempster, 2015; Shirazi, Azizyan, & Akbari, 2012). Ding et al. (2011) explains how historically, pump simulation has been difficult with respect to cavitation until the advent of recent advancements in CFD technology, which has improved the process. Using an axial flow water pump as a test case, Ding et al (2011) was able to detect pump cavitation from CFD simulations.

Similarly, Ramanath and Chua (2006) discuss CFD use in the selection of an optimum design for a water flow-regulating valve trim. The valves are mostly used in water heaters and regulated flow is determined by the shapes of the valve trim. The aim was to keep water flow linear in order to maintain steady temperature at the outlet. CFD was applied alongside Rapid prototyping, three design trims were evaluated using CFD analysis, and prototypes from Rapid prototyping systems were used as base models, with the aid of CFD, the best design model was chosen for manufacture.

In a study by Eesa (2009), CFD Numerical modelling is used to gain insight into complex fluid flow in vibrating pipes as well as heat transfer. The goal was to access the potential for measuring viscous fluids subjected to vibration. The discovery revealed that viscous fluids increased in fluidity with increasing vibrations, which also generate wall heat transfer. This they mention, posseses huge potential for the confectionary industry as it could be useful in enhancing flow of viscous fluids. Applications in Polymer extrusion could also benefit from vibration.

In another case, Ahmed, Leithner, Kosyna, and Wulff (2009) reveal that CFD can be applied as a condition monitoring tool to predict and improve performance and longevity of fluid-related flow systems such as in water pumps and valves. These systems are often subjected to high temperature and pressure in application and similar structural stress. FEA and CFD were used to simulate one of the largest pumps in the world, situated in Germany. The model was generated in CFD modeller and subjected to stationary and transient operating conditions. CFD was then used to predict the hydraulic and mechanical behaviour of the boiler feed water pump. A practical experimentation using sensors was also performed on the large sector and the CFD results matched.

Asim et al. (2017) use CFD technology to model the complex geometry of high pressure severe service control valves within energy systems. They quantify the dynamics of hydrodynamic behaviour to predict local flow contributions of the trim to the global valve flow capacity of the valve. This was useful in providing better optimization of flow characteristics for improved control of the energy system.

2.9.4.2. FAN AND BLOWERS INDUSTRY

Prior to the introduction of CFD, firms in the Fan production industry would primarily design a fan blade by building a prototype of the proposed design (Spann, 2005), and measuring its pressure and flow rates at multiple rotational speeds (Dvorak, 2003). However, the experimental method is limited in the amount of detailed information it provides for specifying reasons the design does not perform soundly (Dvorak, 2003; Spann, 2005). According to Dvorak (2003), after CFD simulations were carried out on a fan design and the results were verified with actual experimental data, it was noticed that CFD even gave more complete information than the experimental testing. The colour coded patterns were one of the features exclusive to CFD that revealed information that could not be easily seen using prototype testing.

Spann (2005) shares this perception and adds that CFD is more effective when applied earlier in the product development process. A CFD simulation was carried out on fan design and placement in an ultrasound system. Prototypes were necessary for the firms operations, as clients and regulatory authorities required it to make their own validations before the product was approved for release. Additionally, it was a requirement for the fan to operate quietly. And from experimental analysis, the designers noticed the electronic parts were too hot but the analysis could not show what changes would solve the problem. Notwithstanding, instead of re-building the prototype based on speculation of where to place the fans, they eventually ran CFD simulations which exposed a filter that was meant to protect the printed circuit boards that would have been difficult to notice from the experimental test.

2.9.4.3. BIO-MEDICAL INDUSTRY

Prior to the use of CFD, most medical firms were building and breaking several prototypes till they could eventually find one worth presenting for clinical trials and regulatory approval (Sidawi, 2004). Research proved that CFD can be applied to the development of virtual biological models to predict the performance of the product before committing resources to produce a prototype. One of such instances where CFD has made significant progress is in Cardiovascular medicine. Morris et al. (2016) share their experience using CFD and refer to the technology as a rapid, economical, low risk virtual prototyping way of enhancing their research, resulting in innovative devices like vascular valve prostheses, stents etc. They also comment on the fact that CFD can be used to measure complex flow fields that can not other wise be accessed physically. This presents a huge potential for simplifying clinical trials, risk prediction and virtual treatment plans when combined with various other medical technology tools.

CFD is also used in other biomedical cases for simulating concentrated suspension shear blood flow, phase distributions and pressure/stress on artery walls (Jung & Hassanein, 2008). This method has proven to reduce lead-time and cost that would usually be involved in building real prototypes.

2.9.4.4. AUTOMOBILE INDUSTRY

CFD application has proven to be very useful in Automobile industry. Schmitz (1999) describes the initial use of the application of CFD in a firm as complex and reserved for trained PhD specialists during the earlier years of CFD. Even so, use of CFD was mostly restricted to external aerodynamic applications such as bumpers, side mirrors and hoods. However, with repeated use of CFD, they have soon begun to carry out more complex under hood simulations, Engineers have seemed to gain an extra boost in design capabilities, emerging with sleek designs that optimise airflow and reduce drag, the firm even developed their own software that improves their processes.

CFD has also been seen to help quieten cars. Acoustic fields are considered difficult to simulate around automobiles as a result of the difficulty in obtaining accurate simulations for unsteady flow. However, Thilmany (2001) believes, this has been achieved by Toyota using a proprietary CFD code. The code generates an overset boundary fitted grid that partially covers the model and the surrounding region. These grids are then overlapped with each other for computations. According to Toyota, the code gives highly accurate unsteady flow simulations that are only obtainable using the proprietary code. The software is called 'Gridgen' and it generates a boundary fitted grid for Toyota analysis.

2.9.4.5. ENVIRONMENTAL ASSESSMENT

CFD has been successfully applied to the analysis of air pollutant emissions from vehicular traffic and industrial plants. The research carried out by Hefny and Ooka (2009), studied concentrations of air pollutants in urban environments. CFD was helpful in detecting areas prone to air quality hazards with the introduction of new industry sites as well as regulation of existing industry facilities to meet sustainability standards for reducing air pollutants. Though modelling the environment with CFD was challenging due to the complexity of geometric variations within the vicinity, they were able to develop this model by computational mesh refinement.

Yadav and Bhagoria (2013) comment on the effectiveness of CFD for analysing predictions in Heat transfer for solar air heaters. The challenge they encountered was in choosing a suitable turbulence model. From the results of five turbulent models used they found out the Renormalization k-ε model provided the best results.

CFD has been used for predicting model behaviour as relates to mixing, mass transfer and fermentation systems of varying scales such as energy dissipation and oxygen mass transfer (Formenti et al., 2014). Though Fermentation as a process has not yet reached similar maturity levels as other traditional chemical processes, it is described as an asset in reducing reliance on fossil fuels. As fermentation experiments are usually expensive, CFD provides a good option for carrying out conceptual analysis. With major advancements emerging through CFD use, Formenti et al. (2014) use CFD to model fermentation processes through the scaling up and scaling down of Bio reactors.

2.9.4.6. OTHER APPLICATIONS OF CFD

In studying the effects of blast wave explosions, Hansen et al. (2010) used CFD for modelling the dynamic effects of Blast waves from explosions in near and far fields. This, they report, is a feat that is not resolvable using simple processes like the Multi energy method. However with CFD, specific estimates of the pressure and energy from the blast wave can be derived as well as the non-symmetrical effects caused by location objects. This can particularly be useful for determining Leak sources in an explosion as well as analysing risks and consequences of an identified leak source.

Li and Nielsen (2011) used CFD to study ventilation in buildings. They recommend CFD as an easy way to reduce experiments. However, they recommend CFD is used alongside experiments and analytic techniques. They also highlight the growing capacity for CFD to open up new research in 4 areas: **Solution Multiplicity:** which means more than one results could be derived with the same boundary conditions and different solutions could arise from different initial conditions. **Inverse CFD modelling:** Useful in tracing the source of origin of a biological outbreak such as in identifying the primary patient with an airborne disease. **Near-body microenvironment**: CFD can compute comprehensive airflow around the body as well as people's movements. **Disease transmission:** It is possible to monitor how disease spreads indoors using CFD in hospital wards. They also anticipate CFD would tackle ventilation problems at City Scale within 10 years. With advancements in computer technology every 2 years.

2.9.5. LIMITATIONS AND MISCONCEPTIONS OF CFD USE

Most inexperienced users expect CFD to make assumptions (Versteeg & Malalasekera, 2007). However CFD codes are not currently intelligent enough to inform the engineer/designer of possible assumptions nor alert the user that a CFD problem would not be physically implementable, the user would have to rely on their expertise of the underlying physics involved to draw their conclusions, as CFD would still present results from the simulation, irrespective of its practicability (Dvorak, 2006; Spalart & Venkatakrishnan, 2016),

Another misconception of CFD use, is the expectation of the time required to run CFD simulations. This would naturally depend on the complexity of the model and the computer's speed (Dvorak, 2006). However as faster computers are being produced with time, CFD simulation times would also reduce.

However, Professional Engineering knowledge is required to use CFD appropriately. While Bachelor degree holding engineers might be able to use CFD productively, basic training is still essential to use the codes. This would enable the user create appropriate geometry and make educated assumptions. Deitz (1996) refers to these two as the most important aspects of proper CFD implementation.

There is a tendency for users to want to rely completely on CFD results, Versteeg and Malalasekera (2007) believe it is currently impossible to verify the validity or accuracy of CFD generated results using any other means than practical experimental test. Therefore, CFD should not be considered a substitute for experimental tests. Notwithstanding, it is an effective complementary tool. However, CFD users can rely on former experiments that are similar in scope and simpler for validation, evaluations can then be made by comparing the analytical solutions of closely related problems obtained in collected literature.

There still remains some scepticism about CFD's reliability in proffering solutions to practical problems and their need to be validated (Oberkampf & Trucano, 2002). The question that applies to CFD and most CAD simulations is: *How good are results from scientific simulations without verification from scientific experiments?* Hatton (1997) conducted a study to find out whether digital simulations are any worse than physical experiments. The findings of that research reveal that physical experiments are every bit as likely to have same errors as simulations are. However, experts suggest CFD should always be validated by real experiments where necessary (Anderson, 1995; Deitz, 1998; Versteeg & Malalasekera, 2007). Some would want to think this would defeat the purpose of CFD in the first place, but in actual fact, it only reinforces the grounds for the establishment of CFD as a complementary tool to the other constituents of CFD. Perhaps sometime in the future, technology would be robust enough to validate results using other means.

According to Spalart and Venkatakrishnan (2016), the challenges of CFD implementation exist for Numerical solution, computing power and physical modelling. Despite increased computational power, reliability is highlighted as a big factor. However, they suggest training users and that CFD is best understood when integrated with other engineering processes and disciplines.

2.10. LITERATURE SUMMARY

The body of literature define the advancements in organisational, process and design development within the flow handling equipment industry.

Based on the research questions of this study, the following findings from literature can be summarised as follows:

2.10.1 ORGANISATIONAL FINDINGS SUMMARY

RQ 1: How do firms in flow handling equipment industry organize their resources and processes for New Product Development?

Organisationally, the implications of the findings in literature reveal that firm sizes and changes in industry trends influence the structure and culture and consequently their decision-making characteristics. Cosh & Fu (2012) is notably quoted for highlighting that most modern firms use flexible systems while mechanical systems would be useful only when applied to firms that are older or experienced. In terms of Culture, firm size also played a major role in deciding if managers or owners are likely to be the decision makers as well as their inclinations towards organisational growth. However, the size differences were not emphasized when it came to technology adoption. While technically-specific firms were likely to practice differentiation strategy in specialised roles, often involving some structure, technically-diverse (such as bespoke oriented) firms focus more on operational ways of meeting their targets. While understanding technical specificity is useful for determining firms that are likely to apply any developed structures, the analogy still leaves room for speculation on other factors that may contribute to the decision making as regards technology adoption. Some of these speculations would depend on whether or not the design practitioners see technology as structural artefacts in line with social constructivism or independent of the technology in a structuration approach.

The choice of emergent or deliberate strategies by decision makers also influence how the firms would prepare for new product development. Their priorities as a firm, e.g globalisation, would also influence their choice of product differentiation or even cost leadership strategies. As most of the firms in the flow handling equipment industry are part of a supply chain, each would possess different needs and require different variations of technological techniques and tools to process information required to carry out their duties effectively. The processes for ensuring this happens are described in the process findings summary.

2.10.2. PROCESS FINDINGS SUMMARY

RQ 2: What New Product Development methodologies are preferred by firms in the flow handling equipment industry?

In understanding process structures for new product development, literary sources highlighted staged and spiral methods as standard NPD methodologies. A variety of best practice tools useful for managing progression through the product development stages also exist as well as tools for prioritising customer expectations, perception and satisfaction. These include Stage gate, QFD, TRIZ, FMEA, KANO model and many more. In terms of how the firms meet and sustain customer needs, quality and design for sustainability, it was discovered that the firms were expected to comply with quality, suitable standards, and a structured NPD plan to achieve the NPD requirements. For firms that have a tendency to rely on unstructured systems aimed at building radically innovative ideas, the problem then lies in managing the process of transforming the innovative ideas into proper products. This process would eventually require some form of structured processes to harmonize the development process particularly in new technology adoption such as with Computational Fluid Dynamics (CFD). Following this gap in assessing how firms manage innovative processes while using unstructured systems, a cross-examination is undertaken during the data collection process of this study to access technology and process adoption and how product development processes are managed with or without a structured process in place at the firms in the flow handling equipment industry.

2.10.3. DESIGN FINDINGS SUMMARY

RQ 3: How do firms react to CFD technology during the NPD process?

The flow handling equipment industry features Computational Fluid Dynamics (CFD) as a nascent technology in determining fluid flow of various systems ranging from single phase to multiphase flows. While CFD adoption in the fluid flow handling equipment industry has increased over time, there are limited accounts of integrated CFD techniques in NPD methodologies. However, a number of isolated accounts of CFD use, demonstrate the efficacy of the technology in resolution of many challenges encountered by firms in the flow handling equipment industry. With varied applications in Valve, Fan, Automotive, Oil and Gas among others, there is not one way to access the entirety of the flow handling equipment industry. However, the prospects for CFD use seem promising in the recorded varied applications, especially with major advancements in computational technology with high performance computers and machinery over the course of time. Global sustainability targets also place CFD in a strategic position for the future as each successive decade features more advancements in technology that can be utilised in fluid dynamics prediction and analysis for green energy sources and virtual sustainment environment CAD integration. The advantages of CFD as a tool for predicting flow in a system include decreased reliance on expensive multiple experimental tests, increased flow prediction and non-intrusive flow analysis of complete systems in parts that cannot be reached physically among others. Notwithstanding the giant strides that have been made in CFD with the development of commercial and open access codes, there are still limitations and challenges with CFD utilization. One of such challenges/limitations that really stand out from the literature is user expectations of the CFD technology's reliability. However, no design technology is 100% perfect and assumptions that a technology would do more than it was actually designed for, could lead to more failed products in the market. This is because, while effective design technology exists, it does not replace the need for the users to be informed about the use of the technology and what it is intended for. These limitations and misconceptions could prove devastating for defaulting firms who make unguided assumptions while attempting to apply CFD. Because proper structures meant to govern the management of the firms interactions with CFD technology are not robustly accessible or are not followed, it is imperative that the industry is assessed through an inquiry to obtain a better understanding of the real situation.

The next chapter of the research will now employ different tools and techniques to discover how firms act around these concepts in the real world based on discovered gaps from literature, this will then enable the research to emerge with a set of tools, processes and structures to help firms optimize CFD technology adoption for product development.

CHAPTER 3: METHODOLOGY

In this chapter, the methods applied to the research and data collection procedure are specified detailing the philosophical constructs, research approach, method choice, strategies, time horizon and techniques along with the theoretical framework. This chapter is organised in three segments. In Segment 1 (Section 3.1), a research paradigm is chosen and explained. Segment 2 (Sections 3.2 and 3.3) describes the selection of methods and approach to data collection. Segment 3 (Section 3.4 and 3.5) discusses useful theories in practice that are resourceful to the area of study.

SEGMENT 1: PARADIGMATIC CONSTRUCTS

3.1. RESEARCH PARADIGM

According to Saunders, Lewis, and Thornhill (2016), research is the practice that fosters a systemic attempt to increase knowledge. Typically, every good research must outline its research methodology design that informs the approach to the study. This design often follows the form of a research paradigm. Frankfort-Nachmias and Nachmias (2008) describe research paradigm as methodological links between theory and processes used in data collection. Saunders et al (2016) provides a useful layered paradigmatic chart for outlining the course of a research design, which is called the Research Onion (figure 18).

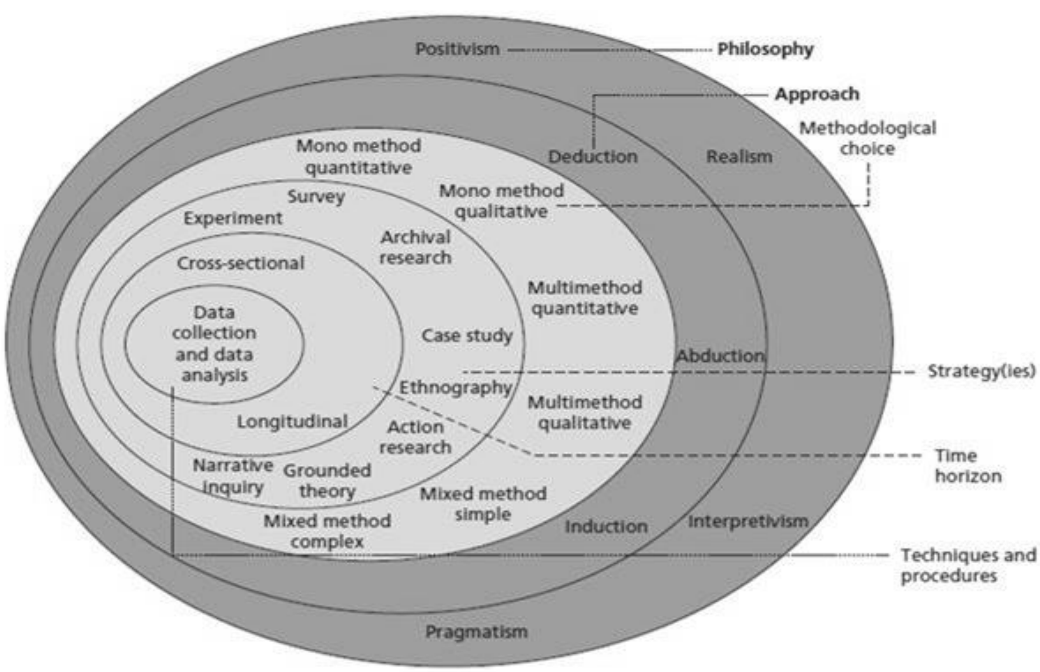


Figure 18 Research Onion Saunders et al (2016) pg 124.

The research onion consists of 6 layers, and draws the focus of the research methodology from a wider philosophical perspective to more specific data collection and analysis techniques at its core as can be seen in figure 18. The following sections explain the steps taken for data collection in this study using the research onion.

3.1.1 RESEARCH PHILOSOPHY (LAYER ONE)

The research philosophy is the philosophical outlook and lens through which the author views and interacts with the subject of study and is contained in the outermost layer of the research Onion. Though numerous philosophical constructs exist in research, the 4 major philosophies as can be seen in the research Onion are Positivism, Realism, Interpretivism & Pragmatism. These philosophical constructs also have certain paradigmatic bias towards the adoption of specific research methods in subsequent layers of the research onion. For instance, Positivism and Realism focus on deductive research as these philosophical positions are inclined to seek reasons for why an event has occurred. Interpretivism on the other hand presents a more inductive nature of inquiry. Pragmatism tends to vary between deductive and inductive research methods and focuses more on the consequences of an action. The flexible nature of pragmatism is often a major cause of criticism for this philosophical construct compared to other more rigid approaches. However, this research adopts the **Pragmatism** construct as it provides the most suitable philosophical approach to the research aim and objectives. Further details about pragmatism is given in the next section.

3.1.1.1. PRAGMATISM

The development of Pragmatism as a Philosophical concept is not new and has been used in several scholarly contributions from scientists such as Dewey, James, Pierce, Mead, and other notable persons (Goldkuhl, 2012; Morgan, 2014). Although this concept has been applied more liberally in modern research, there was a time it faced a lot of criticism often drawn from a belief that practitioners of pragmatism do not adopt strict paradigmatic pathways such as can be defined ontologically or epistemologically (Morgan 2014). Notwithstanding, there have been a large number of research paradigms that were not considered great at inception but have become more indispensable over the course of time (Mertens, 2012). So much so that in recent times, more fields of study have come to rely on the efficacy of adopting the Pragmatic approach for research purposes (Goldkuhl, 2012).

As the term suggests, Pragmatism seeks to find solutions using whatever is necessary. It is often described as being deeply entrenched in action (Dewey, 2017). Denzin (2012) explains this phenomenon further, classifying pragmatism as a philosophical truth that reaches beyond just a research method, and applies a systematic way of viewing things, one that is informed by experience and understanding the consequences of an action. In other words, Pragmatism practitioners look more significantly at a world view that seeks to establish essentially, what works towards solving a problem (Biesta, 2010). The pragmatist is concerned about implementing action where necessary and adopts approaches that negate the classical school of thought prominently used in selection of paradigmatic methods from the philosophical inclinations of positivist, realist or interpretivist paradigms.

The typical positivist and realist views have often been criticised by practitioners of both as being suited for only specific kinds of research. This is especially the argument that ensues during decision making as to whether qualitative or quantitative methods are best suited for the research based on widely known and established paradigm routes for philosophical approach to research. These sort of arguments seem to neglect the fact that a body of research could benefit from both qualitative and quantitative methods. Where both methods are used, it is termed mixed methods research and indeed the Pragmatist tends to apply a variety of methods to obtain the required knowledge and seeks more intently to obtain just as much as is sufficient to solve the problem.

Morgan (2014) provides valuable insight into Deweys work on pragmatism and presents the utility of pragmatism as a philosophical frame of knowledge that draws its strength from actions, thereby encouraging an approach to research that seeks to answer not just the *what* questions but the *why's*. Creswell and Poth (2017) identify Pragmatism as a method not committed to one philosophical system but best suited for studying and understanding relationships with a view to understanding consequences and providing solutions. A key point to recognise is that Pragmatism can be applied to research that is not specifically qualitative or quantitative and it approaches a wider view of a philosophical reasoning without too much emphasis on paradigmatic pathways such as can be seen in the research onion. Pragmatism has often been linked to Mixed Methods Research (otherwise acronymized as MMR) in Social research (Morgan, 2014). As the research questions of this study focus on the internal relationships within organisations, their external environment and new product development methods, as well as the relationships between them and CFD technology adoption, Pragmatism becomes the most suitable philosophy for understanding and developing a solution to questions posed by this research.

Following the adoption of the Pragmatism approach for this study, the research description would be divided into two parts. The Methodical Research (Section 3.2 and 3.3) and the Theoretical Research (Section 3.4 and 3.5).

3.1.2. RESEARCH APPROACH (LAYER TWO)

The Research Onion outlines three areas of research approach. The deductive, inductive and abductive approach. The two common methods used in research are the inductive and deductive approach. According to Saunders et al (2016), the deductive approach explores existing theories that usually form a hypothesis, which is later tested through data collection. In the inductive approach, the researcher uses collected data to develop a solution or theory. The abductive approach infers logical conclusions from presented data. While the abductive method is increasingly being used in modern research, the inductive and deductive approaches are more proven methods of approach to research.

This research applies both the **deductive** and **inductive** approach. The first part of data acquisition focuses on the deductive approach to obtain valuable insight into the companies in the flow handling equipment industry as well as information about the inherent practises that require a solution. The second part of the study then assesses suitable theoretical frameworks that can be applied and modified to achieve valuable solutions to the inherent problems identified from data collection. Their application would result in an inductive inquiry in chapter 5, for the development of a new method. Another deductive approach is then taken to test the theories with an experimental evaluation of the developed theory in chapter 6.

3.1.3. RESEARCH METHODS (STRATEGY AND CHOICES) (LAYERS THREE AND FOUR)

In this layer, the different research methods are outlined alongside the prevalent strategies for quantitative and qualitative research. They are Mono method, Mixed Method and Multi-Method. The Data collection methods include: Experiment, Survey, Case Study, Action Research, Grounded Theory and Ethnography (Saunders et al 2016). A **mixed methods** strategy is adopted for this research in line with Pragmatism philosophy. The reason this method was chosen would be analysed to highlight its strengths and suitability for this research.

3.1.3.1. MIXED METHODS

A mixed method as the name implies, utilizes tools from a variety of sources and approaches problems without research paradigmatic bias in line with the pragmatic philosophy. Sandelowski (2000) aptly defines mixed methods research as a combined array of data collection techniques that affords the researcher the freedom to use more than one method for a research. There are two major methods for carrying out research, the Quantitative and Qualitative research methods. It is common either to find pragmatic researchers applying both qualitative and quantitative methods complimentarily or just to compare results from different approaches.

The Quantitative method's limitation are mostly focused on the numbers. A major limitation of the quantitative method for a research like in this study, is that though it tries to obtain a generalized view, it requires a wide range of sample data to produce a close representation to what is obtainable in reality. The results are usually then statistically analysed and generalized conclusions are generated from the data. This raises a number of issues for a study that is not intended to obtain findings based on a statistical comparison analysis such as to measure the dominance of one area against another. This is mainly because such activity ignores specific cases that may not have popular representation in the sample but that may require adequate attention in the research. In collecting statistical information, such as in a quantitative survey, attempts are rarely made to observe the reasons behind the way the figures turn out. Where the survey is not conducted in person, there is a tendency for respondents to provide inaccurate answers or leave out responses to some important questions without the intervention of the researcher. Even when the researcher is present, there is also a possibility for respondents to provide random responses to questions they had trouble understanding. Apart from Quantitative surveys, Experimental studies may also be carried out quantitatively to test the behaviour of a system.

On the other hand, qualitative research methods, such as an interview, is useful for gathering information that is specific and that require a first-hand account or original understanding of the topic and sometimes the subject (respondent) discussed. Therefore, it would be unnecessary to carry out a large quantitative survey if the information required for the research is dependent on the situation of a few. For research where the aim of the data collection is to achieve both, a mixed methods approach may be applied. Tashakkori and Teddlie (2010) gives credence to Mixed Method research as a technique for obtaining more understanding that could not be captured using either the Quantitative or Qualitative study alone.

In this regard, this study adopts a **qualitative survey** and **interview** for the 1st phase of the research. The Survey is used as an introductory tool to collect useful information about the current practices in the target companies. This is shortly followed by an Interview, which is essentially used to obtain more depth from respondents on their responses to the survey and to also identify and correctly assess areas where the questions were not clearly presented or understood. However, the approach for analysis would mainly be qualitative, reasons for this are discussed in section 3.3.

In Chapter 6, a **simulation experiment** is carried out as part of a pilot study which is majorly quantitative; this makes up the second part of the mixed methods research. However, it is not discussed in this chapter and will be explained in a later part of the study where the pilot test is discussed in chapter 6.

3.1.4. TIME HORIZON AND DATA COLLECTION (LAYERS FIVE and SIX)

For this research, a **cross-sectional** time horizon would be adopted. While the longitudinal approach often takes a very long period of time due to the repeated collection of same data over a period of time, the cross-sectional time horizon only requires data to be obtained once. Considering the time and scope of this research, a cross-sectional time horizon is the more useful option.

SEGMENT 1 SUMMARY

This section provides the framework through which the research is followed. A pragmatic philosophical standpoint is taken, deductive and industive approaches are utilized, a mixed methods research process is introduced utilizing qualitative methods in the data collection and analysis involving a qualitative survey and interview. The quantitative part of the mixed methods research involving simulated experiments on a product design is then applied in Chapter 6 during the pilot test. In the next section, detailed analysis on the implications of the selected research methods for data collection are presented and expounded.

SEGMENT 2 RESEARCH METHODOLOGY CONSTRUCTS

In this segment, the key uses of qualitative methods are highlighted and evaluated in line with their applicability to engineering and management level applications. An overview of the specific methods used as well as discussions on structural strategies to the research are presented.

3.2. QUALITATIVE RESEARCH METHODS IN ENGINEERING RESEARCH

In Engineering design related research, there has been a great deal of focus on the use of Quantitative methods such as Experimental and Quantitative Surveys (Szajnfarber & Gralla, 2017). However, a number of management specialists deploy qualitative methods to tackle design specific research questions (Bucciarelli, 1994; Daly, Adams, & Bodner, 2012). Engineering Systems research has even more recently moved beyond the focus on technicality to the study of sociotechnical interactions from a systematic standpoint (Szajnfarber & Gralla, 2017). It is therefore important to assess the relevance of qualitative approach to Engineering design related topics with a view to deciphering its utility to the aims of this research.

3.2.1. ENGINEERING QUALITATIVE RESEARCH- HISTORY AND PRINCIPLES

Caillaud, Rose, and Goepp (2016) outline the evolution of engineering design research from the experiential phase, which consisted mainly of designers describing product processes they had developed and applied themselves as systematic theoretical frameworks were lacking. The intellectual phase which emerged and was prominent between 1960s to 1980s, saw engineering researchers engaged in the development of frameworks for logical and systematic approaches to design. According to Bayazit (2004), this was seen more as a problem solving activity.

However, with the development of new methods, theories and computational tools, more organisations exhibiting interest in concurrent engineering methods that foster collaboration between teams have ushered in the Experimental phase. As a result, more data collection methods are required to advance the utility of the design process. According to Borrego, Douglas, and Amelink (2009) Engineers that are used to applying Experimental/Traditional research methods may often struggle to understand qualitative methods. The aim of the qualitative research is to develop a deeper understanding of the content being studied which would usually surround the implementation of design processes and from a systems thinking point of view, the sociotechnical constructs that interact with that process.

The results of a qualitative research are usually rich in analogy (Patton, 2005). The focus in utilising this method is not as much on creating a representation of statistical truth as in 'what is' or 'which of these', but to open an exploration into logical cause for 'what might be' and 'what can become'. As is useful in pragmatic research, the focus is on establishing the context within which a phenomenon occurs with a view to influencing its change or adaptation. Typical questions from a qualitative study would aim to establish: "How a particular event functions, why it is happening? What influences its occurrence?" (Borrego et al., 2009; Chism, Douglas, & Hilson Jr, 2008).

The key characteristic of a qualitative research method is the level of detail. Top methods for assessing detail include, interviews and action research (Chism et al., 2008; Golafshani, 2003) or open end surveys, focus groups and documental review (Borrego et al., 2009; Leydens, Moskal, & Pavelich, 2004).

3.2.2. CHALLENGES OF QUALITATIVE RESEARCH IN ENGINEERING

While qualitative research still endures credibility criticisms for its lack of the rigour as compared to the preference for statistical representation from the realist and positivist philosophical thinkers that dominate the field of Engineering, Szajnfarber and Gralla (2017) stipulate that a number of rich theory methods available in social sciences make qualitative research implementation feasible and particularly rewarding. However they caution against naive applications of qualitative research methods and suggest proper validity of methods used are taken into account.

3.2.3. VALIDITY OF QUALITATIVE RESEARCH FOR ENGINEERING APPLICATIONS

For Qualitative research to meet research requirements for validity and reliability, researcher participation in the collection of data is highly recommended (Borrego 2009, Patton 2001). A major difference between Qualitative research and its Quantitative counterpart is that while Quantitative research is used mainly for testing hypothesis extracted from literature. Qualitative research does not rely on a priori information and seeks to find new data that is often ignored or omitted in quantitative research.

While Qualitative research has been used in Engineering research such as for monitoring approaches to design activity by Ahmed (2003). It is often applied in Cross Disciplinary Study such as in the health sector where nurses may be assessed on use of technology (Clancy, Effken, & Pesut, 2008) and now being used in this research, to study the interactions between Engineering teams and Management processes. A recent use of Qualitative research in Engineering is Malik et al (2017) who studied integrative and technical competency areas and utilises qualitative methods to assess further Systems Engineering training requirements. Also observed uses of qualitative methods are detailed in Bucciarelli (1988)'s applied qualitative research and Daly (2012)'s strategy for design solutions highlighting significant use over time.

3.3. DATA COLLECTION APPROACH

This research studies the internal and external relationships that exist between companies and their established processes as well as design related activity with respect to Computational Fluid Dynamics (CFD) technology adoption. As outlined earlier in line with the Pragmatism approach, data collection is focused on obtaining sufficient information to develop a solution. According to Creswell and Creswell (2017), research methods are determined by the research questions. Due to the limited literature in this area of interdisciplinary research, specifically in the area of Computational Fluid Dynamics acceptability in Fluid Flow Handling Equipment Industry and NPD methodology application, an exploratory approach to answer the research questions were initiated through qualitative methods to capture company experience from an organisational perspective.

To evaluate these activities, it is important to recall the research questions:

3.3.1. RESEARCH QUESTIONS

The research questions of this study are as follows:

- **RQ 1:** How do firms in flow handling equipment industry organize their resources and processes for New Product Development?
- **RQ 2:** What New Product Development methodologies are preferred by firms in the flow handling equipment industry?
- **RQ 3:** How do firms in the flow handling equipment industry react to CFD technology during the NPD process?

The above research questions fit the choice of a qualitative approach, with the goal of data collection being to extract background details from the inherent contexts of interactions that exist within an organisation. Consequently, a pragmatic solution can then be developed; providing a new NPD methodology tailored to the needs of the organisations in the flow handling equipment industry that is implementable and easily understood on a variety of enterprise levels. The use of qualitative methods is instrumental to this aim as the study is not restricted to reporting the context alone but also seeks to generate information that can be used in developing industry specific solutions. A more detailed description of the rationale for this choice is elaborated in the next section.

3.3.2. RATIONALE FOR SELECTION OF QUALITATIVE DATA COLLECTION METHOD

Though a mixed methods research design is used for this study, qualitative methods were adopted for data collection instead of a quantitative data collection approach. A quantitative approach is then applied as the second part of the mixed methods process in chapter 6 through a pilot test to assess the viability of the new methodology that this research aims to develop. A qualitative research approach is selected for data collection, as quantitative methods do not achieve the depth required to answer the research questions of this study. Conversely, the detailed analogy from qualitative methods of data inquiry make it a more practical method for exploratory research. As an example, when a large statistically styled quantitative survey is conducted possibly using a lickert scale, the responses from such a survey would generate data that is relevant within the contexts those firms experience them. However, as the data from a large sample size are quantitatively compiled, the information is often generalised and low statistically ranking results are often disregarded. This runs the risk of offering limited coverage of the underlying reasons for the responses given during data collection; thereby undervaluing complex situations made to appear simple and restricted by the choices the respondents are given to the questions presented. There is also the risk of choosing questions that do not cover the range of the subject matter due to limited literature. In other words, the data would be unable to capture a holistic view of the interactions such as in tacit knowledge sharing that may not be documented in the respondent organisations' official approach. Similarly, in cases where some firms apply a best practice approach to their NPD processes but are unable to remember or identify the appropriate titles of the processes in the provided options, responses from statistical analysis may omit those methods. There is also a limitation using the quantitative method, largely due to the complexity of the studied cases which often require responses that go beyond just telling "what happened" to explaining the motive behind the phenomena. By using a Qualitative method, the respondents are able to communicate the circumstance and give examples to substantiate the responses they would give in a questionnaire when followed up with an interview.

Therefore, the respondents from the data collection inquiry undertaken during this research were not limited to multiple-choice questions alone but expanded on their responses through subsequent interview. The next sections provide details how this process is carried out.

3.3.3. DATA COLLECTION PROCESS

The data collection process was executed in two stages. The *Preliminary questionnaire survey* and the *Interview stage*. The semi-structured preliminary questionnaire survey was qualitatively applied and aimed at collecting concise information about the company, which are then further elaborated on in the interview stage. The questions from the questionnaire survey had both closed and open-ended questions and were drawn from the research questions as a guide. The Interview, which followed immediately, was then based on clarification of the responses that were given in the preceding questionnaire sessions.

3.3.4. SAMPLE SIZE SELECTION

Six (6) companies took part in the survey and interview. Table 3 represents the profiles of the companies selected.

Table 3. Sample size distribution

	Small	**Medium**	**Large**	**Total**
Valve	1	1	1	3
Fan	1	1	1	3
Total	2	2	2	**6**

Total Number of Small-sized Companies selected = 2 (1 valve and 1 fan).

Total Number of Medium sized Companies selected = 2 (1 valve and 1 fan).

Total Number of Large sized Companies selected = 2. (1 valve and 1 fan).

Total Number of Valve Companies that took part = 3

Total Number of Fan Companies that took part = 3

Total Number of Companies that took part = 6.

3.3.5. SAMPLE SELECTION CRITERIA

Based on the scope of the research and findings from the literature, demonstrable characteristics of firms in the flow handling equipment industry were specifically observed in terms of their participation in organisational structure, process development and CFD activity. Therefore, the following are the key selection criteria for choosing the companies that took part in the research.

The companies had to be:

- Interested in New Product Development
- Accessible for data collection (Based in West Yorkshire)
- Registered as a Company dealing with Flow Handling Equipment in a Product development capacity.
- Have as minimum, a basic understanding of CFD either through current use, having attempted to apply the technology in the past, or intending to use same in the future.
- One company from each company size group (small, medium, large), one from either valve or fan industry or both.

3.3.6. NUMBER OF RESPONDENTS:

The preliminary questionnaire survey involved six respondents from six companies. Five of the six participants that took part in the semi-structured questionnaire eventually went on to take part in the interview for their companies. The one preliminary study participant that did not take part in the interview (Small Valve firm), was replaced by a more experienced staff from the same company as the primary participant during the interview stage.

In one of the six interviews (Large Valve firm), a secondary participant joined the primary participant and they took turns to provide responses that were peculiar to their roles at the company.

The questionnaire and Interview records were coded using NVivo 12 and themes were developed. Data analysis included the identification of theoretically informed findings as well as emergent themes from the data.

Note: *For simplicity and ease of analysis, as well as in line with Pragmatic research, the number of respondents/interviewees used from this point in the research and in analysis are recorded as 6 (six), therefore the responses are classified by company and not by individual participants.*

3.3.7. PRELIMINARY QUESTIONNAIRE FORMULATION

Barclay, Dann, and Holroyd (2000) advocate for companies to ask the right questions towards improving performance in New product development. In a bid to find answers to the Research Questions with a view to promoting performance improvement, the Questionnaire was developed using insights from the research findings and guidelines from adaptations of research questionnaire design publications such as Barclay, Dann, and Holroyd (2000), Levenson (2014), Edwards, Delbridge, and Munday (2005) and Snijkers, Haraldsen, Jones, and Willimack (2013). All of these resources were instrumental in guiding the theme of the questionnaire.

A copy of the questionnaire developed for data collection in this study with a combined total of 31 questions, has been appended to Appendix A. It consists of an Introduction and the 3 major research sections (Organisation, NPD process and Design/Technology), attempting to address the 3 research questions and satisfy the key areas of the research. The sections are described as follows:

- **Introduction section:** This part was focused on obtaining demographic information about the company.
- **Section A (Organisation):** This part was focused on the organisational preparedness of the companies and contains two parts,
  i. Internal: This section focuses on the firm’s internal strategy such as organisational structure and communication between teams.
  ii. External: This section focuses on examining how the firm handles relationship with external factors such as: customer and competition.
- **Section B (New Product Development)**: This part was designed to obtain an understanding of the ways firms deal with New Product Development as well as their propensity to apply Best Practice methods.
- **Section C (Design – Computational Fluid Dynamics):** This part highlights the use of CFD as an analysis tool in design, to examine preparedness as well as management participation.

A more detailed description of the questionnaire design is given in the following section.

3.3.8. SEMI-STRUCTURED QUESTIONNAIRE/INTERVIEW DESIGN AND JUSTIFICATION

The preliminary questionnaire was designed on a semi-structured question style for data inquiry intended to produce participating company classification and to present a focus for the subsequent interview. Appendix A displays the preliminary questionnaire used in the data inquiry survey.

The introductory section of the questionnaire presents four short general questions to the respondents. The first 3 questions aim is to identify the size and business of the company based on the European Commission (2003) and BEIS (2018) classification of enterprise sizes; by number of employee and turnover margin. The size of the company is a key indicator in this regard, as organisation culture tends to be influenced by size (Eisend et al., 2016; Green et al., 2008). This provides an avenue for assessing the conformity of the literature in practice. The section concludes with the fourth link question to the next section, which is intended to prepare the participant for the questions ahead as well as provide an insight into areas the companies may experience difficulties and seek to improve.

Section A of the questionnaire, presents the organisational structure in two parts: The internal and external relationships of the firm. The first part of the section focuses on the internal structure from a systems viewpoint, the goal is to study the cultural inclinations of the firm towards Traditional or Concurrent Engineering practice. Employee engagement is also taken into account, as it demonstrates the levels of communication between the management and employees. Response to developmental activities are also taken into consideration to evaluate effort and preparedness for process complexity. The second part of section A studies the companies' relationship with external influences and observes how each subject company deals with competition, and customer influence. Again, the last question in this section, links to the next section on customer involvement with NPD processes.

Section B of the questionnaire, deals with the NPD process itself and tries to develop an understanding of the levels of familiarity those at the firm have with established NPD processes. Where it is not likely that the firm uses an established method. The Concurrent Engineering vs Traditional Methods are described in the subsequent interview to ascertain which of the processes the firm applies during NPD projects. An understanding of how these processes are reviewed for improvement is also necessary to ascertain best ways of integrating the new proposed systems from this research. The collaboration methods used between teams are also studied. To examine knowledge integration and how these affect quality, supplier/external specialist influence is investigated to examine if external knowledge is desirable within the firms. The last question in this section of the questionnaire presents a more technical inquiry; focusing on an assessment of the company's disposition to adopting Quality methods that are structured in composition, this question links into the third section of the Questionnaire.

Section C, the final part of the Questionnaire, draws the focus to Computer Aided Design to access the company's preparedness for Digital Engineering and Computational Fluid Dynamics. An assessment of the level of use in practice is sought and open-ended questions are asked to obtain information about their own impressions of simulation software they might use for CFD analysis. The questionnaire concludes with an assessment of the level of acceptance of CFD as a simulation tool as well as any preferences they would like to see in development of the technology as well as in its software platforms.

The sections have not adopted a statistical pattern to them because the questionnaire was only used as a prompt for the interviews that followed. Therefore, the questionnaire was applied qualitatively and not in a quantitative sense.

3.3.9. THEORETICAL SATURATION

According to Denzin (2012) saturation is achieved when data analysis does not produce any new findings, or additional themes (categories). This is where data analysis was concluded.

3.3.10. ASSUMPTIONS, LIMITATIONS AND DELIMITATION

3.3.10.1. ASSUMPTIONS

The following Assumptions were made during the collection of data.

1. Participants are interested in improving research in this area and would present a honest view when responding to the questionnaire and interviews, as well as providing the information necessary for the pilot phase.
2. Participants held significant product development roles within the company
3. The company and the department the participants belong to are still actively involved in new product development or intending to as at the time of data collection.

3.3.10.2. LIMITATIONS

1. Participants may have formed their own opinions, which may not entirely reflect the opinions of the entire organisation.
2. As the data is based on responses to questions asked by the Interviewer, the interviewer's views or interests in specific questions may have slightly influenced the course of the interview or left out information that may otherwise have been useful to the research.
3. Due to the number of companies interviewed (six), analysis may not be construed as generalizable or indicative of all the companies in the respective industries in the area.

3.3.10.3. DELIMITATIONS

1. Participants were asked to fill a questionnaire to obtain valuable information about the company before the interviews began.
2. The questions asked during the interview demanded in depth responses based on earlier responses to the questionnaire.
3. Each Question from the Questionnaire form displayed options for open responses alongside the closed options. This was provided to allow the participants express thoughts that were not accounted for by the interviewer in the questionnaire. An opportunity to explain these were also given during the interview sessions.
4. Participants did not include persons that have a close or supervisory relationship with the researcher.
5. Participants/Companies who were not looking to improve their processes were not interviewed.

3.3.11. VALIDATION METHODS

Four types of triangulation based on Denzin (2012) Triangulation, are implemented during the data collection and analysis phase of this study.

1. **Data Triangulation:** The data is triangulated using multiple data: Qualitative Survey and Interviews, including the Simulated Experiment Pilot Study (detailed in Chapter 6).
2. **Theoretical Triangulation:** Multiple theories are used to access the data during the analysis.
3. **Method Triangulation:** Similar data is collected using two methods, questionnaire and Interview.
4. **Environmental Triangulation:** The data collected is taken from two sub-industries (Valve and Fan) of the Flow Handling Equipment Industry. These companies are from three (3) different sizes of companies (Small, Medium and Large). Therefore, out of the 6 companies, there are 2 companies of each size per industry and 3 companies of each industry per size.

Conclusively, a Pilot Study to test the developed research based solution was used to confirm the data collected from the participants were effectively represented in the new solution methodology.

3.3.12. DEPENDABILITY

To ensure the information collected is dependable, clarifying statements like "So you are saying…", "Do you mean..." are used throughout the interview to ensure the information provided and recorded was the accurate intended position of the interviewee.

3.3.13. TRANSFERABILITY

As the research was conducted in six companies, readers may decide whether or not to generalize the outcome of this research, however the intent of the study is not to generalize the data or to test a hypothesis but to obtain necessary information from a pragmatic philosophical viewpoint geared towards the development of better new product development methods. Following an in-depth analysis of the information, the results may then be transferable to organizations with similar challenges or looking to improve their processes. Readers as well as researchers interested in a more strictly statistically oriented view may also benefit from the unique findings in this study, which may then inspire hypothesis testing in a future study.

3.3.14. ETHICAL CONSIDERATIONS AND CONFIDENTIALITY

The companies that took part have been anonymized for the purpose of this research. The names of individual participants have also been anonymized. The confidentiality statement and details of how the responses they provided were to be used were stated on the header of the questionnaire they were given and explained to the partaking respondents verbally before commencement of the sessions. As all the survey sessions were conducted face to face, the participants were also informed before the beginning of the session that the purpose of the research was for a thesis that would be publishable.

3.3.15. DISSEMINATION PLAN

Valuable efforts would be made to utilize appropriate channels for communicating the findings of the study through publications in notable industry journals in the Systems Engineering and research community. A copy of this thesis is also made available to the University of Huddersfield Repository. Presentations would be made at suitable conferences if applicable.

3.3.16. POTENTIAL IMPACT IN THE INDUSTRY

As this research is aimed at providing multiple novelties using uncommon research methods to Engineering research, the impact of this research is deemed significant. For the Industry, this work provides insight into the modern world of research into systems methods, theories and valuable information for designing NPD processes that would improve the effective design and development of new products and potentially increase radical innovation in the Flow Handling Equipment industry.

SEGMENT 2 SUMMARY

This section describes the methodical constructs, approach and tools deployed towards the data collection phase of the research and highlights company and participant selection as well as Question formulation for the semi-structured interviews. Any assumptions made as well as limitations, delimitations and Validations have been discussed. The next section would describe some useful theories that shape the mind of the author in analysing the results that are obtained from the data collection process.

SEGMENT 3: THEORETICAL CONSTRUCTS

After the questionnaire and interviews have been completed, the analysis and subsequent solutions provided in the next chapter would be based largely on a system of underpinning theoretical constructs. These constructs determine how the findings would be analysed and how solutions would be provided to the problems emerging from the research.

Apart from the individual ideology of the author, one of the major theories applied in obtaining an understanding of how things function, is the field called Systems Thinking, otherwise known as Systems Theory. This research aims to deploy the vital methods and techniques of Systems theory to resolve the problems discovered from the collected data. A justification for the selection of this theory is now provided.

3.4. SYSTEMS THEORY

Systems theory is founded on the principle of the 'whole' being more significant than its 'parts'. This principle can be traced back to the time of philosophers like Aristotle (Teece, 2018).

The development of the concept now known as Systems Theory, was materialized through the compilation of scholarly works by various scholars applying similar principles to a variety of studies in disciplines such as Biology, Cybernetics, Economics, and Mathematics among others. In line with this development, Ludwig Von Bertalanffy in a bid to kick against reductionism, had planned to establish a unified way of approaching science by bringing together these ideologies (Meadows, 2008; Mele, Pels, & Polese, 2010; Teece, 2018; Von Bertalanffy, 1968). Von Bertalanfy (1968) argues that a phenomenon to be studied cannot be comprehended by the disintegration of a whole into parts diagnosed independently of one another but that a holistic approach must be taken to assess the quality in their interaction as a system. Simon (1991) describes it further as, "taking the interactions of constituent parts of a complex system as a whole instead of as a sum of the parts". This tends to suggest that studying single parts of a system without taking the concept of the relationship between these parts as a whole would fail to provide a valuable understanding of a concept or system. Systems Theory is therefore a multidisciplinary theory that describes the constructs of systems in their real and entire (holistic) state, thereby providing a framework for investigative analysis of various phenomena.

Over time, Systems theory has gained significant prominence in management research since the 1960s (Ashmos & Huber, 1987). It is responsible for systems thinking which has been instrumental to the development of a variety of theoretical adaptations being applied in multidisciplinary fields. One example is the Dynamic Capabilities Framework (DCF) developed by Teece, Pisano and Shuen (Teece, 2018) in the field of organisation process management and Systems Engineering.

According to US DOD Systems Management College (2001), Systems Engineering is defined as an interdisciplinary approach that involves the entirety of the processes, techniques and strategies necessary to meet the customer needs through the integration of a life cycle balanced set of systemic solutions. Although the approach to Systems theory may be applied differently between a variety of disciplines, the applications of the principles are predicated on the same constructs. Burns and Stalker (1961), highlights this fact from a managerial perspective, emphasizing the role of managers in the application of systems thinking towards managing the relationships that exist internally and externally between the organization and their environment.

Over time, Systems theory has taken multiple dimensions and can be found in various forms which may at times appear contradictory when placed side by side (Mella, 2012). A review of different approaches to Systems Theory will now be made.

3.4.1. GENERAL SYSTEMS THEORY:

As developed by Ludwig Von Bertalaffy (Von Bertalanffy, 1968), the entirety of General Systems Theory (GST), is modelled on the primacy of interactions. It holds a distinguished stance on the belief that parts act differently in isolation than they would during an interaction with other parts within a system. However, over its life span, Systems Theory has been subjected to criticism, one of such was made by Berlinski (1970) who described various approaches to systems thinking as a grand exertion but lacking any sufficient means. Conversely, book reviews made by Kochen and Deutsch (1977) tend to discredit Berlinski's claims based on a lack of valuable contribution within the work presented in Berlinski's criticism. Adams et al (2014) believe the criticisms might have emanated from the fact that GST did not offer a systems structure, complete with its axioms and propositions for utilizing the theory. Notwithstanding, Systems Theory is still widely practiced and recommended by modern publications (Nasa, Aeronautics, & Administration, 2008; US DOD Systems Management College, 2001)

3.4.2. TYPES OF SYSTEMS

Systems can be categorized as open or closed based on the components they interact with. As described by Mele et al. (2010), an open system is concerned with exchanging energy, matter and information with the environment, while a Closed system exchanges only energy with no material input or output. On the other hand, an Isolated System does not exchange energy, information or matter. The implication of this distinction for organisations is that, in an Open System, the organisational activities would interact with their environment, referred to as a Supra system. While in a closed system, the organisation only operates within itself using its own resources and personnel called a sub-system. In this study, the focus of objective 1 is on the firm's preparedness to adapt to the external and internal factors that influence the activities of the organisation. This may provide insight into types of interactions between organisations and processes as well as their relationship with NPD methods and technological integration. In order to understand how firms use adaptation techniques to deal with the challenges, it is important to study how they respond in a system. To this end, the viable system model and the viable system approach provide useful information on system behaviour.

3.4.2. VIABLE SYSTEM MODEL (VSM)

The Viable System Model (VSM) is attributed to works by Stafford Beer. Beer (1972) describes Viable systems as an autonomous entity that is capable of adapting to the changing requirements necessary for survival in its environment. The Viable System Model applies a cybernetic regulatory systems approach which is concerned with the interactions between an autonomous acting system and its environment in such a way that the environment provides feedback to the entity (organisation) thereby enabling the system to adapt to the new situation. For an organisation, it is therefore important that systems are built to obtain information through feedback that they can apply to improve their ability to survive the market. Viable Systems Model provides an understanding of complexities that may arise and utilises conceptual tools to enable the system redesign itself for the challenges. These tools focus on change management, holistic understanding and an evaluation of valuable functions within the organisation.

3.4.3. VIABLE SYSTEM APPROACH (VSA)

This approach was also introduced by Stafford Beer, and postulates that every system is positioned between higher and lower level systems, ideally referred to as Supra and Sub systems respectively. In an organisation, the Supra systems refer to the organisations external interactions while the sub-systems refer to internal interactions that occur within the organisation. A Systems' boundaries are adaptable and a viable system is one that is able to develop a congruous relationship with its Super and Sub systems, and that can continuously align the complexity of internal relationships with the complexities of the external environment. (Golinelli 2005, Barlie 2009).

From the above, the following deductions about Systems Theory can be made.

1. Systems are organised within Supra (the universal environment) and sub systems (internal environment)
2. Viable Systems are able to self-adapt to changes in the environment
3. Systems possess the ability to cooperate with the external environment and provide influence to the supra-systems

4. Systems acting holistically will reach the same fate even if different paths are taken. (Bertalanffy 1962)

3.5. TECHNOLOGY ACCEPTANCE MODEL (TAM)

Introduced by Davis (1986), the Technology Acceptance Model (TAM) represents a widely accepted prediction construct for individual technology acceptance behaviour. It is based on both Theory of Reasonable Action and Theory of Planned Behaviour and applied majorly in information systems. However, its use has been applied in various other disciplines where the introduction of new technology is concerned especially with computer related technology. As displayed in figure 19, the original TAM model consists of two constructs: Perceived Usefulness and Perceived Ease of Use.

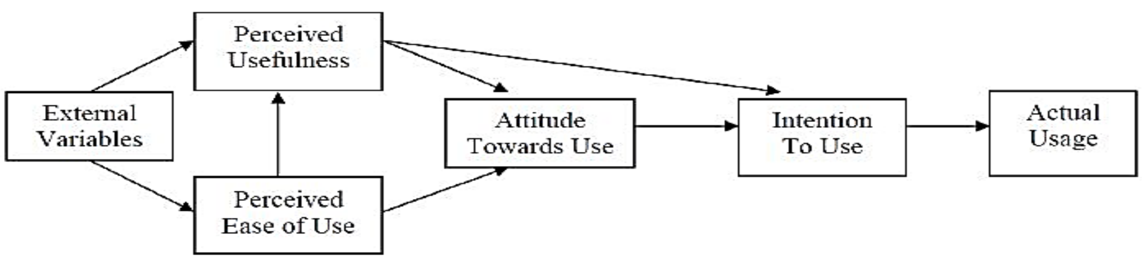


Figure 19 Technology Acceptance Model (Davis, 1989).

'Perceived Usefulness' refers to the likelihood of the user to interact with the technology system in the belief it would enhance their performance of a task. Perceived ease of Use**,** is the degree of a user's expectations for effortlessness in applying the technology to a task. These ideologies influence the user's attitude towards using the technology. The attitude of the user towards the technology then influences their intention and subsequent adoption of the technology for use. While there are modern versions of the TAM model, and these can be found in any good book, this research has chosen this original version of the TAM model as the basis for developing a ground-up approach to technology acceptance.

SECTION 3 SUMMARY

This section highlights the theories that are useful for analysing the collected data, as regards: organisational system behaviour and processes (systems theory) as well as in studying adoption of CFD technology (Technology Acceptance Model).

CHAPTER 4: RESEARCH FINDINGS

As highlighted in the previous chapter, two qualitative methods were used for data collection: preliminary questionnaire and interviews. This chapter discusses the findings from the data collection process in the manner outlined in chapter 3 of this study. It begins with a description of the analysis and coding process. Background information of the companies are obtained from the preliminary questionnaire followed by a narration of the themes from the interview section. The chapter is then concluded with a summary of the findings and their implications for the study.

The main aim of this chapter is to achieve Main contribution 1 of the research aim and objectives.

Main Contribution 1: Develop a novel assessment of Flow Handling Equipment Industry enterprise preparedness for Computational Fluid Dynamics integration to the New Product Development Process.

- **Objective 1:** Outline useful internal and external organisational knowledge resources for New Product Development in flow handling equipment industry.
- **Objective 2:** Outline NPD methods and tools used in practice by firms in flow handling equipment industry for New Product Development.
- **Objective 3:** Outline the reaction of firms to CFD technology adoption for New Product Development in the Flow Handling Equipment Industry.

4.1. THEMATIC ANALYSIS PROCESS

Thematic analysis principles were applied to the collected data to obtain useful information for analysis, which then informs the structure of the intended new methodology. The corresponding emergent codes and themes from the data were grouped in line with the research questions.

To aid theme extraction, the research questions have been expanded in line with the objectives of main contribution 1 as follows:

- **RQ 1: How do firms in flow handling equipment industry organize their resources and processes for New Product Development?**
    - How are firms managing their Sub System (Internal) resources for NPD? (part 1)
    - How are firms managing their Supersystem (external) resources for NPD? (part 2)
- **RQ 2: What New Product Development methodologies are preferred by firms in the flow handling equipment industry?**
    - What Best Practice NPD methods/techniques are firms in the Flow Handling equipment Industry influenced by?
    - How are firms structuring their NPD methods?

- **RQ 3: How do firms in the flow handling equipment industry react to CFD technology during the NPD process?**
    - What criteria determines CFD technology adoption in practice?
    - What are the inherent benefits/challenges of using the CFD Technology in practice?

The following sections describe the preliminary questionnaire and interview coding process.

4.1.1. PRELIMINARY QUESTIONNAIRE CODING PROCESS

A preliminary questionnaire session preceded each of the interviews at six companies in West Yorkshire. The responses collected from the preliminary questionnaire were summarily tabulated as presented in Appendix B to provide company classification information. Subsequently, the data was entered into a Microsoft Excel 2013 spreadsheet such that Companies A – F were labelled to represent the six participating companies, while the header names were created based on question themes from the questionnaire session. Next, the Excel data sheet was imported into NVivo 12 software where the NVivo auto-coding feature was used to generate the company classification attributes based on closed ended responses to the preliminary questionnaire. The questionnaire entry form as well as the tabulated differences between the firms by question-based themes are contained in APPENDIX A AND APPENDIX B respectively.

4.1.2. INTERVIEW CODING PROCESS

In-depth interviews were conducted in six companies in West Yorkshire following the preliminary questionnaire session. The duration of the interviews were between 15 minutes and 1 hour long. All of the data from the interviews were transcribed into six Microsoft Word 2013 documents representing each of the six companies that took part in the interview. The collected data was analysed using thematic analysis. After review and data cleaning, all of the interview transcript files were imported into NVIVO 12 for coding and analysis. Each of the open-ended interview transcripts were read thoroughly to obtain an in-depth understanding of the contents for each interview. A line-by-line scan was then initiated to identify any significant themes that emerged from the data; these themes were noted tentatively in a memo while the reading continued. When there were no new relationships to establish, the interviews were read again. This time, the contents were coded based on the noted themes. 162 codes, 15 themes and 28 subthemes emerged from the interview data. All the themes that focused on similar constructs were grouped into four (4) main theme categories as they emerged from the data. The themes are discussed in section 4.3. Data saturation was determined when every bit of collected data had been successfully coded (including overlapping codes) and any further coding process returned similar results that had already been coded at the same points.

4.2. COMPANY CLASSIFICATION SUMMARY

A brief classification of the participating companies are given below based on findings from the preliminary questionnaire and interview coding process detailed in the previous section (4.1). The emergent themes from the interview are discussed in the next section (4.3).

4.2.1. COMPANY A - SMALL FIRM- VALVE INDUSTRY

Company A is a small valve firm that runs a bespoke service. The participant, a production manager, pointed out that there was no robust product development system in place at the firm but noted that they understood they would need structured methodologies to advance the designs required to break barrier into new market. In terms of Computational Fluid Dynamics (CFD) technology use, the firm still outsourced CFD work. The participant highlighted CFD's as a technical utility in improving design analysis. Some uses of CFD within this firm include determination of force, cavitation area and valve capacity. The Sales department at this company may also use CFD's visual presentations for communication with customers.

Company A	2	8
Attribute	Value	
Size	Small	
Industry	Valves	
Number of Employees	10 to 49	
Yearly Turnover	7-35 million	
Interview date	09/03/2015	
Registered with Professional Body	Yes	
Decision Making	Owner	
Organisational Style	Functional	
Strategy	Routine Specialisation	
Team Awareness	Yes	
Team Participation	Interested	
Technicality	Technically Moderate	
Customer base	Companies and Individuals	
Sales Function	Bespoke	
Product Strength	Differentiation	
Competitive Advantage	Brand Recognition/Supplier Contract	
Innovation Type	Incremental	
Customer Involvement in NPD	Yes - Start, Iterations	
Product Development Influencers	Management and Customers	
NPD method	None	
NPD review period	Yearly	
Team Responsible	Owner and Topmanagement	
Reason to Subcontract	Only to save time and improve quality	
Quality System Experience	High	
Quality Procedures Used	FMEA, Six Sigma, Non-comformance report, ISO 9001 certified	
CFD Package	ANSYS	
Decision to use CFD	At discretion by employee designer	
CFD Benefit awareness	Moderate	
Interest	Internal and External	

Figure 20 Classification Characteristics of Company A.

4.2.2. COMPANY B - SMALL FIRM – FAN INDUSTRY

Company B is a small firm in the fan industry that is involved in batch production of specific ranges of fan products. The participant, a product engineer, confirmed that there was a larger organizational focus on growing the range of their existing products on the production line to meet desired opportunities as they came. However, there was a challenge in keeping up with customer needs concerning old products the company (under previous management) had sold in the past prior to being acquired by the present owners. The user manuals for some of those old products were no longer available and the firm experienced some difficulty in finding better ways of obtaining information about the products' use and full functions. The firm hoped to use CFD as a means to discover some of this information from existing products and to help improve future design. This highlights the potential for CFD technology to be used for obtaining information about already developed/existing products to help in understanding product function or further development. As a maintenance tool, CFD could also be useful in discovering design areas prone to wear and tear, thereby helping to curb product failure.

Company B 2 8

Attribute	Value
Size	Small
Industry	Fan
Number of Employees	10 to 49
Yearly Turnover	Below 1.4 million
Interview date	13/06/2016
Registered with Professional Body	No
Decision Making	Owner
Organisational Style	Unsure
Strategy	Routine Specialisation
Team Awareness	No
Team Participation	Interested
Technicality	Technically Moderate
Customer base	Individuals Only
Sales Function	Generic
Product Strength	Speed
Competitive Advantage	Brand Recognition
Innovation Type	Incremental
Customer Involvement in NPD	Yes - Iterations
Product Development Influencers	Management and Customers
NPD method	None
NPD review period	Never
Team Responsible	Owner
Reason to Subcontract	Only to Utilise technical knowhow
Quality System Experience	Low
Quality Procedures Used	None (ISO 9001 in view)
CFD Package	ANSYS
Decision to use CFD	Brainstorming session
CFD Benefit awareness	Moderate
Interest	Internal and External

Figure 21 Classification Characteristics of Company B.

4.2.3. COMPANY C - MEDIUM FIRM – VALVE INDUSTRY

Company C is a bespoke service based medium valve firm that is also involved in batch production for generic sales. According to the Company participant, a design engineer, NPD here is focused largely on the involvement of the customer throughout the development process. However, management acceptance of CFD appears problematic and most of the work involving CFD that had to be done were carried out using external facilities.

Company C 2 8

Attribute	Value
Size	Medium
Industry	Valves
Number of Employees	50 to 250
Yearly Turnover	7-35 million
Interview date	05/08/2016
Registered with Professional Body	Yes
Decision Making	Top Management
Organisational Style	Functional
Strategy	Routine Specialisation
Team Awareness	Yes
Team Participation	Interested
Technicality	Technically Specific
Customer base	Companies and Individuals
Sales Function	Bespoke and Generic
Product Strength	Differentiation
Competitive Advantage	Substitute Product
Innovation Type	Incremental
Customer Involvement in NPD	Yes - Start, Design and Iterations
Product Development Influencers	Customers
NPD method	Stage Gate
NPD review period	Quarterly
Team Responsible	Top Management
Reason to Subcontract	-
Quality System Experience	High
Quality Procedures Used	FMEA, (ISO 9001 Certified)
CFD Package	ANSYS
Decision to use CFD	At discretion by employee designer
CFD Benefit awareness	Low
Interest	Internal: Improving structural process

Figure 22 Classification Characteristics of Company C.

4.2.4. COMPANY D - MEDIUM FIRM- FAN INDUSTRY

Company D is a medium fan firm specialising in Generic/Batch production. Following the data acquisition process, the participant, a top product manager, seemed to suggest that there was a lot of focus on testing at this firm. However, there was a keen interest in improving efficiency in the manufacturing process. The respondent affirmed that the firm does not use a robust NPD process but would occasionally use its sales records to study trends in the market in order to direct their focus on production. CFD technology was minimally used at this firm due to management belief that CFD results would mostly require validation with a physical test. However, the firm produces for the general market and would require a robust system at some point to best interpret customer needs and ensure consistency in the rate of innovation required to meet them. It would therefore be necessary for the firm to have a systematic product development process to follow-up on the discovery of customer needs and internal efficiency in meeting the requirements.

Company D 2 8

Attribute	Value
Size	Medium
Industry	Fan
Number of Employees	50 to 250
Yearly Turnover	7-35 million
Interview date	13/07/2015
Registered with Professional Body	Yes
Decision Making	Top Management
Organisational Style	Matrix
Strategy	Technology Oriented
Team Awareness	Yes
Team Participation	Interested
Technicality	Technically Diverse
Customer base	Companies Only
Sales Function	Generic
Product Strength	Differentiation/Speed
Competitive Advantage	Brand Recognition/Supplier Contract
Innovation Type	Incremental
Customer Involvement in NPD	No
Product Development Influencers	Management
NPD method	None
NPD review period	Weekly
Team Responsible	Concerned Staff
Reason to Subcontract	-
Quality System Experience	Low
Quality Procedures Used	None (ISO 9001 Certified)
CFD Package	SIMERICS
Decision to use CFD	Brainstorming session
CFD Benefit awareness	Low
Interest	Internal and External

Figure 23 Classification Characteristics of Company D.

4.2.5. COMPANY E - LARGE FIRM –VALVE INDUSTRY

Company E is a large valve firm with ample experience in valve production. Following the questionnaire response and interview session, the firm was discovered to practice both bespoke and batch production to meet demands from a wide range of industries. According to the participant, a New Product Development manager, a robust NPD staged process is used and customer needs are taken into consideration. However, CFD systems have not been purchased for full-time use internally. Instead, they resort to use of external CFD specialists. They attributed the reason behind this decision to the high cost of commercial CFD software licensing, as they do not handle many projects that require full-time CFD use. Therefore, affordability/accessibility of the technology relative to external demand for CFD analysis influences CFD adoption in this firm.

Company E

Attribute	Value
Size	Large
Industry	Valves
Number of Employees	50 to 250
Yearly Turnover	over 35 million
Interview date	24/07/2015
Registered with Professional Body	Yes
Decision Making	Top Management
Organisational Style	Functional
Strategy	Emergent, Flexible
Team Awareness	Yes
Team Participation	Passive
Technicality	Technically Moderate
Customer base	Companies and Individuals
Sales Function	Bespoke
Product Strength	Differentiation/Quality
Competitive Advantage	Brand Recognition
Innovation Type	Incremental
Customer Involvement in NPD	Yes - Start, Iterations
Product Development Influencers	Management, Team & Customers
NPD method	Stage Gate & VOC
NPD review period	Yearly
Team Responsible	Concerned Staff
Reason to Subcontract	Save time or improve quality
Quality System Experience	Medium
Quality Procedures Used	FMEA (ISO 9001 Certified)
CFD Package	ANSYS
Decision to use CFD	Brainstorming session
CFD Benefit awareness	Moderate
Interest	Internal and External

Figure 24 Classification Characteristics of Company E

4.2.6. COMPANY F - LARGE FIRM – FAN INDUSTRY

Company F is a large fan firm that develops products for the general market and carries out a lot of testing activities. Following responses from the company participant, a senior product manager, the firm was found to apply the Voice of the Customer (VOC) technique to aid discovery of customer needs. However, as the company is not into bespoke production, VOC is not used to generate metrics for each new product, but rather to obtain a general understanding of customer needs in the market. Though the employees were aware of their specific roles and functions within the organisation, compliance with the structures that exist (culture) was a challenge. To improve compliance with internal structures, the company created a group to monitor structure compliance and performance evaluation but these systems were not robustly instituted. Issues were discovered pertaining to managerial trust in CFD abilities as against the traditional testing methods the firm had grown accustomed to over the years. Therefore, a major technology management structure is a necessity for employee engagement and development at this firm.

Company F 2 8

Attribute	Value
Size	Large
Industry	Fan
Number of Employees	Over 250
Yearly Turnover	350 million
Interview date	13/07/2015
Registered with Professional Body	Yes
Decision Making	Top Management
Organisational Style	Functional
Strategy	Technology Oriented
Team Awareness	Yes
Team Participation	Passive
Technicality	Technically Specific
Customer base	Companies Only
Sales Function	Generic
Product Strength	Differentiation/Speed
Competitive Advantage	Brand Recognition
Innovation Type	Incremental
Customer Involvement in NPD	No - but VOC only
Product Development Influencers	Management
NPD method	VOC + Stage Gate and Spiral
NPD review period	Monthly
Team Responsible	Concerned Staff
Reason to Subcontract	Save time or improve quality
Quality System Experience	Low
Quality Procedures Used	None (ISO 9001 Certified)
CFD Package	ANSYS
Decision to use CFD	Brainstorming session
CFD Benefit awareness	Low
Interest	Internal and External

Figure 25 Classification Characteristics of Company F.

4.3. INTERVIEW THEMES

Following the coding process highlighted in section 4.1.2, the following themes emerged from the interview data.

The four main theme categories from the interview process are:

- Subsystems,
- Super systems,
- Methods
- CFD technology in Organizational use.

Each of these theme categories consist of themes and sub themes that emerged directly from the interviewee responses. A list of the main theme categories and emergent are outlined in Table 4.

Table 4 List of Themes

Name	**No. of Subthemes**	**Companies**	**Coded References**
Subsystems - Internal	**8**	**6**	**25**
Internal Collaboration	4	6	18
Internal Stakeholder Influence	2	3	4
Internal Strategy	2	1	2
Super systems - Externals	**7**	**5**	**38**
External Influence	2	5	10
External Strategy	2	3	6
External Support	3	3	22
Methods	**7**	**6**	**47**
NPD Influencers	4	5	20
NPD Structure	3	6	19
PD Structure	-	2	2
Quality	-	2	2
CFD Technology in Organizational Use	**6**	**5**	**52**
Ease of Access	-	4	6
Ease of Use	-	2	7
Expected Usefulness	2	2	7
Functional Usefulness	2	4	18
Technological Validation	2	3	14

As illustrated in Figure 26, each of the themes are defined alongside their implications to the organisational composition of the participating firms.

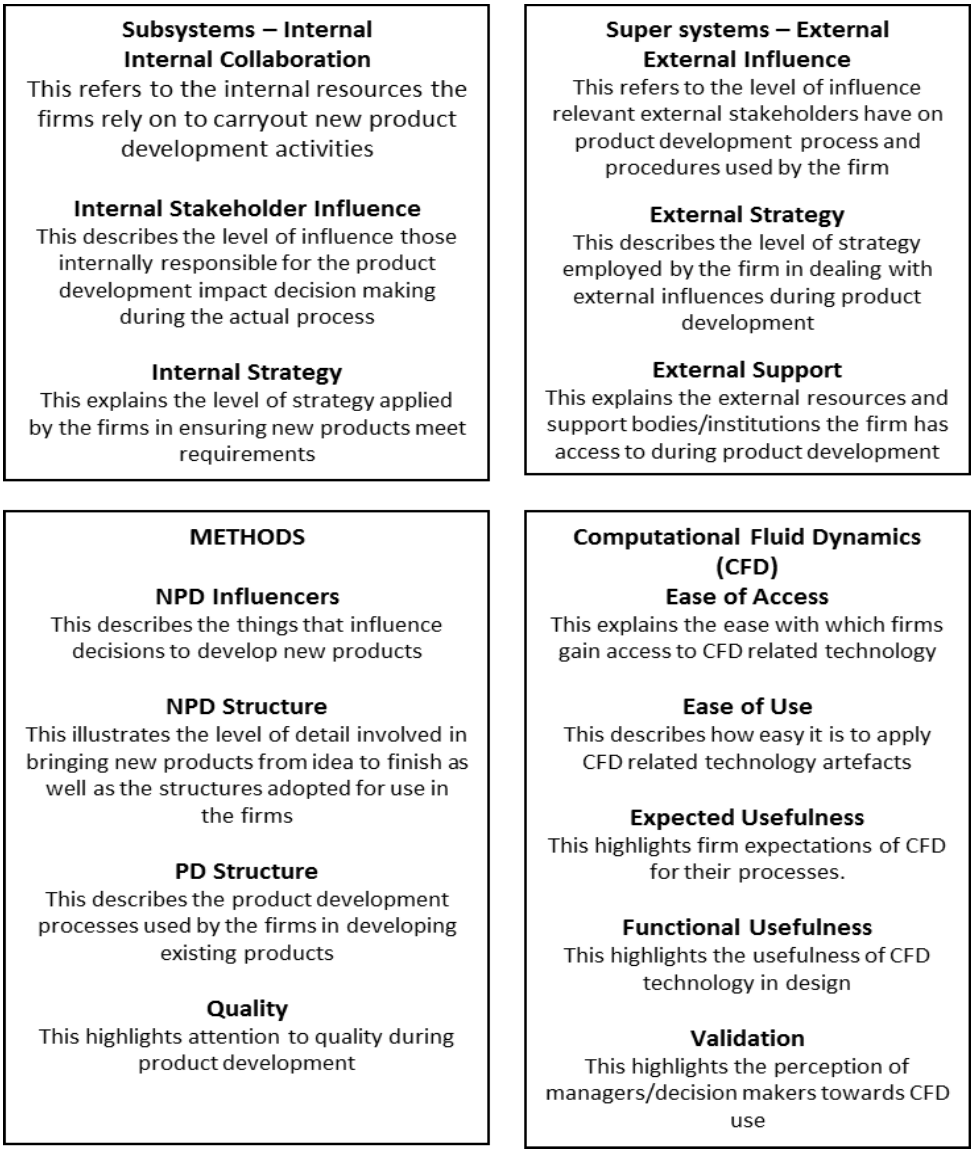


Figure 26 Theme description

Subsystems and **Super systems** themes both represent internal and external preparations made at the organisational level of the firms in order to answer **RQ1** of the research questions in this study.

The **Methods** theme presents an understanding of the methods applied as well as the processes used by the firms in the flow handling equipment industry to answer **RQ2** of the research questions in this study.

The **Computational Fluid Dynamics (CFD)** theme assesses CFD adoption in the flow handling equipment industry application and studies the prospects for integration to the NPD process. This is to answer **RQ3** of the research questions in this study.

A detailed analysis of the various themes illustrated above is given in the following sections.

4.4. ORGANISATIONAL SUBSYSTEMS - INTERNAL

This theme category focuses on providing insights into the ways flow handling equipment firms manage their internal (subsystem) resources for new product development to answer the first part of RQ1 in the expanded research questions detailed in section 4.1. Following a thematic data analysis, it was discovered that internal collaborative efforts, stakeholders and strategies were key determinants in how the firms managed their NPD processes internally. These findings emerged from the three themes that have been extracted from the data related to this theme category. They are thematically identified with their respective subthemes as detailed in Table 5:

Table 5 Organisational Subsystems - Internal Theme table

Themes **Sub-themes**	**Internal Collaboration**	**Internal Stakeholder Influence**	**Internal Strategy**
1	Brainstorming	Managers decision	Incremental Innovation
2	In-house Experienced Design Specialist	Owners decision	Radical Innovation
3	Internal Memos		
4	Training		

4.4.1. INTERNAL COLLABORATION

This theme is describes collaborative efforts made by firms to develop and retain knowledge resources necessary for product development practice. A review of the data identified four subthemes that emerged from the discussions on key internal knowledge resources the firms use to facilitate their product development process. They include Brainstorm, In-house experienced specialist, Internal Memos & Training.

- **Brainstorming**

Brainstorming activities emerged as a major source of knowledge generation in the firms especially as it relates to the new product development process. Three of the interviewees identified brainstorming sessions as an activity they would use for idea generation during product development. Company A interviewee, a production manager, explains how their brainstorming sessions are initiated.

> We'd start by having a design review meeting, we'd start to just brainstorm on a few of the conceptual designs that we could use. **(Company A).**

Apart from its use in ideation, Company C interviewee, a design engineer, highlighted its use in problem solving during testing operations.

> So if a product is not passing a particular test, we brainstorm, and contribute to sorting the problem **(Company C).**

Brainstorming could also be a valuable means for planning future projects. This is highlighted by Company E interviewee, an NPD manager:

> So we've run a blue sky thinking session last year, and a number of ideas came up about it and a couple of those are being put forward for an R&D project this year. **(Company E).**

Finding Implications: Internal collaboration for idea creation is a valuable technique applied by the firms in the flow handling equipment industry. It helps firms generate insights into problems that may develop during product development as well as how to manage them.

- **In-house Experienced Design Specialist**

In-house experience was highlighted as a useful source for knowledge generation by the respondents. Five of the interviewees identified having an internal design specialist or team that is knowledgeable about producing designs to meet expected product specifications.

> We'll give it to a designer to do some layouts, and work out some things generally. **(Company A)**
>
> If there's people that have the knowledge we would sit in into how the problem can be solved. **(Company C)**

As Company A interviewee highlighted above, design related product development hinges on inhouse capability to provide a concept drawing for product development. However, Company C interviewee highlights collaborative knowledge sharing among the experienced design specialists as a useful way to promote preparedness for product development.

Finding Implications: In house experienced design specialists possess knowledge that is essential to the product development process. Knowledge sharing activities may also help to increase robust solutions.

- **Internal Memos**

Two interviewees, a production manager at Company A and a top product manager at Company D, both identified various internal documents as internal knowledge resources they utilise during product development. They explained how these are used in practice.

> We've got our own design manuals, multiple design manuals that we've got. Those are backed up with certain excel spreadsheets, calculations, formulas and whatever we got on here. **(Company A)**
>
> Well, companies have sales records, all companies can investigate their sales records and from that they can see trends in the market. **(Company D)**

Finding Implications: Design manuals are especially useful as they provide guidance on design strategies and solutions. Sales records also help in determining customer reaction to previous products. Therefore, documented processes should be prioritized during NPD development.

- **Training**

One of the interviewees, the design manager from Company C, identified Training as one of the major internal resources for generating knowledge.

> Sometimes they train, and in these trainings they teach you how to mesh, teach you how to read the results, teach you how to get the images, they teach you how to use programming. **(Company C)**.

Finding Implications: Provision of training to users of CFD is essential to provide them with the skills necessary for product development.

4.4.2. INTERNAL STAKEHOLDER INFLUENCE

As identified by the interview participants, the Managers and owners emerged as the primary decision makers within the firms.

> The Owner makes all strategic decisions in the firm. If the product engineer comes up with new innovations and plans they have to be something because he's got to take current products off the production line, so they would have to convince the boss before it is done. **(Company B).**
>
> The owner is the director but the decisions to do with Engineering are taken by a senior team that sits in meetings to make the decisions on critical issues **(Company C).**

From the responses, the finding suggests owners are more likely to take business decisions while management teams manage decision making for specialised issues. This corroborates the finding from Zahra (2005) in literature section 2.1.5.

Finding Implications: Decision makers are mostly identified as either owners or managers and are mostly responsible for key decisions during the product development process. It is therefore imperative that decision maker perceptions are understood and taken into consideration when attempting to carry out product development processes.

4.4.3. INTERNAL STRATEGY

In examining the strategies used by the firms to ensure new products meet requirements, all of the interview participants identified using incremental strategies for product development.

> Yes incremental, not radical new product development. **(Company E)**

Finding Implications: The firms identified internal strategies as influential in determining how new product development is carried out. It is therefore expedient that product development methodologies are focused on the internal strategy of the firm.

4.5. ORGANISATIONAL SUPER SYSTEMS - EXTERNAL

This theme category refers to the external relationships and resources that companies encounter and interact with during new product development. It answers part 2 of RQ1 in the expanded research questions detailed in section 4.1. The theme category is divided into 3 emergent themes as detailed in table 6: External Influence, External Strategy and External Support.

Table 6 Organisational Super systems - External Theme table

Themes **Sub-themes**	**External Influence**	**External Strategy**	**External Support**
1	Customer Influence	Product Strength	External Knowledge
2	Standards Influence	Supplier	Industry Affiliation
3	-	-	Subcontractor

4.5.1. EXTERNAL INFLUENCE

As discovered from emerging data, the level of influence relevant external stakeholders have on product development processes is determined by the level of relationships that exist between the firm and the external systems. Two subthemes emerged from the interview: customer influence and standards influence.

- **Customer Influence**

Five of the six interview participants identify customers as vital influencers of their product development process. Their interactions with customers during the product development process seemed to be influenced by whether they operate a bespoke or batch production arrangement.

> The way the design process works is that we would get an inquiry into our sales department and it will either be: an existing product or an existing product that needs a slight modification, or a brand new product. **(Company A).**
>
> Well, usually customers request for a range amongst the Batch Produced Specs. So they would have a predefined range, size, capacities, say pressure, minimum volume movement and so on, and then they would choose from a range of products on the production line. **(Company B)**
>
> The customer is constantly involved from the initial order and still going back and forth. Even after you got the order documents, they are agreed upon by customer and firm, so there are initial discussions with the customer, based on what materials, what form, even up until the testing, the customer is involved, especially if the product is constantly failing in the test, there is constant interactions with the customer. **(Company C).**

From the above, it is evident that customer demand and/or requirements determine the kind of products that are likely to sell. For the Company C, the customers are involved in the process till testing. This suggests that changes may occur in the design and have to be accounted for prior to testing.

Finding Implications: Customer input during the process is prioritized to consider changes in design during the NPD process to meet dynamic customer needs.

- **Standards Influence**

In keeping to quality expectations, standards play a major role in industrial and regulatory authority acceptance of products and practices that are used or developed by the companies in the flow handling equipment industry. In monitoring and ensuring compliance, one of the interview respondents highlighted training as a key part of the activities they undertake to meet industrial standards.

> They do send people for valve training, different aspects of training. People have gone with respect to standards **(Company C).**

Finding Implications: It is therefore crucial for the product development process, that methods identify and maintain steady consonance with customer and standardized requirements.

4.5.2. EXTERNAL STRATEGY

Identifying the ways firms deal with the aforementioned external influences on product development is essential in order to obtain an understanding of the strategic priorities that would influence decision making within the organisational framework. The sub themes: Product Strength and Supplier emerged from the data.

- **Product Strength**

In terms of strategy, two respondents identified Product strength as an important factor that determines their strategic positioning. This, they described as being the bane of what differentiates them from the competition.

> You probably look at what's existing now, how big is it, how much does it weigh? Can we improve it, can we cut down on our cost, how can we sell it based on that, delivery, time, performance, looking at general things, the particular selling points of the valve, you know, long lifetime, etc, Is it certified for gas emissions? fire safe? It's the same product but we add additional benefits to it. **(Company C).**

> The intellectual property comes not in the nature of the description of the body but obviously the key machining, the design tolerances, the sizes, the internals of the valve in particular as that's where the intellectual property lies. Not in the fact we call our valve a globe valve or an angle valve, that's just standard. Its then how big we make the center module of the valve, where we put, what surface finish we apply to things etc etc. That's the intellectual property of the part of the valve. **(Company E).**

Finding Implications: It would therefore be important that the products from an NPD process meet all relevant stakeholder requirements effectively and products are effectively design-managed to include parts modification on a substantial level to increase the chances for innovative results.

- **Supplier**

Three participants confirmed that Suppliers were a major part of their product development external strategy. This they believe helps them achieve certain aspects of the product development that they cannot afford to do in-house.

> If it's something that's just made out of bar material or forged material, we generally just get the contract machine shop to buy it themselves and we just pay them one purchase order to supply that component, they'll buy the material and make it. **(Company A).**
>
> …however we are predominantly supply chain led. So we probably 85% of our components are purchased rather than manufactured in house… It keeps overhead cost down not necessarily speed up the production, tied down to lead times and shipping times for supply chain, we don't just use local supply chain, we use global supply chain. **(Company E).**

The responses above reveal that the firms have the option to choose to have individual parts manufactured in-house or buy them from a supplier.

Finding Implications**:** Suppliers are part of the NPD process design may experience changes depending on part availability.

4.5.3. EXTERNAL SUPPORT

Understanding affiliations and existing relationships companies have with external bodies explains the extent of the body of knowledge the firms have access to. Three of the six interviewees confirmed seeking external support when confronted with new product development challenges. The emergent subthemes from this theme include: External Knowledge Share, Industry Affiliation and Subcontractor relationship.

- **External Knowledge Share**

Two of the interviewees highlighted Collaborations with Universities as the primary external knowledge share affiliations they initiate.

> They might contact a university on an existing product, more or less find out what can be done or what can be improved and do it **(Company C).**

This does indicate that access to university facilities and research is a useful resource firms in the flow handling equipment industry could rely on for advancements in product development.

- **Industry Affiliation**

Two of the interviewees confirmed involvement with Industry affiliated groups. However, one participant stated that their involvement is based on keeping informed about industry dynamics.

> This business has a lot of moral defining that, we want to show off to our customers not our competitors. So for me, its just lets find out what the changes in industry are. **(Company E).**

This seems to suggest that the industry is highly competitive.

- **Subcontractor Relationship**

In one of the interviews, one of the external partners also contributed to the interview and explained that they provide insights into the NPD process internally but do not meet with the customers directly themselves.

> The KTP-rep is invited to a biweekly R&D review meeting and he sits in and listens to other programs.**(Company E).**

> Usually when we're deliberating on a project in a meeting, I am thinking we could do a simulation on this and I present the idea, but then it depends on what the team decides. **.....**No, I don't actually talk to customers, its on a minimum. They do the conversation with the customers. **(KTP-rep subcontractor at Company E)**

This finding reveals a trend in outsourcing CFD related activities the firms are unable to handle internally, the external resource may also collaborate in influencing decision making.

Finding Implications: Contributions from external sources help extend the knowledge base of the firm.

4.6. METHODS

This theme category presents the findings from the interview relating to methods used for New Product Development (NPD) activity in the flow handling equipment industry. It is intended to answer RQ2 of the research questions contained in section 4.1.

Four themes emerged as detailed in Table 7. They are: NPD Influencers, NPD Structure, Product Development (PD) Structure, and Quality.

Table 7 Methods Theme table

Themes Sub-themes	NPD Influencers	NPD Structure	PD Structure	Quality
1	Requirements Extraction	Modified Stage Gate	-	-
2	Research and Development	Structure NPD Process	-	-
3	Equipment	Unstructured NPD Process	-	-
4	Standards	-	-	-

4.6.1. NPD INFLUENCERS

This theme focuses on the factors in the flow handling equipment industry that influence new product development. Under this theme, four subthemes emerged from the study.

The Subthemes are:

- Requirements Extraction
- Research and Development
- Equipment
- Standards

- **REQUIREMENTS EXTRACTION**

This sub-theme details the ways firms obtain customer requirements. Requirements extraction is an integral part of any product development process. The methods and processes through which firms manage the extraction of customer/stakeholder requirements were found to vary by production style of the firm. i.e: bespoke or batch production. Using company profile information gathered from the survey, it was possible to assess how this affects the responses to the interview.

Company A, a bespoke business, receive direct specifications from the customer as communicated by the sales team.

> We would get an inquiry into our sales department and it will be, either an existing product or an existing product that needs a slight modification, or a brand new product. **(Company A)**

Company B seem to have a range of product parts, which they put together and produce for sale.

> So they would have a predefined range, size, capacities, say pressure, minimum volume movement and so on, and then they would choose from a range of products on the production line. **(Company B).**

In Company C, customer details are used in determining product specifications.

> From the mandate from the customer, and then going on to the specifications. **(Company C).**

In Company D, a batch production firm, the interviewee explains not carrying out any market survey but rather conducting an internal review of sales records**:**

> Now what would happen is, there wouldn't be anything that you'll call close to market survey, as the people feel that this would be a good product for the market then they develop it. And maybe it is or maybe it isn't. **(Company D).**
>
> Well, companies have sales records, all companies can investigate their sales records and from that they can see trends in the market. **(Company D).**

This seems to suggest that Company D is more keen on selling more of what they already produce. However, there is a potential for such existing products to be improved through product upgrades.

Finding Implications: From the above statements, all the firms consider customer needs prior to production. However, the way they go about obtaining that information varies. The bespoke oriented firms appear to obtain product specific information directly from the customer while the batch production firms focus on building innovation through market surveys or previous customer feedback. This then informs the basis of their product architecture.

- **RESEARCH AND DEVELOPMENT**

This sub-theme highlights Research & Development (R&D) as an important function for knowledge generation in the flow handling equipment industry. From the literature, it is evidenced that companies need to find ways to innovate in order to stay competitive (Atkinson, 2013; Gad, 2016). The findings from the data inquiry give an instance of how R&D processes are initiated for flow handling applications.

> R&D is done based on how important [the situation is]. It [R&D] is important… but they tend not to utilize rigid or robust NPD process, even not following it through even if it is simplified, it's not done. You see, for most of the companies…… …I think they take R&D as perhaps something which is not critical to their process, that's what I've seen in many of these companies. So R&D exists, its there, as a technical part of the company, now the R&D they practice is just continuous improvement of products that's already existing. In the case of New products the R&D is not robust enough and the end result is a failed product. **(Company C)**

This statement by Company C interviewee seems to suggest that the firm is actively producing products of the same kind and do not make radical shifts in innovation due to the lack of focus on robust research and development. It therefore implies that if firms are not looking for new information or likely to be interested in developing new products, they would likely not be interested in a new technology that offers same either.

> …locally our development is very very keen on intellectual property and development of new intellectual property, as such, we've got quite a lot of links through the universities and we have our own research hub, so we have an advanced research centre, and they dictate things to us like New product introduction strategies… **(Company E)**

Observing the interest Company E has shown in R&D, it is important that preparations are made to advance capacity to increase knowledge creation within the firms.

Finding Implications: Identifying useful avenues for generating the information and methods required to develop a new product is essential in ensuring the customer needs are met. A number of best practice systems and tools for new product development highlighted in the literature review section of this study may be useful in helping firms meet their NPD performance goals.

- **EQUIPMENT**

This sub-theme describes the need for use of relevant NPD tools and equipment to facilitate product development.

Company A interviewee expressed the company's interest in investing in new ways to improve the product development process including the enabling equipment that would encourage the workers to develop better products.

> So we're looking at getting our production methodology sorted out. And Equipment that would get these guys to get their work done a lot faster. **(Company A)**

This demonstrates interest in new methodologies that encourage freedom to use a varied range of tools and equipment.

Finding Implications: The necessary tools to aid new product development are required for improvement to product specification. Therefore, a new methodology that incorporates the freedom to apply different tools to the process is essential.

- **STANDARDS**

This sub-theme specifies the importance of standards in the design of an NPD process. The following statements explain how standards are used to contribute to NPD knowledge in some of the firms.

COMPANY A interviewee, in describing how the design engineer would use standards in practice, says:

> He would have any particular international standards that we need to comply with then available, then he would... maybe, it may tell you what the wall sections got to be, it may tell you different things about what the hand wheel size should be or whatever. They have those standards…**(Company A)**

COMPANY E interviewee in describing how standards relate to a product design says:

> So there's a lot of standards to determine the length of the body so, we can make it look physically different so that it fits in an envelope shape. **(Company E)**
>
> That's basically the process, you've got to fit into design standards. **(Company E)**

Finding Implications: The ability of firms to meet required industrial standards is an essential part of new product development.

4.6.2. NPD STRUCTURE

This theme details the NPD processes and structure used by firms in the flow handling equipment industry. Most of the firms mentioned that they do not have a structured process for managing new products. While some of them used Stage Gate process, they have modified most of its functions.

- **MODIFIED STAGE GATE**

This sub-theme explains the staged processes utilised by firms in the flow handling equipment industry and describes how they have been modified or applied to product development activities. **Company E** interviewee in describing the product development structure at the firm comments on a method they use which is similar to the stage gate process:

> So the [Parent company] have developed a process that loosely follows well… very similar to the Stage Gate product introduction innovation processes which is, you know, from a discovery through to launch, through the six phases….six?…five or six phases with a gate between each stage. Which we finally do a kill-hold-recycle and a review but through the key stakeholders of the project. The key stakeholders would normally not include our customer, apart from at the discovery phase, or the initial scoping phase, so the discovery scoping, feasibility etcetera etcetera would go through. So we would probably discuss with our customer on what we're proposing to do before we move on to the other stages. Not all processes are run through the NPD programme. **(Company E).**

Company C interviewee also highlights that they use Stage gate, and gives a detailed description of how it is used.

> I think we use stage gate. That is how the process works with the company. From the mandate of the customer, and then going on to the specifications, then the initial review, what the product is required to do, what is required, the resources etc. then from there on to conceptual design, then after that, then also you go to the next stage where they report on the progress of what really has been completed in reference to what goals that were set in the first meeting and then going forward till you get to the actual model of the product. **(Company C)'**

However, Company C interviewee also highlighted that the Staged process is mostly simplified depending on availability of resources.

> If you're going to follow the actual process as you maybe understand, if you want to follow every step of it, it seems to take away… time, e t c in implementation, it's very difficult for the whole process and the resources to actually carry that forward. You find that it's actually modified! Not to encompass the whole Stages. It is just tailor made to suit…. to fit the resources they have and it's simplified basically. **(Company C).**

Finding Implications: The firms practice modified versions of stage gate.

- **STRUCTURED AND UNSTRUCTURED PROCESSES**

This sub-theme describes how structure is implemented in NPD projects within the interviewed firms.

Company A interviewee mentioned that it is difficult to develop a standard structure as a bespoke service business.

> We've got so many variations and different industries that we deal with and different types of product that its very difficult to get a standard way of working. **(Company A)**

In describing the way the designer handles NPD projects, Company A respondent also says:

> If it's a brand new design, there is no set way that we do a brand new design, sometimes it would be a case of, here's a valve design, it would go in there, the guy in there might get it and he would say, well we want a valve of a certain size and we've never done. Then perhaps he would start to do a layout drawing in CAD of the valve."

In Company A interviewee's statement above, the approach to product development appears to be informal and reliant on prior experience of the product concept or design. However there is no structured way of handling a new product development at this firm. This is possibly because of the variations in designs that they encounter as a bespoke business.

Company D interview participant highlights that there is currently no structured process for customer requirements extraction at the firm.

> They are obviously talking to customers and asking the customers what they want. But there is no, let's just say, there is no… structured process of extracting information from those conversations. So it tends to be someone would talk to the customer then they would say this is a good idea, rather than any sort of structured process **(Company D)**

However, regarding product development implementation after idea generation, **Company D** interviewee highlighted some structure was beginning to develop around implementation:

> People have different responsibilities and we are becoming more structured in the development process here. **(Company D)**

At company F, an attempt to manage a structured process for project implementation was not fully suitable to the cultural inclinations of the organisational process as highlighted by the interviewee.

> They had a steering group to oversee the process, but I wouldn't say they were very much involved in the process. Tended to be a Talk Shop. **(Company F)**

This may be evident of the firm's adoption of new processes that were not compatible with the internal culture at the firm.

However, for both companies D and F, there was mention of having some structure when it came to development of New Products. This indicates that the companies aspire to possess some structured framework for managing NPD related activities. However, the firms would prefer one that is optimised for peculiar nature of the culture in which the firms function.

In applying structured methods, **Company F** respondent explains the importance of time scale in executing NPD techniques or processes:

> "…We are supposed to use Voice of the Customer, but to me, it came across as a very clunky process. It normally takes 6 months to a year to come up with an answer. One of the problems in product development is people forget the impact of time scale, it's sort of acute management. If you gave someone something with a time scale of 6 months, the process would be very slow. If you gave people steps with it, with short timescales, you tend to get faster progress and you tend to see the progress, and a lot of companies fall into the trap of giving someone a 6-month development project with a 6 month target and so on. So one of the things you need to do is chop down the horizons (time) of your process. And that, as I have seen, is a big problem. **(Company F).**

As Company F interviewee mentioned above, time can be saved using a structured process. However, the interviewee suggests that these should be prioritized to take the steps involved in the process into account. This demonstrates therefore, the efficacy of structured processes that detail the steps involved in completing the project.

Finding Implications: Detailed steps for the product development process in an organisational framework could be provided to aid organisation wide application of structural framework.

4.6.4. PD STRUCTURE

This theme captures information about the ways firms go about reproducing existing products. Two respondents described their product development structure as follows:

> If it's an existing product, the sales order will be etched onto our MRP system and that would already have all the information necessary to manufacture. It wouldn't go into the technical department, it would go straight to production control and planning and they would just make it. **(Company A)**

> The wider organisation has another [process] loosely attributed to that setup of stage gate for product development rather than new product development. So we use NPD when we're developing new products while we use a slightly bastardised programme when we're doing development to existing products..... They would follow some kind of review of certain points and there would be things done that are done as part of the NPD process, like FMEAs, like Process Flow Control Charts would be done, but not in a structured manner with kills and holds through various circles, its just managing it internally of our business. **(Company E)**

It can be inferred from the above that the firms feel a lot more confident reproducing already existing products compared to venturing into unknown territory with the design of a novel product.

Finding Implications: The firms seem confident about current product development techniques. The aim therefore, would be to assemble a methodology that bears a semblance to product life cycles they are conversant with.

4.6.5. QUALITY

This theme describes attempts made by flow handling equipment firms to achieve quality in their NPD processes. In evaluating Quality techniques used by the firms to ensure customer needs, sustainability and standards are met, the following responses emerged from the interview.

> I think pretty much based on ISO 9000. Which is what you have to really follow through quality wise. You know, you have your inspection, foreign goods coming in. Internally, they are inspected if they are being machined outside, and also when you're designing the components of a product, we have a check-in process, where the field people actually check the drawings to determine where it is derived from the initial concept. Obviously following on the quality processes, and checking the products, checking testing procedures in effect, which actually entail the development methods, hoping that they would comply to standard test specifications. They have their own procedures which are set to certify that the product comes out with the highest quality, pretty much in line with ISO 9000. Quality. **(Company C)**
>
> So where the project or the customer requirements vary, we would look to use best cost sourcing in our strategy which could be not just low cost it could be achieving the best cost at the best level of quality for that cost. It's a balance between quality and components, speed and price. (**Company E)**

Finding Implications: Requirements optimization is essential and can be prioritised by balancing design contradictions with respect to quality, speed and cost.

4.7. CFD TECHNOLOGICAL THEMES

This theme category focuses on the themes that emerged from the interview process as it relates to technology adoption of CFD in flow handling equipment industry and answers RQ3 of the research questions contained in section 4.1 of this study. The technology acceptance model from section 3.5 is also utilised in detecting emerging themes from the research data that are similar to the TAM constructs. Following thematic coding of the interview data, five themes relating to CFD Technology in Organizational use, emerged as illustrated in Table 8. They are: CFD Ease of Access, Ease of Use, Expected Usefulness, Functional Usefulness and Validation.

Table 8 CFD Technological Themes Theme table

Themes Sub-themes	**CFD Ease of Access**	**CFD Ease of Use**	**CFD Expected Usefulness**	**CFD Functional Usefulness**	**CFD Validation**
1	-		Benefit Expectation	Function in design process	Cultural Acceptance
2	-		Functional Expectation	Technological Functionality	Personal Perception

The following sections highlight the themes and their implications to the study.

4.7.1. CFD EASE OF ACCESS

This theme describes the perceptions of the interviewees regarding access to CFD related technology within their respective companies. Four (4) of the six (6) companies gave detailed responses to questions bordering on 'Ease of access' to CFD technology in the Flow Handling Equipment Industry.

Company C interviewee, a design Engineer, noted that while CFD was a tool of personal interest, the company management never purchased any CFD related software or license for internal use. The typical management decision was to subcontract any activities relating to CFD analysis to specialists who already have access to the technology. Company C interviewee articulates this point with the following response:

> They don't use CFD at all, by this I mean, We don't do it full on. I mean, I have done work for them using CFD, but they don't have software packages. It was having to come in the university to use it". **(Company C).**

This tends to suggest, that at Company C, there is no access to CFD software internally, but the technology could still be used if accessed externally through partnership institutions.

Company C interviewee went further to suggest that the possible reason for this situation may be due to management miseducation or the lack of it on the utility of CFD, then goes on to add:

> "They may be looking at the person that they would need to keep it [CFD] running. Does he need to be highly skilled that they need to be paid £80 to 100k a year? but if not really, then they need the basic understanding, a map or procedure of checking Validation. How do you validate it? Physics? How close am I? What are the benefits? They are huge. The cost is amazing, the cost in prototyping. I have not seen [CFD do] anything that it wasn't meant to do [and achieve] first time" **(Company C).**

Company D interviewee, a top product manager, was of the impression that CFD has not yet had the opportunity of becoming a key part of the company as they engage in robust testing activities. In terms of the number of people using it in the Company, Company D interviewee had this to say:

> Here we have just one person working on CFD, just one. We have quite a rapid way of testing our products. So we… our problem has been that CFD has been happening at the same time as testing and it takes just as long. **(Company D)**

Company E interviewee, a new product development manager, also commented on the fact that they do not own CFD Licenses anymore. This was attributed to the perception that it was not a cost effective option as it was rarely ever used internally but they were comfortable paying a subcontractor or institution such as a University (if they absolutely required it) to do it on their behalf. Company E interviewee had this to say:

> We actually don't have CFD license here anymore. We got rid of it about 4 years ago. That was probably more to do with the cost of the license: the fact that we were not using it. But also in 2011, we started quite an in-depth collaboration with the University. We did a knowledge transfer partnership then and we've obviously got another one now [pointing to the Knowledge Transfer partnership representative by the side], so most of our work is several, what's the point in paying for a license? Now we have this collaboration with the University so we don't have in-house CFD capability. There are people for example like myself who can use it [CFD] but we just don't. I employ KTP-rep [Knowledge Transfer Partnership representative] and he uses it". **(Company E).**

Summarily, it can be inferred from the responses that most of the managers thought CFD was either inaccessible or not worth the cost for internal use. This assertion is based mostly on the findings that suggest most firms prefer to get help from institutions where CFD may be required. Alternatively, they may simply choose not to carry out projects that require them to rely on the use of CFD.

Company E interviewee continues:

> CFD costs a lot of money, unless you're using open source software, which we are not. And licenses for CFD are across the region of £25,000 a year for businesses and for a company that's had zero use…. Half the problem with CFD is, its changed significantly within the last 5 years and the only people that really get the benefit out of keeping up with those changes are research organizations, particularly universities. Companies get no benefit from CFD if they don't update software or keep with the times on what's going on. Much like the 1990s, where you had to work in 1993 with a 386 processor and now we're talking gigahertz, not bytes. Its completely different than [a CPU] processing speed change. Virtually, you've bought a computer and six months later it was out of date, that's the case with CFD. Now we are not keeping up to date enough, we are not doing a lot of work on CFD, which is why I continually recommend to my department team that we do not invest in CFD. The standpoint this industry has is when required to use CFD we will outsource that work, because in order to use it, we have to buy licenses we have to buy machines that are capable of running the simulations, an expensive outlet for something that may have significant value when its needed. But like I said whatever our development has been on, where it has been on new product development, has been on developing much of the same, because that's what we already do, so changing the valve to an angle valve or a new shape of body for an angle valve, surge valve, there's no change in actual valve performance. **(Company E).**

While none of the interviewees criticize the utility of CFD, the dispute seems to centre on internal access to CFD which according to some of the respondents, places huge demands on their resources. This perception is relative; based on the needs of each company and what priorities they have set as a business. Company C, D and E interviewees have claimed they used the product at some point but that they outsourced the resources for its use. It is important that if CFD must be used effectively, the flexibility that allows organisation decision makers and designers to decide and understand parts during the product development process that require CFD analysis is essential.

Finding Implication*:* Accessibility of CFD technology is a key construct to its adoptability

4.7.2. CFD EASE OF USE

Another theme that emerged from the process based on CFD, was Ease of use. This theme matches one of the constructs of the Technology acceptance model highlighted in section 3.5 of this study. In assessing the Ease of CFD technology use by Industry professionals, the interview participants describe their perceptions as well as possible motivation or demotivation towards the technology's use.

During the interview, the **Company C** interviewee was asked if the cost of the software contributed to the poor adoption across the industry to which he responded:

> There is Open foam but even Open foam is not user friendly. The biggest challenge to CFD implementation is convincing the top people of the result. **(Company C).**

The interviewee also shared his experiences using CFD software:

> Yes, the ANSYS Design Modeller doesn't handle complex geometries very well as compared to SOLIDWORKS for instance. **(Company C).**

COMPANY F interviewee is quoted as saying:

> "….you then have the problem that the management team needs a knowledge of CFD. So you need to spread it into the company. So the problem is that as the experts are called experts, people are producing reports that most people don't understand…" **(Company F).**

A common trend in codes that seem to have emerged from interviewee responses so far are: "*management team needs a knowledge of CFD*" and "*Convincing the top people*". This recurring ideology seems to suggest that another constraint is driving the application of CFD apart from the aforementioned *'Ease of Access' that solely emerged from the interview data* and the *'Ease of Use' construct* that is cross referenced in the Technology Acceptance Model. It seems to suggest that implementation is influenced by Management perception. In this case, it may be that the Managers at these firms have not received adequate attention from the CFD community on the utility of CFD related work, or the managers themselves have no interest in CFD.

In the next section, attempts are made to uncover possible reasons behind the managerial stance on issues concerning CFD application. Sub-themes focused on 'Expected Usefulness' are drawn out of the collected data to inform the research of any specific 'benefits expected' from the use of CFD technology as well as its 'expected functionality', both of which may also be seen in managerial terms rather than entirely technical. As found in the literature, benefits such as "a practicable means to save time and cost" may appeal more to a manager/owner if such function is demonstrated to help generate sales and cut time to market as opposed to being told it helps makes the Engineer's job easier. In other words, what can CFD do for them that they cannot already do for themselves? What makes CFD standout? In addition, what could be a possible reason for their refusal to utilize something that may improve their productivity? The next extracted theme throws more light on this area.

Finding Implication*:* Ease of Use is a key construct to CFD adoptability

4.7.3. CFD EXPECTED USEFULNESS

It is important to note that perhaps the company managers do not need to have an expectation before they decide whether to adopt CFD technology, it could be a case of them never having a meeting to discuss it and so the knowledge of it has not been communicated in a way the managers prefer. However, obtaining more views on expectations would help measure the logic of its influence and help gauge the ways managers may prefer to come to the knowledge/awareness or acceptance/rejection of it.

Another point to note is, the current ways firms utilize the advantages of CFD through subcontracting may give the impression that the expertise or technical know-how required to completely utilize it in-house may be short in supply or expensive to accomplish.

For all of these notions, CFD may seem like a classic case of being handed a great tool in the wrong environment. Firm managers therefore need to see the immediate need for the technology in their current situation to adopt it.

Two sub-themes emerged from the data, assessing the level of expectations for CFD use: **CFD Benefit Expectation** and **CFD Functional Expectations**.

- **CFD BENEFIT EXPECTATIONS**

It was identified from the interviews that the firms in the study wanted to see the advantages of CFD as it affects the productivity of the engineering team but ultimately an expectation of a correspondingly appreciable yield in sales as well as better designs that could translate into more sales.

Company A interviewee, a production manager, pointed out that the sales department have identified a use for the figures that are generated from CFD software. This would seem to be a top manager's priority as identified earlier in the decision making section of the literature review.

> From the sales point of view, the marketing point of view, they want us to be able to come up with a way of quickly generating sales and marketing information for the customer that looks impressive quickly and automatically. **(Company A).**

Company D then adds:

> Improving the efficiency of the designs is what we are looking at right now. In addition, we are looking for manufacturing processes, which impact on the designs. **(Company D).**

On one hand, it may appear that the benefits could be achieved using technology. However, the managers may take process complexity from the integration of new technology, as a negative and as such, the manufacturing processes they need may be simpler but effective ways of accomplishing tasks. This raises the question, what current functions of CFD do firm managers find useful? But first, what functional expectations of CFD for it to be considered useful?

- **CFD FUNCTIONAL EXPECTATIONS**

Company A interviewee would like to see CFD technology embedded in the design phase of product development. Specifically, as part of an automated process where CFD is tied in as an analysis utility tool during design. This, he believes, would help the firm obtain information that could aid design changes.

> But what we want is to integrate CFD into the design process so that as you're doing your models in say SOLIWORKS or whatever, it automatically does the analysis for you but also automating what's the information that comes out. **(Company A).**

Company D interviewee also focused on the ability of CFD to influence technological design paths.

> Improving the efficiency of the designs is what we are looking at right now. And in addition to that we are looking at manufacturing processes which impact on the designs. **(Company D).**

While the above interviewees desire functional capability upgrades, the other interviewees seem to focus more on the importance of managerial perception when it comes to prospects of CFD use in their firms. This may be as a result of organisational culture dynamics as highlighted in the literature.

Finding Implications: Management Perception should be taken into account in NPD.

4.7.4. CFD FUNCTIONAL USEFULNESS

This theme describes the perceived usefulness of CFD technology, which matches the *Perceived usefulness* construct highlighted in the Technology Acceptance Model as illustrated in section 3.5 of this study. The following emergent themes were discovered: CFD *Function in design process* and *Technological functionality*.

- **CFD FUNCTION IN DESIGN PROCESS**

In analysing the functions of CFD within the companies, the following statements were given describing how CFD has been applied:

> At the moment, we design the provisional valve design and then we run a CFD analysis on the valve. And then with the results of the CFD analysis, we modify the design, so it is in a loop but it's not automated…**(Company A)**

> …We then look at it and then we run in parallel: maybe some CFD, maybe some FEA, in parallel with the manual calculations, so it's a bit bitty, its not really structured together.. **(Company A).**

The varied uses of CFD for New Product Development very well attests to the need for this project, as firms would likely benefit from a structured process.

***Finding Implications*:**, Systems could benefit from automation in future work.

- **TECHNOLOGICAL FUNCTIONALITY OF CFD**

An observation of current CFD practices may help to provide an understanding of the technological functionality of the present CFD technology. The interviewees identified CFD functionality at various capacities.

> Concerning CFD, I have not seen any failure to the work I have done using CFD. **(Company C**)

> There are things that you literarily can not test but that you can check in CFD, because in CFD you can make geometry change with the exact value within a millimetre you can do a geometry change in CFD and you can look at the effect as well of that 1mm change. You can't do that in testing**. (Company F)**

Finding Implications: From the above it can be seen that there are advantages to adopting CFD for New product development.

4.7.5. CFD TECHNOLOGICAL VALIDATION

This theme develops an assessment of how CFD technology is valued by decision makers for implementation. As highlighted in previous themes, CFD adoption may be subject to managerial validation of the technology. In order to build an understanding of managerial acceptance, it is important to understand how the managerial culture of CFD technology adoption is perceived in industry.

- **CULTURAL ACCEPTANCE AND PERSONAL PERCEPTION**

These themes are analysed concomitantly as they both provide insight into cultural perception and its effect on CFD technological validation and adoption. All of the interviewees appeared to understand the importance of CFD.

> CFD is certainly valid. **(Company C).**

> CFD as a design tool is quite good looking at changes, but even then you have to put constraints on it. **(Company D).**

Emerging themes from the interview indicate that the firm decision makers had problems adapting to a different way of doing things than they had known for years.

However, they cautioned that their personal acceptance of CFD is not indicative of a company wide acceptance.

When asked about the organizational inclination towards future CFD use, **Company A** interviewee had this to say:

> So we obviously would like to…not obviously on every design, because some designs are not that complex…. but we would like to get CFD built into the process. **(Company A)**

Company C interviewee mentioned:

> If I would be honest, in Yorkshire, most companies …Some valve companies… are on board with CFD. It's not that the people in charge would not sit and say we are going to outsource for CFD, they do not appreciate it to understand the need to implement CFD…. The biggest challenge to CFD implementation is convincing the top people of the result…… Again, I think the problem is appreciation, the directors would say they don't really need it so they don't use it, so they are just not interested and they aren't the only ones. Plenty. The culture is responsible" **(Company C).**

Company F interviewee also said:

> "…But you then have the problem that the management team needs knowledge of CFD. So you need to spread it into the company. So the problem is that as the experts are called experts, people are producing reports that most people don't understand".
>
> *"…At Company F, there is a big issue with management belief in CFD. The senior engineering managers had come through to the point that Company F traded itself on testing everything. And Company F would say they tested things properly whereas every other person or company didn't test them properly and so on. So there was also that going on as well and also a culture of testing internally at Company F. Although, they have not tested anything from about 20 years, management have spent a lot of their career when all the testing was happening. They also didn't believe, didn't trust CFD too much…"* **(Company F).**

Finding Implications: The Cultural inclination of the decision makers has been highlighted throughout this section as one of the major influences that decide if firms would eventually adopt CFD technology.

4.8. SUMMARY OF FINDINGS

The fundamental findings based on the four central themes that emerged from the interview answer the 3 research questions and meet objectives 1-3 of Main Contribution 1 which was to:

Main Contribution 1: **Develop a novel assessment of Flow Handling Equipment Industry enterprise preparedness for Computational Fluid Dynamics integration to the New Product Development Process.**

Organisational Subsystems – Internal Summary Discussion

Objective 1: *Outline useful internal and external organisational knowledge resources for New Product Development in flow handling equipment industry.*

- ***RQ 1: How do firms in flow handling equipment industry organize their resources and processes for New Product Development?***

How are firms managing their Sub System (Internal) resources for NPD? (part 1)

It was discovered from this theme category that the firms managed their internal resources for new product development by collaborating with knowledgeable personnel within the firms to generate ideas and manage the new product development design process. When compared to organisation findings from literature, it was discovered that the firms that had owners making the decisions focused on profit and took sole decisions while those that used senior managerial team would collaborate to reach a decision. Also highlighted in literature, the choice of strategies influence the ways firms prepare for new product development. Following the emergence of the Internal Strategy theme from the collected data, the firms are influenced by incremental innovation, which does suggest as reflected in the body of literature that they react to external market competition. The next theme category explains how the firms manage external resources.

Organisational Super Systems – External Summary Discussion

- ***RQ 1: How do firms in flow handling equipment industry organize their resources and processes for New Product Development?***

How are firms managing their Supersystem (External) resources for NPD? (part 2)

Findings from this theme category revealed that external influence from customers specifically decide how well the products would do in sales. One of the respondents, from Company C, highlighted the fact that the customer can be involved throughout the process until testing. This suggests that the customer may still choose to make changes to the requirements after commencement of the new product development process. Similarly, Standards were considered during product development. Firms were also poised to tackle competitive challenges by putting forward their best product to meet stakeholder requirements and excite the customer. Supplier relationship also influence how parts may change during the process due to availability or delays.

In terms of external support, a lot of firms had access to external support. The major source for external support that emerged from the interview were Universities, Industry affiliation and subcontractor relationships. The input from the design engineer at company C seemed to suggest that as a subcontractor they can collobarate with other firms on a project. Specifically CFD was being outsourced to other firms.

Methods Summary Discussion

Objective 2: *Outline NPD methods and tools used in practice by firms in flow handling equipment industry for New Product Development.*

- ***RQ 2: What New Product Development methodologies are preferred by firms in the flow handling equipment industry?***

How are firms structuring their NPD methods?
What Best Practice NPD methods/techniques are firms in the Flow Handling equipment Industry influenced by?

Based on the findings from this theme category, it was discovered that customer requirements, research and development, equipment and standards were some of the essential factors that influence NPD among the interviewed firms. As highlighted earlier in the literature, a number of tools exist which may be useful for ascertaining customer hidden needs such as KANO model and QFD. When applied to firms that do not receive bespoke product specifications directly from the customer but have to rely on market metrics, these tools could be useful for accelerating customer need optimization and standards. However it was discovered that the firms admitted to not being structured for NPD activities. A look at some of the best practices applied in industry revealed that most of the firms used Stage Gate or a closely similar method. The challenge was that the staged process they had modified for use were not designed specifically in line with the product lifecycle of product concepts using CFD implementation. Furthermore. the firms that did not invest in new processes appeared to just focus on the re-development of already existing products. Quality expectations in the flow handling equipment industry as noted in literature also emerged during the interview. It therefore became necessary for a new methodology utilising a structured process to be developed for flow handling equipment industry use. An understanding of CFD adoption prospects in the industry would help integrate the technology to the process.

CFD Summary Discussion

- **RQ 3: How do firms in the flow handling equipment industry react to CFD technology during the NPD process?**

What criteria determines CFD technology adoption in practice?

What are the inherent benefits/challenges of using the CFD Technology in practice?

Following the Technology acceptance model highlighted in section 3 .5 of this study, the themes that emerged from the interview data included the two constructs of CFD *ease of use* and CFD *usefulness*. In terms of Ease of Use, the interviewees commented that the firms believe the user codes are too complex for non-technical expert use and therefore not user friendly enough. In terms of the usefulness of CFD technology, the designers identified its function and validity in practice. However, two new criteria for assessing CFD technology adoption emerged from the process: *Cultural Acceptance'* and '*Access*ibility' coined from the emergent themes 'CFD validation' and 'CFD Ease of access' respectively. Findings from the inquiry revealed that while CFD was a tool of interest to designers, management decision making usually involved subcontracting CFD related activities to external bodies to carry out the analysis on their behalf. There are many reasons why this may have been the case. However, one of such reasons that stood out were the high running costs of the commercial CFD codes as well as the cultural perception of management decision makers who relied on older test methods and appeared unsure of the viability of new CFD technology. Understanding what aspects of the new product development process requires CFD technology is essential. One of such was discovered in the sub-theme "*technological functionality of CFD*" where CFD could be applied in the virtual testing of products that are not viable using physical tests. Managers also seek ways that CFD could translate into more sales and profits for the company. One of the firms confirmed using the technology for promoting sales through the provision of quick analysis results and diagrams. However, the challenges for CFD use as highlighted in literature are evidenced in the sub-theme, 'functional expectation', where there is an expectation for the technology to make assumptions that were not within the purview of its current advancement. In the Cultural Validation theme, CFD technology was identified as valid method and in evaluating changes but that required guidance to place appropriate constraints. One of the companies also explained that they would like to get CFD built into some of their design processes. As it was highlighted in the methods summary that a new methodology became necessary for flow handling equipment industry, a CFD integrated methodology would be essential for bringing the advantages of the technology to the product development process.

4.9. IMPLICATION OF FINDINGS FOR NEW METHODOLOGY CREATION

The following points have been extracted from this thematic analysis to for the creation of a new methodology.

SUBSYSTEMS: The new system would be expected to encourage collaborative work by promoting knowledge sharing. It would also be expected to provide a procedural process structure with steps and a method for navigating through the process. Decision makers should then be able to use the methodology in monitoring compliance with objectives and increase potential for radical innovation. The resources as obtained from the themes include: Brainstorming, In-house specialists, Internal memos and Standards.

SUPER SYSTEMS: The new system would also be expected to prioritise product strength through ensuring customer requirements and feedback at various stages in the product's early development are met. This implies that the system must be dynamic to accept design changes in specifications from changes in customer requirements. Therefore, the new methodology would consider standards and relevant stakeholders' requirements as well as how they can be met. The process would involve dynamic capabilities to support supplier input i.e supply of alternative parts based on availability and provide opportunities for design collaboration.

METHODS: A resource group of useful tools and techniques would be required to help decision makers and product developers make informed decisions to combat design contradictions. This group would be open to inclusion of new tools and processes that implementing firms believe would aid product development (for the purposes of this research the tools and techniques from literature such as TRIZ, QFD, and others would be useful as additional resources).. Structure with detailed steps to product development that would save time would also be beneficial to meet agreed requirements. The method would be scalable such that irrespective of company size or production method (bespoke or batch production), the new method would allow the firms to initiate NPD activities. This can be achieved if they can apply the new methodology process to their own new product development life cycles that the firms are conversant with (for purposes of this research an optimised product life cycle would be useful).

CFD TECHNOLOGY USE: In the new methodology, product design concepts would typically undergo CFD simulation tests before physical prototyping. This will ensure the number of physical testing activities are kept to a minimum. This process would also be useful in prioritising strategic product strength using CFD simulations This would ensure a cheaper and faster way of trying new designs for radical innovation and checking for product defects which would ultimately improve organisational ability to break into new market with innovatively optimised products. Product concepts can then be continuously digitally modified until CFD produces a result that can be put through physical testing for validation. Where cultural barrier to CFD implementation may exist, the new method would be made iterative. This is in order to allow for external collaboration in cases where CFD related work has been subcontracted. Simultaneously, decision makers can still choose to use conventional physical testing methods and compare with or validate CFD results later on.

4.10. CFD-OPTIMIZED TECHNOLOGY ACCEPTANCE MODEL

As highlighted in the description of the Technology Acceptance Model in section 3.5, certain constructs that contribute to the adoption of technology are usually based on *Usefulness of the technology* and *Ease of Use*. However, it was discovered from the interview analysis that two more phenomena were useful in providing insight into the adoptability of CFD technology. These two phenomena were identified as '*Accessibility for use*' and '*Cultural Validation*'. Therefore this research presents a CFD-optimised technology acceptance model for evaluating how firms in the flow handling equipment industry react to the adoption of CFD technology. The TAM model in section 3.5 can be redrawn with "cultural perception and accessibility of technology" as illustrated in the figure 27.

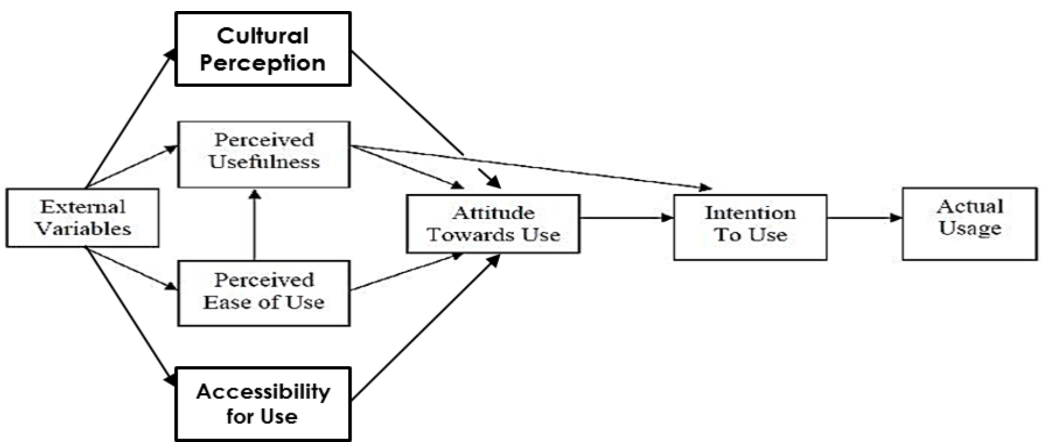


Figure 27 CFD-Optimized Technology Acceptance Model

4.11. CHAPTER SUMMARY

This chapter has presented a novel assessment of the flow handling equipment industry utilising the TAM model to study CFD adoption in the flow handling equipment industry. This also led to the optimization of the standard TAM model for CFD technology acceptance assessment and evaluation. Following the objectives of the research, the study answers the research questions and therefore fulfills Main contribution 1 and objectives 1-3 of the research. Using the results from the data enquiry, the author will now develop a Novel CFD-assisted methodology in the following chapter. A real practical application of the developed tool is then given in Chapter 6 of this study.

CHAPTER 5: DEVELOPMENT OF A CFD-ASSISTED NEW PRODUCT DEVELOPMENT METHODOLOGY FOR FLOW HANDLING EQUIPMENT INDUSTRY

From the previous chapter, the implications of the findings that emerged from the data collection process necessitate the development of a new product development (NPD) methodology specifically for the purpose of CFD design technology integration and NPD process management in firms within the flow handling equipment industry. This chapter utilises the themes that have emerged from the previous chapter in selecting techniques for methodology creation to meet the objectives of the research.

The main aim of this chapter is to achieve Main Contribution 2 of the research aims and objectives:

Main contribution 2: Develop a novel methodology to help firms integrate the best tools and methods to their processes.

- **Objective 4:** New Methodology should utilize key unique internal and external organisation resources for NPD.
- **Objective 5:** New Methodology should utilize procedures for dynamic product lifecycles.
- **Objective 6:** New Methodology should enable systematic integration of CFD technology as part of the design phase of the NPD process.

As identified in section 3.4, Systems theory considers the entirety of a system and not just a sum of the parts (Teece, 2018). Similarly, CFD analysis is often used to evaluate performance of a product based on its flow behaviour within a system. Systems Engineering is the branch of Systems theory concerned with Engineering applications and it utilises solutions that are applied across entire lifecycles (US DOD Systems Management College, 2001). Therefore, Systems engineering principles have been applied to this study to facilitate the design of a dynamic and encompassing methodology system for CFD technology integration based on the findings from the research.

In accordance with these objectives, the chapter is structured in seven sections. Section 5.1 introduces constituents that make up a Systems Engineering process. Section 5.2 presents an evaluation of two Best Practice Systems Engineering processes that have been selected for methodology creation along with their limitations and capabilities. Section 5.3 develops a New Systems Engineering Method for New Product Development from the systems engineering principles. In Section 5.4. The novel methodology is illustrated and sections are explained.

Section 5.5. develops a novel systems engine framework for navigating the new methodology and integrating the tool into the management of the NPD Product Life Cycle. Section 5.6. then presents a guide for the application of the new methodology, and in conclusion, Section 5.7 presents a summary of the key points from the chapter.

5.1. SYSTEMS ENGINEERING PROCESSES

According to the US DOD Systems Management College (2001), Systems Engineering refers to an approach that utilizes the entirety of the processes, techniques and strategies that are essential to meet the customer needs following the integration of a set of systemic solutions that are life cycle balanced. The function of Systems Engineering is to provide a dynamic but structured process for transforming requirements into specifications, structural designs and configuration baselines.

The US DOD Management College (2001) goes further to highlight three fundamental constituents of Systems Engineering.

- **Development Phasing**: Controls the Formulation of Concepts as well as the organisation of design-led activities. It does this by setting baselines at each stage of the development process from which each process can be assessed to determine its viability.
- **Systems Engineering Process**: A framework to coordinate the flow of activities based on requirements.
- **Life Cycle Integration**: A part of the design process that manages the systems to ensure they fulfil their purpose throughout their lifetime.

These three constituents are highlighted in figure 28 to illustrate this construct.

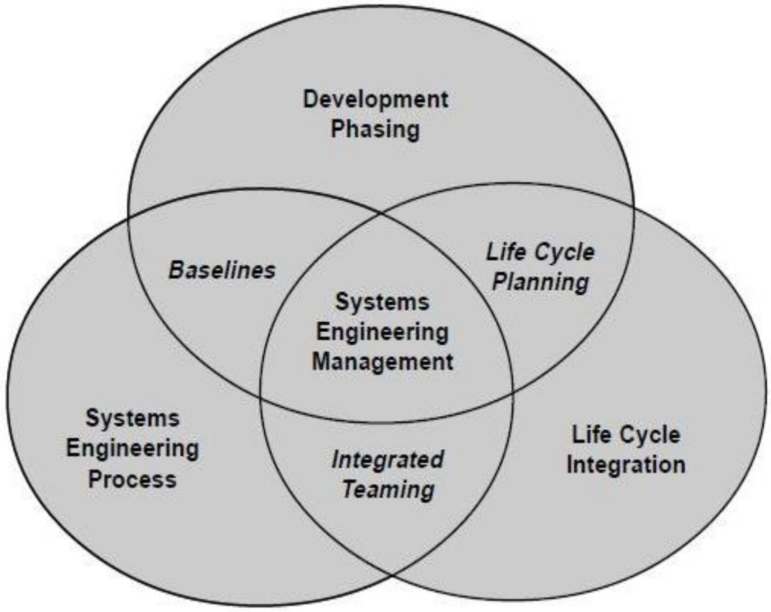


Figure 28 Activities in Systems Engineering Management. (US DOD Systems Management College, 2001).

Fundamental Systems Engineering practice also prioritizes planning of product and process development and integration of multiple functional solutions into the design and engineering process. This, according to US DOD Systems Management College (2001), would reduce cycle time and place redesign and rework at the absolute minimum. They then suggest Three qualities Systems Engineering processes should possess to prevent any uncertainty.

Coordination:

- A procedure for application

Control

- A management Function

Traceability

- A visual way to track progress

After a rigorous search of Systems Engineering management principles and processes, two systems engineering practice methods were discovered that closely fit the findings from the research in section 4.9 and that satisfy the research objectives for this study. These methods are elaborated upon in the next section.

5.2 AN EVALUATION OF TWO BEST PRACTICE SYSTEMS ENGINEERING PROCESSES

In this section, two highly detailed Systems Engineering Practices are analysed based on the three fundamental constituents and the 3 qualities highlighted in section 5.1 of this study. They are then assessed relative to the findings from the implications of the findings in section 4.9. The goal of this analysis is to present two example perspectives from the systems engineering field in order to establish the suitability of Systems Engineering processes for tackling design problems and subsequently, its adoptability for use with core engineering practices within the new NPD process.

The analysis begins with a description of the US Department of Defence Systems Engineering Process (US DOD Management College, 2001) alongside its limitations to the aim of the study. The National Aeronautics and Space Administration Systems Engineering Process (NASA, 2007) is then analysed alongside its limitations relative to the study. Subsequently, the core principles from both processes are evaluated in line with the discoveries made in this study. An ideal process is then developed and applied towards the development of a novel and pragmatic methodology that utilizes internal and external knowledge resources and integrates the use of CFD into the design process for NPD in the Flow Handling Equipment industry to satisfy the implications of the data collection findings and the objectives of the research.

5.2.1. THE DEPARTMENT OF DEFENSE SYSTEMS ENGINEERING PROCESS (US DOD Systems Management College, 2001)

Systems Engineering Process (SEP) is an iterative and sequential problem solving process. It identifies needs and requirements which are subsequently transformed into a group of systems, product and process descriptions. The aim of the Systems Engineering process is to provide decision makers with information as well as provide input for the next level of the process.

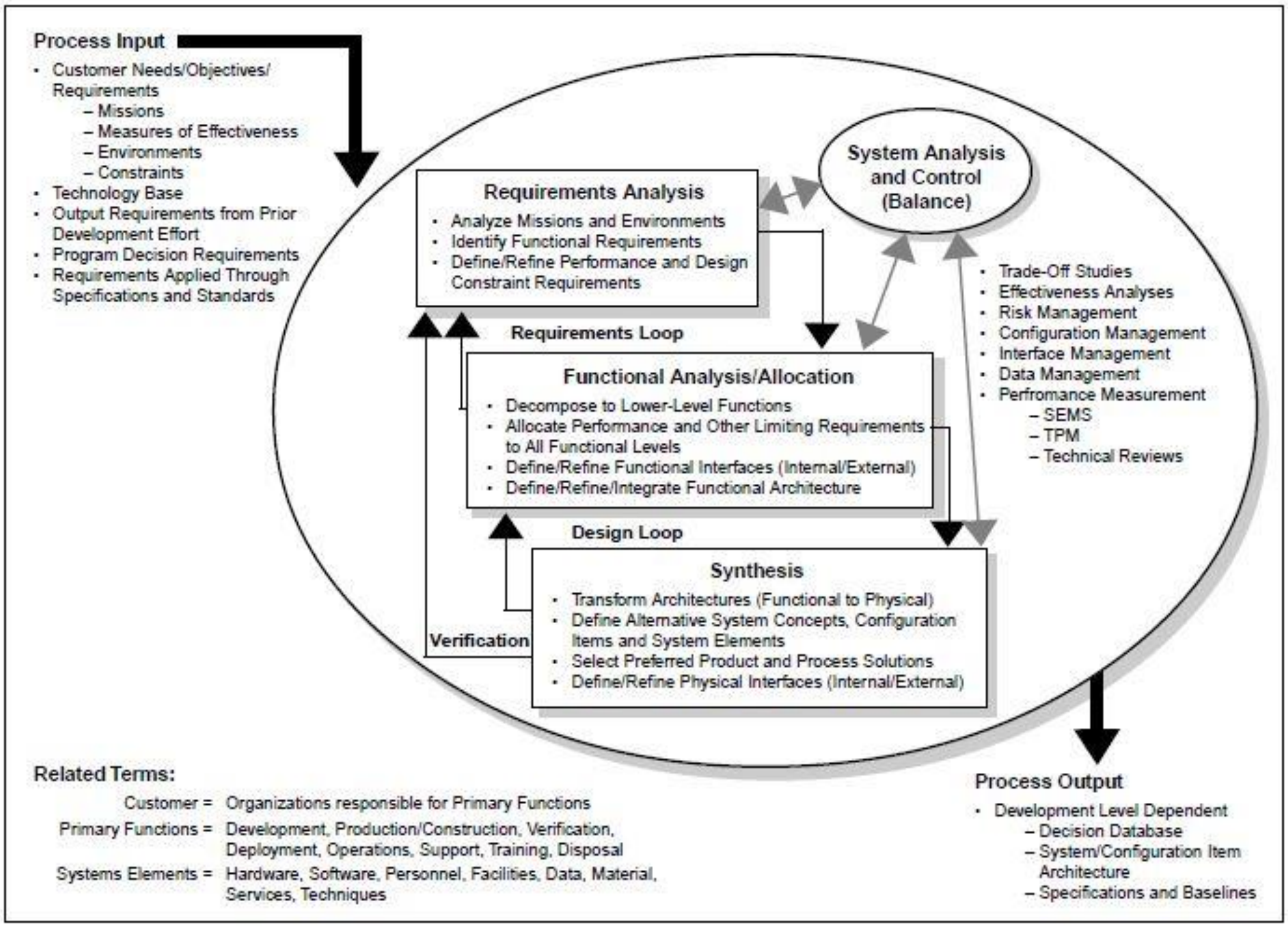


Figure 29 Systems Engineering Process (US DOD Management College, 2001).

As seen in figure 29, there are nine (9) sequential phases in the process: Inputs, requirement analysis, functional analysis and allocation, requirements loop, synthesis, design loop, verification, and system analysis and control. Each of these phases are described as follows:

5.2.1.1. PROCESS INPUTS:

These are the inputs to the systems process. They are identified here as customer needs, requirements, technology, output requirements from a previous product development attempt, standards and any other requirements necessary to aid product development.

5.2.1.2. REQUIREMENT ANALYSIS

In this phase, the process inputs are first analysed and customer requirements are converted into functional requirements that describe what the product is expected to do as well as its level of performance. The requirements analysis is what should determine the products functional requirements as well as constraints.

5.2.1.3. FUNCTIONAL ANALYSIS & ALLOCATION

Functional analysis is initiated by decomposition from higher to lower hierarchy levels of the identified functions from the requirements analysis. The functional product architecture that outlines the logical functionality of the product along with its corresponding performance requirement, are established as well as any conflicts with functional properties of the lower level hierarchies. All of the information gathered at this phase are critical for optimization of the product’s function.

5.2.1.4. REQUIREMENTS LOOP

This represents a series of iterative loops between the functional and requirements analysis stages. The aim is to ensure there is a traceable link between the requirements and the functions/allocations. Based on the composition of hierarchical product levels.

5.2.1.5. DESIGN SYNTHESIS

This represents any links between hardware or software elements, depending on if the product is a smart product. This link is usually referred to as the Product Architecture.

5.2.1.6. DESIGN LOOP

This an iterative design loop, the aim of this loop is to verify that the physical design can perform the functions at performance levels required.

5.2.1.7. VERIFICATION

This refers to the creation of a baseline to verify that each application meets the requirements. This implies that each of the requirements at each phase must be verifiable. Therefore, methods used for verification of the requirements must be established. Examinations, modelling and simulations as well as Testing (Formal and Evaluation testing) are useful ways of systems verification for Computational Fluid Dynamics.

5.2.1.8. SYSTEMS ANALYSIS AND CONTROL

These technical management activities oversee the whole of the development and would usually run concurrently with all the development phases. It consists of all the technical control activities to be managed such as progression monitoring, alternatives selection, as well as the documentation of data and design decision-making. Systems analysis focuses on meeting the strategic goals. It would look for alternatives to the current design in other to meet technical requirements as well as the objectives of the project. Control deals with aspects that control and regulate the functionality of the process and would include constant reviews by the technical team to execute management practices such as risk management, data management as well as configuration management and Technical Performance Measurement.

Seven points can be outlined from the DOD approach to Systems Engineering practice:

- Impacts of solution alternatives on system efficiency, customer requirements and resources, must be taken into account first before any decision to execute the alternative is made.
- The outputs of the systems engineering process at different phases determines the technical decisions and specification requirements.
- Traceable links between the input and output of the systems engineering process should be sustained throughout the project.
- Development and delivery schedules are co-dependent
- Ensuring suitable technical functionality is a part of the systems engineering process
- Customer requirements are monitored to examine their impact on emerging functional and performance requirements to ensure consistency, desirability and attainability.
- The design of the product and process design requirements are linked with the functional and performance requirements they aim to meet.

5.2.1.9 OUTPUT

This refers to the output of the system, which would vary at different times during the process based on achieved levels of development. It would also include all of the materials that are proceeds of the entire process based on level of completion. Examples include baseline processes, systems architecture as well as specifications and any other information that is used to control the process and product configurations.

5.2.1.10 LIMITATIONS OF DOD SYSTEMS ENGINEERING PROCESS TO THE STUDY

The DOD Systems Engineering Process (SEP) provides excellent coverage of the systemic interactions between decomposed hierarchy of product composition but does not define a procedural Engine for management of the loops. As discovered in Chapter 4 of this research, firms are more likely to adopt a practice that they can apply effortlessly. As such, it would be difficult to Co-ordinate and manage tracking of procedural progression alongside the loops without a visual engine to aid ease of use. The authors of US DOD Systems Management College (2001) also state that the method is not prescriptive and recommend users develop their own systems engineering management process using the principles they have given. Therefore, a second Systems Engineering Process that provides a visual engine would be observed.

5.2.2. NASA SYSTEMS ENGINEERING PROCESS (NASA, 2007)

The NASA Systems Engine (NASA, 2007) from the US National Aeronautics and Space Administration, is another known Systems Engineering Process for maximizing management of the Product Development Process in order to meet stakeholder and technical requirements. They merge the core areas of project management practice: Systems Engineering (which are the technical constructs and inputs) with the Project Control (which refers to program schedule control inputs).

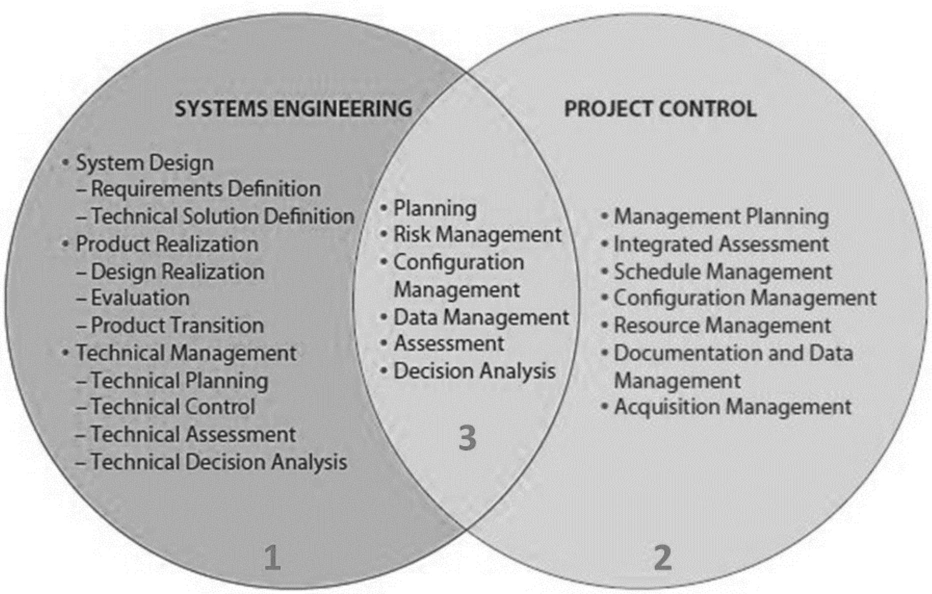


Figure 30 Overlap between Systems Engineering and Project Control (NASA, 2007, p.4)

As illustrated in figure 30, the core processes of Systems Engineering (1) are traversed with Project Control processes (2) to develop overlapping core management practices (3) that are applied towards the management of product development process.

The first two processes of Systems Engineering viz: Systems Design and Product Realization labelled (1) in Figure 30, form the left and right sides of the NASA Systems Engine respectively as displayed in figure 31. The core management practices from Label 3 in figure 30 are then used to augment the Technical management functions of the Systems Engine illustrated in figure 31.

5.2.2.1. NASA SYSTEMS DESIGN PROCESS (SYSTEMS ENGINEERING ENGINE)

The systems design process referenced in (NASA, 2007) is the Systems Engineering (SE) Engine. The processes outlined in the NASA Systems Engines as illustrated in figure 31, begins with Requirements Definition, which is essentially the process of defining the baseline expectations from the stakeholder. The Stakeholder expectations are then used to generate the technical requirements baseline on which the rest of the processes are built.

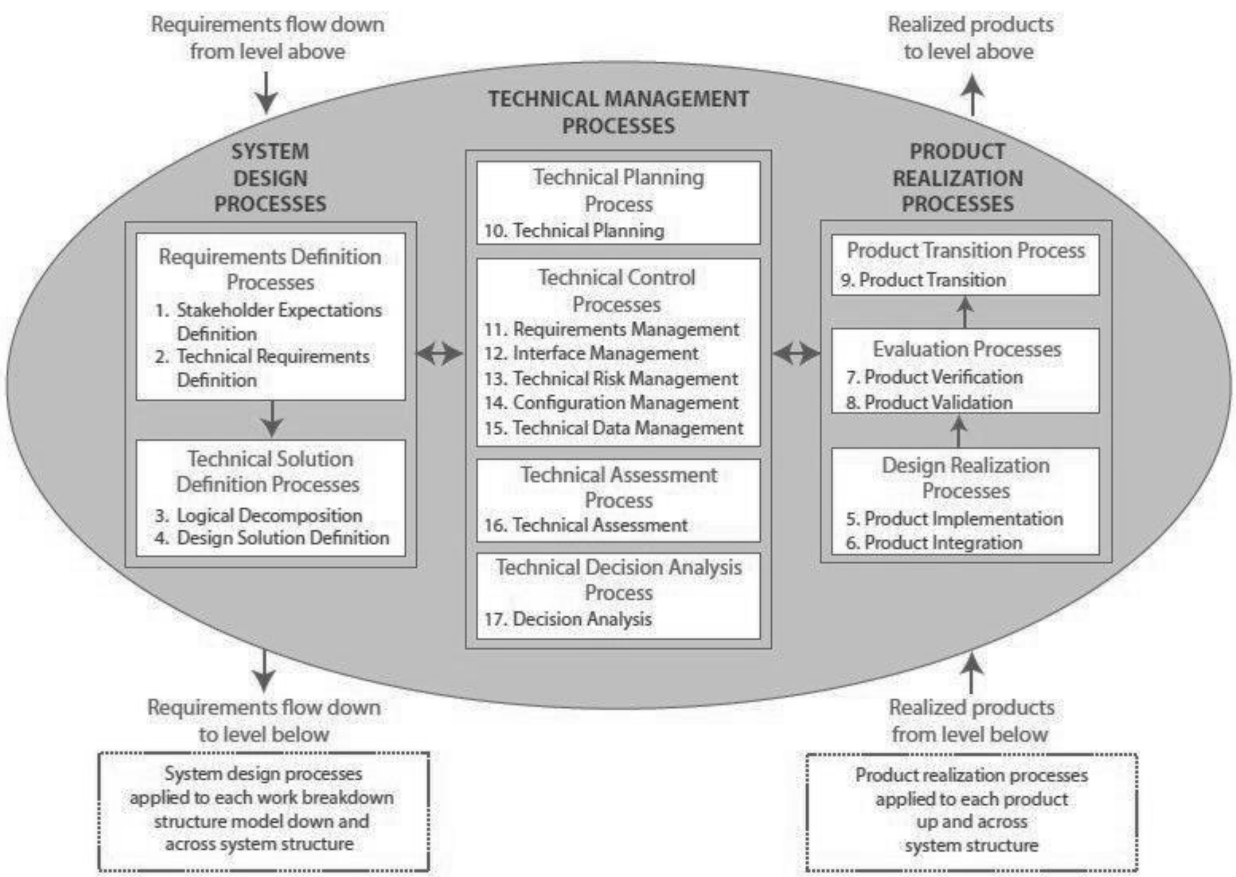


Figure 31 NASA Systems Engineering Engine (NASA, 2007, p.5)

In the Technical solutions definition phase of the systems design process, the technical requirements baseline are transformed into technical solutions that are expected to meet the stakeholder expectations. Both of these processes are applied systematically to each product on the Systems product hierarchy until each component product is defined enough in functionality, to be acquired or built. Designers are majorly responsible for developing the requirements and solutions.

5.2.2.2. PRODUCT REALISATION PROCESSES

Design efforts towards actualizing the design solutions from the Systems Processes are applied from the lowest tier of the product hierarchy through to the fully integrated product at the top tier of the product hierarchy chain to meet the stakeholder expectations.

5.2.2.3. TECHNICAL MANAGEMENT PROCESSES

These processes are located in the middle column of the SE engine and manage the flow of the product development process utilizing cross-interface communications, development of technical plans as well as progression to meet the milestones of the project. These processes are applied iteratively and recursively to each tier of the product hierarchy as well as the life cycle stages of the process.

5.2.2.4. NASA PRODUCT LIFE CYCLE

The product Life Cycle defines the stages through which the SE engine is applied. An outline of the NASA Product Life Cycle stages are given in Table 9.

Table 9 NASA Product Life Cycle. (NASA, 2007)

	Phase	Purpose	Typical Output
Formulation	Pre-Phase A Concept Studies	To produce a broad spectrum of ideas and alternatives for missions from which new programs/projects can be selected. Determine feasibility of desired system, develop mission concepts, draft system-level requirements, identify potential technology needs.	Feasible system concepts in the form of simulations, analysis, study reports, models, and mockups
	Phase A Concept and Technology Development	To determine the feasibility and desirability of a suggested new major system and establish an initial baseline compatibility with NASA's strategic plans. Develop final mission concept, system-level requirements, and needed system structure technology developments.	System concept definition in the form of simulations, analysis, engineering models, and mockups and trade study definition
	Phase B Preliminary Design and Technology Completion	To define the project in enough detail to establish an initial baseline capable of meeting mission needs. Develop system structure end product (and enabling product) requirements and generate a preliminary design for each system structure end product.	End products in the form of mockups, trade study results, specification and interface documents, and prototypes
Implementation	Phase C Final Design and Fabrication	To complete the detailed design of the system (and its associated subsystems, including its operations systems), fabricate hardware, and code software. Generate final designs for each system structure end product.	End product detailed designs, end product component fabrication, and software development
	Phase D System Assembly, Integration and Test, Launch	To assemble and integrate the products to create the system, meanwhile developing confidence that it will be able to meet the system requirements. Launch and prepare for operations. Perform system end product implementation, assembly, integration and test, and transition to use.	Operations-ready system end product with supporting related enabling products
	Phase E Operations and Sustainment	To conduct the mission and meet the initially identified need and maintain support for that need. Implement the mission operations plan.	Desired system
	Phase F Closeout	To implement the systems decommissioning/disposal plan developed in Phase E and perform analyses of the returned data and any returned samples.	Product closeout

The NASA Product Life Cycle is divided into two parts: Formulation and Implementation. The formulation part covers all of the activities for the development and design concept of the product and includes the following phases: **Pre-Phase A:** Concept studies; **Phase A:** Concept and Technology Development; **Phase B:** Preliminary Design and Technology Completion.

The Implementation part focuses on actual production and includes the following phases: **Phase C:** Final Design and Fabrication; **Phase D:** System Assembly, Integration and Test Launch; **Phase E:** Operations and Sustainment; **Phase F:** Closeout. A summary of the how the SE Engine is used is described below.

Pre-Phase A - Concept studies: At the beginning of the process, the SE engine is applied methodically towards the development of initial concepts. High-level requirements would be developed using different methods and models. Tentative verification and validation of the concepts would also be carried out at this stage of the process. The goal at this point is not to test the final product but to verify that the concepts developed, actually meet the stakeholder requirements. Consequently, only the left part of the SE Engine is used (figure 31). The entirety of the product hierarchy levels would also be developed at this stage of the process to conceptualize the main and sub-level products.

Phase A - Concept and Technology Development: The SE Engine is applied recursively utilising the validated outputs from the Pre-phase stage. A baseline is set for the systems requirements as well as presentation of a conceptual framework of operations (referred to as ConOps). High risk and sub level details that might have been overlooked in the previous phase are taken into account in detail. Simulations also take place in this stage as well as an identification of verification and validation techniques for use in later phases.

Phase B - Preliminary Design and Technology Completion: A recursive application of the SE engine to all of the sub-products in the product hierarchy are implemented. Preliminary ConOps designs are developed and a feasibility analysis is carried out on the verification and validation concepts to ensure stakeholder expectations are practicably met.

Phase C - Final Design and Fabrication: All of the requirements on the left side of the SE Engine are finalized as well as the ConOps. The final designs for all the product hierarchy levels to the lowest level are completed.

Phase D - System Assembly, Integration and Test Launch: The SE Engine crosses over to the right side of the SE Engine. The verification and validation of the end product are finalized. After final iteration of the SE engine, the finalized product is passed on to the end user.

Phase E - Operations and Sustainment: This phase applies the Technical management processes in the middle of the SE engine, which used for monitoring the entire process as well as decision-making.

Phase F - Closeout: All of the technical management activities required for eventual system closeout are implemented. Any new capabilities or upgrades to the existing system would then re-enter the SE engine as new developments.

Summary: Where Phases A and B focus on the design and prototypes, identified mistakes made when reports are drawn from the verification and validation processes are less costly to correct than after the product has already been built (manufactured or assembled). Phases C and D would usually be recursively applied to the actual product itself. The fully realized product emerges in phase D.

5.2.2.5. LIMITATIONS OF THE NASA SYSTEM TO THE STUDY

While the NASA systems engineering process follows a more prescriptive approach with an exceptional visual-tracking theme than the previously observed Systems Engineering Practice from DOD. It does not take into account the possibility of conflicts/constraints arising between sub-component phase products in the requirements or design loops within and between the tiers of hierarchy. During the interviews, it was discovered in one of the companies that the customer is involved throughout the entire process and continuously influences the decisions made even after the stakeholder requirements have been conceptualized. Although many companies tend to freeze the requirements when actual prototyping has begun, it is possible that they will experience problems with meeting the expectations of the customer at any stage. This could possibly be because of external influences such as changes to technology or customer/stakeholders' changing need (in both cases of companies initiating bespoke or batch production). This is particular true for the Flow Handling Equipment industry.

A dynamic NPD process would consider the uncertainty and seek to balance the life cycle of new products to maximize the potential of meeting the stakeholders' expectations. As a result, alternatives should be developed alongside the main and phase products. There needs to be a provision in the SE engine for these alternatives to be introduced at any stage. Another team may be assigned to handle the alternatives through the systems Engine, but there needs to be a phase where these alternative parts are combined and evaluated in light of the main product hierarchy. As this capability is not reflected in the NASA Systems Engine, a new one has to be created that considers this functionality.

5.2.3. SUMMARY OF LIMITATIONS IN NASA AND DOD SYSTEMS ENGINEERING

As has been discovered in the flow handling equipment industry from Chapter 4, most of the interviewed companies do not use very structured processes for their New Product Development. The Stage gate NPD process that most of the companies in the interviews seem to be aware of, attempts to give a form to the Product Life Cycle and firms implementing it eventually go on to modify the stages and gates to suit their processes. While they do this with good intentions, often the modified processes do not account for the criteria used in setting the gates at strategic points. This is mainly because; different kind of products may have slight or major variations at different stages of the product life cycle that they identify as critical. As more firms are structured around the kind of products that they sell, problems arise in implementation. This is because; the Stage Gate™ process was originally built around a product life cycle that may be incompatible with the product life cycle of the specific products the firms intend to develop. Attempts to modify the original Stage Gate may then over define the process. It is therefore important that firms find systems that are closely linked to their situation to ensure an easier fit when modifications are made.

For the circumstances peculiar to the Flow Handling Equipment industry, the DOD and NASA systems were found to be a close match due to their combined features. However, individually, they may not. While the DoD Systems Engineering process takes the dynamic nature of NPD and later introduction of design modifications into account, it does not present a structured process for implementation and integration into the product life cycle. This the DOD authors believe, should be left to each firm to choose how best to implement their designs. On the other hand, the NASA system presents a systematic way of working through the process for the product life cycle but does not give options for modifications of the design at later stages in the process. These individual limitations do not to imply that the NASA and DoD Systems Engineering Processes would not be effective for other kind of projects other than the ones they were designed for. On the contrary, both of the identified functions in each of the identified Systems Engineering Processes, when used side by side, would be very useful to the execution of any Systems Engineering oriented product development endeavour. However, this would be a challenging undertaking for companies that do not want to complicate their processes further. To enable a seamless assimilation in practice, a Novel Application of the Systems Engineering Process is necessary to provide a suitable platform for firms to meet the stakeholder requirements in a way that is useful, presents effortless use, accessible and acceptable to cultural patterns identified within the firms.

This is where the project takes a step closer to the companies than just reporting their current state and provides a structured methodology template that can be applied to any desired NPD project irrespective of company size or project complexity, thereby leaving room for adopters to apply the framework based on their uniquely prioritized product life cycles.

5.3. TOWARDS A NEW CFD-ASSISTED INTEGRATED SYSTEMS ENGINEERING NPD PROCESS FOR FLOW HANDLING EQUIPMENT INDUSTRY

This section outlines the procedures taken to develop the new methodology for the Flow Handling Equipment Industry informed by the research findings in chapter 4 and augmented using principles from the two Systems Engineering Processes discussed in previous sections of this chapter. A detailed Novel framework would then be integrated into the product life cycles that best reflect the kind used in companies within the flow handling equipment industry.

As highlighted earlier in section 5.1, Systems Engineering Process characteristics should demonstrate:

- **Co-ordination**: A Procedure for application
- **Control:** A Management Function
- **Traceability:** A visual way to track progress along the process.

For simplicity, the impliications of the findings from section 4.9 are summarised as follows:

The new methodology should:

1. Encourage Collaborative work
2. Exhibit a procedural structure with steps
3. Provide a method for navigating the process
4. Prioritise Stakeholder(customer/standards) requirements
5. Be dynamic to accept later changes in the product design from customer requirements
6. Account for supply of alternative parts that may change design
7. Possess a resource of useful tools (TRIZ, QFD etc)
8. Be capable of utilising a Product life cycle
9. Optimize repeated CFD simulation tests
10. Function as an Iterative process

5.3.1. A COMPARISON BETWEEN THE TWO SYSTEMS ENGINEERING APPROACHES

It was discovered that both processes had functional capabilities that would be very useful if applied synchronously. However, the challenging complexity of managing two systems instead of one may discourage implementation among firms desirous of a system that is easy to apply.

A pragmatic solution to this situation would be to adopt the functional capabilities of the two systems in developing one that provides practicable solutions to the aims of the study. This new Systems process would not be a reduction of each but an integration of only useful traits in line with Systems Thinking. In the following sections, efforts are made to demonstrate how a unification of the systems engineering processes can be accomplished.

5.3.2. DEVELOPMENT OF THE NEW SYSTEMS ENGINEERING CONCEPT

First, a comparison of the Systems Engine Processes is carried out and the relevant overlapping functions are synchronized.

As illustrated in figure 32, the DoD and NASA systems engineering processes on the left and right sides each have very similar concepts. While two loops occur between the Requirements and Design phases in the DOD system, the NASA system performs recursive passes at each stage until all of the processes in the tree have been completed.

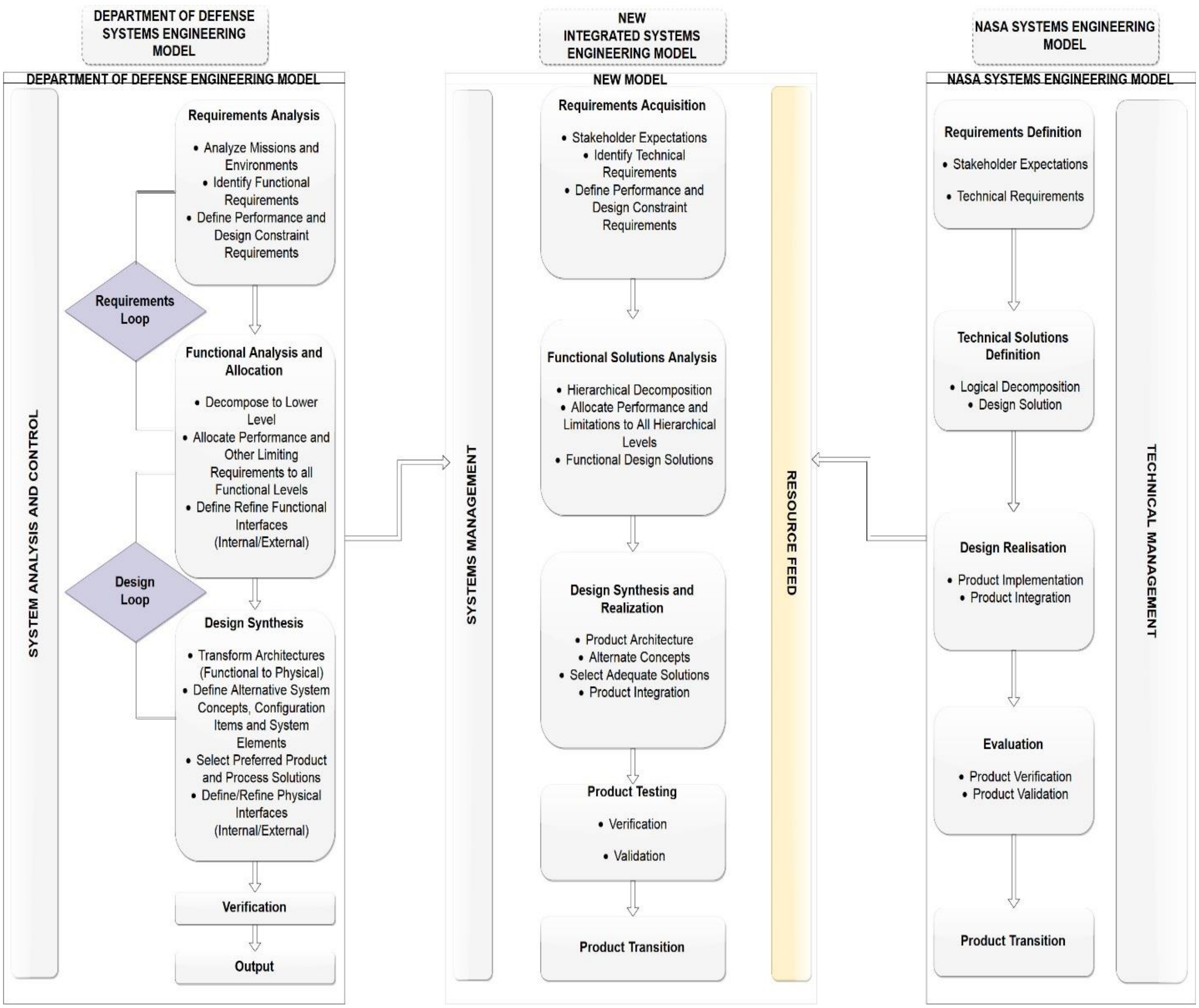


Figure 32 Integrated Conceptual Framework.

Given at face value, it can be identified that the similarities between the two processes far surpass the contrasts. These functions are then unified in the new Integrated Systems Engineering Model.

An extraction of the similarities and contrasts of both systems and how they inform the build of the developed model are explained in the following subsections. A more detailed functional description of each construct is given in the section 5.4.

5.3.1. REQUIREMENTS ACQUISITION

The section identified as "Requirements Acquisition" in the new model of figure 32 is a merger of the "Requirements Analysis" and "Requirements Definition" sections of the DOD and NASA systems respectively. A number of significant similarities have been identified in both systems processes. However, one of the contrasting elements spotted was that DOD identified "Performance and Design Constraints" as Requirements. Indeed this is a pragmatic way to account for contradictions in expectations and the uncertainty of meeting the requirements. The NASA system does not present that on the block diagram in Figure 32. However, in NASA Systems Engineering programme, it is suggested that Stakeholders take part in the process of preparing a Concepts of Operations document (otherwise referred to as the ConOps). It can be surmised therefore, that a good practice is to ensure the stakeholders are understood and that they understand the limitations of the company meeting their requirements. The setting of constraints as suggested by DOD would seem to be a suitable entry to the ConOps document suggestion from the NASA systems. This finding is reflected in the new integrated model as well as the rest of the contents of the requirements process that are quite similar and easy to identify. The contents chosen for the Requirements Acquisition section of the new model are: Stakeholder Expectations, Identification of Technical Requirements, Setting Performance and Design Constraints Requirements.

5.3.2. FUNCTIONAL SOLUTION ANALYSIS

This segment is titled "Functional Solution" as the major output of the segment is an attempted Solution to the identified Technical Requirements. In comparing the systems processes as illustrated in Figure 32, "Hierarchical decomposition" appears to be a common trend in both. Again, DOD suggests constructs that seeks to define/refine limitations to the functional solutions in response to the technical requirements. While these are not accounted for in the NASA systems, they are taken into consideration in the new model alongside the other contents that are identical. The contents chosen for this segment in the new model' – Functional Solution Analysis are: Hierarchical Decomposition, Allocation of Performance and Limitations at all Hierarchical Levels and Functional Design Decision.

5.3.3. DESIGN SYNTHESIS AND REALIZATION

In the design stage, both systems seem to suggest that the design levels be evaluated collectively and consolidated at each design level, hence the title "Design Synthesis and Realization" has been chosen for this segment of the new model. A major difference between the DOD and the NASA systems. Where the NASA systems seeks to consolidate sub-tier products, the DOD looks at alternative concepts and seeks to select and evaluate suitable alternatives for selection and integration which was the major cause for the merger of the systems. The other functions are very similar and are used in the new model. The list of processes attributed to this segment in the new model – Design Synthesis and Realisation are Product Architecture, Alternate Concepts, Selected Adequate Solutions and Product Integration.

5.3.4. TESTING

"Product Verification" and "Product Validation" are two of the key processes recommended by NASA systems. DOD lists just "verification". While the two words have often been used interchangeably, the NASA Systems Process distinguishes between the two concepts. Referring to Verification as confirming all the technical functions of the product act as designed, and Validation as checking that the product meets the stakeholders' expectations. The new model therefore enlists both processes "Product Verification" and "Product Validation".

5.3.5. PRODUCT TRANSITION

The term "Product Transition" is used to define the final segment in line with NASA systems engineering process' use of the term, which is to transition the product to the next phase of iteration or to end the process which would be the same as DoD's choice of Output as the last phase. The process attributed to this segment in the new model is – Product Transition.

5.3.6. SYSTEMS MANAGEMENT:

The term "Systems Management" is a merger of the "*technical management"* process from NASA systems as well as "*Systems Analysis and Control"* process from DoD Systems.

5.3.7. RESOURCE FEED

The "Resource Feed" section is a new addition to the model independently of the NASA or DOD system. More of their function is described in subsequent sections.

Summary notes: The loops from the DOD process are not applied to the new system because the new system engine would have iterative loops. Having determined the Processes that would make up the new model, a process description and discussion is required in terms of their new implications for NPD systems engineering. This is done in the following section.

5.4. THE NEW INTEGRATED SYSTEMS ENGINEERING PROCESS MODEL

In this section, a description of the New Integrated Systems Engineering process in relation to its application to the Fluid Flow Handling Equipment Industry is given. A New Systems Engine is also provided in the subsequent section.

As described in the previous section, The New Integrated Systems Engineering Model presents a valuable set of processes that have been identified as useful Systems Engineering practices for managing the Product Development Process.

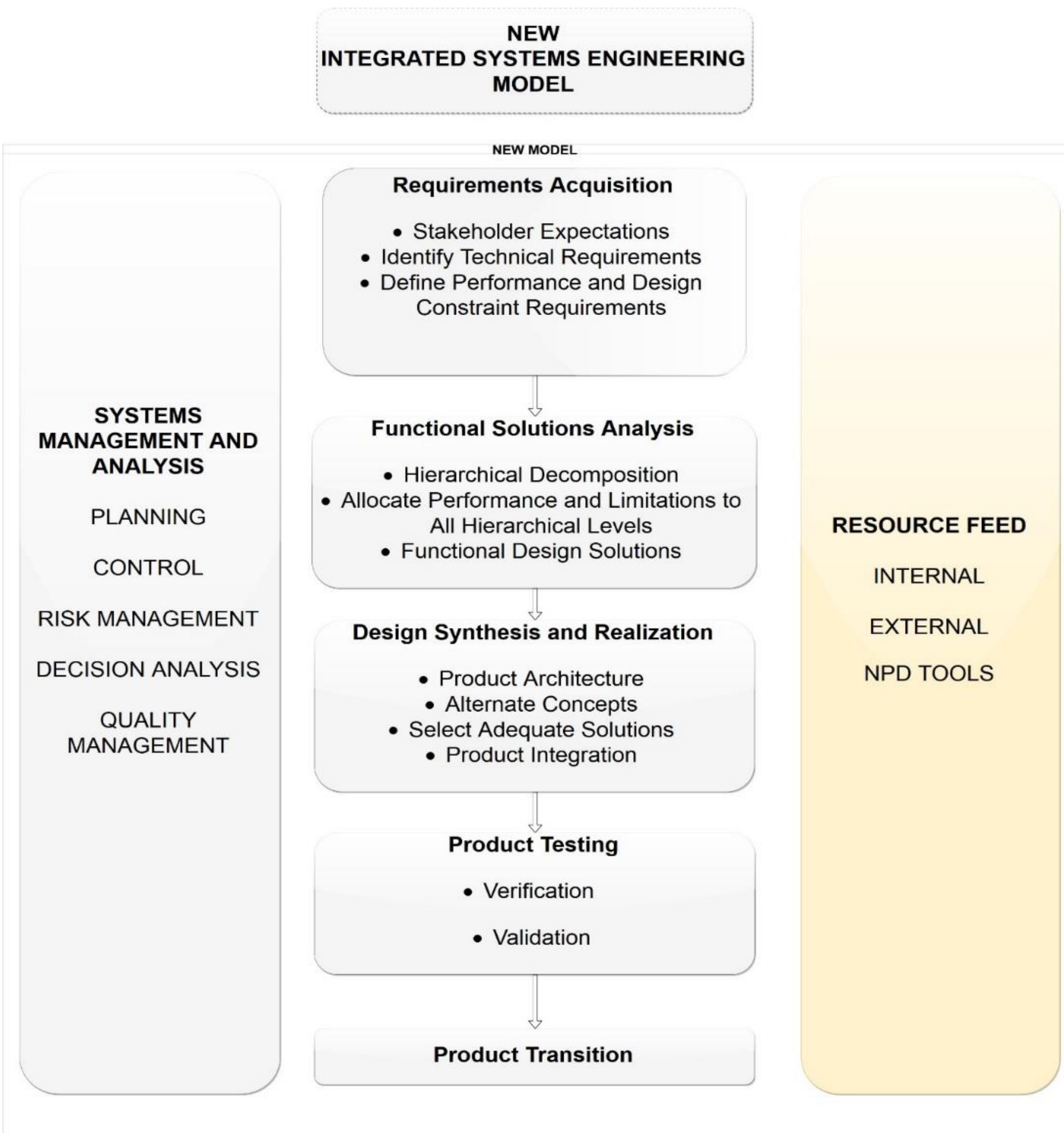


Figure 33 New Integrated Systems Engineering Process Model

In the new Systems Engineering process framework (figure 33), the product goes through five major development systems processes and is guided by the firm's Systems Management and Analysis Process as well as a Novel Resource Feed feature that was did not exist in either the DOD or NASA Systems process.

The NPD process begins from the Input and proceeds downwards through the processes outlined in figure 33 to the Product Transition phase in successive iterations until the product has completed the stages of the product life cycle. Each of the systems processes in the new model would now be discussed to determine their roles in the NPD process.

5.4.1. REQUIREMENTS ACQUISITION (RA)

This process consists of Stakeholder Requirements, Technical Requirements as well as Product and Process Constraints.

The stakeholders usually comprise of the intended customers or anyone who has a significant impact on the product's life. The product requirements are first obtained based on the expectations of the stakeholders. It is essential that the requirements are achievable and therefore the expertise of persons who are conversant with similar products is required. An Operational Concept description (OCD) document similar to the ConOps from the NASA system may also be used at this point. As most firms in the flow handling equipment industry run a bespoke service or supply to other businesses, the stakeholders are likely to be known. In cases where the products are meant for general production, the needs of the target market can be prioritised using voice of the customer (as described in literature).

Next, these stakeholder requirements are converted into technical requirements, taking note of any design and performance constraints requirements. Quality Function Deployment (QFD) House of Quality (HOQ) tool (also described in literature) might prove useful for this activity. These technical requirements form the baseline for the entirety of the development process therefore sound engineering judgement would be required. The author recommends that these processes be attempted only by persons highly skilled at using such tools. The proceeds from this process are utilized as inputs for the next process - Functional Solution Analysis (FAS).

5.4.2. FUNCTIONAL SOLUTION ANALYSIS (FSA)

This process consists of Hierarchical Decomposition, Allocation of Performance and Limitations at all Hierarchical Levels and Functional Design Decision.

During this process, the product concept is decomposed into hierarchical levels of sub-systems products. Design led Solutions are then sought for the technical requirements of each. This process undergoes both iterative and recursive loops in a bid to match the design with the technical requirements, the limitations of meeting each functional performance and design solutions are also set. When design solutions have been developed, the next process is activated.

5.4.3. DESIGN SYNTHESIS AND REALISATION

The design solutions from the previous phase for each hierarchical level are used as inputs for this process. The sub-level products are consolidated up to the highest level of the hierarchy and tested for compliance with the Stakeholder expectations. Alternative Concepts are also studied at this stage at both sub-level hierarchical tiers and system level tiers. The aim is to find out if there is better precision in meeting the desired objectives (stakeholder expectations). A prototype or main product is then realized or built depending on the phase of the product's development in the life cycle. If still in digital prototype mode, the product would be run multiple times through CFD simulations to see its functions. If any mistakes are observed it is still less costly to correct than in a finished product or managing a recall process. The outputs from this process are used as inputs in the next process.

5.4.4. TESTING

The realised product goes through a series of tests to determine its ability to meet functional solution targets and constraints, as well as Stakeholder Expectations. For the flow handling equipment industry, this would mainly be done using CFD simulations, but at later phases of the development, real tests would be conducted to validate the procedure.

5.4.5. SYSTEMS MANAGEMENT AND ANALYSIS

Throughout the development process, there are people, resources and risks that have to be managed organizationally. The success of any systems management process would rely heavily on these practices. The technical and management capabilities of the organization is brought in to bear on the responsibility of executing and completing the project, which would largely affect the outcomes of the processes. These outcomes also have to be analysed as they happen, in order to increase organizational level awareness on the project and adjust or adapt accordingly to any changing trends in the process.

5.4.6. RESOURCE FEED

The author deems this function as significant enough to be highlighted and included in the Systems Engineering Process as it relates specifically to New Product Development and not just Systems Engineering.

There are a number of internal and external organizational resources identified from the interview sessions in Chapter 4 of this study. The firms can utilise these resources to assist in the development of new products. While existing processes could be managed effectively by the organizations and technical managers using resource management practices and techniques, the identification of new useful NPD tools discussed in literature would be an effective boost to the realization of a new product. For example: The Quality Function Deployment (QFD) and Failure Modes and Effects Analysis (FMEA) for managing the NPD process would come in handy in the requirements and testing phase of the development respectively. Although, these best practice NPD tools are well known, firms need to expand their field of resources and it may prove useful for firms to consciously sought new best practice tools that may be suitable for their NPD projects but which are currently unknown to them. One of the Interview participants from Company F had stated that they used both Stage Gate and Spiral NPD processes in the preliminary questionnaire and acknowledged that they were supposed to use Voice of the Customer (VOC). However, they had never heard of the KANO Model, which is a very useful tool for prioritizing customer needs.

> [Company F] is supposed to use Voice of the Customer. But KANO Model? Never heard of it. ***(Company F interviewee).***

A robust R&D process is therefore required for the identification of new tools that would help improve the organizations' position in terms of managing the above listed System processes as well as the optimization of available resources. A real pilot project would be used to illustrate how these are implemented in the next chapter. For now, the next section would describe a CFD-optimized Systems Engineering Engine for New Product Development.

5.5. A NOVEL DYNAMIC SYSTEMS ENGINE FOR NEW PRODUCT DEVELOPMENT (QUADRANT ENGINE).

In the previous Section, a new set of processes guaranteed to take the dynamism of NPD projects into account was developed. In this section, a new Systems Engine built from those processes is introduced, with its operation and functions analysed.

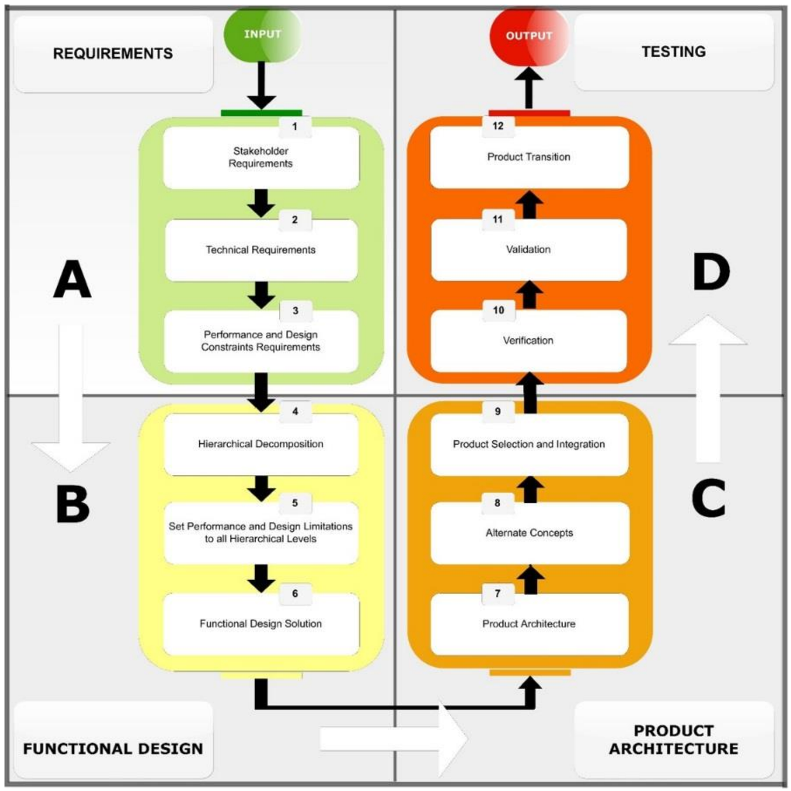


Figure 34. The new systems engine (Quadrant Engine)

The new systems engine utilises all of the processes from the integrated systems engineering process model. As displayed in figure 34, the Engine is divided into 4 Quadrants labelled anticlockwise as A, B, C and D each representing Requirements, Functional Design, Product Architecture and Testing process groups respectively. Each process in Each Quadrant is labelled with a unique identifier number (a total of twelve across the process groups) indicating the progress made within each process group and in the overall system. From an example illustration shown in figure 35. Each Quadrant when highlighted (with a blue background) indicates that the highlighted process group is active and concurrently supported by the Resource Feed and Systems Management functions.

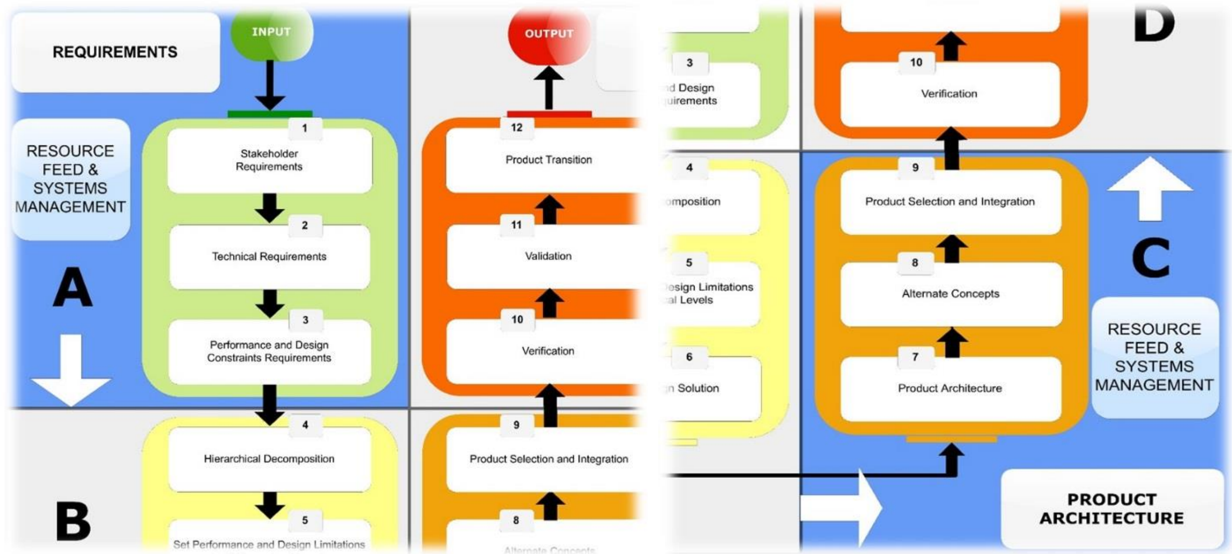


Figure 35 Identification of an Active Process Quadrant.

From the excerpt displayed in Figure 35, the Quadrant A process is active as well as the resource feed and systems management processes which indicates that the process is being worked on. On the right side of the excerpt, the numbers 1 to 3 representing the processes would also be highlighted one after the other to indicate active processes. The unshaded numbers indicate that none of the processes have begun, but the number of the process being implemented would usually also be highlighted to indicate the process being utilized by the systems engine.

The black arrows are used to indicate the process-to-process flow for the entire system. White arrowheads resting against the blue background in an active quadrant indicate the Quadrant-to-Quadrant direction of flow from input to intended output. As can be seen in Quadrant A (left side of figure 35), only one white arrow can be identified which is indicative of a starting Quadrant, the direction of the arrow indicates the direction of process activation within the Quadrant as it moves through the processes and towards the intended output of Quadrant A (to Quadrant B). In Quadrant C (right side of figure 35), it can be observed that there are two white Quadrant to Quadrant arrows, one indicating the flow from input (and the other indicating flow to the intended output).

Now that a description of the systems engine features has been given. It is necessary to demonstrate how it can used. To do this, a project life cycle would be required. In the next section, an attempt is made to put together an original Product Life Cycle by merging functional stages from various sources including literature, interviewed companies, and the product life cycle used for NASA version of the Systems Engine.

5.5.1. OPTIMIZING THE PRODUCT LIFE CYCLE

As this study is focused on the Flow Handling Equipment Industry, the Product Life Cycle suggested here would be optimized from existing and suggested themes that emerged from the interviews. These would then be augmented with new development cycle stages identified from works of notable scholars in literature having explained therein their relative life cycle representation for the majority of products. Key identified Product Life Cycles for Flow Handling Equipment Industry products are prioritized and the others retained in order to extend the usability of the new methodology to other companies.

It is important to note that the above developed systems Quadrant engine can be applied to any product life cycle. However, the following integrated product life cycle was generated to ensure maximum utilization of a Dynamic Systems Engineering process.

5.5.2. PRODUCT LIFE CYCLE INTEGRATION PROCESS

The following Product Life Cycles from literature were considered: Stage Gate™ (Cooper, 2011), NPD process (Eppinger and Unger, 2011), Design and Manufacturing Process (Rooney and Steadman, 1993) as well as Systems lifecycle from DOD (US DOD Systems Management College, 2001) and NASA (NASA, 2007).

Of the above product lifecycle stages, Stage Gate™ is used in three out of the six interviewed firms. Of the other three firms that do not use Stage Gate™, two use an unstructured process that is very much similar to a loosely modified stage gate process. The third firm (Company B) has yet to begin any New Product Development and so does not have any NPD Product Life Cycle plan as at the time of the interview. The original version of Stage Gate as indicated in chapter 2 is assessed alongside the other identified NPD cycles from notable literature sources as mentioned above. There are nine combined product life cycle phases that emerged from a consolidation of the life cycles for the flow handling equipment industry. They are:

- Conceptualization
- Ideal development
- System Level Design
- Consolidated Design
- Testing and Validation
- Operations and Sustainment
- Launch
- Maintenance
- Post Launch Review

A complete list of the phases of the Integrated Product lifecycle are presented in table 10 as well as a description of the activities that can be expected and the resultant output.

Table 10 Integrated Innovative Product Life Cycle

	Phase	Activity	Expected Output
Development	Conceptualization	A collection of ideas and concepts are generated. Some patterns start to emerge and ideal concepts are formed	Realistic Product ideas and Concepts, CAD models are built and preliminary CFD Simulations are run
	Ideal development	Conceptualized ideals are described and projected in line with the objectives intended for the development of the new product	Refined CAD models are built and CFD Simulations are run
	System Level Design	Detailed product description can be expected at this stage, final product models encompassing all hierarchy levels are also expected at this stage	Defined CAD Models, CFD Flow Analysis & Prototypes
Deployment	Consolidated Design	Design is finalized at this stage, the first product is built with all of its real features	Actual Product
	Testing and Validation	Finalized product is tested for compliance to standard objectives, put through standard screening industry level exercises and prepared for final launch	Verified and Validated Product
	Operations and Sustainment	Management practices are put in place, as well as Iterative Learning Curves, Training Requirements, Decision to Launch, Maintenance checks, Upgrades, Product Development and Management File is finalized.	Management Lessons, Resource Expertise
	Launch	Product is Closed out and Preparations for Launch are put in Place	Product Closeout
After Launch	Maintenance	The CFD version as well as product prototypes are re-visited and re-evaluated for failure modes or Value for subsequent Batch Productions	Early detection of problem areas and identification of probable fixes
	Post Launch Review	Product file is reopened and checks are made for adaptation to a new cause or to manage a new discovery about the product's behaviour, Product undergoes scrutiny using the engine but with new requirements.	Updated Versions of Product Range/Alternatives

5.5.3. DESCRIPTION OF NEW SYSTEMS ENGINE USE WITH INTEGRATED PRODUCT LIFE CYCLE

Having integrated the Process (figure 36) into the Product Life Cycle (Table 10), the operation of the Systems Methodology would be given in detail.

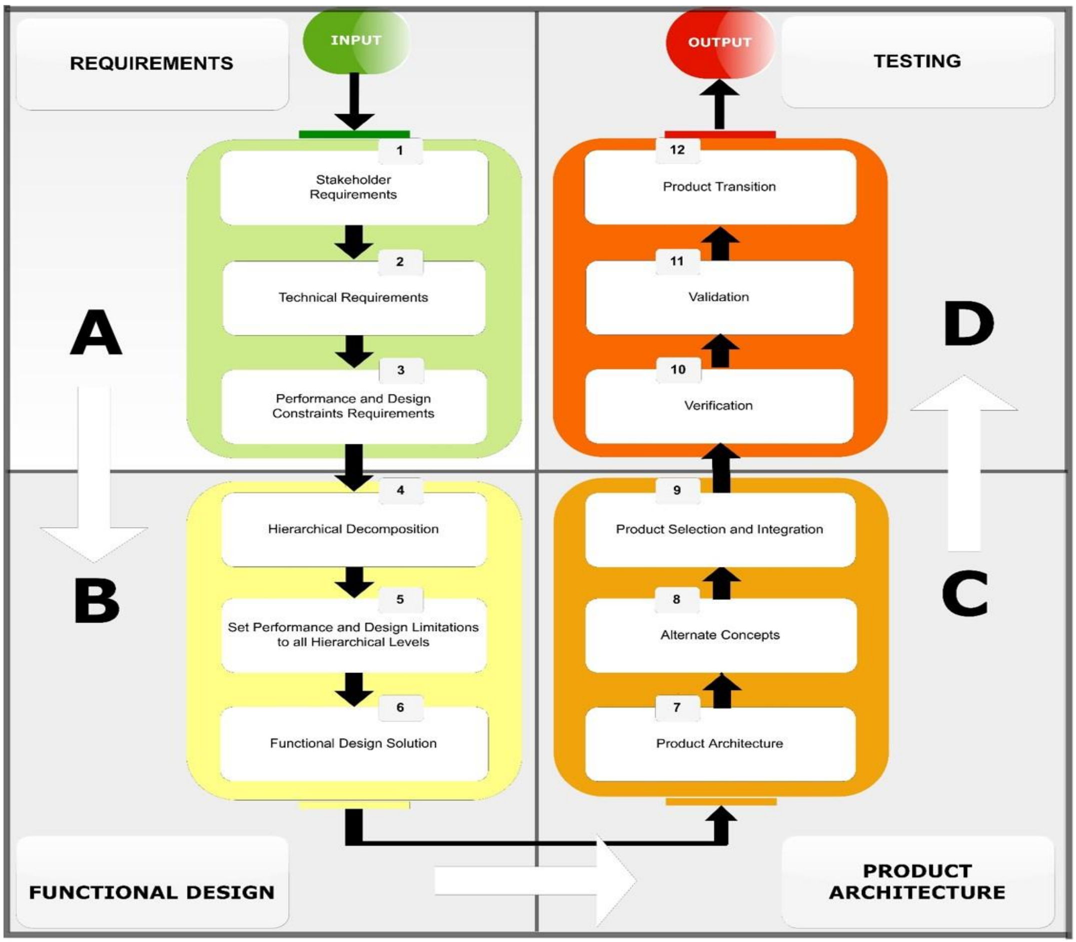


Figure 36 The New Systems Engine Methodology

5.5.3.1. PHASE 1: CONCEPTUALIZATION

The duration of the first phase is used to scan through the Systems Engine, and establish the baseline for the rest of the product development procedures. Different methods and resources are chosen tentatively for the project. The initial requirements of the stakeholders are identified and the Operations Concept document is drafted while procedures for the verification and validation are also decided on at this stage. No detailed design is done at this stage. Occasional simulations and mock-up diagrams or prototypes may be drafted in a bid to get a sense of the stakeholder needs. Preliminary tentative requirements are specified in statements such as 'A Control Valve' and 'an x control valve that exhibits y control valve flow characteristics'. Only Quadrants A and B are likely to be utilized at this stage of the Product Development Process.

Ideas of probable product hierarchies also begin to emerge in this Phase. The output is a baseline for the rest of the project.

5.5.3.2. PHASE 2: IDEAL DEVELOPMENT

First pass: A quick run through the engine is done, stakeholder expectations are defined in technical terms and technical requirements are developed in line with the stakeholder expectations, any design or product performance constraints to be met are also set, all of these processes would occur in Quadrant A. In Quadrant B, tentative hierarchies are built for any sub level products that make up the main product of the project. At this stage, the concern is not to build a full hierarchy tree of sub products but to establish probable products as well as identify their limitations in design. Draft designs are worked out in this phase but are not detailed enough to build anything. The designs are prepared on CAD software and simulations are used to study the systems behaviour. Simple CFD related tasks like Mesh Independence tests may also be carried out at this stage and digital models are tested to determine the limitations of the design. However, the designs are not detailed enough for any actual products to be built.

Second Pass: The system engine is followed chronologically from Quadrant-to-Quadrant and from Process-to-Process. Process-to-Process movements occur between processes within a quadrant as illustrated in figure 37. This would be referred to in this project as process movements. The movement from one quadrant to another quadrant only occurs when all the processes including the last process from a quadrant is completed as shown in figure 38.

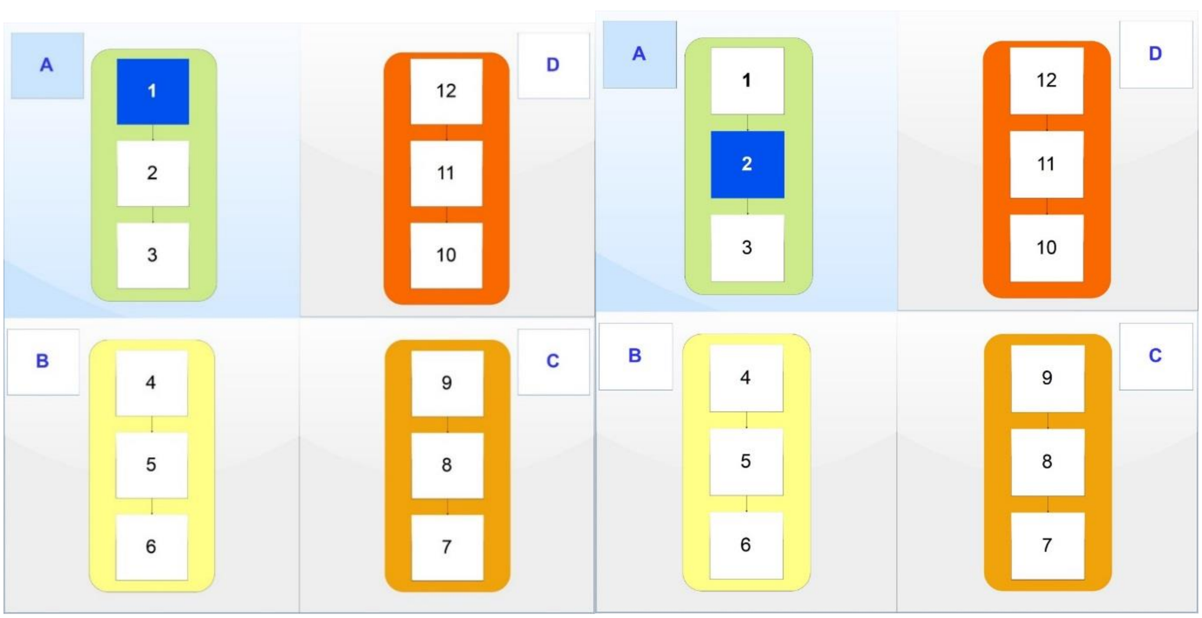


Figure 37 A Simplified Model showing Process level movement from A1 to A2.

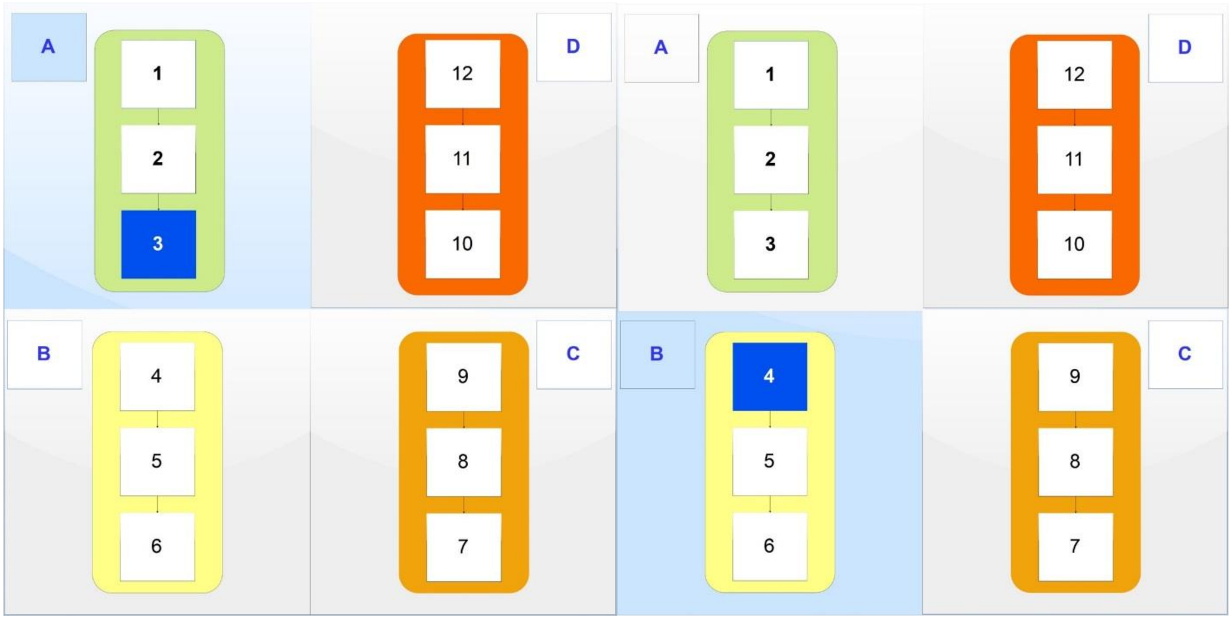


Figure 38 Simplified Model showing Quadrant-to-Quadrant movement from A3 to B4.

The draft designs in this phase are expected to be more detailed and purposeful; therefore, technical requirements (A2) that mirror the stakeholder expectations (A1) should be established alongside performance and design constraints (A3) in Quadrant A. As the systems engine process moves to Quadrant B, the Product Hierarchy (B4) is drawn and Sub-component products are tentatively developed. The product design constraints are also determined (B5) and a Functional Design (B6) is developed to meet the previously generated technical requirements (A2). The Product Hierarchy and Tiers at this stage would usually look similar to the one in figure 39.

Figure 39 Single Tier Product Hierarchy

The Product Hierarchy can be any number of Tiers depending on the product complexity. At this stage, the main product would likely be in a position to go through the Engine but the Sub-products are necessary for the main product to be successful, therefore the sub-products would each be individually taken as a product and run through the Systems Engine from Quadrants A to D in a number of subsequent passes. Using the example in figure 39, the Subproduct A, Sub-product B and Sub product C would each be run through the system quadrant engine per pass, such that all parts of the system would have been completed at Tier 1 after the 4th pass.

Assuming this single Tier Hierarchy of Products is sufficient for the design to be successfully built and tested, even in a virtual environment, a 5th pass would then be run for the main product incorporating all of its product parts.

Alternatively, for a Three Tier Product Hierarchy like shown in figure 40, the system would be used recursively. Therefore, there would be 11 number of passes until all of the 9 sub products as well as the main product and overall system can be compiled and built or adequately modelled for simulation based on its complete systems form.

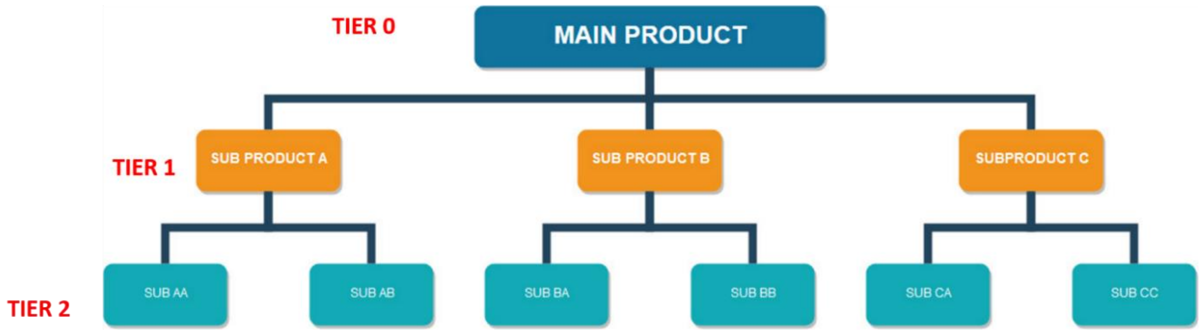


Figure 40. Three Tier Product Hierarchy

As suggested even in the NASA systems model, the risk of too many sub tier levels might make the project extremely costly and expensive, therefore engineering judgement is required to decide when the hierarchy has reached a reasonable sub-tier level. For each product or tier and sub-tier phase product that has reached an engineering solution level (B6) such that it can be built to a testable model or prototype, the product concept enters the C Quadrant (Product architecture) and the product is built electronically at the C7th process (figure 41)

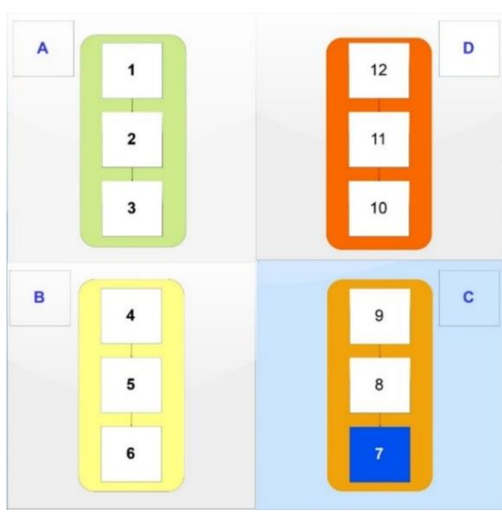


Figure 41 C7th process

Still in the second Phase of the product life cycle, figure 42 illustrates a product concept in the C8th process of the C-Quadrant, which represents alternative design concepts being considered that may have risen during an analysis of potential alternative sub-product designs that are likely to meet the main product design solution. A suitable design would then be decided and the product Hierarchy is updated. A possible design of the hierarchy before and after the alternative product is chosen is given in figure 43.

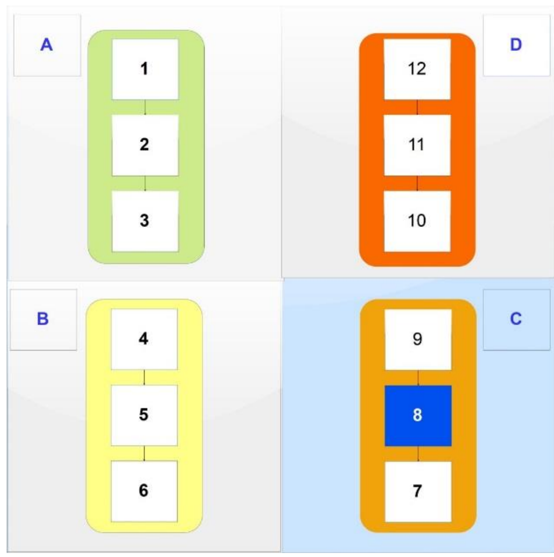


Figure 42 C8th Process

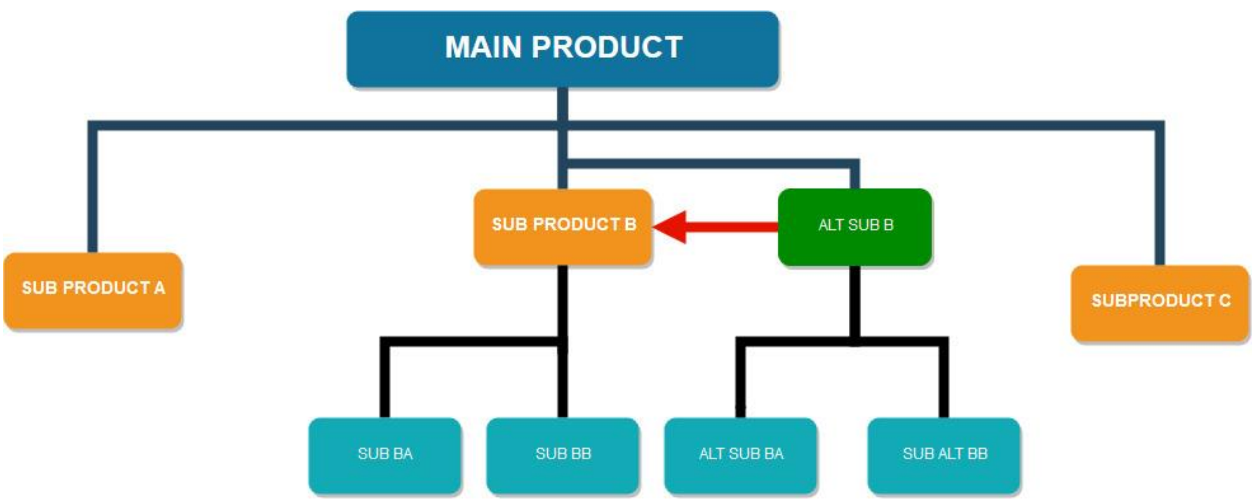


Figure 43 Alternative Product Concept Introduced to Product Architecture

Figure 44 displays a main or sub level product design concept is at the C9th process (Product Selection and Integration) of the C Quadrant (Product Architecture). Perhaps having considered all the alternatives at C8, the designer is confident that the product would meet the specifications based on the CAD model. These ought to have been carefully thought out and designed while applying appropriate mathematical deductions in its construction.

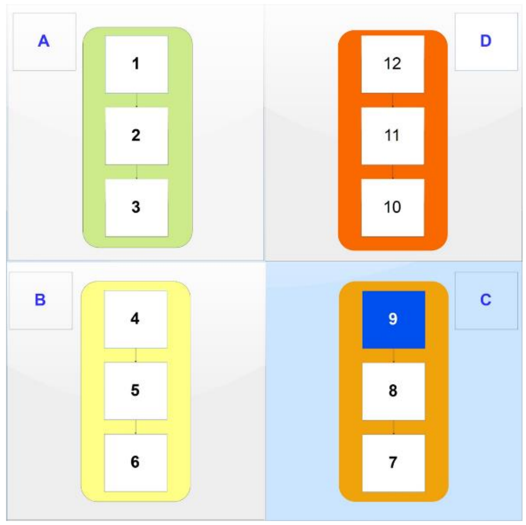


Figure 44 Product concept at C9

The product concept would then have go through more iterative checks using CFD software to verify the electronic design meets the specifications electronically. This process of iterative checks signifies that the product has entered the D Quadrant (Testing) and is undergoing verification checks in the D10 (Verification) process as illustrated in figure 45.

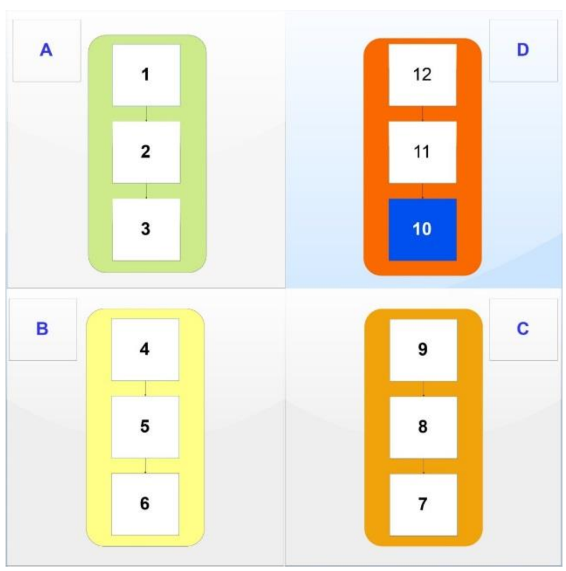


Figure 45 Product concept at process D10.

If successful, the number of passes completed to get to this point have finally paid off for this Phase of the NPD life cycle. The product is no longer just a concept as it is now Idealised and would be transitioned to the next phase of the Product Life Cycle.

5.5.3.3. PHASE THREE: SYSTEM LEVEL DESIGN

The same iterative and recursive process is followed through the Systems Quadrant engine in the previous phase. However, the aim is to build a complete Physical Prototype on entering Quadrant C, using information from the Idealized product phase to build the component parts. This phase of the product life cycle is very important, as it is more cost effective to realize a mistake at this stage than at a time when the product has already been built and sold.

The phase is initiated from Quadrants A and closes out at Quadrant D. However, the first two Quadrants A and B may not require as much passes or alternative concepts as the parts to be prototyped have already been idealized by the electronic versions of the design. If a well done Failure modes and effects analysis (FMEA) test was conducted during the previous phase on the selected CAD models such as with other simulation processes such as Finite Element Analysis (FEA) for testing the structural compositions of the digital models, then good results demonstrates prototypes can be built on a reliable design framework.

The product enters Quadrant C when the first consolidated prototype and all its constituent parts are ready to be built. Rigorous testing is then carried out on the prototype to verify (D10) and validate (D11) the product design. If the product design is successful, the product prototype is then transitioned to the next phase of the product's life cycle from the D12th process of the D Quadrant as shown in figure 46.

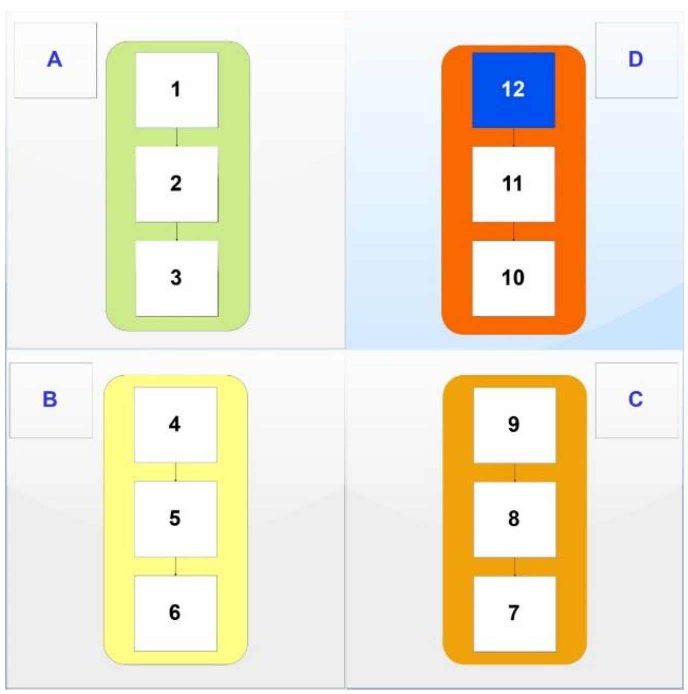


Figure 46 Product design at Product Transition process D12.

5.5.3.4. PHASES FOUR AND FIVE: PRODUCT AND TESTING

This process is carried out in the same manner as the previous phases by re-entering the Systems Quadrant engine at the C-Quadrant but this time the actual finished product is built in full detail with all of its real features. The product is then put through the D Quadrant for Phase 5 (Testing) one final time to validate its ability to meet the stakeholders requirements and verifying it meets any safety and regulatory standards where the products would be used. The product design phase closes out at D12.

5.5.3.5. PHASE SIX OPERATIONS AND SUSTAINMENT:

The Systems Management processes and resources or tools deployed are taken into account, any lessons to be learned are recorded, and possible trainings are decided upon for the staff to be better prepared for subsequent New Product Development processes.

5.5.3.6. PHASE SEVEN PRODUCT LAUNCH:

Preparations for Product Launch are made and the NPD project closes out.

5.5.3.7. PHASE EIGHT AND NINE: MAINTENANCE AND POST LAUNCH REVIEW

The Systems Engine is revisited if any maintenance works or upgrades are required on an existing product that has been designed using the Engine. The Quadrants C and D are used mainly for these functions. Other projects that have not been designed using the Engine would have to be assessed as New Product Development projects and re-enter the product development cycle from the beginning.

5.6. NPD TOOLS RECOMMENDATION

The Resources function of the New Systems Engine is used to recommend tools and resources for any NPD project. Some recommendations for NPD tools that may be useful in the management of the NPD process are highlighted in literature. The following processes and life cycle stages have been highlighted with the corresponding recommended tools in implementation.

5.6.1. KANO MODEL FOR CUSTOMER/STAKEHOLDER EXPECTATION PRIORITIZATION

As discussed in the previous chapter, customers are major influencers of firms' processes and strategies. It is therefore important to figure ways to meet these needs, but first it is imperative that the needs are understood. Kano (1988) explains that in understanding a customer's need, one must not only rely on visible but also hidden expectations. In accordance with this directive, a tool that matches the potential to identify customer/stakeholder needs in terms of achievable levels of satisfaction is required. The **KANO** Model does this quite well and be effective if used during the first phase of the product life cycle and in the A-Quadrant.

5.6.2. QUALITY FUNCTION DEPLOYMENT (QFD) FOR REQUIREMENTS

After identifying customer needs, it would have to be transformed into product concepts. These concepts form the baseline of the product development process. As identified in the previous chapter, most of the firms go into a Brainstorming/Blue sky thinking process to generate possible product ideas.

Company A interviewee said: *We'd start by having a design review meeting, we'd start to just brainstorm on a few of the conceptual designs that we could use, on those conceptual designs.*

Company C interviewee was also quoted as saying: *So if a product is not passing a particular test, we brainstorm, and contribute to sorting the problem.* ***– Company C Participant***

It is therefore important to find an optimization tool for use during these sessions to increase team productivity. The goal of these meetings would be to develop well-articulated requirements for the needs of the customer. A good tool to use for this is **Quality Function Deployment (QFD)**, which would be useful for translating requirements into technical specifications.

5.6.3. TRIZ FOR FUNCTIONAL ENGINEERING

At this point, the output of the Requirements have to be turned into design specifications. In order to meet this specification list, the firm has to rely on their knowledge bases, these would either be In-house Specialists, Standards, Internal Manuals and Memos, as identified from Chapter 4. If these specifications are not met using the proceeds from the internal resources, the external subcontractors can be contacted to get specialist advice. A good tool for systematically deciding trade-offs or contradictions between different functionalities of an ideal product is ***THEORY FOR INVENTIVE PROBLEM SOLVING*** (otherwise known in Russian as **TRIZ)**. In order to visualize these interactions, the design team may make models of the product and test in line with the suggestions from TRIZ. To maximize results, this process would run concurrently with any internal sources of knowledge and external support resources available.

5.6.4. CAD/CFD FOR PROTOTYPING (Systematic Engineering)

A number of the interviewed personnel from the companies identified the functionality of CFD technology. During the Prototyping phase, the results from the functionality identification process can be visualised using the CAD software available to design and CFD software to test digital prototypes. As most current CFD platforms have a geometry modelling function, these conceptual design models could be created using CFD software too. For this phase, the expertise of the designer would be an asset as well as any access the company has to Sub-Contractor or Knowledgeable personnel who are experienced with the use of CFD. As all of the interview participants had positive personal appreciation of CFD or at least had someone employed who did, the goal would be to work closely with the expert to test the results of the design process using CFD. CFD simulations would also take place iteratively at this stage to refine and test the relationships between the product prototype and the functional specifications. When a result has been reached that is consistent enough, the physical prototype can then be built to match the digital version and tested to validate the model. In understanding, how CFD can do this effectively for the companies, Company C interviewee discusses how effective CFD has been in practice:

"…And I found the first time it [CFD] was doing exactly what it was supposed to do exactly as it was designed and First time…". **(Company C respondent).**

Company F interviewee uses an example to explain how CFD can be used in practical terms:

"..CFD as a design tool is quite good looking at changes, but even then you have to put constraints on it. So you have to say that this model has to be within… I think it's 10 percent we used at Company F... the model has to be within 10% of the actual number and then we would look at changes from that model. And if the model can prove the performance by 5%, the test results tended to show that as well. But one of the companies at [Company F] was trying to run

a CFD analysis and get within 1 and a half percent of performance, they were getting absolutely no where. Because that's difficult to do in CFD. Reasonable accuracy is quite easy to get in CFD, well not easy but it's not too difficult. **(Company F Respondent)**

Company F respondent had made the above statement in line with the intentions of the firm to get a 1% tolerance range. It was unlikely he noted, that they would have been able to get the result of the design that they wanted as measurements on a computer are a lot more precise than measurements in real life due to issues such as instrument calibration error or human error.

5.6.5. FMEA FOR TESTING

Following the completion of CFD design, it is important for the products to undergo testing for possible design failures in operation. This can be done using FMEA. However, even with FMEA, it is difficult to detect failure modes that are not visible in a static model but more likely to be noticed in the product's operation. For example, a noisy valve could be experiencing cavitation, but it is impossible to visualize the actual local flow patterns with the naked eye in order to determine exactly what is responsible while the valve is in operation. Failure modes in operation can be investigated using CFD simulation to define and locate fault areas. Real tests should be run concurrently with CFD failure modes to validate CFD results.

5.6.6. CFD FOR PRODUCT LAUNCH

The Marketing/Sales department may also benefit from having the pictures and data generated from the CFD simulation process. These could then be displayed alongside the finished products as they are being advertised (in the case of batch producers) or to communicate progress with the customer during the product development phase based on how often the firm interacts with the customer.

5.6.7. CFD FOR AFTER SALES MAINTENANCE

After the Product is Launched/Sold, the physical model would no longer be available, however the firms can monitor the lifeline of the product by reviewing product models in CFD and testing new failure modes that may affect the product.

5.6.8. CFD FOR UPGRADE OR UPDATE FOR FUTURE DEVELOPMENT

Product development trends worldwide have experienced a rapid approach to product upgrades within shorter periods. In order for firms to keep up with this trend, development teams have to initiate and continue subsequent planning development activities way after product launch in anticipation of the next product upgrade. Especially where the entire development capabilities are applied through the simulation of new conceptual designs.

5.7. CHAPTER SUMMARY

In this Chapter, systems engineering processes have been introduced and a description of their function in methodology creation has been enumerated. The newly developed novel methodology is based on systems principles and meets the criteria from the findings in Chapter four. A novel systems engine framework for navigating through the NPD product lifecycle was also developed. A guide is then presented to help in the application of the process alongside suitable NPD tool recommendations to aid in the utilisation of the methodology.

This chapter satisfies main contribution 2 of the project aim which is to **develop a novel methodology to help firms integrate the best tools and methods to their process.** A detailed description of how it meets the objectives is given in chapter 7 of this thesis.

CHAPTER 6: DEVELOPMENT OF A NOVEL PRODUCT USING NOVEL CFD ASSISTED NPD METHODOLOGY

This chapter demonstrates the use of the New CFD assisted Systems Quadrant Engine that has been developed in Chapter 5 by applying it to a real life project executed by the author in a valve firm. The goal is to test the efficacy of the new method using a pilot test applying a quantitative simulated CFD experiment to test valve performance following the design optimisation.

The main aim of this chapter is to achieve Main Contribution 3 of the research aim and objectives:

Main Contribution 3: Develop a Novel Product using CFD analysis as an integrated technological approach to inform product development.

- **Objective 7:** Product should meet organisational design specifications
- **Objective 8:** Provide documented procedure for Product's development using novel methodology.
- **Objective 9:** Product design should be optimized using CFD technology.

The chapter is divided into 5 main sections. Section 6.1. introduces the pilot company and the reason for the Pilot. Section 6.2. outlines the basics of valve systems. Section 6.3. explains how the New Quadrant Engine is deployed to the valve development process and provides a CFD analysis of the newly developed product's performance. Section 6.4 then concludes the chapter with a summary of achieved objectives.

6.1. PILOT STUDY

Companies in the flow handling equipment industry are constantly looking for ways to maximize the amount of control they have over fluid flow. The need for specialized technology to predict and manage this flow has become a subject of one in several discussions. This is especially true for firms in the valve industry. As the results from interviews indicate, all of the participants from the valve industry at least acknowledged they understood what CFD was used for or were quite aware of it. While they know accurate flow control is achieved via an adequate understanding of the flow patterns within the valve and system, the application of CFD at an organization wide level to the point where the practitioners within the firm can be labelled as having adopted a structured CFD approach to their new product development, is simply non-existent.

This research therefore follows on from the literature and data collection to the development of a new methodology for integrating CFD into the NPD process (Quadrant Engine). It now seeks to test the new methodology using a pilot study. Consequently, a valve firm's real life project was chosen to apply the new methodology and observe its effectiveness in yielding the expected results.

6.1.1. ABOUT THE PILOT COMPANY

A valve firm with keen interest in breaking into new markets took part in the Pilot Study. As at the time of this research, they had discerned that a new valve to add on to their valve product range would be required to do a little more than just restrict or allow fluid flow. Of particular interest to the firm, are valves that are designed to control the given flow characteristics in ways a standard open/shut-off valve would not be likely to accomplish. Therefore, the company management wanted to be able to introduce a new control valve to their current range of products by exploring ways to re-engineer one of their already existing standard globe valves. They wanted the new valve design to exhibit a different flow characteristic from what it was normally able to achieve. The aim is to increase the control capability of the valve to achieve equal percentage capabilities.

6.2. VALVE DYNAMICS

Before the details of the Pilot study itself are outlined, a brief refresher analogy about valves may be necessary to assist readers from other fields in understanding the nature of the pilot.

Among various kind of valves that exist, such as ball valves, gate valves, butterfly valves, and others, the globe valves are the most prominent. This is due to its unique geometry that allows for the achievement of varied flow patterns in relation to its plug shape. The valve flow characteristics of the valve is determined by the design of the Valve trim (which refers to the valve plug and valve seat area).

6.2.1. VALVE FLOW COEFFICIENT (CV)

The Valve flow Coefficient (Cv) is defined as the number of gallons per minute (US GPM) that can pass through a valve at 60°F with a pressure drop of 1psi. The Cv is used in valve sizing and selection. In order to measure the flow Coefficient of a Valve. The following formula is used:

$C_V = Q\sqrt{\frac{SG}{\Delta P}}$ ………. [Equation 1]

Where:

Cv = Valve Flow Capacity

Q = Flow Rate in US Gallons per minute (GPM)

ΔP = Pressure Drop across the valve in Psi

SG = Specific gravity of water (usually 1)

6.2.2. CONTROL VALVES AND DESIGN IMPLICATIONS

In general, valves are used mainly for controlling fluid flow. Control Valves on the other hand, are designed specifically to specify a given flow characteristic at each % of opening of the valve. These would usually come into effect when it is set up within a system of flow piping that conveys the fluid it is meant to control. Therefore a control valve has to be designed systemically, which means the wider system the valve is a part of the system to be considered.

6.2.3. INHERENT VALVE FLOW CHARACTERISTICS

The inherent flow characteristics of a valve are used to establish the relationship between the flow through the valve and the percentage (%) opening of the valve.

In terms of the operating Valve flow characteristics, there are categorically three different kinds of Valves: Quick Opening, Linear and Equal Percentage Valves.

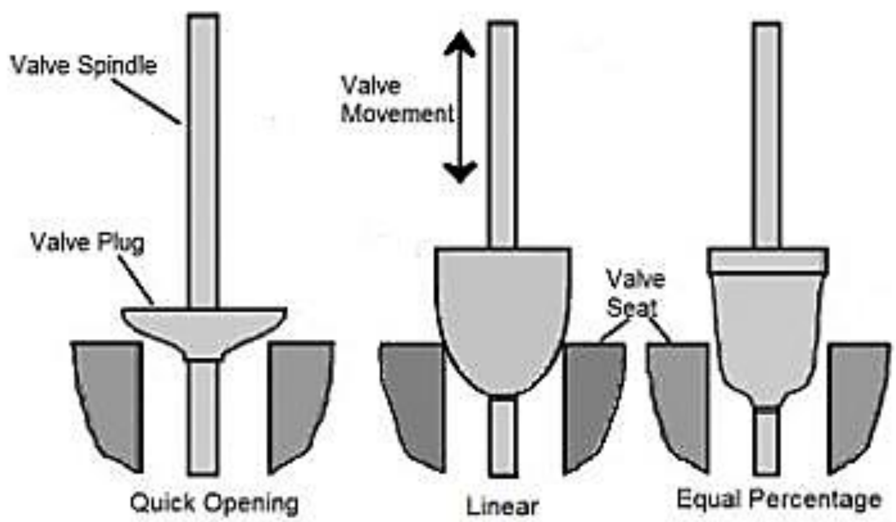
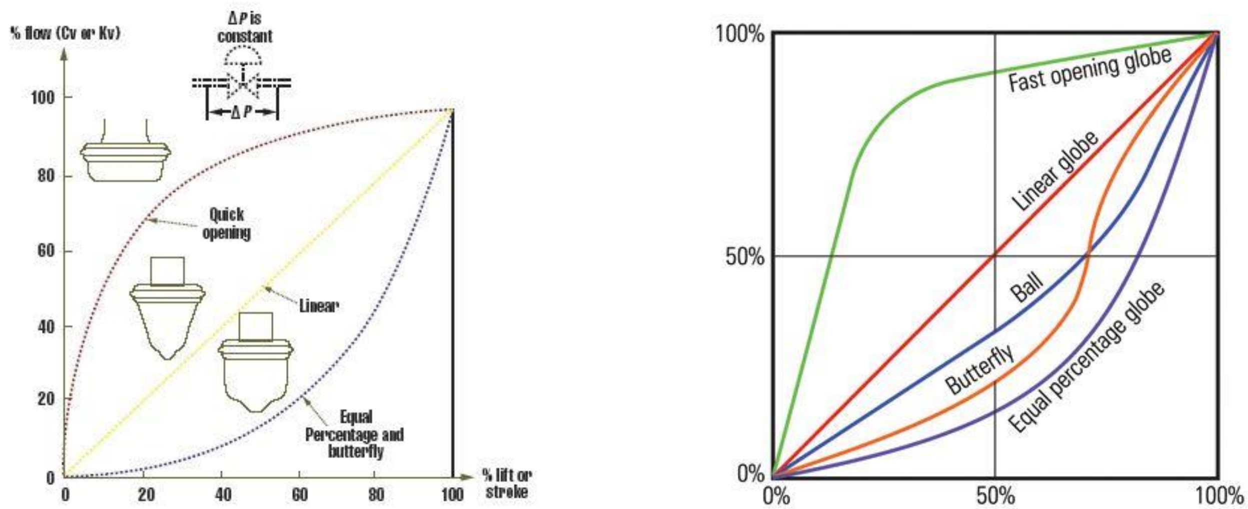


Figure 47 Inherent Valve Flow Characteristics (Dutta, Sarkar, Samanta, Das, & Ghosh, 2014)

- **Quick Opening Valve:** Also known as on/off valves, the Quick opening valve is practically used to restrict the flow through a system. These valves provide very large flows for very little lift. For example, a valve lift of 40% may deliver 60% of the flow from the valve.
- **Linear:** Valves with Linear flow characteristics permit flow that increases linearly with plug movement. Therefore, a 50% lift will deliver 50% of the flow.

- **Equal Percentage Valves:** This refers to valves that exhibit equal increments in flow for equal percentage changes per opening. Therefore, if a valve lift of 30% produces a certain flow, a further 20% of lift from that point should equally produce a 20% increase in flow.

As represented in figure 47, the fluid flow is determined by the shape of the Valve Plug. The valve flow characteristics in figure 48 (a) also show what their flow versus lift curves would look like depending on the plug shape of the valves. Valve Flow characteristics for globe and other valves are also shown in figure 48 (b).



(a) (Shinjo, 2018) Valve Flow Characteristics Curve (**b) (Spiraxsarco 2018)**

Figure 48 Valve Flow Characteristics Curve

The Linear and Equal Percentage Valve Flow characteristics Globe valves are desirable valves due to the amount of control they have over the flow as opposed to the Quick opening valve that is used mostly for shut off operations. There are other rare kinds of valves such as the modified parabolic which is a hybrid kind of valve that keeps linear for half of the flow and become equal percentage or vice versa.

In the following sections, a detailed approach to the New Product Development practice introduced in Chapter 5 is exemplified through a Pilot project organized to test the New NPD methodology (NPD) that has been developed to see its efficacy in the development of a new product. For more details about the methodology's design and prospects, please refer to the previous Chapter.

6.3. DEVELOPMENT OF THE NEW PRODUCT

6.3.1. OVERVIEW AND SCOPE

To aid in this task, the New Quadrant Engine is deployed alongside the product lifecycle (figure 49). The Quadrants from the newly developed Quadrant Engine system are used throughout the development process and the product is moved through the product lifecycle.

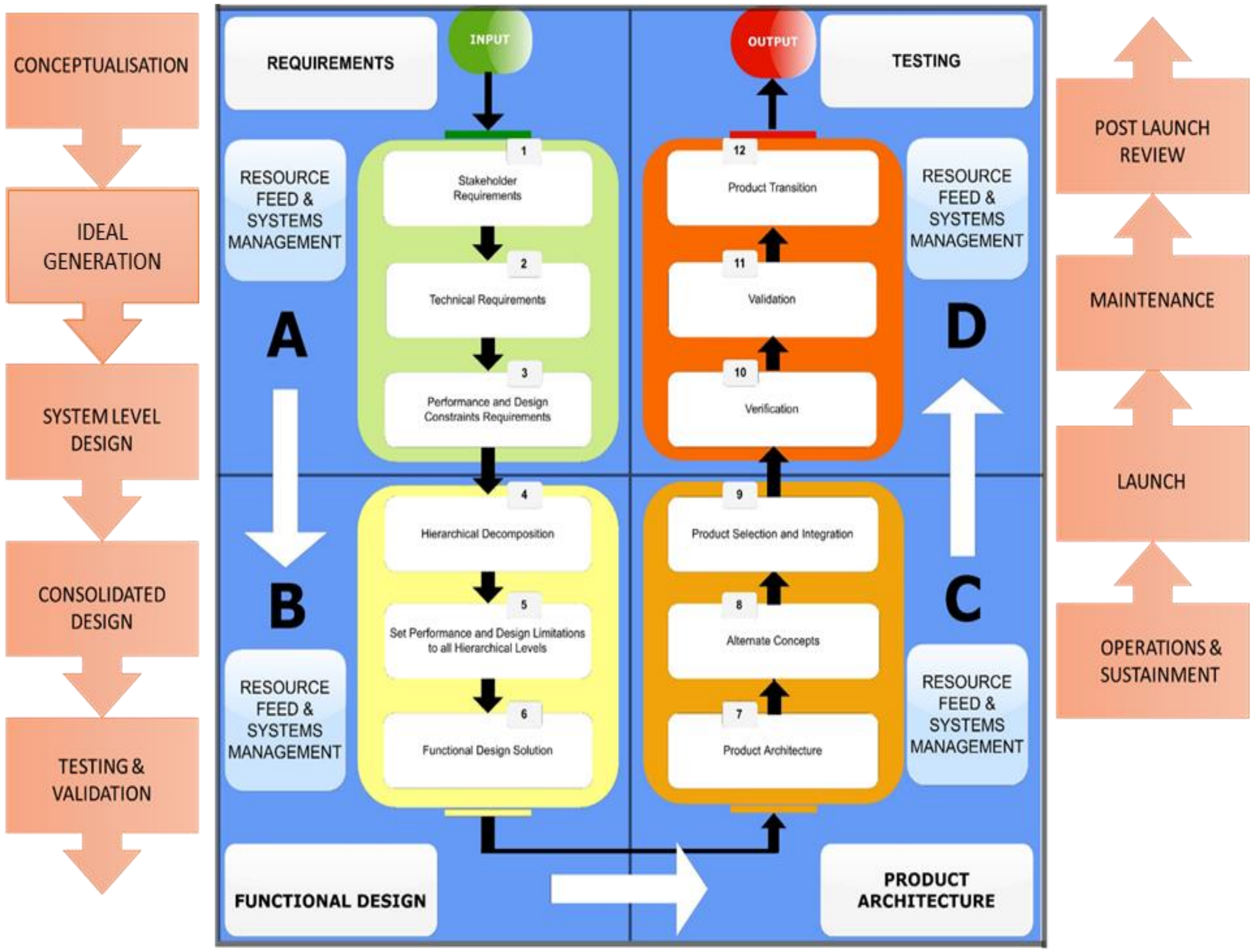


Figure 49 The Quadrant engine & Product Life Cycle.

The fully developed Quadrant Engine is capable of taking the development of the product through the entire Product Life Cycle from conception to the finished product. However, it was decided that for the purpose of this thesis, product development would close out when a satisfactory virtual model has been built that performs as expected when tested through simulated experiments i.e Development section of the product lifecycle (Phases 1-3 of Table 10).

The next stage after the Ideal product phase would have been, as designed in the Quadrant System, to build a physical prototype, and the finished product. However, a cause for concern is the time scale for procurement of the materials required at such a point, which is beyond the scope and resources of this study. This is especially as this study seeks only to demonstrate the applicability and efficacy of CFD in the development of a new product.

In addition, it is worthy to note that the ANSYS 18.2 CFD package was the current version of the software at the time of the study and has been used for all CFD related work in this thesis.

To begin the project, the product enters immediately into the first phase of the product's life cycle as an idea.

6.3.2. SEQUENCE OF PROCESSES

The following quadrants and processes would be applied to the study, but first a Life Cycle layout of the process would be given:

DEFINING THE LIFECYCLE OF A VALVE

PHASE 1 LIFE CYCLE (CONCEPTUALISATION PHASE):

Determine the Operating procedure for obtaining the Inherent Flow Characteristics of the Valve and the Maximum Cv value using Standard Procedure for CFD Analysis. As obtained from Versteeg and Malalasekera (2007) in literature CFD, processing is divided into pre-processing, processing and post processing. For this pilot, the following activities would be carried out:

- **Pre-processing**
    - Create Geometry of current Valve in CAD Software
    - Import Geometry to Simulation Software (ANSYS)
    - Extract Flow Domain
    - Meshing
- **Processing**
    - Solver Settings
    - Boundary Conditions
- **Post Processing**
    - Plot Valve Flow Characteristics Curve
    - Details of Discovered Contours (Pressure & Velocity)

LIFE CYCLE PHASE 2 (IDEAL GENERATION):

Determine the Optimum Procedure for obtaining the Design Solution

- Apply Resource Feed solutions: TRIZ technique to determine design solution
- Develop conceptual baseline solution design model for CFD analysis
- Repeat the Standard Procedure for CFD analysis from Life cycle phase 1
- Obtain CFD results and evaluate performance of new design model

LIFE CYCLE PHASE 3 (SYSTEM LEVEL DESIGN):

- Determine the Optimum Design by Interpolating Geometric dimensions between the previous designs and Cv with expected Cv results to obtain new dimensions.
- Refine Conceptual baseline model based on new dimensions.
- Repeat Standard Procedure from Life Cycle phase 1 until optimum design is achieved.

6.3.3. APPLICATION OF THE QUADRANT ENGINE

The Quadrant Engine is applied to the Life Cycle definitions to structure the product development process.

A-QUADRANT: REQUIREMENTS

At this stage, all of the requirements for the project were decided to populate the resource feed of the Quadrant Engine (QE).

(A1) STAKEHOLDER REQUIREMENTS

A meeting was held with the stakeholders (company representatives). Their expectations of the product were discussed and approved. The Company had requested for their standard 4" class 900 valve to be modified into a new Control Valve that is capable of controlling the flow per percentage opening of the valve. Prior to this project, the valve could only be used for on/off operations.

(A2) Technical Requirements/Resource Identification & Systems Management:

AIM: To create a Control Valve that controls the flow, preferably a valve with Hybrid Valve Characteristics.

During this stage, all of the resources for the project were defined. The following were the items used for the Project.

- Software Used:
  - CAD PACKAGE: SOLIDWORKS 2017 (For CAD Geometrical Modelling)

    - CFD PACKAGE: ANSYS WORKBENCH 18.2 (For Flow Domain Extraction, Meshing and Fluent Solver)
- Main Valve Equations
    - Valve CV Equation
    - Equal Percentage Equation
- Tools to be Deployed
    - TRIZ
    - QFD was not used during this pilot, but it would have been applied if the product had several parts in the hierarchy tree (in B4).

(A3) Performance and Design Constraints Requirements

Processes for checking design and performance are determined by the Phase of the Lifecycle.

- Mesh Independence Test was conducted in the first phase to obtain best results.
- Inherent Valve Characteristics Curve was checked to understand current design
- In subsequent phases, Valve Characteristics Cv values were checked after re-design to evaluate how the valve exhibits flow control properties (Equal Percentage or Linear).

B-QUADRANT: FUNCTIONAL DESIGN

(B4) Hierarchical Decomposition

To determine the interacting Products or Sub-products, a hierarchical structure of product composition was created. The following are the parts of the valve that make up the fluid flow domain.

- Valve Plug (Determine Shape)
- Valve Seat (Orifice Size - Fixed)
- Valve Piping (fixed diameter, d = inlet diameter of valve,
- Piping Lengths fixed: 2 x d at inlet and 6 x d at outlet, provided by valve piping standards BS EN 60534-2-3.

(B5) DESIGN LIMITATIONS AND CONSTRAINTS

- Valve Lift: Lift may be increased if necessary to meet the design expectations
- Valve Seat Orifice Size: (Fixed) It is not possible to extend the horizontal width of the internal valve seat.

(B6) FUNCTIONAL DESIGN

- Run the EQUAL PERCENTAGE CALCULATION
- Determine Desired Flow Coefficients (Cv)
- Establish Relationship between Plug Shape and Cv.
- Define Corresponding Valve Geometric Shape for desired Cv.

C-QUADRANT (PRODUCT ARCHITECTURE)

- (C7) Determine Product Architecture of the Valve
- (C8) Refine Geometry through Alternative Part Concepts
- (C9) RUN SIMULATION

D-QUADRANT (TESTING)

- (D10) Perform the CV CALCULATION at each opening
- (D11) Check CV Results and Flow Characteristics to determine what kind of Valve it is.
- (D12) Check Contour Maps for Verification (Run SIMULATION to check for errors)

The process is then repeated for subsequent phases until product Architecture has been defined and verified to meet the desired Cv values.

PHASES OF DEVELOPMENT: (IDEAL DEVELOPMENT)

- FIRST PASS: DESIGN 1 (To decide Valve Plug).
- SYSTEM LEVEL DESIGN (Decide Valve)
- ONE (1) PASS: WITH DESIGN 2
- CONSOLIDATED DESIGN
- ONE (1) PASS: DESIGN 3

6.3.4. AIM 1: DETERMINE THE INHERENT FLOW CHARACTERISTICS OF THE VALVE AND OBTAIN THE MAXIMUM Cv.

Create Geometry of Inherent Valve in CAD Software.

The CAD model document of the 4” Class 900 Globe Valve model was received from the Company via email in SOLIDWORKS format as illustrated in figure 50.

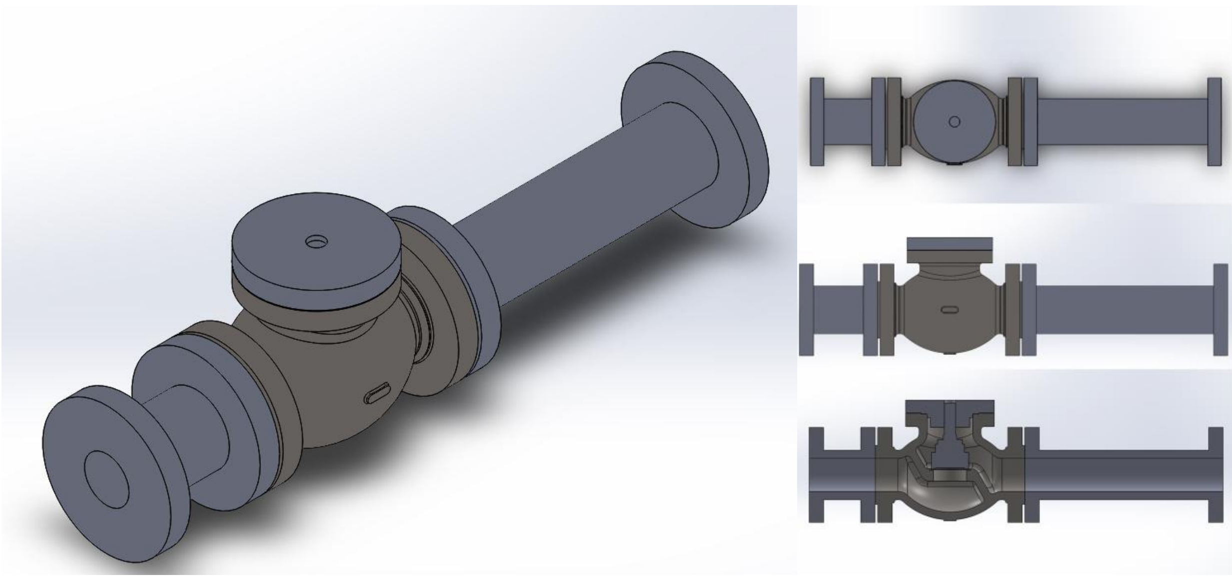


Figure 50. The 4” Class 900 Globe Valve

Within the SOLIDWORKS application, the “distance mate” function was applied to mate the surfaces of the valve plug to the 4” diameter seat orifice area. This was done in order to determine and control the lift of the valve trim for different simulations. The maximum lift of the current valve is 1 inch at 0.1 inch per percentage opening. The valve also has 4” diameter orifices at both of its ends to which two straight pipes are connected at the inlet and outlet ends of the valve, measuring 8 (2 x d) and 24 (6 x d) respectively, where d represents the diameter of the valve orifice in accordance with Industrial valve standards (IEC 60534-2-1).

Valve Plug Characteristics

The geometry of the Valve Plug as displayed in Figure 51 was noted, as well as it's open and closed position relative to the Valve seat orifice.

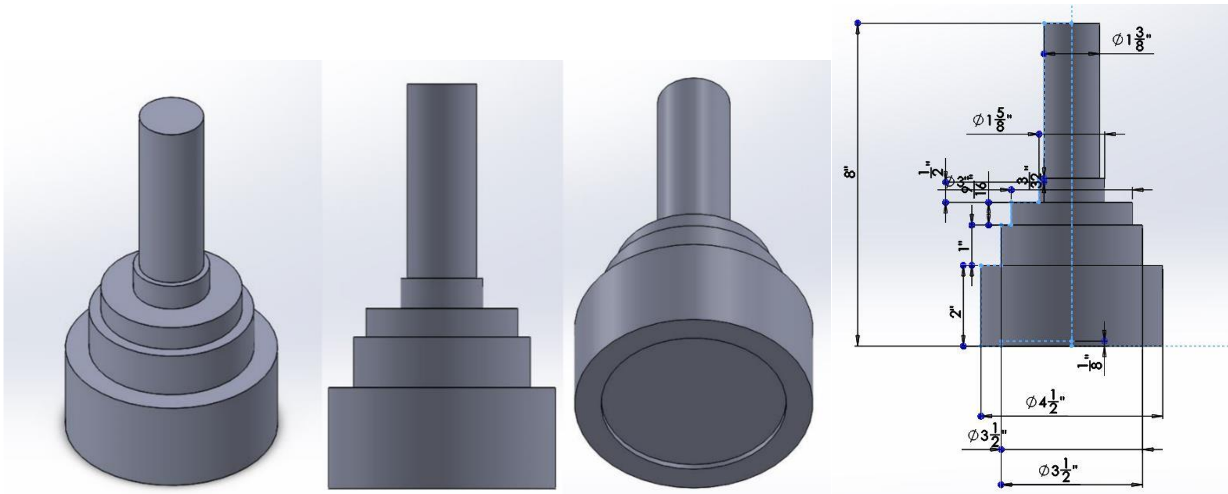


Figure 51 Standard 4" Class 900 Globe Valve Plug

A Trimetric view of the Valve Plug at 10% open position (almost closed) in figure 52 shows that the valve plug stops fluid flow by resting on top of the orifice area of the seat, thereby sealing the orifice and stopping the flow.

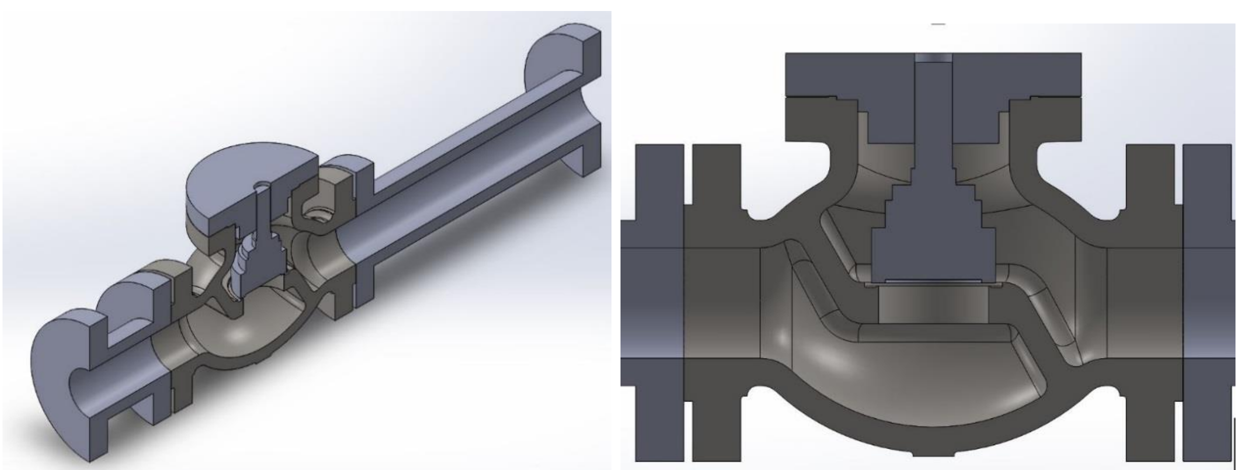


Figure 52 Cross sectional area of Valve assembly indicating Valve Plug position

It allows maximum flow through the valve to the outlet when the plug is raised to a height 1inch from the valve seat. The flow medium of the valve is water and the direction of flow is from the bottom-up.

Import Geometry to Simulation Software

After each of the percentage openings of the valve were determined and the pipes were attached to the model, the valve CAD model was imported into ANSYS Workbench Geometry Modeller to set it up for simulation.

Extraction of Flow Domain and Name

The flow domain was extracted from the valve geometry using 'ANSYS Space Claim' volume extraction function as displayed in figure 53. The two ends of the pipes on the flow domain were named as Inlet and Outlet to enable the Solver automatically pick out the right ends of the pipe when setting the Boundary Conditions.

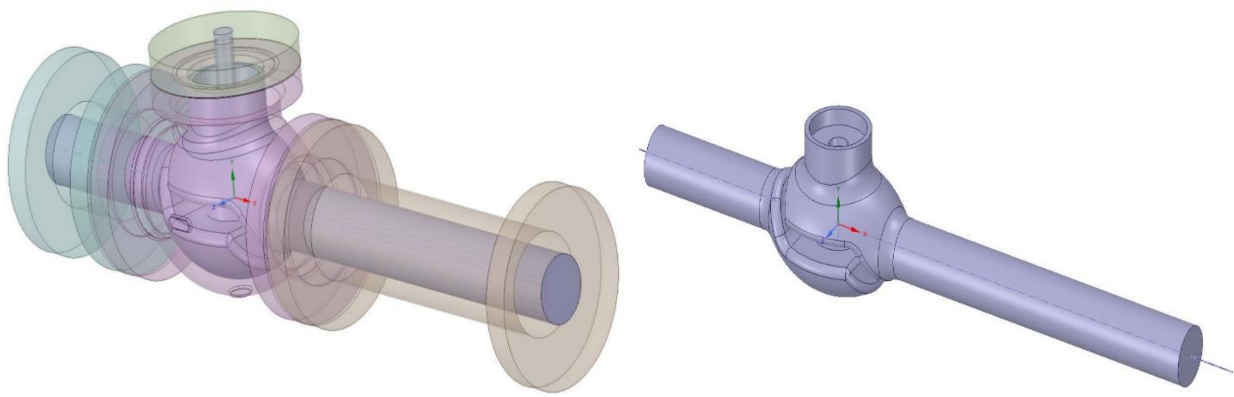
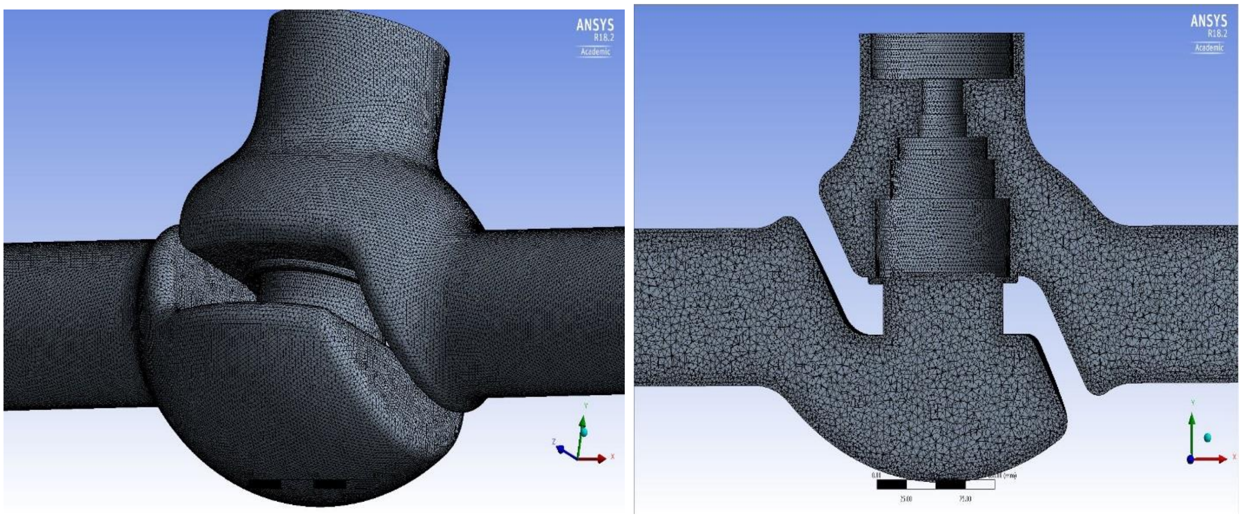


Figure 53 Extracted Flow Domain

Mesh Settings

The internal flow domain of the valve was meshed to define the cells that the solver would use to calculate and determine the flow properties of the valve during the simulation.

The 'proximity and curvature' feature on "ANSYS Mesh" was applied to maximize the efficiency of the flow calculations by the allocation of more mesh cells within and around the edges and curves of the valve trim where the flow is likely to undergo major changes, such as along the walls of the valve including the inlet and outlet pipes and the space between the plug and the valve as shown in figure 54 (a and b). Tetrahedral meshing was used for the valve trim and set at a maximum face size of 3mm, mesh defeature size was set to 2mm to reduce unnecessary complexity of the geometry during flow calculation. The number of cells across gaps was left at 3. 4 Inflation layers were also specified to manage the boundary layers. Number of cell elements after meshing was 1.8 million.



(a) **(b)**

Figure 54 Mesh definition (a) and Cross sectional view of the mesh (b)

Mesh Independence Test

As with most globe valves, the meshing component is a very important feature as it determines the accuracy of the results. A decision therefore has to be made between faster solve times and accuracy. A mesh independence test is used to find out if the results obtained from the solver could be influenced by the mesh. The goal is to optimize the ability of the solver to provide accurate results and to do so without taking too long. To this end, a Mesh Independence Test was conducted using three different mesh elements of 1.8 million, 2.7 million and 4.8million. In Table 11, the Pressure and CV values show a difference of less than 1% and so the Mesh of 1.8 million is used for the rest of the simulations.

Table 11 Mesh Independence Values

No. of mesh elements	Inlet (Pa)	Outlet (Pa)	Pressure Drop (Pa)	Pressure Drop (PSI)	CV	% Difference
1835461	3973201	0	3973201	57.626394	33.825	0.3181
2789296	396060	0	396060	57.44364	33.879	
4853885	392220	0	392220	56.8867	34.045	0.9790

Solver Settings

The following Solver settings were used in 'ANSYS Fluent' (which is the solver application for ANSYS 18.2) to simulate the flow characteristics of the valve.

As the flow in a valve is often Turbulent, the K Epsilon Realizable Model was chosen to model that capability. This is because the K-Epsilon model is useful for modelling fluid flow in areas where the pressure gradient is very steep these would usually occur between the plug and orifice area.

The material selected is water-liquid (h20) with density 998.2kg/m^3 and viscosity at 0.00103Kg/m-s.

Boundary Conditions

The valve Inlet velocity at the inlet pipe is specified as any integers ranging between 1m/sec and 5m/sec as this defines the achievable flow velocities for these kind of valves. Velocity is set to 2m/s at the inlet pipe, Pressure at outlet end pipe is set to 0 Pa (Pascal) which is the atmospheric pressure. The hydrodynamic properties of the wall presents no roughness that may interfere with the fluid flow so this setting is left as Stationary which represents no roughness. Turbulence Specifications are set at 5% Intensity and Hydraulic diameter 0.1 for both Velocity and Pressure Outlets.

RESULTS

After setting up the CFD Solver, the valve flow is simulated at various lift positions (VOP) to obtain the inherent valve flow characteristics.

The following results in Table 12 were obtained from the simulation:

Table 12 Results from CFD Simulation of Inherent Valve Flow Characteristics

VOP (%)	Flow Rate	Pressure Drop (Pa)	Pressure Drop (PSI)	CV	% of Max Cv
0	0	0	0	0	0.0
10	256.78	19350.4	2.806544	32.6	16.0
20	256.78	14482.29	2.100483	58.2	28.5
30	256.78	11817.98	1.714056	87.4	42.8
40	256.78	10214.24	1.481452	117	57.4
50	256.78	9206.987	1.335363	144	70.6
60	256.78	8680.431	1.258992	162	79.4
70	256.78	8304.475	1.204464	177	86.8
80	256.78	8079.379	1.171817	187	91.7
90	256.78	7851.745	1.138801	198	97.1
100	256.78	7735.417	1.121929	204	100.0

RESULTS ANALYSIS

The results as shown in Figure 55 show the flow characteristics of the valve as plotted from the % cv values against % opening. The flow characteristics depict a flow through a Valve with Quick Opening Characteristics.

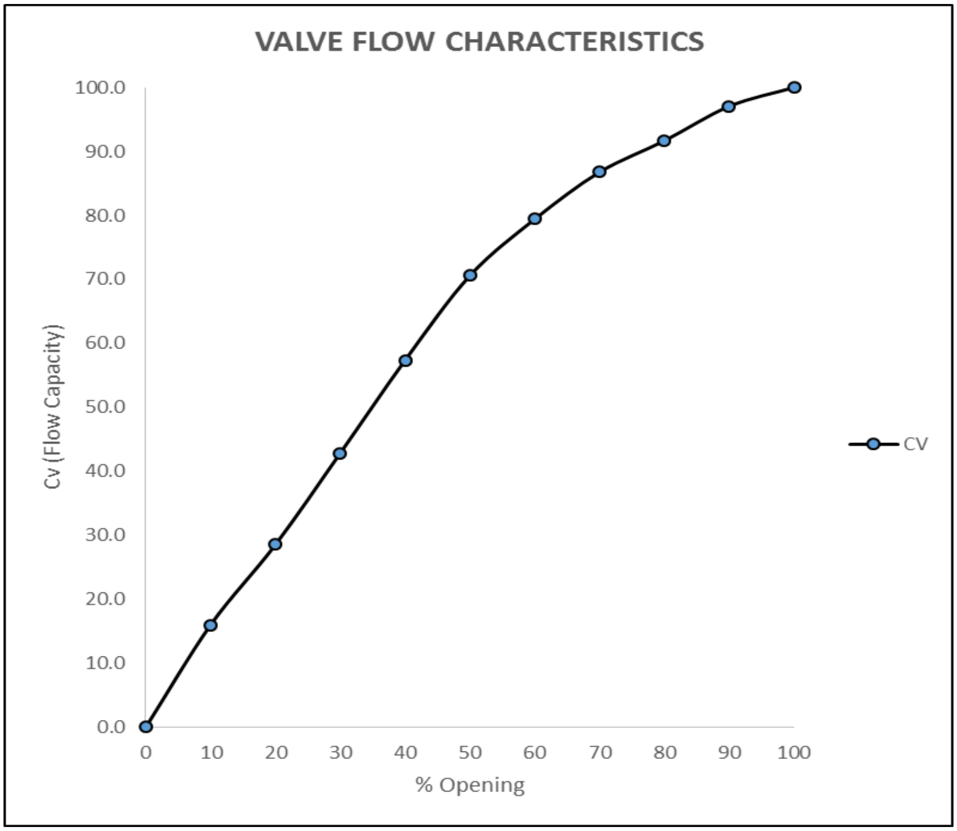


Figure 55 Valve Flow Characteristics of the Standard Globe Valve

The inherent flow characteristics curve demonstrates that the valve is a quick opening one. These kind of valves do not control flow as they are very sensitive to small changes in lifts from valve closed position.

The company would prefer to have an Equal Percentage Valve so it is the intent of this study to design one.

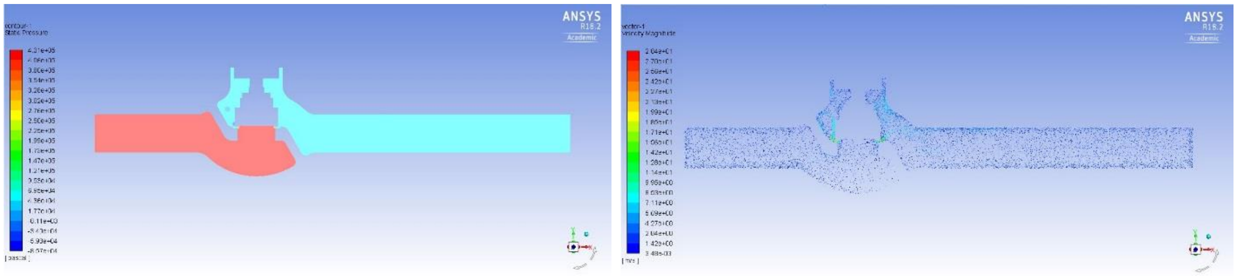


Figure 56 Pressure and Velocity contours at 10% valve opening for standard valve.

Figure 56 illustrates the variations in pressure and velocity at 10% valve opening. As can be seen from the pressure contours, there is a lot of concentration of pressure at the inlet pipes and in the valve. This is due to the flow being restricted at 10% opening by the Valve Plug. As the flow approaches the valve plug, the cross-sectional area of flow passage reduces considerably. The pressurized flow then drops abruptly as it passes this obstruction and on to the outlet. It is also evident when observing the velocity vectors that the flow occurs very rapidly as the cross-sectional area reduces between the plug and the seat. However, when the flow goes through the orifice, the velocity tends to increase momentarily and then recovers afterwards.

Velocity contour maps, the pressure across the valve changes drastically as the plug is close to restricting the flow.

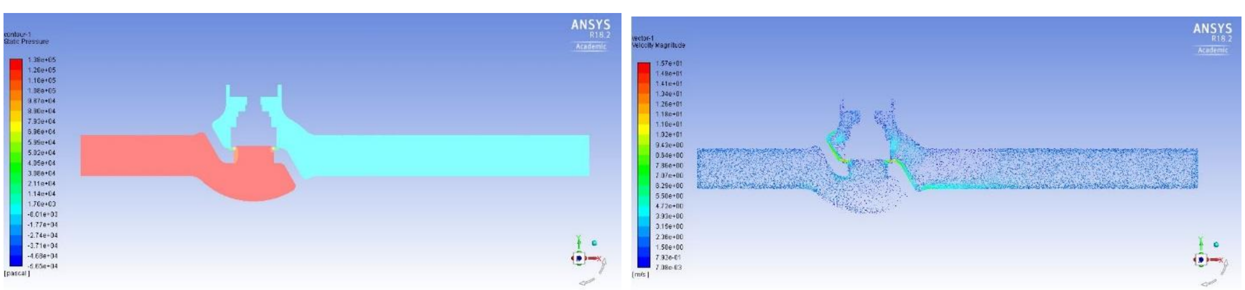


Figure 57 Pressure and Velocity contours at 20% valve opening for standard valve.

Figure 57 illustrates the variations in pressure and velocity at 20% opening. The pressure distribution seems similar to that at the 10% opening. However, the pressure stabilizes close to the seat as more flow area is made available by the lift of the valve plug. The velocity also changes considerably as it approaches the valve trim area, there also appears to be an increase in velocity around the walls of the valve.

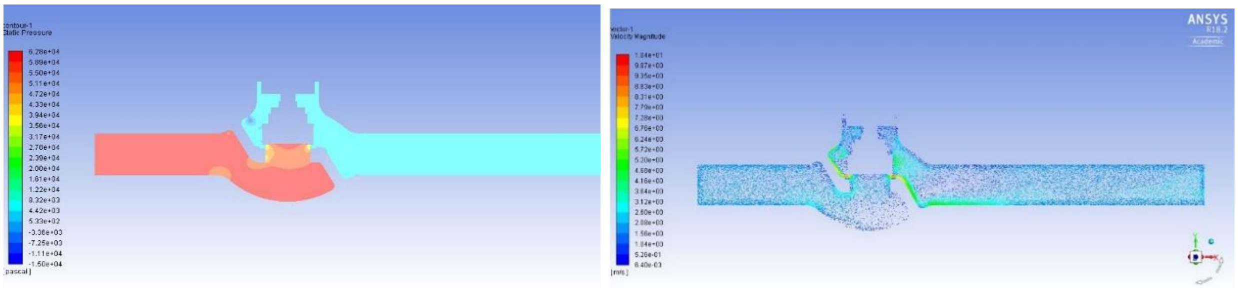


Figure 58 Pressure and Velocity contours at 30% valve opening for standard valve.

At 30% opening as shown In figure 58, the pressure contours show a lot of variations around the valve plug, as the flow gets through the narrow cross sectional area, it recovers quickly and continues on to the outlet of the pipe. The velocity vectors tend to depict higher velocities occurring around the plug and close to the wall area. This explains the concepts of a Quick opening valve and shows how fast the flow recovers and fully reaches around and about the valve.

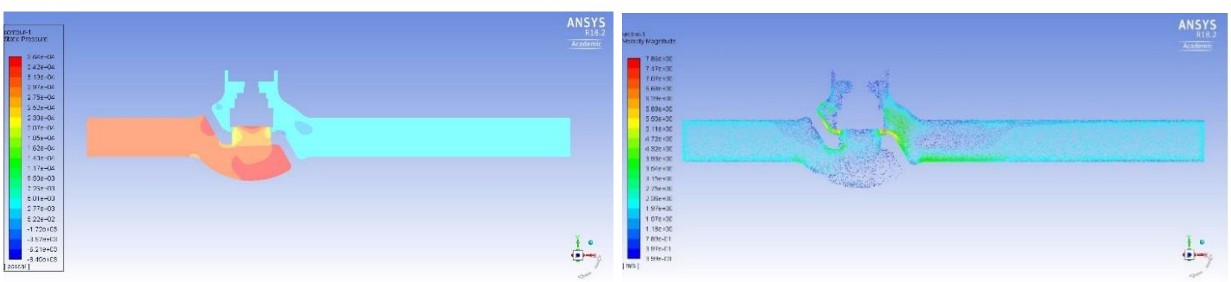


Figure 59 Pressure and Velocity contours at 40% valve opening for standard valve.

The figure 59 displays the valve’s pressure and velocity distributions. The pressure appears to have reduced considerably at the inlet at 40% opening, except at the shaded region at bottom left position below the seat where a lot of the velocity flow direction seems to be low. Probably due to its flow path being directed upwards through the valve orifice area.

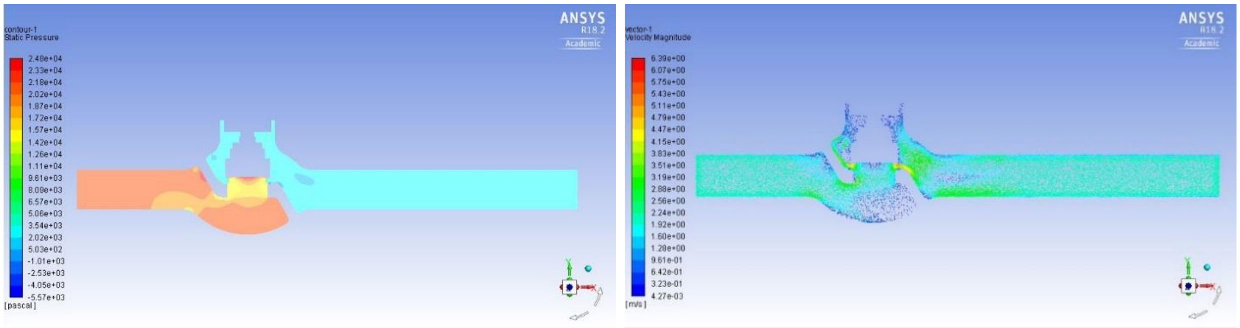


Figure 60 Pressure and Velocity contours at 50% valve opening for standard valve.

The figure 60 illustrates some variations in the pressure pattern mostly as a result of the valve being half way open. Pressure in the downstream part of the valve and pipe has practically reduced by now, but the velocity seems to have increased considerably now, hitting peaks of about 4.47m/s to 5.1m/s momentarily when it hits the valve plug at the top. Pressure drop also seems to have reduced compared to the previous valve positions.

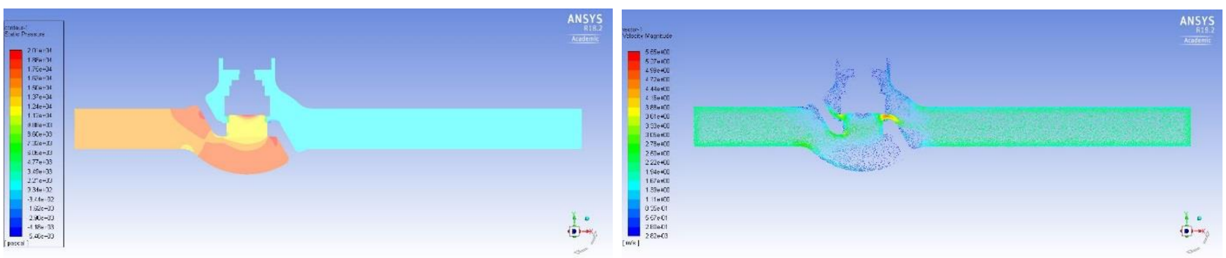


Figure 61 Pressure and Velocity contours at 60% valve opening for standard valve.

As displayed in figure 61, the velocity vectors flow has basically stabilized. There are still areas where the velocity of the flow increases around the edges of the plug, however, the pressure drop seems to not have changed much from the previous opening.

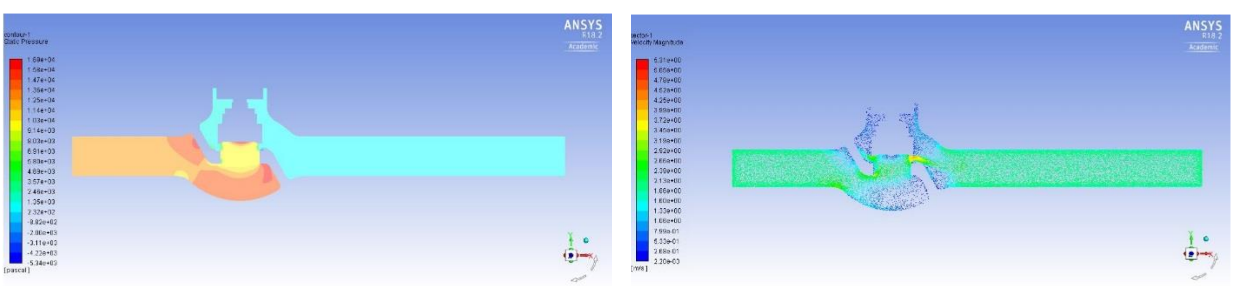


Figure 62 Pressure and Velocity contours at 70% valve opening for standard valve

As illustrated in figure 62, the velocity and pressure contours seem not to have changed much at 70% opening, As the flow cross sectional area is increased due to the lift of the valve, all of the flow properties seem to have occurred already and variations to their properties have not changed much. This gives an indication yet again that the flow through the valve has opened very quickly as compared to any of the control valves that would present a more gradual process for any changes in flow patterns.

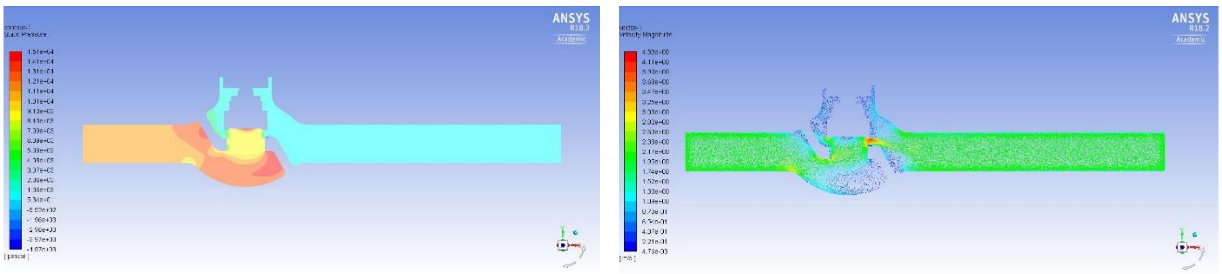


Figure 63 Pressure and Velocity contours at 80% valve opening for standard valve.

As illustrated in figure 63, at 80% open, again the changes to the flow are minimal. The pressure contours directly under the plug shows pressure drop of about 8.95×10^3Pa. The velocity also shows substantial effect in and around the areas where the fluid flow is not restricted.

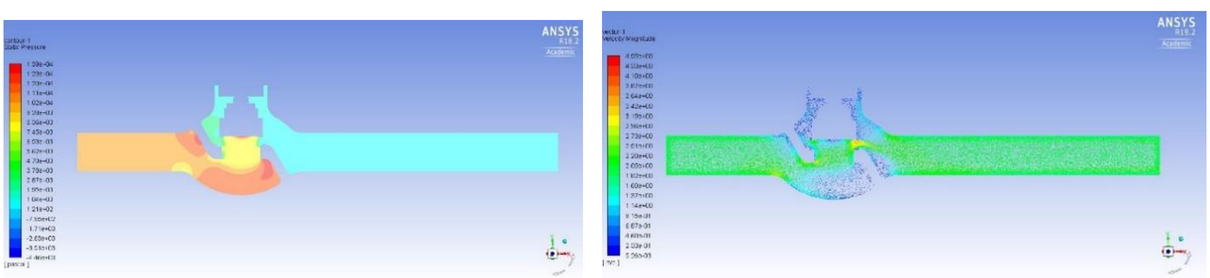


Figure 64 Pressure and Velocity contours at 90% valve opening for standard valve.

At 90% open as illustrated in Figure 64, there are practically not much effects the plug has on the fluid flow, as the pressure contours do not display much variations in the behaviour of the flow.

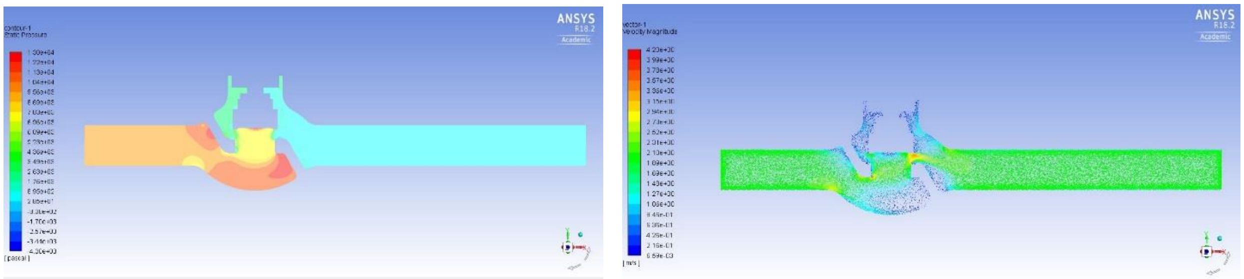


Figure 65 Pressure and Velocity contours at 100% valve opening for standard valve.

Figure 65 illustrates the valve plug position at 100% open, As there has likely been no significant change that has occurred between the inlet and outlet of the valves, It is evident then at this point, the velocity and pressure flow are likely at their most natural flow forms within the valve without any changes. This stability of the pressure contours and velocity vectors contribute to the reasons behind the valve flow characteristics curve in figure 55. and therefore explains why the curve does not increase any further but forks towards the right indicating that as the velocity and pressure are not changing considerably, the valve CV does not change considerably at this point in the opening of the valve as well.

B-QUADRANT OF THE SYSTEMS ENGINE

When the settings on the solver software have been determined and the baseline requirements have been set, the Systems Engine would progress to the B-QUADRANT of the novel systems Engine.

Note: This quadrant runs concurrently with Quadrant A of the Valve development Process.

HIERACHICAL DECOMPOSITION

The Valve is taken as a System and segmented into the following 3 Hierarchical sections and their accompanying parts: Valve Inlet Pipe, Valve Mid-section, Valve Outlet Pipe.

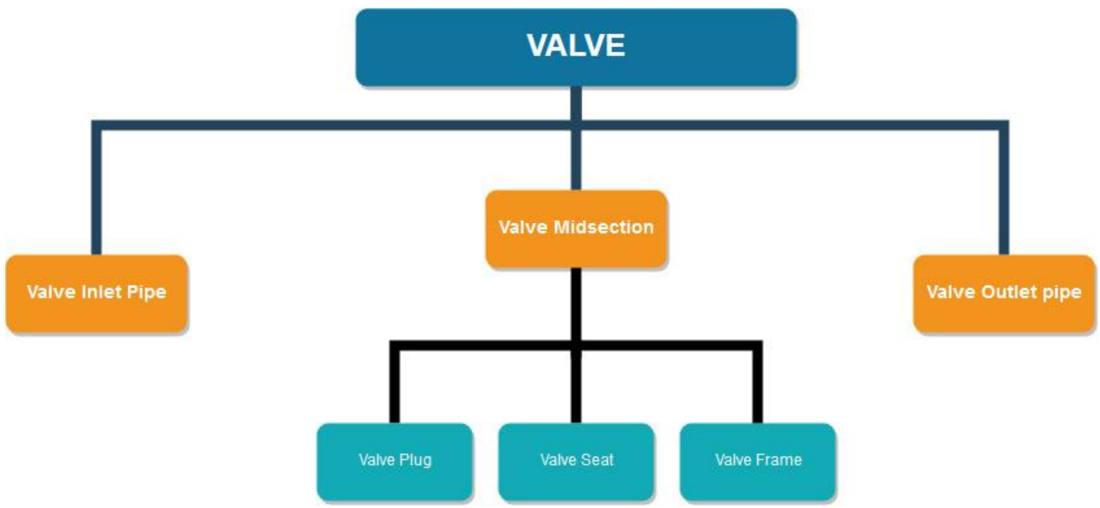


Figure 66 Hierarchy Tree of Valve Component Parts

As can be seen from figure 66. The Valve Midsection is made up of 3 main parts. The Valve Plug (Movable manually or with the help of an actuator) and the Valve Seat (which is the orifice between the inlet and outlet sections of the valve. The Valve Frame (otherwise known as valve bonnet or walls of the valve) also plays a role in determining the flow characteristics of the valve. However, the prominent modifiable contributors to flow characteristics modification are the Valve trim (valve plug and seat) and piping. Within the context of a standard sized valve body which would be applicable to many valves of similar type, the valve frame would remain the same as the size of the valve body is determined by the industry standards. The Valve Inlet and Outlet pipes are also designable by standards. The Valve Inlet and Outlet pipes are set as 2d = 4 while the Outlet pipes are set as 6d = 24 (where d is 4" diameter of the valve orifice). By temporarily freezing the parts that are fixed by standards, the focus can now be placed on the parts that can be modified in this case, the Valve Trim. The Hierarchy would now look different from the one that was illustrated in figure 57.

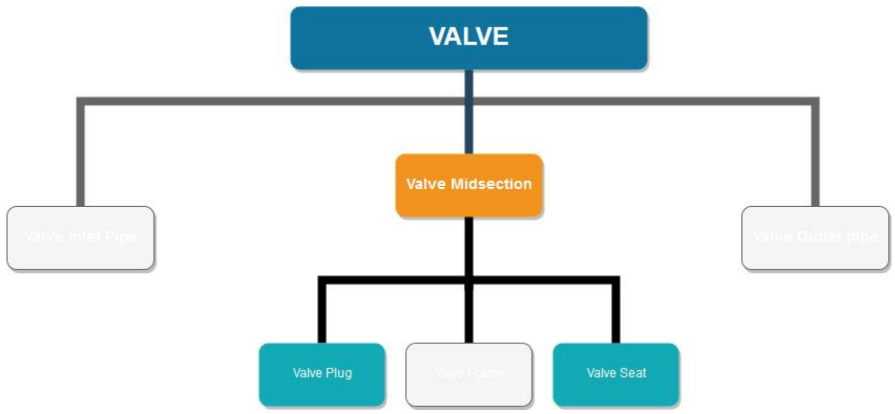


Figure 67 System Components

In figure 67. The modified Valve Hierarchy is focused on the Parts making the most impact on the valve and while it is possible to modify both, the easier and cost effective option would be to modify the Valve Plug and check its relationship with the valve seat. To optimize this relationship and solve any conflicts that may arize, TRIZ's 40 Inventive Principles would be utilized.

The following contradictions were checked using TRIZ's (Theory of Inventive Problem Solving) Contradictions. Only the selected solutions are defined for the purposes of this research. A detailed list of all 40 of the contradictions and inventive principles is not given here but there are many books and open websites publishing a full list. The following queries and results from the TRIZ mechanism produced the following findings in Table 13.

Table 13 Results from TRIZ search

Product Affected	To Improve	To Preserve	Full Design Solutions	Selected Solutions Defined (TRIZ number)
Plug	Shape (12)	Pressure (11)	34, 15, 10, 14	Spheroidality (Curvature) (14),
Plug	Shape (12)	Volume of moving object (7)	14, 4, 15, 22	Spheroidality-Curvature(14), Asymmetry(4), Dynamics(15)
Seat and Plug	Shape (12)	Area of Moving object (5)	5, 34, 4, 10	Merging (5), Asymmetry(4)
Seat and Plug	Shape (12)	Volume of Stationary (8)	7, 2, 35	Nesting (7), Taking out (2),

In conducting a contradiction match based on the 40 Inventive Principles of Problem Solving in TRIZ, the following Contradictions were used to determine a probable design solution.

The following themes emerged from the TRIZ check and is presented in descending order of recurrence alongside their Principle numbers

- Spheroidality or Curvature: (14)
- Asymmetry (4)
- Dynamics (15)
- Merging (5)
- Nesting (7)
- Taking out/extraction (2).

The relationships between the seat and the plug can be optimized. As the valve seat cannot be changed, its modification is frozen but its design function allows it to interact with the Valve Plug.

From the above design solutions that were suggested by TRIZ: The Valve Plug could be made curved or spheroidal in shape, the valve plug could also exhibit some asymmetric features in relation to the walls of the valve, taking note of the dynamics of the flow relationships between shape and the changing volume to optimize the relationship, also products could be merged in an assembly of similar parts to function in parallel. Nesting refers to stacking objects in to other objects or allowing objects to pass through another, Taking out/extraction was already applied to select the parts that have more interactions with each other.

As the valve plug has been singled out for modifications, CFD simulations would be used to examine how its relationship with the seat has changed.

PRODUCT ARCHITECTURE (C-QUADRANT)

A randomly designed valve plug was to be made as a test phase to exemplify all of the design solution suggestions obtained from the TRIZ exercise. As the Maximum Cv obtainable from the valve is already known from the simulation of the already installed valve plug, finding the optimum design for equal percentage increments at random and the minimum Cv value may prove futile without some structure. The resource feed function of the Systems Engine was then applied by researching to discover any equations for determining the expected Cv at different points. The valve flow formula for Equal percentage was used to determine maximum and minimum lift as well as the percentage intervals that should occur between each of the Percentage (%) level of openings.

$$\overset{*}{V} = \frac{e^x}{\tau} \overset{*}{V}_{max}$$ ………. [Equation 2]

Where $\overset{*}{V}$ is the volumetric flow per opening, τ is the rangeability (typically at about 50 for globe valves), Vmax is the Maximum flow rate of the valve and e^x where $x = (\ln \tau)\ x\ H$.

As the valve Cv is the primary data of interest, the Cv can be used in place of $\overset{*}{V}$ in equation 2 above.

The following Cv values (expected) that define an Equal percentage valve were obtained using Equation 2. (see Table 14)

Table 14 Desired (Expected) Cv Values for Equal Percentage Valve

% Opening	Expected Cv for Equal Percentage Valve	Percentage increment
0	0	0
10	5.987903	-
20	8.862096	0.48
30	13.1159	0.48
40	19.41153	0.48
50	28.72907	0.48
60	42.51903	0.48
70	62.92816	0.48
80	93.13367	0.48
90	137.8378	0.48
100	204	0.48

The Valve trim interactional priority is then to obtain a valve Cv as close to the expected Cv points as possible.

To this end, the author made a decision to create an initial random valve plug model for CFD simulations, it is to be designed using the details from the TRIZ exercise. The decisions concerning the plug's positioning and shape were:

- Valve plug should be made spherically shaped (Spheriodality/Curvature)
- The Valve Plug should be asymmetric (Asymmetry)
- Unlike the standard valve plug, the test valve plug should go into the seat area (Nesting)
- The distance spacing between the Outer Radius of the Valve Plug and the Wall of the Valve Seat must be recorded and compared with the resultant Cv value at each opening. (Dynamics)
- Valve plug would close the flow by being lowered down into the valve seat where the shape of the top of the plug head would close the valve and not the tip at the bottom (as with the installed valve). (Merging)

- The results should be able to provide a baseline from which the Cv values could be perfected through subsequent designs. Therefore it should provide a suitable range of Cv values from which the results could be interpolated along side the geometric spacing. Cv and expected Cv.

6.3.5. AIM 2: DESIGN ONE – CREATE A TEST BASELINE FOR NEW VALVE

Following the process outlined in section 6.3.3. for the setup of the CFD solver and simulations, the following design in figure 68 was created in line with the TRIZ informed design decisions.

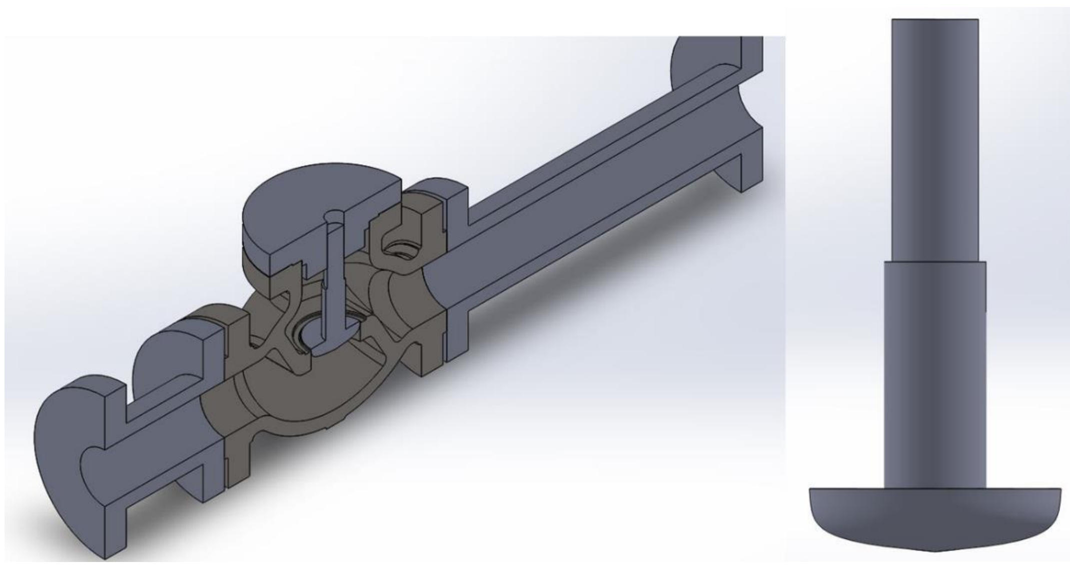


Figure 68 Views of the Plug and in its almost closed position in the valve.

Notice that unlike the previous valve stopper, this plug does not close the valve by resting on top of the seat but by submerging itself into the orifice area, such that its entire width is used to control the flow and closes the valve at its top when it is fully submerged.

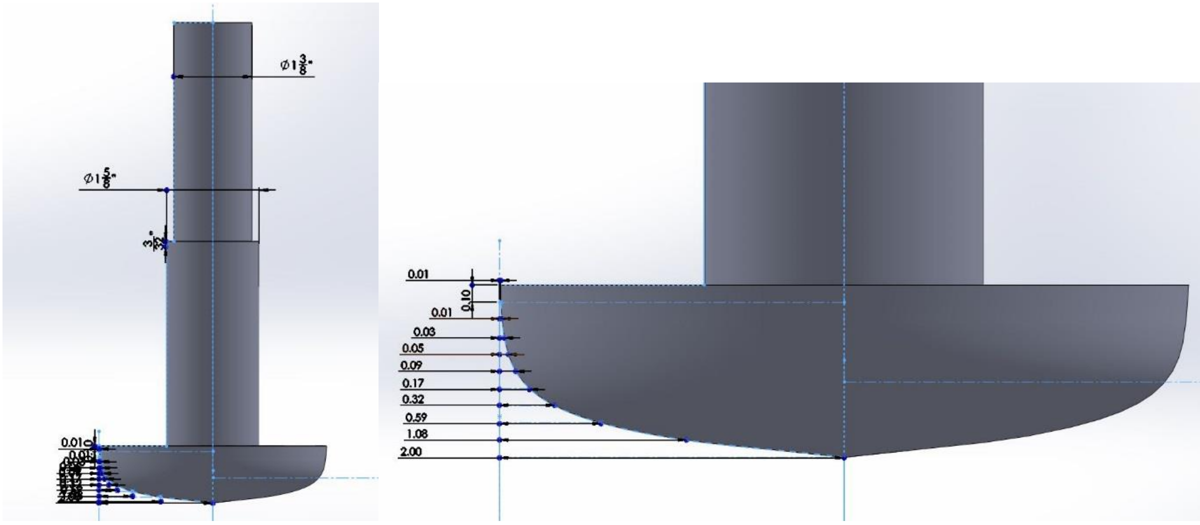


Figure 69 Dimensions of the design valve plug 1

As can be seen, from figure 69, the spacing between the valve plug and the walls of the valve seat are set at very small values (in inches).

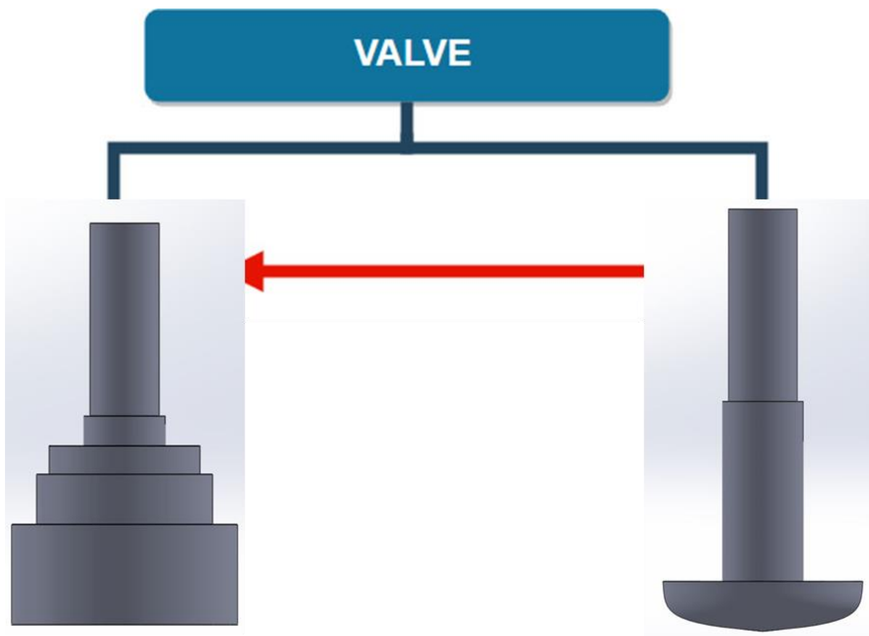


Figure 70 Design 1 plug replaces the standard plug

The alternate new plug (design one) is swapped into the main assembly of the valve (figure 70). The dimensions are then compared with the corresponding CV values as shown in Table 15.

Table 15 Design 1 Valve Cv and % opening results

DESIGN 1					
% Opening	Outer radius	Pressure Pa	Pressure (Psi)	CV from Simulation	CV Expected
0	0	0	0	0	0
10	0.008181	56017.535	8.124671241	3.89	5.98
20	0.014989	43136.69574	6.256460076	6.56	8.86

The Simulation is only run for the 10% and 20% open position as illustrated in Table 15. This is because only the Cv values at those points indicated would be used along side their corresponding values for % opening for interpolating and finding a more accurate geometry at the point that meets 5.98 Cv. To illustrate this from table 15, consider the expected Cv value at 10% opening of the valve = 5.98”, this falls between the 1st and 2nd realized Cv values of the test valve plug (at 3.89” and 6.56”). The Cv and Cv expected value from table 15 is then used to interpolate for a closer value to the outer radius (between the valve plug and the wall of the valve seat orifice). The orifice radius distance to the valve plug side at 10% valve open is taken as 0.013504”.

As a workable baseline design has been achieved, the Conceptualisation phase can transition to the next phase of the Product Life Cycle.

SECOND (2ND) PHASE: IDEAL DEVELOPMENT

6.3.6. AIM 3: DESIGN TWO – CREATE A SECOND BASELINE PLUG

During this phase, a different approach to the design was taken. An alternative valve plug is introduced into the system as shown in Figure 71.

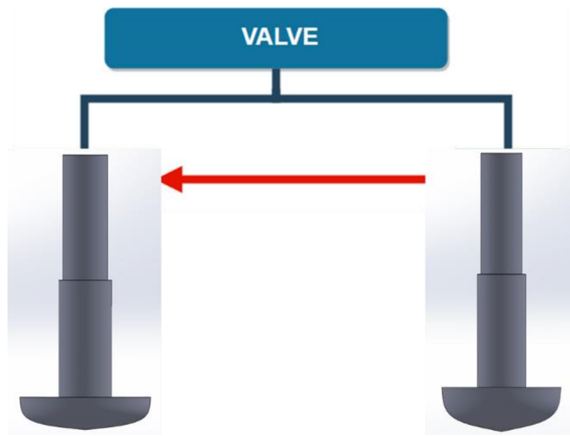


Figure 71 Design 2 replaces Design 1 in the Valve assembly

This plug design as shown in figure 72, is not another random build but is based on what has been learnt about the valve from the previous simulation.

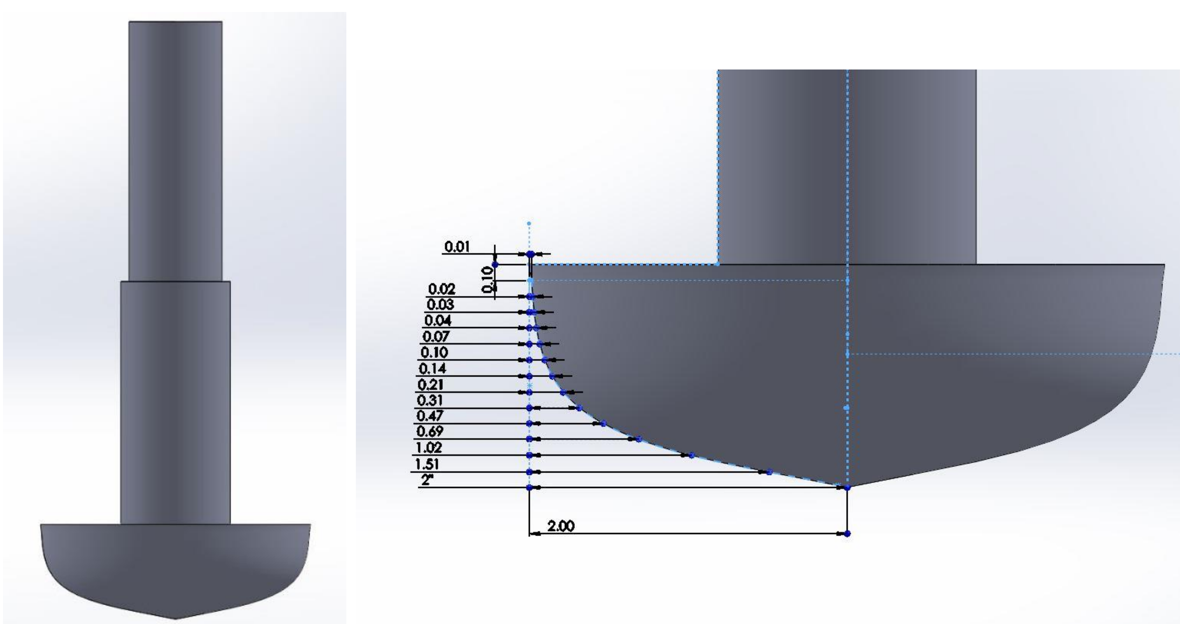


Figure 72 Design Valve 2

The Cv values of the previous designs were compared with their corresponding geometrical distances between the wall and the valve plug shape. Using interpolation, the distance, 0.013504” from the wall was chosen and specified at 10 percent opening position on the plug in order to achieve an expected Cv value of 5.98”. The rest of the dimensions for other open positions were then populated by progressively adding 48% increments (see equation 2) to the initial values to get the values of the outer radius as shown in the table 16

The following values were specified for the spacing between the outer radius of the plug to wall spacing at each position of lift and the simulation was run using same settings. The table 16 shows the results for design 2 valve plug

Table 16 Cv results for Design 2 plug from simulation

DESIGN 2			
VOP	Outer radius	CV Expected	Real CV from Simulation
0	0	0	0
10	0.013504	5.98790262	5.724
20	0.020249	8.862095877	8.9
30	0.029969	13.1159019	14.028
40	0.044354	19.41153481	18.5
50	0.065644	28.72907152	26.235
60	0.097153	42.51902585	36.951
70	0.143787	62.92815825	49.855
80	0.212805	93.13367421	64.942
90	0.314951	137.8378378	80.98
100	0.466128	204	98.636

As can be seen from Table 16, the Cv expected and Real Cv are quite close at 10% percent opening. This confirms that the interpolation of valve plug and seat wall spacing could be used to determine the Cv at each % opening.

The results also indicate the valve achieved equal percentage from 10% opening till about 50% opening.

THIRD (3rd) PHASE – SYSTEM LEVEL DESIGN

6.3.7. AIM 4: DESIGN THREE: CREATE FINAL MODIFICATION TO PLUG

While the previous design already met part of the requirements as an ideal product, a further attempt was made to increase the number of % openings in the valve that maintained equal percentage flow characteristics.

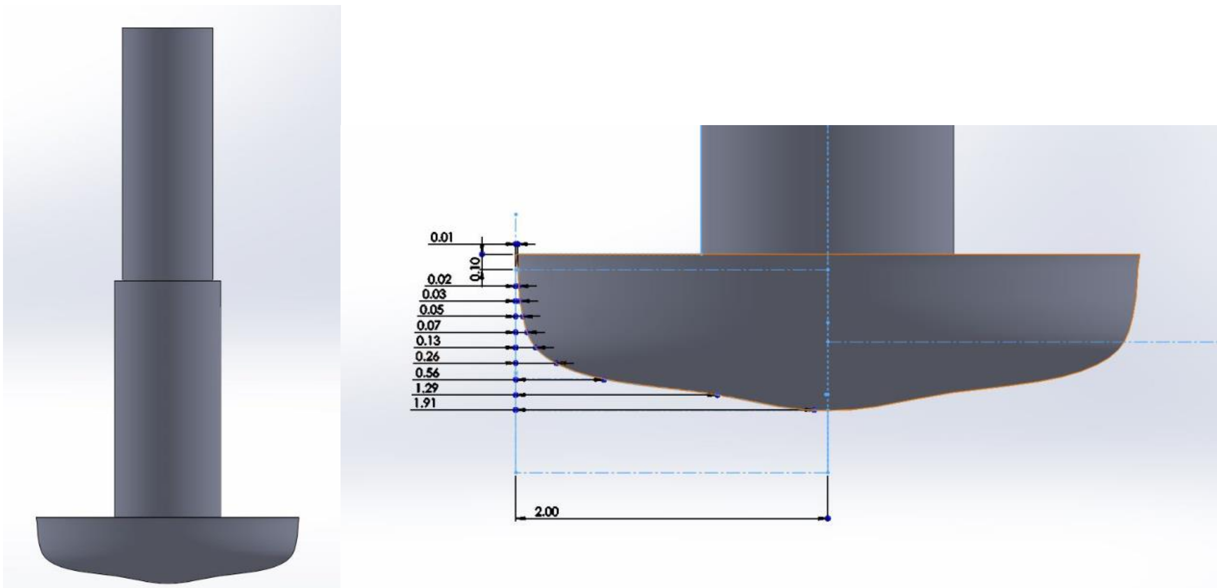


Figure 73 Design Valve 3

This time, the geometry spacings for design 3 which would influence 10% to 70% opening of the flow were optimized for equal percentage output by using interpolation of closely related values to specify the optimum shape of the valve plug geometry shown in figure 73. In the previous phase, the geometry spacing (distance) from the wall of the seat to the side on the valve plug was specified for just the 10% opening and the rest set at 48% increments. But in this phase, the distances between the orifices and the valve plug were each specified per % opening of the valve via interpolation. As shown in figure 74, the new shape replaces the old in the valve assembly.

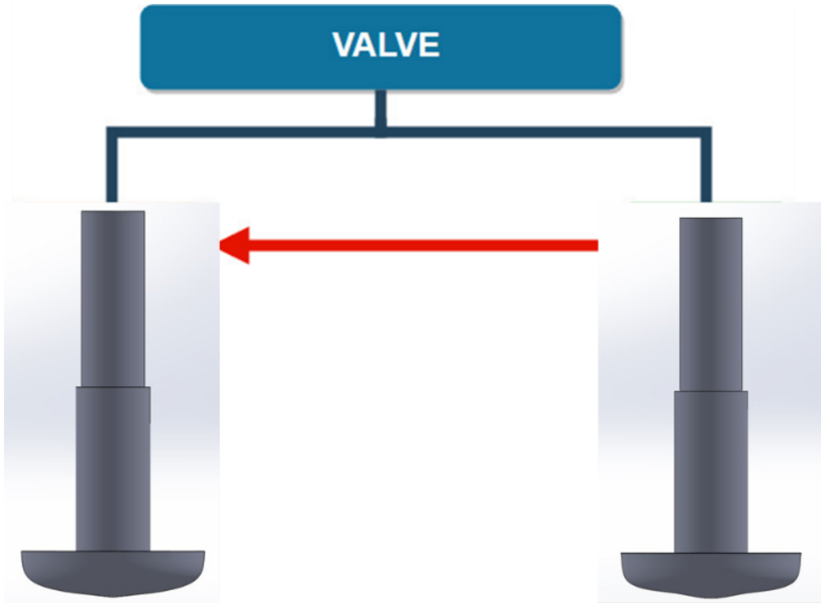


Figure 74 Design 3 replaces design 2

The assembly is built up for simulation in order to obtain the parameters for calculating the Cv of the valve.

Table 17 Interpolation of Radial Spacing Values

Interpolation			
Radial Spacing from w	CV	Interpolated Radial Spacing	CV
0	0	?	0
0.013504	5.724	?	5.98790262
0.020249	8.9	?	8.862095877
0.029969	14.028	?	13.1159019
0.044354	18.5	?	19.41153481
0.065644	26.235	?	28.72907152
0.097153	36.951	?	42.51902585
0.143787	49.855	?	62.92815825
0.212805	64.942	?	93.13367421
0.314951	80.98	?	137.8378378
0.466128	98.636	?	204

As can be seen in the table 17, the interpolation is done to find the required geometry spacing for an expected Cv value.

Table 18 Interpolation values obtained for Design 3 Geometry

Interpolation			
Geometry Spacing	CV	Interpolated Geometry	CV
0	0	0	0
0.013504	5.724	0.014127	5.98790262
0.020249	8.9	0.020021	8.862095877
0.029969	14.028	0.02802	13.1159019
0.044354	18.5	0.046539	19.41153481
0.065644	26.235	0.071885	28.72907152
0.097153	36.951	0.128577406	42.51902585
0.143787	49.855	0.261026352	62.92815825
0.212805	64.942	0.564961807	93.13367421
0.314951	80.98	1.291843974	137.8378378
0.466128	98.636	1.911929	204

Table 18, represents the results of the simulation using the interpolated values from Table 18 as Outer radius. The corresponding Cv results were obtained from the ANSYS Solver and are presented in Table 19.

Table 19 Simulation Results using Interpolated Values

VOP	Outer radius	pressure (Pa)	Pressure (psi)	CV
0	0	0	0	0
10	0.014127	45180.20559	6.552846659	5.98
20	0.020021	37117.77492	5.383487839	8.86
30	0.02802	30507.01717	4.424676756	13.1159
40	0.046539	25686.97308	3.725587202	18.5
50	0.071885	20837.48012	3.022226442	28.113
60	0.128577406	16919.00893	2.453899217	42.643
70	0.261026352	14163.54844	2.054252738	60.849
80	0.564961807	12218.04713	1.772081119	81.77
90	1.291843974	10799.25775	1.566302745	104.667
100	1.911929	9676.796682	1.403503237	130.357

Table 20 Tabulated Comparison between Design 3 and CV expected.

DESIGN 3		
VOP	CV from Simulation	CV Expected
0	0	0
10	5.98	5.98790262
20	8.86	8.862095877
30	13.1159	13.1159019
40	18.5	19.41153481
50	28.113	28.72907152
60	42.643	42.51902585
70	60.849	62.92815825
80	81.77	93.13367421
90	104.667	137.8378378
100	130.357	204

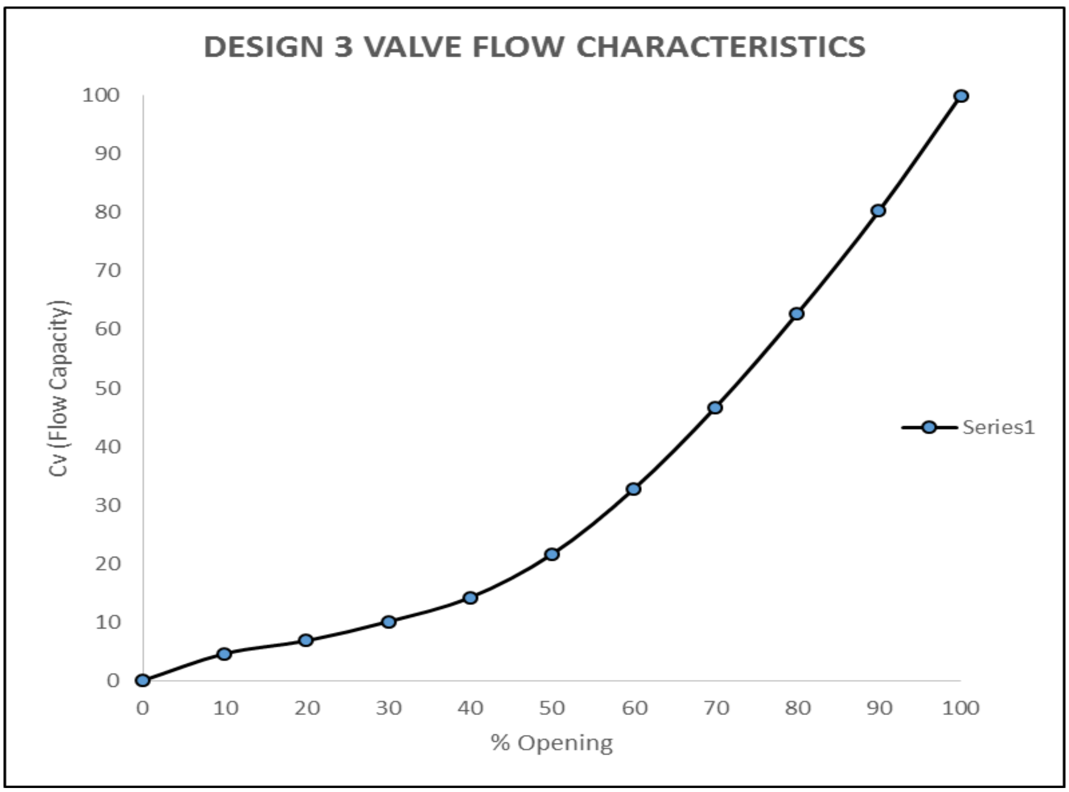


Figure 75 Graph of Hybrid Valve Flow Characteristics for Design 3.

As can be seen from table 20 and Figure 75, the valve Cv for design 3 closely matches the Expected Cv from 10% to 70% and exhibits linear characteristics from that point onwards.

Therefore, Design 3 can act both as an Equal Percentage valve and Linearly as well. An analysis of the results from the simulation would now be done to visualize the actual flow behaviour of the new valve.

ANALYSIS OF SIMULATION RESULTS FOR DESIGN 3

After the simulation, the velocity contours are checked and analysed to explain the flow occurring in the valve.

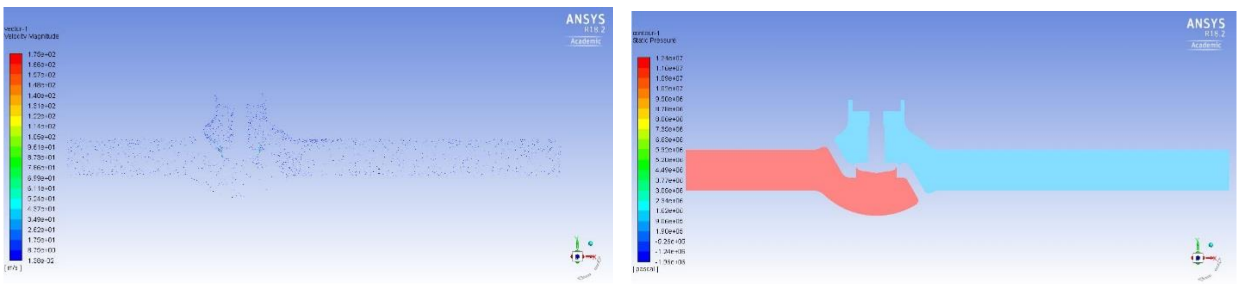


Figure 76 Velocity and Pressure contours at 10% valve opening for new valve

Figure 76 illustrates the velocity and pressure contours at 10% opening. It can be observed here that on the inlet side there is very high pressure while on the outlet side there is lower pressure. This shows the new valve is restricting most of the flow at this point and from the velocity vectors, it can be seen that the amount of flow is reduced to the minimum, which implies the importance of valve seat-plug spacing in the valve trim for obtaining the desired flow characteristics. However Pressure peaks of about 2.63×10^{6} and velocity flows of about 1.36×10^{6} depict high levels of valve flow restrictions, and a higher pressure drop than in the Standard Quick Opening valve. This also contributes to the lower CV obtained from the valve at 40% opening.

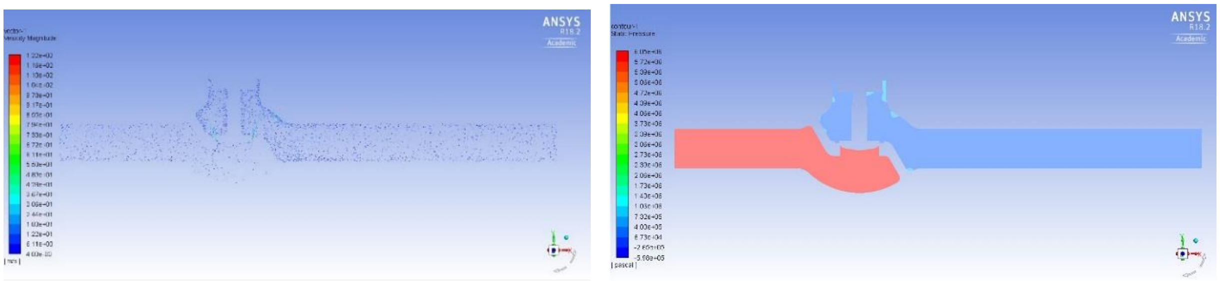


Figure 77 Velocity and Pressure contours at 20% valve opening for new valve.

As the valve opens up to 20% of lift (figure 77), the pressure variations occur on the outlet side. Velocity also seems to remain the same as at 10% except around the openings between the plug and valve seat (valve trim) where the velocity has increased considerably.

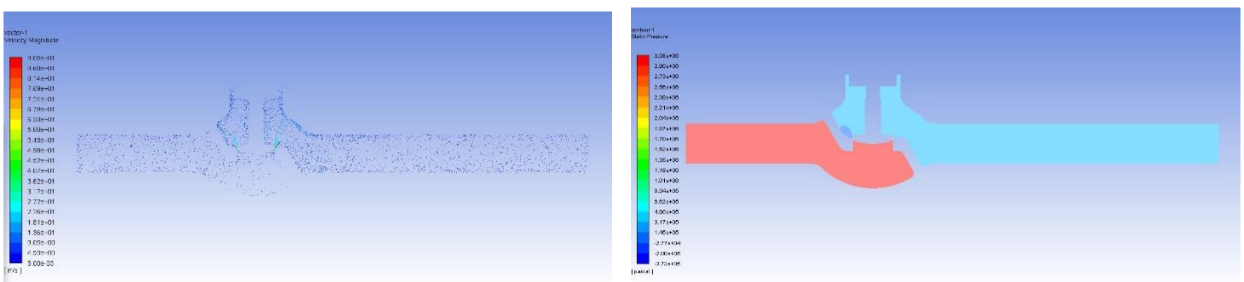


Figure 78 Velocity and Pressure contours at 30% valve opening for new valve.

In observing the velocity and pressure flow at 30% from figure 78, the pressure seems to be extremely high at the inlet, and much unlike the standard valve, that would have considerable amount of flow at this point, the new valve plug still restricts the flow and permits only a fraction of this flow through the valve, The velocity vectors show that flow is occurring at a reasonable rate but not as rapidly as it would in a valve with quick opening characteristics.

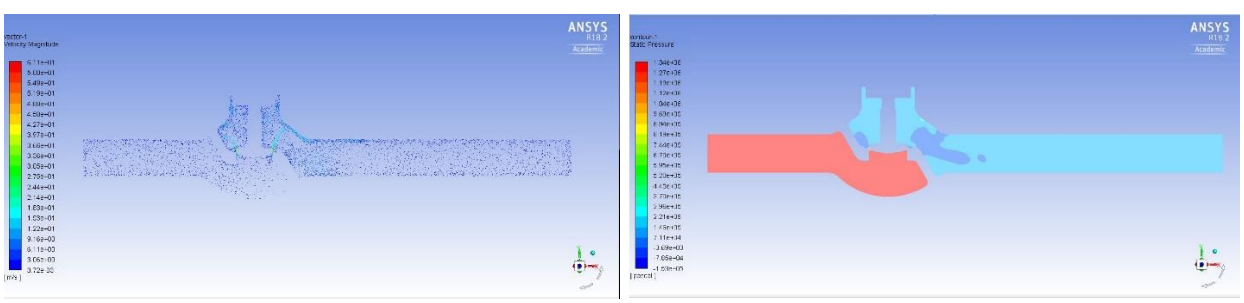


Figure 79 Velocity and Pressure contours at 40% valve opening for new valve.

Figure 79 illustrates the velocity and pressure contours at 40% opening. In addition to the ability of the valve to now restrict more flow, this also illustrates that small amounts of water can be dispensed at a time, thereby reducing resource wastage which is exactly what the company intends to achieve with a New Product. Again, this slow opening design achieves the said aim as a result of the small cross-sectional area between the valve plug and the valve orifice through which the flow must pass through from as low as 10% up till 40% opening where it is more likely to make a significant leap in flow increase.

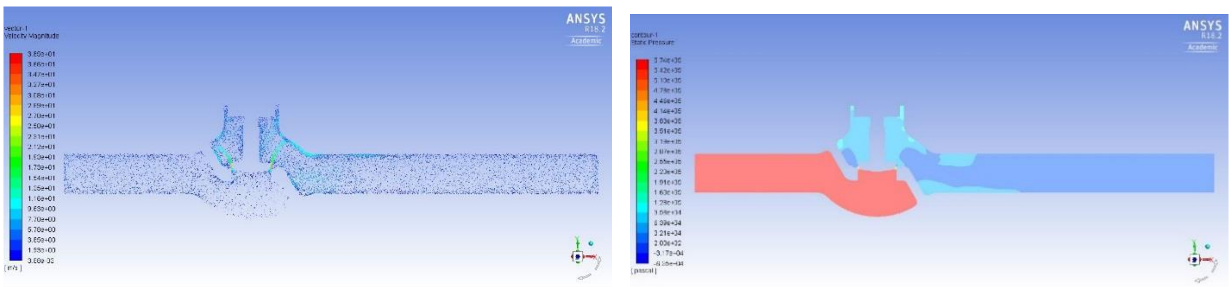


Figure 80 Velocity and Pressure contours at 50% valve opening for new valve.

Figure 80 illustrates the velocity and pressure contours at 50% opening of the valve with the new plug. The velocity vectors show that substantial flow has occurred at this point and that there is still a high pressure drop across the valve which implies that the Cv at this point is still low enough to exhibit control of the fluid flow in the valve.

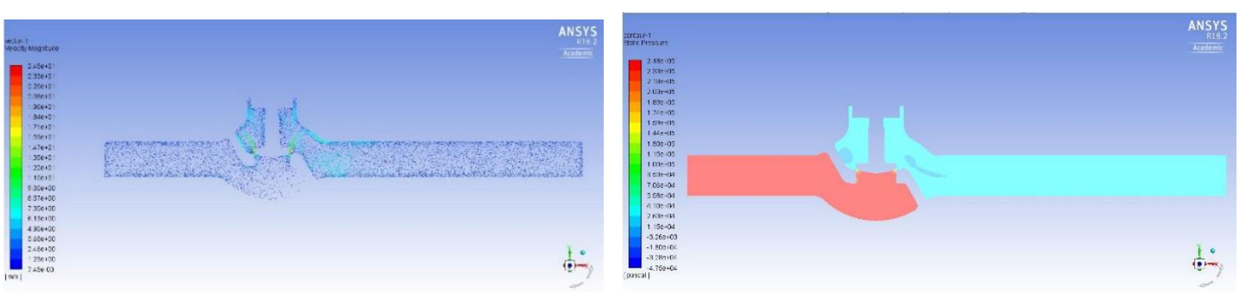


Figure 81 Velocity and Pressure contours at 60% valve opening for new valve.

At 60% opening as illustrated in Figure 81, the velocity maintains good flow and the valve still controls the flow as shown in the pressure contours, which as exemplifies the behavior of an equal percentage valve. At this point in the quick opening valve, most of the flow had already reached it's maximum but the new control valve still maintains the control over the flow. The Pressure contour appears to also show that the valve maintains good control of the flow.

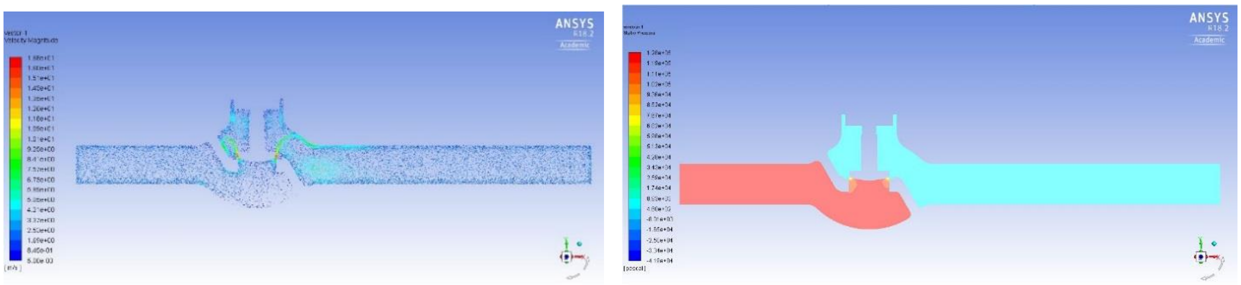


Figure 82 Velocity and Pressure contours at 70% valve opening for new valve.

Figure 82 highlights the flow behaviour of the new valve at 70%. At this point, the valve tends to still control the flow even while there seems to be increase in velocity. This demonstrates fully functional control of the valve. As seen in the valve flow characteristics curve in figure 75. The valve exhibits an equal percentage characteristics till the 70 percent lift of the valve plug. After the next lift, the valve might then start to behave linearly allowing more flow through the valve but controlling more of that flow.

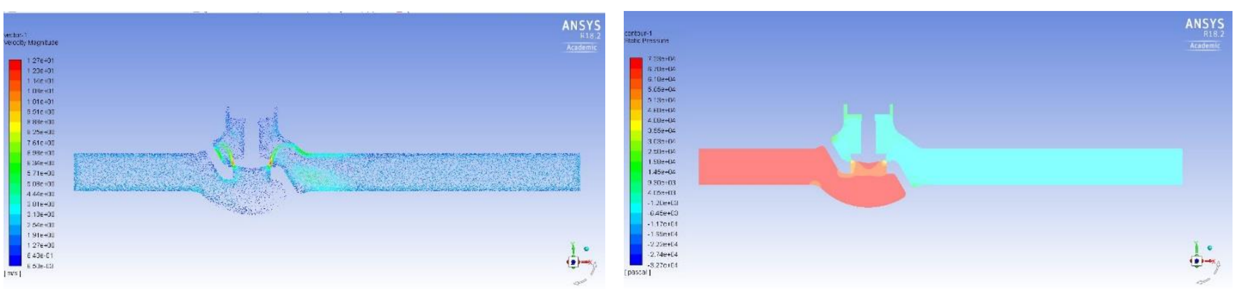


Figure 83 Velocity and Pressure contours at 80% valve opening for new valve.

Figure 83 represents the flow contours for pressure and velocity at 80% opening of the valve. The new plug has held up quite well and as stated in the last segment, the pressure in the inlet starts to change to a more linear performance characteristic from 80% open position of the valve.

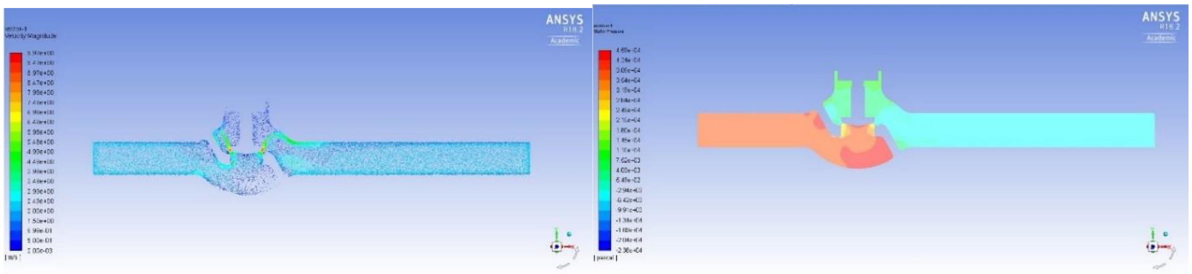


Figure 84 Velocity and Pressure contours at 90% valve opening for new valve.

At 90% opening, as displayed in figure 84, more flow is allowed through the valve. The velocity and pressure contours reveal a lot more happening in the valve and points to the fact that the flow is still being controlled even at 90 percent. The changes in velocity and pressure show that the valve is effective in managing the various complexities of the flow.

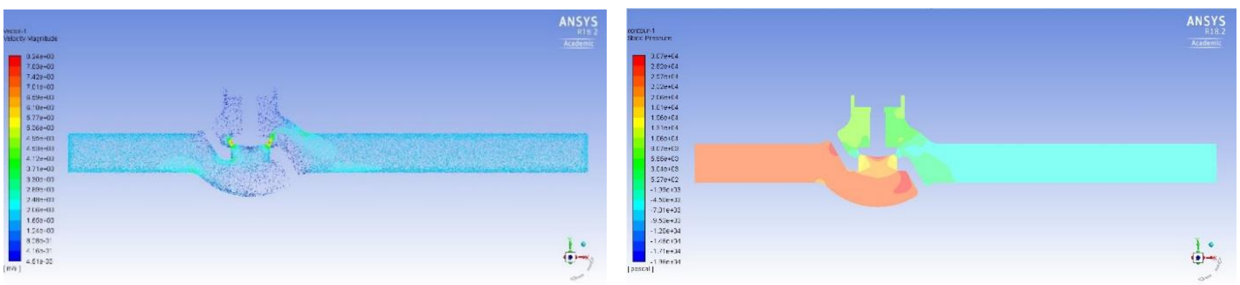


Figure 85 Velocity and Pressure contours at 100% valve opening for new valve.

Figure 85 displays the velocity and pressure at 100% opening of the valve. The valve plug is way off the seat at this point and the pressure reduces in the lower quarter of the valve. The velocity vectors also demonstrate the uniformity of flow through the valve. At points close to the stem, the pressure and velocity increase considerably but due to the streamlined nature of the plug, the intensities are handled. It possess the advantages of an equal percentage valve and also exhibits many of its' functions as pointed out at various points throughout the analysis.

6.4. CHAPTER SUMMARY

This chapter develops a Novel product using CFD analysis to inform the modification of the design. The pilot firm had requested for a valve with controllable flow characteristics as the previous design was an open-close valve with no flow control capabilities. Using the Novel CFD-assisted NPD methodology developed in Chapter 5 of this study, A hybrid valve was successfully designed and the performance was analysed using CFD technology. The hybrid valve possesses both linear and equal percentage characteristics presenting the host firm with an opportunity for flow to be controlled effectively. In comparison to the quick opening valve that the firm previously had, this new hybrid valve opens new doors for innovative product developments for years to come.

This chapter satisfies Main contribution 3 of the project aim and objectives which is **to develop a Novel Product using CFD analysis as an integrated technological approach to inform product development.** A detailed description of how it meets the objectives is given in chapter 7 of this thesis.

CHAPTER 7: CONCLUSION AND RECOMMENDATION

This concluding chapter is organised into five sections. It begins with an outline summary of the research aim, contributions and objectives then summarises the steps taken to accomplish them. Secondly, the major conclusions based on the objectives are presented. Novel Contributions to the research including the limitations of the study, recommendations and future work are also outlined accordingly.

The main aim of this study has been to *build an authentic system that integrates CFD into the operational framework of new product development processes in the flow handling equipment industry.* This aim consists of three main research contributions:

(1) To develop a novel assessment of Flow Handling Equipment Industry enterprise preparedness for Computational Fluid Dynamics integration into the New Product Development Process.

- **Objective 1:** Outline useful internal and external organisational knowledge resources for New Product Development in flow handling equipment industry enterprise.
- **Objective 2:** Outline NPD methods and tools used in practice by firms in flow handling equipment industry for New Product Development.
- **Objective 3:** Outline the reaction of firms to CFD technology adoption for New Product Development in the Flow Handling Equipment Industry.

(2) To develop a novel methodology to help firms integrate the best tools and methods to their process.

- **Objective 4:** New Methodology should utilize key unique internal and external organisation resources for NPD.
- **Objective 5:** New Methodology should utilize procedures for dynamic product lifecycles.
- **Objective 6:** New Methodology should enable systematic integration of CFD technology as part of the design phase of the NPD process.

(3) To develop a Novel Product using CFD analysis as an integrated technological approach to inform product development.

- **Objective 7:** Product should meet organisational design specifications
- **Objective 8:** Provide documented procedure for Product's development using novel methodology.
- **Objective 9:** Product design should be optimized using CFD technology

The need for the study was brought about by the recent global sustainability challenges and the increasing digitization of the processes involved in new product development and product design. A mixed methods inquiry was organised using qualitative surveys and interviews to obtain data information necessary for the design of the new methodology. Subsequently, the new methodology was used in a quantitative simulated experiment using CFD technology to determine the efficacy of the new method in practice through this resulted in the design of a hybrid control valve.

An analysis of how the aim, contributions and objectives have been met in the study are highlighted as follows:

7.2. MAJOR CONCLUSIONS FROM RESEARCH OBJECTIVES

7.2.1. MAIN CONTRIBUTION 1: Develop a novel assessment of Flow Handling Equipment Industry enterprise preparedness for Computational Fluid Dynamics integration into the New Product Development Process.

This contribution has been made following a novel application and CFD-optimisation of the standard Technology Acceptance Model.

This contribution was divided into 3 objectives.

Objective 1: Outline useful internal and external organisational knowledge resources for New Product Development in flow handling equipment industry.

This objective has been met in chapter 4 of the study.

In this study, findings relating to firms' preparedness for internal and external sources of organisational knowledge were obtained from literary and data collection sources. A major aspect of the internal dynamics within the organisations, was for workers to engage in collaborative work and promote knowledge sharing opportunities to build a strategically informed labour force. Decision making among management staff also revealed how culturally those in charge set the tone for operations. The most common form of internal resource generation would usually be a brainstorm session after which they would seek external help. Externally, Customer needs and ability to meet standards were treated with high priority. It was also discovered that many of the firms resorted to outsourcing parts of the product development process when they encounter difficulties in the process. It was therefore necessary to develop systems that demonstrate dynamic capabilities in order to cater for potential changes in customer inquiry or standards over the duration of a project. New areas for knowledge creation were also discovered such as the use of In-house specialists with experience, training and memos or standards.

Objective 2: Outline NPD methods and tools used in practice by firms in flow handling equipment industry for New Product Development.

This objective has been met in Chapter 4 of the study.

This objective focuses on understanding the inclination of firms to use organised and structured processes for their new product development. It was discovered that some of the firms used internally modified versions of stage gate. However, they had to modify the process as the original stage gate was not made specifically for flow handling equipment industry firms. The stage gate system alone was therefore not compatible with the kind of processes that were utilised in the companies, thereby revealing the need for a more structured process to fill the gap in knowledge. As none of the companies used a strictly structured process, the unstructured processes used by the firms were analysed for distinguishable patterns. A structured new product development process that could be used within different product lifecycles and have different tools applied to the process was therefore created to facilitate better use.

Objective 3: Outline the reaction of firms to CFD technology adoption for New Product Development in the Flow Handling Equipment Industry.

This objective has been met in Chapter 4 of the study.

It was discovered from the data collection process that most of the firms either had issues with access to the technology or had decision makers who did not think the technology was important. One of the respondents highlighted licensing costs as a challenge and having to buy new computers to keep up with the technology. For a lot of the interviewees, it seemed like too much work to possess CFD in house. Most of them resorted to using partnerships with research institutions to fulfil CFD related needs only when they were absolutely necessary. A major highlight from the findings section revealed that while CFD had made giant strides in conceptual literature, accessibility of CFD technology and the cultural perception of the technology within the industry played substantial roles in technology adoption. In response, a new method was developed in the succeeding chapter to integrate CFD to the design process of the NPD methodology. This developed method incorporated easy access to CFD technology as well as aiding decision makers in visualising the stages CFD can be applied to during the NPD process, to enable them plan financial costs upfront whether in-house or external collaboration.

7.2.2. MAIN CONTRIBUTION 2: Develop a novel methodology to help firms integrate the best tools and methods to their process.

Overall, this contribution has been made following the development a novel sustainable CFD-assisted New Product Development methodology for managing fluid flow handling equipment industry product solutions. It encompasses all three of the objectives in the body of work. This contribution consists of 3 objectives.

Objective 4: New Methodology should utilize key unique internal and external organisation resources for NPD.

This objective has been met in Chapter 5 of the study.

The New Methodology includes a novel resource feed function that helps firms list and apply the internal and external resources at their disposal to a project. A list of industry best practice techniques as obtained from literature are also outlined to aid the processes outlined in the quadrant engine from chapter 5.

Objective 5: New Methodology should utilize procedures for dynamic situations.

This objective has been met in Chapter 5 of the study.

The New Quadrant Engine was optimised for use in any company of any size by developing a large product life cycle that can be followed using the tool. It would not matter at this point; how large the company that plans to use it is, as it would be applicable to a large range of companies that need a structured process for managing their product lifecycle.

The novel process is even more effective as it recognises the introduction of constraints and alternative components at any point during the product development process.

At the end, a CFD-Assisted New Product Development Methodology was developed for this aim, that is:

- **Flexible** by adopting any company's identified product life cycle.
- **Dynamic** because it allows firms to deal with the changes in product development component parts so they can factor it into the process early.
- **Simplifies CFD Integration**.

Objective 6: New Methodology should enable easy integration of CFD technology as part of the design phase of the NPD process.

This objective has been met in Chapter 5 of the study.

This method takes into account all of the core functionalities of a Systems Engineering process and provides a method for reducing the complexity of CFD use. Two key renowned Systems Engineering Processes from NASA and US Department of Defence Systems Engineering (NASA, 2007; US DOD Systems Management College, 2001) were analysed, their individual limitations were noted and a systematic method was developed to fill in the gaps in the process. This NEW novel process was analysed and supported by a novel navigation system named the **Quadrant Engine**. As identified in Chapter 4, the firms recognised the importance of CFD but experienced difficulty in accessing or incorporating it into their NPD process. This new methodology helps firms to apply CFD to their NPD process by using an Iterative process that ensures the process can be project managed with subcontractors while carrying out validation tests.

7.2.3. MAIN CONTRIBUTION 3: Develop a Novel Product using CFD analysis as an integrated technological approach to inform product development.

The final aim of this study was divided into 3 objectives which have all been met.

Objective 7: Product should meet organisational design specifications:

This objective has been met in Chapter 6 of the study.

A novel hybrid valve performing both equal percentage and linear flow control functions was developed from a globe valve that could previously only perform quick opening functions. Following the application of the novel NPD methodology, the valve function was optimized for control operations. As the participating pilot firm required a valve to control flow, the conceptual design was developed.

Objective 8: Provide documented procedure for Product's development using novel methodology:

This objective has been met in Chapter 4 of the study.

The steps taken using the Quadrant Engine were outlined in chapter 5 to enable other companies produce same or adapt the process to discover even more novel products.

Objective 9: Product design should be optimized using CFD technology:

This objective has been met in Chapter 4 of the study.

The goal of the product design was to use the creation of a product in CFD to communicate, to the firms who were unsure about using CFD in their NPD processes that the process could be applied in a simple manner to help deliver faster and efficient products.

This research digs deep and identifies the real issues affecting a lot of companies in the world today, particularly in the Flow Handling Equipment industry. It finds and establishes the gap in literature and attempts to galvanise the best resources of systems engineering to bring about a revitalization of the Fluid flow handling equipment sector.

7.4. NOVELTIES RECORDED

Among the many novelties in the application of this research style and philosophical framework, the following novelties are presented in the order they have been achieved.

1. **Original research work incorporating findings of the current state of flow handling equipment-producing companies.**

   Following a thorough research in the literature, An extensive study of the valve and fan industry was carried out from a pragmatic standpoint. The findings from the research answer the research questions and present a novel modern analogy of the current preparedness of the Fluid handling equipment industry for CFD adoption in an industry that requires firms to design sustainable product sustainably. Prior to the study, there have been grossly limited publications in literature developing a systematic framework of this magnitude in research. A data collection process was initiated among six firms and new data was obtained detailing the level of preparedness of the industry for CFD integration to the NPD process. The findings from the study answer the questions about the preparedness of firms in the flow handling equipment industry for systematic new product development, a number of implications from the findings revealed the kind of NPD methodology that would suit the application.

2. **A novel CFD-optimised Technology Acceptance Model**

   The CFD-optimised Technology Acceptance Model features two novel additions emerged from the themes of the research carried out in the study, to the original TAM model. These constructs are 'Cultural Perception and 'Accessibility for use' . The importance of these additions present a viable model that can be applied to monitor the fluid flow handling equipment industry amidst various changes in market and industrial situations for managers perception of CFD adoptability as well as the accessibility of the CFD technology which can reveal emerging trends in associated areas that affect its affordability or usability.

3. **A novel CFD assisted NPD methodology:**

   The need for a systematic framework for managing New Product Develoment activity that is assisted by CFD technology has been highlighted throughout this study as essential. The methodology was created using information from the interviews and application of systems engineering principles. The methodology features brilliant features that could help firms in the flow handling equipment industry stay sustainable in their testing process. The potential for development of fluid flow handling equipment solutions are also enormous as has already been demonstrated in this study with a hybrid control valve.

4. **A novel systems engineering process – Quadrant Engine**

   A novel systems engineering process for navigating between the novel methodology and the product lifcycle was developed to help users apply the new methodology seamlessly. The process features an innovative 4 quadrants and focuses providing the user with a framework for completing the product development process dynamically and iteratively.

5. **A novel Hybrid Valve Product design**

   A novel Hybrid Valve featuring both equal percentage and hybrid flow characteristics was developed using the novel CFD assisted NPD methodology as part of a Pilot test. The process involved a standard globe valve with quick opening valve characteristics. After the application of the Novel CFD-assisted NPD methodology and Quadrant engine, the valve was redesigned for control capabilities. This is essentially useful for conserving water as flow from the valve can be controlled to only allow as much as flow as is required by the operator. While standard control valves already exist, the valve developed in this study is novel due to its hybrid capability to act linearly and like an equal percentage valve as well. This is evidenced from the flow characteristics curve in chapter 6.

6. **A novel prescriptive step-by-step application of the process used to develop a new product**

   A description of the new process is given in chapter 5 as well as a description of the process used in the development of the novel hybrid control valve. These prescriptive step by step guide was inspired by the internal memos subsystems theme in chapter four that indicated how important firms manage and process records of successful development. The novel prescriptobe process been made available in this study and presents an additional contribution to the work.

7.3. LIMITATIONS OF THE WORK

A number of limitations are highlighted in connection with the study. First, the study does not apply a generalizable data collection technique, six in-depth interviews were conducted following a pragmatic preliminary survey exercise. Therefore, while the findings provide susbstantial evidence of information obtainable in all six firms, it may not represent a vast majority of the firms in the flow handling equipment industry. There are some limitations in the application of the new developed system in the design of the hybrid valve. While the new methodology prescribes an entire product development process, the hybrid control valve is only developed to the level of a workable digital prototype design. This is because the scope of the study limits the product development process to the development of a concept design to test CFD use. Therefore, future work can be initiated to test the product concept design in using a physical prototype for validation. While great care has been taken to ensure the

7.5. RECOMMENDATIONS AND FUTURE WORK

This research works at promoting the use of CFD to grow sustainability practices in design and testing. As this is done, and more firms key into the development of NPD focused CFD solutions, the cost of purchasing or owning CFD software platforms would reduce. Faster and stronger processors and computers are also being produced by the day so it is believed that advancements in this field of research are promising.

Future work would primarily focus on improving the developed methodologies and verifying its applicability to similar and diverse situations. Potentially, the novel CFD assisted NPD methodology can be applied to a wider range of product development projects that involve fluid flows. The method can then be developed further to include software capabilities and applied in virtual environments to simulate fluid flow in real time to improve collaboration. The current limitations in technology might mean that this would depend on general computing capabilities. However, it is an interesting field to consider when the time for it comes. One of the key findings from literature and data collection revealed that the firms in the fluid flow handling equipment industry believe in the efficacy of CFD technology, however they feel the advancements are still a inaccessible to common users. This is especially the perception as it relates to issues like cost and user friendliness of the available codes. The need for simplification of the technology may then encourage widespread use.

In this regard, the new CFD-optimised technology acceptance model can then be applied in future studies periodically to monitor the changes in perception of managers in the flow handling equipment industry, in relation to global changes in sustainability events and how these affect the industry. It would also play a huge role in determining the effects of high performance computing and the affordability of some of these technological artefacts on cultural perceptions of CFD adoption. As the digital revolution era continues to improve, this is a future work possesses a lot of potential to develop interesting discoveries as it would help shape prediction of future technology adoption and provide a consistent update about the effects of industry trends on technology use particularly in the fluid flow handling industry.

Also in future work, but not too far from now. it is possible to immediately test and validate the new hybrid valve product design that has been developed from this study in chapter 6. Utilising modern 3D printing additive technology, the design can be prototyped and validated.

It is the hope of the author that through the proper dissemination of the materials from this study more innovative discoveries can be made that would benefit from the application of the processes. It is also recommended more product ranges are developed using the Engine to verify its utility in different scenarios and circumstances perhaps more complex than has been exemplified here.

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APPENDICES

APPENDIX A: COPY OF QUESTIONNAIRE USED FOR THE PRELIMINARY SURVEY

THIS IS A COPY OF THE QUESTIONNAIRE USED FOR THE PRELIMINARY SURVEY

UNIVERSITY OF HUDDERSFIELD

Thank you for accepting to partake in answering these few questions about the New Product development process. Your responses would be kept confidential and would be of tremendous help to the development of better New Product development processes.

For more space to explain your selections, additional notes have been added after this questionnaire.

QUESTIONNAIRE

1. How many personnel are currently employed at your firm?

• Less than 10	
• 10 to 49	
• 50 to 250	
• Greater than 250	

2. What is the turnover margin (in £ - Pounds Sterling)

• Below 1.4 million	
• 7 to 35 million	
• Above 35 million	
• Other (Please specify): ………………………………………………………………………………….	

3. Is the firm registered with any official organisations or associations interested in improving development in the field?

• Yes (Please Specify): …………………………………………………………………………………..	
• No	
• No but intend to (Please specify): ……………………………………………………………………	

4. Which of the following best describes where you still need to improve?

• Internal: Improving structural process for better organisational effectiveness in relation to product development.	
• External: Improving market compliance for better patronage, regulatory authority compliance and competitive advantage	
• Both of the above	
• Other (Please specify): ………………………………………………………………………………….	

INTERNAL

5. Which of the following structures is most likely to mirror your organisational structure?

• Functional (Different Departments each working on different specific aspects of same project at successive intervals)	
• Matrix (Teams drawn from different specialisations to work collaboratively in parallel with project specific goal)	
• Both of the above	
• Not specified at the moment	
• Other (Please specify):	

6. On average, how would you rate employee awareness of the firm's organisational goals?

• Very aware and participate actively	
• Aware but participate passively	
• Unsure of employee awareness	
• Not Aware but likely to participate in the future	
• Not aware and not likely to participate if informed	

7. Who makes most of the firm's strategic decisions?

• The Owner	
• Centralised (Top Management staff)	
• Decentralised (Non-top management staff)	
• Other (Please specify) ……………………………………………………................................	

8. How would you describe the bulk of your development activities?

• Technically specific (Product requests are usually consistent in development patterns as defined by the client/customer)	
• Technically diverse (Product requests usually vary and brand new development patterns have to be developed each time a request is made by different clients/customers).	
• Technically moderate (Product requests are sometimes consistent and vary)	

9. How does the firm usually relate to the development activities as you have selected in (8) above?

• Apply deliberate, routine specialisation strategy on product development to solidify quality consistency	
• Apply emergent, variant flexible strategy on product development to build innovation and tackle uncertainty.	
• Apply technological tools to cater for product development (in place of practical strategy), while focusing on building practical strategic tools for the business (market) and administrative functions side of the business.	
• None of the above	
• Other (Please specify) ………………………………………………………………………………..	

EXTERNAL

10. Who are the firm's target customers?

	• End customer population	
	• Client companies in a supply chain relationship	
	• Other (please specify): …………………………………………………………………………………….	

11. What value is your firm recognised for in comparison with competitors?

	• Product type	
	• Service style	
	• Cost Leadership	
	• Speed of production	

12. Which of the following earns the strongest competitive advantage for the firm?

	• Entering New market with New Product	
	• Introducing substitute product(s) to an already existing product in market	
	• Brand recognition	
	• Supplier relationship (e.g contract established with customer/clients)	
	• Other (please specify): ……………………………………………………….............................	

13. Which of the following tends to be a frequent outcome of existing NPD processes in the firm?

	• Radical Innovation – (Totally Novel Products)	
	• Incremental Innovation – (An incremental improvement of previous versions)	

14. How do you determine Customer/Client requirements?

	• Customers/Clients usually provide specific requirements	
	• Market Survey	
	• Brainstorming sessions within the firm.	
	• Management decision	
	• Other (please specify):………………………………………………………………………………………	

15. At what time are customers involved (for feedback) in the product development process? *Tick all that apply.*

	• Before the product is developed	
	• After fabrication, right before the product goes on to launch	
	• After the design stage.	
	• During the design stage – iterations.	
	• Other (please specify)	

NPD PROCESSES

16. Do you have a structured procedure for your New Product development processes?

• Yes	
• No	

17. Which of the following widely used New Product Development systems and tools do you apply to your New product development processes? *Please tick as many as apply*

• Stage Gate	
• TRIZ	
• QFD	
• Affinity Diagrams	
• Mind Map	
• Voice of the customer (VOC)	
• Kano model	
• Other (Please specify): ………………………………..	
• None	

If the process used is specifically exclusive to the firm, please enter name in 'Other' and use the additional note form to be supplied with this questionnaire to explain the process in further detail.

18. Does your New product development process appear to be oriented in any one of the following ways?

• Staged – Set of distinctly defined stages in the product development process each successive process dependent on the outcome of the previous.	
• Spiral – Concurrent Iterative processes usually run simultaneously with other required product development aspects of till the project is completed.	
• Both of the above	
• None of the above	

19. How often are NPD processes in the firm reviewed?

• Yearly	
• Bi- Annually	
• Quarterly	
• Bi - Quarterly	
• Monthly	
• Weekly	
• Daily	
• Other (Please specify): ……………………………………………………………………………….	
• Never	

20. What is the usual review team made up of? *Please tick all that apply*

• Owner(s)	
• Top management	
• Concerned staff	
• All members of staff	

• Other (Please specify) ……………………………………………………………………………………….	
• No reviews have been conducted so far	

21. When tough challenges/difficulties arise during product development, how does the firm respond? (*Please arrange the following tolerance options in ascending order by affixing the numbers 1 - 4 in the respective boxes, '1' being first course of action and '4' being last course of action. You can stop at any number between 1 to 4 if the number of actions that apply in most scenarios is usually less than has been presented below. Also, if the actions are different or more than 4, please use the space provided in 'Other'……).*

• Subcontract specific parts to an external body	
• Consult external specialists for additional support	
• Conduct a brainstorming review session and try to solve the problem internally	
• Terminate the project	
• Other (Please specify): ………………………………………………………………………………………	

22. When subcontracting specific functions to an external body, what do you find is the most consistent reason for the decision?

• To save lead time	
• To reduce cost	
• To utilise the technical know-how of the specialist in improving quality.	
• Other (please specify): …………………………………………………………………………………….	

23. How would you rate the experience of the firm in using standard quality systems for ensuring product quality in the NPD process?

• Very Experienced	
• Moderately Experienced	
• Less Experienced	

24. What Total Quality Models are being used?

• Six Sigma	
• FMEA	
• Other (Please specify): ………………………………………………………………………………………	

25. What relevant Quality and Sustainability Certifications/Awards does the firm currently possess? *Please tick all that apply.*

• ISO 9001	
• Others (Please specify): …………………………………………………………………………………….	

DESIGN PROCESSES

26. What technological packages are currently used by your firm for completing CAD (Computer Aided Design) flow handling product designs? *Please tick all that apply.*

• CFD – Computational Fluid Dynamics. (Please specify what package): …………………………………………………………………………………………	
• FEA – Finite Element Analysis	
• Other (Please specify): …………………………………………………………………………………………….	
• None of the above	

If you answered affirmatively to 'CFD' in (26) above, Please answer questions 27 – 29 as well, if not please go to 30.

27. How does the firm interact with the CFD software in the firm? *Tick as many as apply.*

• Clearly outlined guidelines to aid designers in the design are integrated in the structured NPD process as part of the firm's requirements.	
• Employees Interact with CFD systems using their own discretion when needed during design.	
• Designers brainstorm on solutions before using CFD	
• External specialists are invited to conduct CFD simulations per required project	
• CFD designs are only implemented when the customer/client requests for it.	
• Other (Please specify): ……………………………………………………………………………..	
• None of the above - the firm has CFD software but has never used it.	

28. What benefits would you link to the firm's use of CFD?

- ………………………………………………………………………………………………..
- ………………………………………………………………………………………………..
- ………………………………………………………………………………………………..
- ………………………………………………………………………………………………..
- ………………………………………………………………………………………………..
- ………………………………………………………………………………………………..

29. What Challenges do you encounter using CFD?

- ………………………………………………………………………………………………..
- ………………………………………………………………………………………………..
- ………………………………………………………………………………………………..
- ………………………………………………………………………………………………..
- ………………………………………………………………………………………………..
- ………………………………………………………………………………………………..

30. Do you foresee implementing a new product design using CFD in the near future?

• Yes	

• No	

31. What would you prefer to see in future developments of CFD technology as it relates to your NPD process?

- ……………………………………………………………………………………………………
- ……………………………………………………………………………………………………
- ……………………………………………………………………………………………………
- ……………………………………………………………………………………………………
- ……………………………………………………………………………………………………
- ……………………………………………………………………………………………………

NOTES

APPENDIX B: TABULATED DIFFERENCES BETWEEN FIRMS FROM PRELIMINARY SURVEY

RESEARCH AREA	Research Points	Company A (Small-Valve) 09/03/15	Company B (Small-Fan) 13/06/16	Company C (Medium-Valve) 05/08/16	Company D (Medium-Fan) 13/07/15	Company E (Large-Valve) 24/07/15	Company F (Large-Fan) 13/07/15
ORGANIZATIONAL	**Decision making**	- Owner	- Owner	- Top management staff (Centralized)	- Top management staff (Centralized)	- Top management staff (Centralized)	- Top management staff (Centralized)
	Organizational style	- Functional	- Unsure	- Functional	- Matrix	- Functional	- Functional
	Strategy	- Routine fixed strategy with occasional improvements	- Routine specialization strategy, within range	- Routine specialization strategy, within range	- Strategy is mostly applied towards technology tools than physical	- Emergent, Flexible	- Strategy is mostly applied using technology tools than physical
	Team Awareness of Company Policy/Participation	- Yes/Medium	- No/Active	- Yes/Active	- Yes/Active	- Yes/Passive	- Yes/Passive
	Technicality	- Technically moderate	- Technically moderate	- Technically Specific	- Technically Diverse	- Technically moderate	- Technically Specific
	External Influence	- Open to external input (customer, external support, subcontract	- Open to external input	- Open to external input (For supply of parts)	- Open to external input (External support when challenges arise)	- Open to external input (VOC strategy, external support and dependent on subcontract for CFD)	- Open to external input (VOC strategy, external support and dependent on subcontract for CFD)
PROCESS	**Customer base:**	- Companies and individuals	- Individuals (no supply chains)	- Companies and individuals	- Companies	- Companies and individuals (Supply chains)	- Companies
	Product type:	- Valves	- Fans	- Valves	- Fans	- Valves	- Fans
	Product Strategy/Strength	- Bespoke service/Differentiation	- Speed of production/Generic production	- Product type	- Product Market/ Speed	- Product type Market/Quality	- Product type Market/ Speed
	Competitive advantage:	- Brand recognition and Supplier contracts	- Brand recognition	- Substitute product	- Brand recognition and Supplier relationships	- Brand Recognition	- Brand recognition -
	Target Market:	- Product Specific (Valves made to suit orders)	- Fan industry market (customers select from range of offerings)	- Valve (Range of Products/Bespoke)	- Fan industry Market	- Valve (Range of Product Offerings)	- Fan industry Market
	Innovation Type	- Incremental	- Incremental	- Incremental	- Incremental	- Incremental	- Incremental
	Customer involvement in NPD	- Yes (start and iterations)	- Yes(iterations)	- Yes(Start, design and iterations)	- Nil	- Yes (start and iterations)	- None within NPD (Only at VOC, not product specific)
	Product development Influencers:	- Management and customers	- Customers and Management	- Customers	- Management only	- Customers, Team and Management	- Management only
	NPD method employed:	- None or basic (staged)	- None or basic(staged and spiral combination)	- Stage Gate (Stage)	- None or basic (Staged and Spiral combination)	- Structure (Stage Gate + VOC) + Staged and spiral combined	- Structured (VOC) + staged and spiral combined
	NPD review period/Team responsible	- Yearly/top management and owner	- Never/Owner makes decisions when deems fit	- Quarterly/Top Management	- Weekly/Concerned staff	- Yearly/Concerned Staff	- Monthly/Concerned staff
	NPD Procedure sequence:	- Brainstorm, external support, subcontracting (only to save time or improve quality), terminate project).	- Brainstorm, subcontracting (to utilize tech know how), external support, terminate project if not resolved.	- Brainstorming	- Brainstorm, external support and terminate project if earlier is not met.	- Brainstorm, external support, subcontracts specific parts to an external body(save time or improve quality) and terminate project if earlier is not met.	- Brainstorm, external support, subcontracts specific parts to an external body(save time or improve quality) and terminate project if earlier is not met.
	Quality System Experience:	- High	- Low	- High	- Low	- Medium	- Low

	Quality procedures used:	- Six sigma, FMEA and Non-conformance report. ISO 9001 certified	- Nil (ISO 9001 in view)	- FMEA. ISO 9001 Certified	- Nil (ISO 9001 certified)	- FMEA (ISO 9001, SASME N-Stamp, API monogram certified)	- Nil (ISO 9001 certified)
DESIGN	**Current CFD Use:**	- Redesign products, predictions and troubleshooting error prone areas	- Visualization of issues, effects and conditions	- Solutions to Product failure, Product performance requirements	- Test changes and establishing New Concepts	- Reduce number of experiments, Visualization of issues, effects and conditions	- For faster results than experiments, Test changes and establishing New Concepts -
	CFD package(s):	- ANSYS	- ANSYS	- ANSYS	- SIMERICS	- ANSYS	- ANSYS
	How CFD is used	- On request from clients	- At designers discretion after brainstorming session	- At designers discretion	- To visualize data after Brainstorming session	- At designers discretion after brainstorming session	- To visualize data after Brainstorming session, external specialists then carry out CFD.
	Decision to use CFD:	- At discretion by employee designer	- Brainstorming session	- At discretion of employee designer	- Brainstorming session	- Brainstorming session	- Brainstorming session
	CFD awareness:	- Moderate	- Moderate	- TBA	- Present but Low	- Moderate	- Low (Needs improvement)
	CFD challenges:	- Limited Experience, Low frequency, Non research and development to improve	- Approach vs Understanding Best Practice, and Limited knowledge of when and how to apply tools	- Complexity, Disbelief in Accuracy	- Accuracy vs Run time and Availability of experts	- Run time, Validation	- Meshing Models, Accuracy vs Run time, Availability of experts and poor belief in CFD.
	CFD Future Requirement	- Firm is open to using CFD more frequently if simplified and more functionality	- Firm is open to new CFD approach if robustness, scalability, validation and is independent of platform	- Firm is open to new CFD approach with better conceptual design, performance verification and optimization	- Firm is open to using CFD more frequently if faster, better design evaluation, rapid meshing	- Firm is open to using CFD more frequently if improved user interface, reduced license cost, simpler boundary condition selection	- Firm is open to using CFD more frequently if faster, better design evaluation, rapid meshing