DEVELOPMENT OF A CONCEPTUAL DESIGN TOOL FOR MECHANISM DESIGN

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A thesis submitted for the degree of Doctor of Philosophy

Declaration of Originality

Data collection of Mechanisms and Machine Elements Taxonomy and designs of surgical platform were accomplished in collaboration with Szu-Hung Lee. Except where otherwise stated, this thesis is the result of my own research. This research was conducted in the Design Engineering Group at Imperial College between Oct 2011 and Aug 2015. I certify that this thesis has not been submitted in whole or in parts as consideration for any other degree or qualification at this or any other institute of learning.

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Nov, 2015

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Abstract

Engineering design can be seen as a problem solving process in which engineers and designers convert their thoughts and ideas into real-life designs satisfying market and customer needs. The conceptual design process is crucial in engineering product design since it determines fundamental design features with respect to design requirements. Any decisions made at this stage have a significant impact on later stages of design. However, connection between system functional requirements and selection of actual mechanical components in mechanism designs is severely lacking. With the purpose filling this gap and assisting engineers and designers to obtain in-depth understanding on commonly seen mechanisms and machine elements a database (MMET) was established and programmed containing detail information of these components including technical functional attributes, movement attributes, pictures/drawings and merit analysis. A conceptual design tool built on MMET was then developed aiming to help the user to explore a broad range of mechanical components regarding system requirements. The database and conceptual design tool were validated and improved through industrial case studies which suggest the addition of Function Means tree and Functional Analysis Diagram. The value of MMET and the new conceptual design tool are indicated via positive outcomes of case studies, asserting their capability of offering assistance in understanding engineering product functions and how these functions are achieved, enabling comparisons regarding same functional requirements and finally providing opportunities for conceptual design improvements based on a cyclic process containing detail functional analysis, function-means tree construction and design optimisation.

Acknowledgements

I would like to thank my supervisor Professor Peter Childs for his continual support throughout this research. He is patient, nice, willing to offer me guidance whenever I needed. I would also like to thank my secondary supervisor Dr Marco Aurisicchio for his support and guidance.

I enjoyed very much working with my colleagues in the Design Engineering group in at Imperial College London. A special thanks to my colleague Szu-hung Lee and Weili Dai for their support during my research.

I would also like to express my gratitude to Keith Gilroy, Julie Campbell, Mathew Holloway, Amanda Squires, Simon Dobson and Dr Connor Myant, thank them for offering me opportunities and providing support for my research case studies.

I would like to thank my friends in London and China who have supported my research and filled my spare time with joy.

I am really grateful to my parents who have sponsored my Phd study and being one hundred percent supportive to my study and plans after.

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List of Abbreviation

MMET	Mechanisms and Machine Elements Taxonomy
FM Tree	Function-Means Tree
SCAMPER	Substitute, Combine, Adapt, Modify, Put to another use, Eliminate, Reverse
TRIZ (TIPS)	Theory for Inventive Problem Solving
IBIS	Issue Based Information System
FAD	Functional Analysis Diagram
PDS	Product Design Specification
QFD	Quality Function Deployment
DFA	Design for Assembly
DFM	Design for Manufacture
SWOT	Strength, Weakness, Opportunity, Threats
CPS	Creative Problem Solving

Chapter 1 Introduction

1.1 Chapter Introductory Statement

In this chapter research background and motivation are introduced, followed by brief review of nine commonly seen engineering design models which contextualise this thesis's research. Research problem and objectives are then defined through a series of questions aiming to offer a structural approach to research.

1.2 Background

The engineering product conceptual design process has drawn attention since the industrial revolution and it is still the focus of significant research effort. Engineers and designers convert their thoughts and ideas into real-life designs satisfying market and customer needs, pushing engineering product design forward. In the field of mechanism design, there have been a number of design processes and methodologies proposed for people to use containing the conceptual design stage in which raw ideas and thoughts are embodied onto designs. This may require creativity and the employment of creativity tools in order to help engineers and designers look into design problems in different perspectives and develop new designs. For both novice and experienced engineers and designers the requirement of a solid understanding on commonly used machine elements and mechanisms in terms of their functions and merits are obvious in order to perform successful mechanism designs. However for novice engineers and designers it is difficult for them to conduct complex mechanism design which exceeds their knowledge scope. For experienced engineers and designers they sometimes intend to ignore areas they are not familiar with which may result in a limited range of solutions. Therefore it can be seen that there is a need for a design tool that is able to help both novice and experienced engineers and designers to gain in-depth understanding on commonly used machine elements and mechanisms and use them to conduct mechanism conceptual designs as well as developing existing designs by identifying design flaws and exploring alternatives.

1.3 Engineering Design

1.3.1 Definition

Design is commonly defined as the action of conceiving and producing a plan or drawing of an object before it is made (Oxford Dictionary, 2012). Design in the engineering field involves much broader issues including people, organisations, decision making and compromises. Engineering design has been defined as the process by which requirements and needs related to a product are converted into knowledge about a product (Allen and Mistree, 2014). SEED Ltd (Sharing Experience in Engineering Design), a now superseded UK based organisation of engineering designers and the engineering design lecturers (Hurst, 1999), defined engineering design as:

> *"The total activity necessary to establish and define solutions to problems not solved before, or new solutions to problems which have previously been solved in a different way. The engineering designer uses intellectual ability to apply scientific knowledge and ensure the product satisfies and agreed market need and product design specification whilst permitting manufacture by the optimum method. The design activity is not complete until the resulting product is in use providing an acceptable level of performance and with clearly identified methods of disposal."*

Peter Childs recently defined 'design engineering' as the fusion of design thinking, engineering thinking and practice, within a culture of innovation and enterprise (Private communication 29th September 2014). Most engineering design contains multi-disciplinary activities including mechanical, mathematical, electrical, chemical, control and software engineering.

1.3.2 Engineering Design Models

Nearly all products or systems introduced into the marketplace have experienced a long journey from identifying customers' needs, conceptual idea generations to final design before being launched into the market. There are procedures that can be followed as guidance from years' research and experiences, helping engineers and designers convert their thoughts into real-life products. These guidance or patterns are normally called design methodologies or design models. These models may have different characteristics and focuses but they all intend to provide engineers and designers visibility to the design process and predict the nature and behaviour of products (Radhakrishnan, 2001). A unified design model is rarely seen in industry since most companies and individual designers tend to develop their own even if these often have common themes (Childs et al., 2001). Most engineering design models focused on in this research consist of necessary procedures required to address design problems, explore solutions and evaluations.

Attempts have been made to model design processes in different ways such as maps and flowcharts. One way of classifying design models proposed by Wynn and Clarkson (2005) is regarding *abstract* vs *procedural* vs *analytical* approaches:

- *Abstract approaches*, *which are proposed to describe the design process at a high level of abstraction. Such literature is often relevant to a broad range of situations, but does not offer specific guidance useful for process improvement.*
- *Procedural approaches, which are more concrete in nature and focused on a specific aspect of the design project. They are less general than abstract approaches, but more relevant to practical situations.*
- *Analytical approaches, which are used to describe particular instances of design projects. Such approaches consist of two parts: a representation used to describe aspects of a design project, such as the design structure matrix or DSM (Steward, 1981); and techniques, procedures or computer tools, which make use of the representation to understand better or improve the process of design; see Browning (2001)*

Since procedural approaches are more concrete than abstract approaches and analytical approach are more focused on particular instances of design projects, procedural approaches were mainly focused in this thesis's author's research.

Finger and Dixon (1989) have categorized procedural design approaches into two main types: Descriptive models and Prescriptive models.

- Descriptive models

Descriptive models of design process usually describe a typical engineering design process in terms of sequences of activities. Descriptive models can be seen as the hypotheses of how designers design, a cognitive model constructed from the observation of designers' behaviours (For example, see Warfield, 1986; Adelson, 1989). In a descriptive model its solution-focused nature is reflected on early generation of solutions in the process and then subjected to analysis, evaluation and development (Cross, 2008). Therefore a typical descriptive model usually contains five main procedures (Cross, 1997): (1) analysis and state the problem; (2) concepts generation; (3) evaluation and choose the most promising concept; (4) concept development and (5) communicate the final design. Sometimes analysis and evaluation of the chosen concept reveals critical flaws and therefore it has to be revised or abandoned, leading to a new cycle of concept generation. Figure 1.1 shows a typical descriptive model of design process proposed by French (1999).

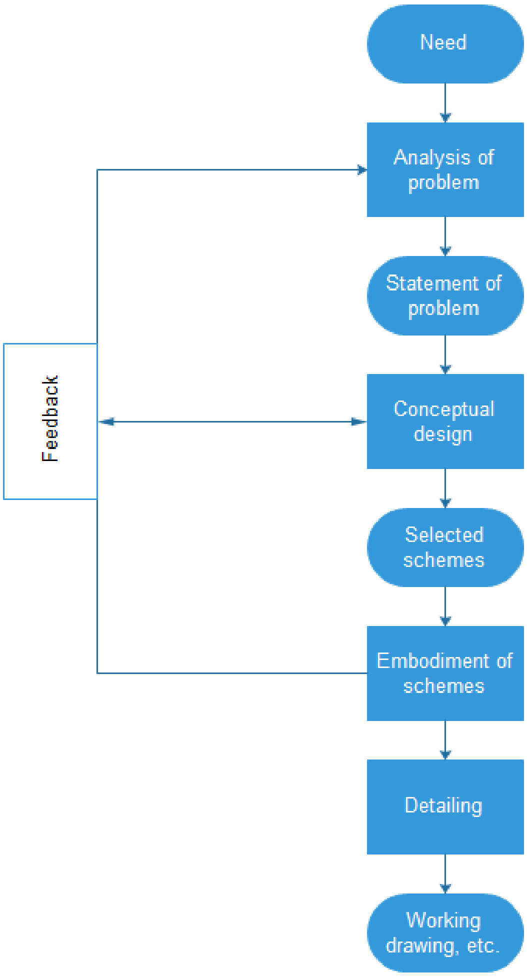


Figure 1.1 French's model of the design process (Reproduced from French, 1999)

- Prescriptive models

Prescriptive design models tend to suggest and encourage engineers and designers to follow more organised, systematic procedures to perform designs, focusing on the understanding and identification of the problem before the generation of solutions (Cross, 2008). Prescriptive models define how the design process should be or what attributes a product ought to fulfil (For example, see Pahl and Beitz, 1996; Pugh, 1991; Allen, 1952; Prasad, 1996). These models emphasise improving efficiency and outcome of the design by providing guidelines to engineers and designers.

There also have been research on design methodologies with particular focus. For example, Parameter Analysis (Kroll, 2001; Condoor et al., 2008), an approach focusing on developing innovative conceptual designs, Concurrent Engineering (Sohlenius, 1992) aiming to decrease product development time, improve productivity and reduce cost, a Framework of Decision-based Design (Hazelrigg, 1998) which "enables the assessment of a value for every design option so that options can be rationally compared and a preferred choice taken." Table 1.1 shows a selection of design models reviewed, whose purpose is to provide an overview of commonly seen engineering design models and their characteristics. Systematic Design Approach and Total Design are mainly focused and employed as frameworks of design in this thesis's author's research due to their broad application among novice engineers and in engineering education, providing the author with a sophisticated environment and solid basis for understanding engineering design.

Table 1.1 Design models and their characteristics

Design Models	Characteristics
Stage-based model by French (1999)	• A typical prescriptive design model proposed based on observations from industries • Performs as a non-linear hierarchical manner where iterative process can be conducted if necessary
Systematic Design Approach (Pahl and Beitz, 1996)	• Provides an effective way to rationalise the design and production process • Perform design in a sequential manner which may have tendency to put intuitive and impulsive design off • The model can only be applied efficiently when all team members are trained and well communicated
Total Design (Pugh, 1991)	• Can help designers cut out the superfluous design input but will require experience to do so • Design methods and technologies can be used to assist the implementation of this design model • Iterative process is necessary for optimised design outcome • Modern methods and technologies are recommended to minimize the cycle time for completion of Total Design

Concurrent Engineering (Prasad, 1996; Sohlenius, 1992)	• Various of engineering design activities are integrated and performed in parallel rather than sequence, result in a significant lead time saving in product design process • Design methods and tools such as QFD, Design for Assembly(DFA) and Design for Manufacture (DFM) can be used to assist the completion of the design process • Specific manufacture system need to be designed to fit in this design model
Parameter Analysis (Kroll, 2001; Condoor et al., 2008)	• Provide a systematic approach to develop initial and rough ideas into viable concepts • Perform cyclic manner through steps • Suitable for both novice and experienced engineers and designers by helping them avoid missing important considerations
Decision-based Design Model (Hazelrigg, 1998)	• Focused on the assessment of a value (vN-M utility) for every design option, enables the comparison between options • This approach emphases on the prediction of proposed system design's performance, use modelling and analysis on the value to obtain improved information for design decision making, which requires a high level of ability to address each variable in the framework in order to make rational decisions
Axiomatic Approach to Design (Suh, 1990; Finger and Dixon, 1989)	• This is an approach based on design axioms containing the relationship between functions and physical variables and the complexity of design • It defines that a good design meets its various functional requirements independently and simply
The Taguchi Method (Pugh, 1991; Sullivan, 1987)	• Focuses on the minimizing the quality loss (defined to be the deviation from desired performance) over a product's design life, in other words, reducing variability and achieving target values • This method enables design and manufacturing process become less sensitive to uncontrollable factors (e.g. Environmental usages and customer abuse) in an optimized manner
Double Diamond Design process (Design Council, 2005)	• Developed based on case studies from eleven global companies • Focuses on divergent-convergent thinking style in design process, recommending perform design by Discover, Define, Develop and Deliver

Systematic Design Approach provides an effective way to rationalise the design and production process. It also suggests designers need to be aware of the flow process and the task described which would help them in planning their work, and avoiding missing important steps and information. However, this model tries to consider everything possible in a sequential manner. As a result, this model has the tendency to jeopardize intuitive and impulsive designs (Childs et al., 2001). Research by Kroll (2001) has indicated that the systematic design approach has a very linear nature an opinion with which the author disagrees. This method is an iterative process rather than linear, and repetition of procedures could be done if necessary leading to better designs.

Total Design model can help designers cut out superfluous design inputs but this may require experience to decide which inputs can be removed (Childs et al., 2001). As the design technologies and theories evolve, some of them can be used to assist the implementation of this model, for example, Quality Function Deployment (QFD) can be used here to describe the customer requirements in a tabular format. Other tools such as Failure Mode and Effects Analysis, Function-Means Tree and decision support tools can also be applied to enhance the effectiveness and efficiency of the Total Design model. This model is sometimes regarded as focusing on the technical aspects in solving design problems by prescribing the procedures to devise solutions. However, according to Wynn and Clarkson (2004),

"….such models and methods are limited by their product-focused perspective, which implies that the key difficulty in a design project lies in finding solutions to the technical problems. In reality, however, even the simplest design process is a highly complex socio-technical activity requiring a much broader range of skills, from marketing to human resource management."

Standard systematic design models like Systematic Design Approach and Total Design are capable of providing a framework which engineers and designers can follow with clear definition of activities even if they do not know where to start. These models also help to reinforce the iterative process of design, which means the development of more robust solutions, by either reworking with the initial idea or finding alternatives. Therefore, in the educational context, these generalised models can be effective for teaching novice engineers to learn engineering design.

However, generalised models are not often adopted in industry because of the obvious diversity in different fields, for example, mechanical, electrical, architecture and chemical engineering. Individual design approaches are seen instead, along with the widespread use of stage gate or waterfall project management based methodologies. Nevertheless, generalised design models are able to provide a framework or basis for the development of unique models which become more suitable in specific fields. Leenders (2007) indicated that systematic design models have become widely used in new product developments and proposed that the design team can only become effective with collaboration between all four principles underlying modern design methodology which are hierarchical deconstruction, systematic variation, satisficing and discursiveness. The research also suggested that excessive function deconstruction will have a negative effect on innovation and creative performance. Therefore close collaboration between teams and departments are necessary when using systematic design models.

Another important factor in adopting these methodologies is time scale. Typically a design project needs to be delivered in time with promising quality. Therefore determination of time scales for each stage when employing systematic models is recommended before actual design. There have been a few methods or tools proven to be effective and efficient to assist completing tasks in the design process. For example, SWOT analysis (1997) and Six Thinking Hats (1987) for market opportunity exploration, Brainstorming (1986), TRIZ (2011) and Morphological Analysis (1998) for idea generation and finding alternatives and IBIS (1970) and Screening Matrix (2002) for decision making. Three examples of implementing theoretical design models into real problems are considered here.

By comparing four different design methodologies (Suh, 1990; Clausing, 1994; Altshuller, 1988; Hubka, 1992), Tate (1995) proposed that companies should be able to articulate their objectives for product development and the design theories and methods are presented in a way that companies can match their needs with the respective capabilities of each theory and method. Tan (2010) adopted the Total Design model to design a low cost aircraft cabin simulator for the SEAT (Smart technologies for stress free air travel) project. The original model was modified into three main stages shown in Figure 1.2. Brainstorming and a Morphological Chart were used in conceptual idea generation. The Weighted Objective method was applied in final concept evaluation. The review of the design stated that Total Design process is useful for the development of projects from concept to real build-up, helping delivering the design goals. Liu and Peng (2010) have adopted the Systematic Design Approach as a basis to configure the optimal performance of a hybrid vehicle between different design parameters such as motor size, battery size, and planetary gears. They suggested that systematic design approach can be valuable for a wider range of hybrid vehicle design problems. Efatmaneshnik (2010) proposed a simulation based model which was applied in complex system engineering design focusing on the organizational structure developed from a concurrent engineering model (For example, Reidsema and Szczerbicki, 2001; Prasad, 1996). They suggested using low-level knowledge of the design problem to configure and reshape the high-level organizational structure by blending engineering design with organization design.

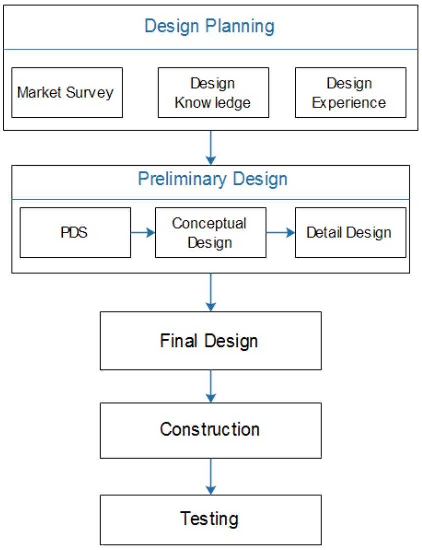


Figure 1.2 Design process for an aircraft cabin simulator

1.3.3 Conceptual Design

After reviewing nine commonly seen engineering design models and their application in industry it was found that systematic design models like Systematic Design Approach and Total Design is broadly applied in different industries with slight modifications related to specific fields. These models normally contain a conceptual design stage where the generation of design solutions are carried out to satisfy design requirements. Stated by Pugh (1991),

> *"A conceptual design, or concept for short, may be defined as that which represents the whole or totality of the projected artefact. In other words, it represents the sum of all of the sub-systems and of the components parts which go to make up the whole system."*

Conceptual design can be seen as the most critical and important stage of product design process since it determines the product's fundamental design features regarding its design requirements. Any decisions made at this stage have a significant impact on later stages of design including quality, cost, and manufacturability (Woldemichael, 2009). A general conceptual design stage can be divided into two main phases: Generation of ideas and Evaluation of the ideas.

- **Generation of ideas**

In this phase it is important to generate as many ideas as possible regardless of their feasibility. "The more ideas are generated, the more likely a better solution arrived at (Thompson, 1999)." In idea generation process creative thinking are encouraged to help engineers and designers understand the problem better and devise more creative solutions. There are a few popular methods available for engineers and designers to use which can assist them to generate ideas, for example, Brainstorming, SCAMPER, Morphological analysis, Function-Means tree and Theory of Invent Problem Solving (TRIZ).

- **Evaluation of ideas**

Idea evaluation is essentially a decision making process which requires the selection of the most promising concept to be further developed regarding its potential. There are some methods which can be used to assist engineers and designers with decision making such as Evaluation Matrix, Screening Matrix and Issued Based Information System (IBIS) based Design Rationale.

The significance of conceptual design implies that it is essential for engineers and designers to deliver good quality outcomes at this stage. However, a gap was spotted when reviewing those models and their application in mechanical design, indicating the lack of link between system functional requirements and actual component selection. This led to the identification of research problem and objectives.

1.4 Research Problem and Objectives

With the increasing demand of more complex mechanism designs, the capability of knowing machine elements and mechanism among engineers and designers become vital, especially to novice engineers who may not familiar with the design process and suitable use of machine elements and mechanisms. For experienced engineers some of them have a tendency to avoid areas they are not familiar with due to design fixation therefore resulting in a limited range of solutions. Together with the lack of rigorous attention of exact mapping between system functional requirements and component selection in mechanism conceptual design, led to the need of a conceptual design tool which is able to help both novice and experienced engineers and designers on mechanism conceptual design idea generation and evaluation by encouraging creative thinking, structural system break down and analysis and component identification.

Research hypothesis was developed regarding successful implementation of the conceptual design tool (also refers as 'the Tool'), suggesting that for the purpose of helping engineers and designers on mechanism conceptual design and improvement, the Tool should be able to fit into commonly seen engineering design models, offer assistance in solution finding and provide insights for design improvement. Therefore, the main research objectives have been defined by finding answers to following research questions which are believed can help the author conduct research in a more organised manner:

- How to define and analyse functions of products?
- How can the Tool assist novice and advanced engineers in exploring broader range of solutions in conceptual design?
- How can the Tool provide assistance to product design analysis and product or system improvement?
- The value of the Tool in terms of helping engineers and designers overall or limited the possibility in solution finding?

1.5 Research Methodology

Design behaviours of novice engineers were investigated at the beginning of this research through an analysis of reports of a design project conducted by second year mechanical engineering undergraduates at Imperial College London, provided further support for the development of the conceptual design tool (For detail, see Jiang, 2014). Research was then carried out through literature review on key elements of the Tool and a series of industrial case studies which validate and provide feedbacks and insights for the Tool improvement.

1.6 Thesis Structure

Figure 1.3 illustrates the research structure with emphasis on key research questions stated earlier. With respect to research objectives this thesis was divided into six other chapters. In Chapter 2 definition of product functions is introduced, along with the introduction of Quality Function Deployment (QFD) and Product Design Specification (PDS) which define the boundaries of design activities. In order to express product functions in a systematic approach to avoid confusion Function Basis is introduced and adopted in this author's research.

Functional analysis using Functional Analysis Diagram (FAD) is then introduced aiming to help engineers and designers to study and develop products, reveal critical points in design from functional perspective. It is mainly adopted as a validation tool for generated conceptual designs. Chapter 3 introduces creativity and creativity tools and their significance in idea generation. Brainstorming, SCAMPER and TRIZ are introduced as typical example creativity tools. Then decision making methods such as Evaluation Matrix, Screening Matrix and Design rationale are demonstrated with examples.

Chapter 4 describes the requirement of having a database that contains commonly used machine elements and mechanisms leading to the establishment of Mechanisms and Machine Element Taxonomy (MMET) and a conceptual design tool based on MMET whose purpose is to assist engineers and designer to devise broad range of conceptual solutions. The database and approach are validated through a surgical table design project. The feedback for which indicated a requirement of a more structural approach of representing system deconstruction and the validation of component selections. Therefore Function Means tree and Function Analysis Diagram were employed to perform system deconstruction and components validation respectively. Chapter 5 and 6 demonstrates two design case studies using the developed conceptual design process, providing support for its value in mechanism conceptual design and design improvement.

Chapter 7 concludes the author’s research on the development of the mechanism and machine element database and the conceptual design tool, recommending potential improvements and further research on the database and the design approach.

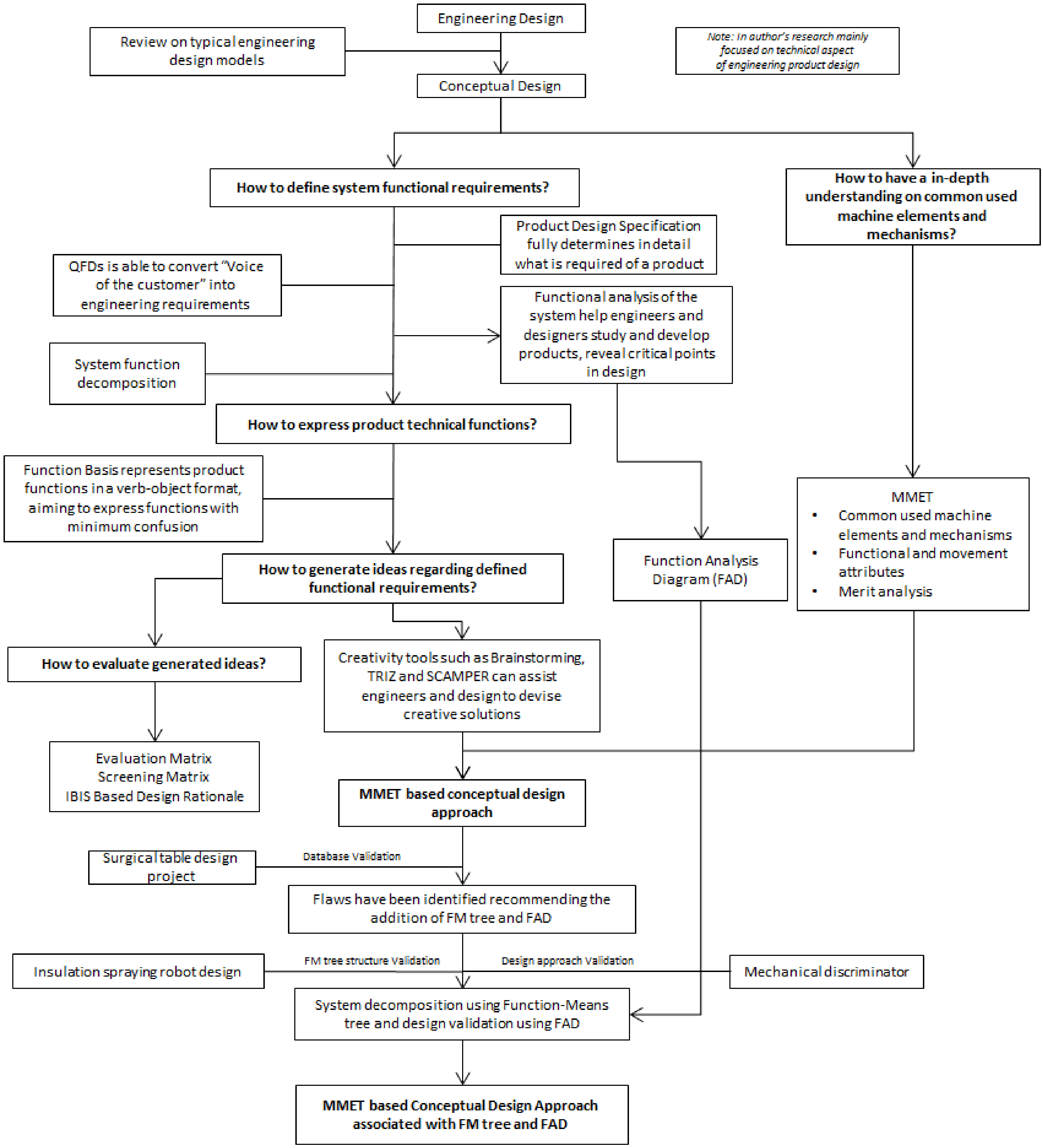


Figure 1.3 Research structure

1.7 Chapter Summary, Findings & Learnings

This chapter has introduced the research background and motivation of this thesis, and indicated that conceptual design phase exists in majority of systematic design models, but it appears that these models do not provide link between system functional requirements and actual mechanical component design within the conceptual design phase. This authenticates the value of the conceptual design tool developed in this thesis. The Tool should be applicable to commonly used engineering design conceptual design phase and offer assistance to both novice and experienced engineers and designers by providing valuable insights.

Systematic Design Approach and Total Design were selected to be the basis of author's research since they have clear frameworks for both novice and advanced engineers to follow and their iterative nature provides reasonable time scale and enables effective modifications of designs. However, effective use of these models requires engineers and designers to have related experiences in the field of working, for example, within product design specification, descriptions of different types of product functions or functions the product can fulfil are identified before the design. Therefore it is necessary for engineers and designers to have a very good understanding of product functions. In Chapter 2 functions of product are introduced with emphasis on the significance of function terminology and system functional analysis.

Chapter 2 Functions of Product

2.1 Chapter Introductory Statement

In this chapter types of product functions are introduced to provide in-depth understanding on different product purposes. For the purpose of standardising function expression in this thesis Functional Basis terminology is introduced and applied. Product Design Specification and Quality Function Deployment are introduced to provide approaches for function identification in mechanism design. The Functional Analysis Diagram approach is introduced as a method to analyse product composition and component relationships, aiming to provide in-depth understanding on the product being designed and offer opportunity for improvement.

2.2 Introduction

The Oxford Dictionary (2012) defines function as an activity that is natural to or the purpose of a person or thing. In product development business it can be expressed as the competence to satisfy customers' demands. Functions of a product can reflect the purpose of why this product is designed and developed. It also provides a good approach to explore and analyse the relationship between products and their consumers. A product can contain a range of functions that satisfy customers' needs simultaneously. For example, a floor lamp can be used for illumination and meanwhile designed aesthetically for decorating. Some products are designed to have symbolic meanings rather than practical functions such as relating to an owner's social identity in the case of a valuable automobile or a luxury watch. From engineers and designer's point of view, functions are the links between artefacts and users. Product designs have the capability to fulfil customers' demands and sometimes provide add-on values. Five definitions of function from design literature have been proposed and listed in Table 2.1.

Table 2.1 Reviews on function definitions

Researchers	Function definition	Insights	Classification
Chakrabarti, A and Bligh, T.P. (2001)	Function is a description of the action or effect required by a design problem, or that supplied by a solution	These authors stated that engineering design should be guided by functions where engineers and designers are able to transfer functional requirements into ideas and solutions.	Engineering Design
Otto,K. N. and Wood, K.L. (2001)	A function of a product is a statement of a clear, reproducible relationship between the available input and the desired output of a product, independent of any particular form	This definition focuses on functions in products, indicating that all products do something, i.e. the reason behind the existence of products. These authors also stated that products have secondary functions and constraints such as inexpensive which should be considered dependant on principal solutions.	Product Design
Vermaas, P.E. and Dorst, K. (2007)	Function are those physical dispositions of an artefact that contributes to the purpose for which the artefact is designed	Based on the review of Function-Behaviour-Structure model of designing in the version as developed by John Gero (1990) and collaborators, the research has indicated the unstable definition of the key concept of function in general design methodologies. Therefore these authors combined three function theories (Casual-role (Cummins, 1975), Intentional (Searle, 1995) and Etiological theory (Millikan, 1984)) and proposed to define function of an artefact as stated in the column to the left.	Design Theory

Galle, P (2009)	Function serve given purposes: A set of physical disposition such that any material object having them can be used in a way that contributes to the purposes.	This author reviewed Vermaas and Dorst's modified FBS model and further developed this with regard to the distinction between structure and material objects embodying that structure.	Design Theory
Aurisicchio, M. et al (2011)	. Function are actions performed by a product accomplishing consumers' needs	In this author's research actions performed by products were explored across different dimensions including technical, aesthetic, social, economic and emergent, indicating that in engineering design the term function is generally used to refer to the technical actions performed by a product.	Engineering Design

Research has been conducted aiming to categorize different types of functions in different disciplines (for example, see Aurisicchio et al, 2011; Bailey, 1994; Bowker and Leigh Star, 1999; Crilly, 2010). Aurisicchio (2011) has summarized the functions of products into five main perspectives: technical, aesthetic, social, economic and emergent, where author's research on product functions was mainly established on, while Childs (Private Communication 2014) uses the following expanded classes for function: technical, aesthetic, social and economic, psychological, latent and emergent.

- **Technical Function**

In the early 1970s Value analysis (Miles, 1972) defined technical functions as the basic purpose of each expenditure whether it is for hardware, the work of a group of men or a procedure. This introduced the representation of functions by a combination of an active verb and a measurable noun, with the aim of exploring potential opportunities to improve the overall value of a product by eliminating unnecessary functions and minimising resources. Technical functions can also be seen as the reason why customers purchase the product. It stands for the main purposes of the product. For example, a lawn mower has a technical function of removing grass. Technical functions were mainly the focus in the research reported in this thesis, i.e. the term 'function' refers to technical function.

- **Social Function**

A product's value is embodied on not only on its technical aspects but also reflects its social impact to its owner. This is an interaction between the product and its owner. A customer may purchase a product which looks more professional, showing their 'good taste'. It depends on the mutual understanding and agreement of the agents that make up the relevant community (Crilly, 2010). For example, providing precise time is one of a watch's technical functions, but it may embody its owner's identity, group membership and culture values, which can be seen as social functions.

- **Aesthetic Function**

Aesthetic function can be considered as an interaction between the user and a product, but from emotional perspectives. Aesthetics is subjective and everyone has their own judgements, however there are a few principles that are helpful in the development and realisation of style and form proposed by Aurisicchio et al. (2011):

- *Exploration of the design space*
- *Consideration of human behaviour*
- *Ergonomics*
- *Technology selection*
- *Colour*
- *Use of organic and inorganic form*
- *Development of relationships between form and function*
- *Use of metaphor in design*
- *Visual identity or branding*
- *Material selection and finish*

- **Economic Function**

Economic function of a product can be understood through two aspects, profitability and circular use. One traditional way of measuring economics is profitability, which has been the dominant factor of driving commercial product design for years. There are two main types of profitability: one-off sell and continuous sell. For instance, mobile phone is a typical one-off sell example and company gains profit when phones were sold. However, some products require replacement of components to maintain their operation such as a printer. Ink cartridges need to be bought after the printer has been sold. The service that comes with the product after selling is another factor which affects profitability. Customer service needs not only human resources but also spare products or components. This will essentially increase the cost of the every sold product and eventually decrease the profit. This leads to the other aspect called circular use or in a more simple term: recycle. If a product design can allow some of the components or all of them to be reusable, this will dramatically reduce the cost of the initial product.

- **Psychological Function**

Psychological function can be seen as consumer's psychological response to a product. This can be understood in terms of cognitive and affective responses (for example, see Crilly, 2004). It concerns the experience, response and feeling to the product through senses (Hekkert, 2006). A product can communicate with a user through, for example, vision, touch, smell or hearing. Feelings can be positive, negative, indifferent or more complex. The feelings based on the information perceived by the user will affect judgements and actions on the product, for example, with an amusement response will lead to further investigation of the product.

- **Latent Function**

When considering functions from the level or degree being recognised or acknowledged, latent function are neither intended nor recognised by participants (Crilly, 2010). The term latent function was mentioned by Merton (1957) when investigating functional analysis in the social science field. Latent function is unintended, unconscious but beneficial to the development of product, for example, a latent function of a mobile phone is the development of multimedia tools such as web browsing, cameras and virtual assistants.

- **Emergent Function**

Emergent functions are unexpected and unpredictable functions performed by a product which may not be part of original design intent (Auriscchio, 2011). Examining emergent functions of a product can help engineers and designers learn about the relationship between the product and its environment, providing potential opportunities for further improvement and development. Emergent function plays a significant role in mechanism design since it may affect product's performance in various aspects, providing a powerful way to conduct future design work.

Table 2.2 show a summary definition of different types of functions categorized in this research programme. In-depth understanding on technical functions in mechanism conceptual design will enables engineers and designers to identify the mapping between system requirements and component selection. Therefore it is essential for them to become capable of identifying and expressing standardised mechanism technical functions based on customer requirements.

Table 2.2 Summary of function types

Function Type	Definition
Technical Function	Main purpose of a product
Social Function	Social impact of a product to its owner

Aesthetic Function	Emotional response of the user through senses
Economic Function	Profitability and circular use of a product
Psychological Function	Psychological response of the user to a product based on the information perceived
Latent Function	Unintended and unrecognised function of a product
Emergent Function	Unexpected and unpredictable function performed by a product which may not be part of original design intent

2.3 Function Terminology – Functional Basis for Design

In establishing the link between system functional requirements and mechanical components it becomes important that functions are expressed in standardised format to avoid confusion. A design language developed by Stone and Wood (1999), called Functional Basis which represents product functions in a verb-object format was adopted in this thesis, whose aim is to describe design comprehensively in a set of simpler sub-functions while showing their connectivity.

The development of Functional Basis had been motivated by six product design areas stated by Stone and Wood (1999), in which the significance of development of a common design language was indicated. Table 2.3 summarises some literature on representing product functions:

Table 2.3 Literature review on product function representation

Value Engineering (1993)	Proposed the idea of describing functions in the form of verb-action pair but did not specify the content of verbs and actions
Collins et al (1976) and Caldwell (2011)	Summarized 28 groups, 105 unique elemental mechanical functions through helicopter failure investigation

Pahl and Beitz (1991)	Proposed five highly abstracted general valid functions and three types of flows
Gadd (2011) and Alshuller (1984)	Use of 30 functional descriptions to represent all mechanical design functions
Hundal (1990)	Summarized six function classes with more specific functions in each class

More sophisticated than these approaches, Functional Basis is able to extend the scope of definition for each function. As indicated above, Functional Basis operates as a format of verb-object, which is defined as function-flow in general. The entities functions acted on are called flows in Functional Basis. The terminology used was developed from serious and careful case studies and has been validated. Stones and Wood (1993) stated that energy, matter and information are the key concepts in any design problems. Therefore they are used as basic flows in Functional Basis. More accurate and standardized forms of flows were defined to help matching with the verb-object format (for examples, see Table 2.4). Functions in Functional Basis are classified into eight classes and then extended to primary, secondary, tertiary and correspondents (for examples, see Table 2.5). The detail definitions of functions and flows can be found in Appendices 1 and 2.

Table 2.4 Flows in Functional Basis (Reproduced from Stone and Wood, 1999)

Class (Primary)	Secondary	Tertiary	Correspondents
Material	Human		Hand, foot, head, etc.
	Gas		Homogenous
	Liquid		Incompressible, compressible, homogeneous
	Solid	Object	Rigid-body, elastic-body, widget
		Particulate	
		Composite	
	Plasma		
	Mixture	Gas-gas	
		Liquid-liquid	
		Solid-solid	Aggregate
		Liquid-gas	
		Solid-gas	
		Solid-liquid-gas	
		Colloidal	Aerosol
Signal	Status	Auditory	Tone, Verbal
		Olfactory	
		Tactile	Temperature, Pressure, Roughness

		Taste		
		Visual	Position, Displacement	
	Control	Analog	Oscillatory	
		Discrete	Binary	
Class (Primary)	**Secondary**	**Tertiary**	**Power conjugate complements**	
			Effort analogy	**Flow analogy**
Energy	Human		Force	Motion
	Acoustic		Pressure	Particle velocity
	Biological		Pressure	Volumetric flow
	Chemical		Affinity	Reaction rate
	Electrical		Electromotive force	Current
	Electromagnetic	Optical	Intensity	Velocity
		Solar	Intensity	Velocity
	Hydraulic		Pressure	Volumetric flow
	Magnetic		Magnetomotive force	Magnetic flux rate
	Mechanical	Rotational	Torque	Angular velocity
		Translational	Force	Linear velocity
		Vibrational	Amplitude	Frequency
	Pneumatic		Pressure	Mass flow
	Radioactive		Intensity	Decay rate
	Thermal		Temperature	Heat flow
Overall increasing degree of specification →				

Table 2.5 Functions in Functional Basis (Reproduced from Stone and Wood, 1999)

Class (Primary)	**Secondary**	**Tertiary**	**Correspondents**
Branch	Separate		Isolate, sever, disjoin
		Divide	Detach, Isolate, release, sort, split, disconnect, subtract
		Extract	Refine, filter, purify, percolate, strain, clear
		Remove	Cut, drill, lathe, polish, sand
	Distribute		Diffuse, dispel, disperse, dissipate, diverge, scatter
Channel	Import		Form entrance, allow, input, capture
	Export		Dispose, eject, emit, empty, remove, destroy, eliminate
	Transfer		Carry, deliver
		Transport	Advance, lift, move
		Transmit	Conduct, convey
	Guide		Direct, shift, steer, straighten, switch
		Translate	Move, relocate
		Rotate	Spin, turn

		Allow DOF	Constrain, unfasten, unlock
Connect	Couple		Associate, connect
		Join	Assemble, fasten
		Link	Attach
	Mix		Add, blend, coalesce, combine, pack
Control magnitude	Actuate		Enable, initiate, start, turn-on
	Regulate		Control, equalize, limit, maintain
		Increase	Allow, open
		Decrease	Close, delay, interrupt
	Change		Adjust, modulate, clear, demodulate, invert, normalize, rectify, reset, scale, vary, modify
		Increment	Amplify, enhance, magnify, multiply
		Decrement	Attenuate, dampen, reduce
		Shape	Compact, compress, crush, pierce, deform, form
		Condition	Prepare, adapt, treat
	Stop		End, halt, pause, interrupt, restrain
		Prevent	Disable, turn-off
		Inhibit	Shield, insulate, protect, resist
Convert	Convert		Condense, create, decode, differentiate, digitize, encode, evaporate, generate, integrate, liquefy, process, solidify, transform
Provision	Store		Accumulate
		Contain	Capture, enclose
		Collect	Absorb, consume, fill, reserve
	Supply		Provide, replenish, retrieve
Signal	Sense		Feel, determine
		Detect	Discern, perceive, recognize
		Measure	Identify, locate
	Indicate		Announce, show, denote, record, register
		Track	Mark, time
		Display	Emit, expose, select
	Process		Compare, calculate, check
Support	Stabilize		Steady
	Secure		Constrain, hold, place, fix
	Position		Align, locate, orient
Overall increasing degree of specification→			

Functional Basis for design realises the establishment of a bank of commonly used functions in mechanism conceptual design which is used as the most important searching criterion of MMET, i.e. all functions within MMET is expressed in Functional Basis format. It was also applied in FM tree and FAD to maintain consistency of the developed conceptual design tool.

After gaining primary understanding on function and its terminology, it is essential to explore the identification of function in engineering design. A product design specification is broadly used to specify the information required for the product being designed such as technical and aesthetical functions. A similar approach called Quality Function Deployment is also widely used for addressing product design information based on customer requirements. PDS and QFD are introduced in Section 2.4 as methods to identify system technical functional requirements. They are powerful tools in helping engineers and designer gain insights on understanding product functional requirements and therefore create a starting point of subsequent design activities including the realisation of system functional requirements.

2.4 PDS and QFD

2.4.1 Product Design Specification

A product design specification (PDS) provides documentation that fully determines in detail what is required of a product before it is designed, giving a framework which design activities can follow. A PDS specifies a design problem instead of providing solutions. Engineers and designers can overlook customer's own judgements when they design a product, which may result in criticism from consumers regarding various perspectives such as appearance, reliability, and price. A PDS is able to help engineers and designers to consider the product design from the customer's point of view and determine the market demands for the product (Innovative Design and Manufacturing Research Centre, 2014).

Generally a PDS is written in a form of a statement, determining the boundaries of design parameters such as size and weight as well as the control of design activities as the project goes on. A PDS can have a dynamic rather than static nature, which means if the emerging design departs from the original PDS as a result of a better insight then the PDS can be then revised after consultation and agreement with the principle stakeholders.

As mentioned above a PDS determines the boundaries of design parameters and activities which will likely require multi-disciplinary skills and knowledge to accomplish. Therefore, with the aim of helping engineers and designers, a standard proforma approach to produce PDS with 32 primary criteria to consider was provided by Pugh (1991), shown in Table 2.6.

Table 2.6 32 primary criteria for PDS (Detail can be found in Pugh (1991))

1. Performance	**9. Quantity**	**17. Ergonomics**	**25. Company constraints**
2. Environment	**10. Manufacturing facility**	**18. Customer**	**26. Market constraints**
3. Life in service	**11. Size**	**19. Quality and reliability**	**27. Patents, literature and product data**
4. Maintenance	**12. Weight**	**20. Shelf life**	**28. Political and social implications**
5. Target product cost	**13. Aesthetics, appearance and finish**	**21. Processes**	**29. Legal**
6. Competition	**14. Materials**	**22. Time-scales**	**30. Installation**
7. Shipping	**15. Product life span**	**23. Testing**	**31. Documentation**
8. Packing	**16. Standards and specifications**	**24. Safety**	**32. Disposal**

Design processes without a PDS are commonly unstructured and not able to address market requirement properly. A poor PDS is a common reason for unsuccessful designs (For example, see Cooper and Kleinachmidt, 1986). Good PDSs provide explicit goals for engineers and designers to achieve nevertheless they do not necessarily result in the best designs since they include a wide range of considerations.

An example PDS of an automated cordless hand-held potato slicer is shown in Table 2.7. This is adapted from a second year Mechanical Engineering undergraduate design project at Imperial College London, more detailed PDS is likely to be seen in industry.

Table 2.7 Cordless hand-held potato slicer PDS

Aspect	Objective	Criteria	Test conditions
Performance	Stable slicing speed	1 second per revolution	Test model and then measure time
	Cut even slices	Less than 1mm difference	Test model and then measure potato slice thicknesses
	Fit in various sizes of potatoes	Able to fit in potatoes with between 7mm to 12 mm in diameter	Test model with different sizes of potatoes
	Low noise level	Less than 40db	Noise meter

	Low vibration	Must not cause uncomfortable experience during use	Test model use vibration test shaker

Aspect	Objective	Criteria	Test conditions
Environment	The tool set should be fully operational at room temperature with water, oil and other kitchen fluids.	Operational at temperature between 5°C and 30°C with kitchen fluids	Test model under extreme temperatures with kitchen fluids
Life in service	Maximise	The warranty life of the machine should exceed 500 hours with 30 min of use per charge each day.	Test under high intensity operation condition
Maintenance	Minimise	Interchangeable blades should be washable and body should be easy to clean	Test model under everyday intensive use
Target product cost	Low	For domestic use, under £40	Obtain quotations for constituent components from OEMS and estimate for in-house manufactured components and assembly costs
Shipping	Easy to deliver	Use commercial couriers	Use established couriers
Packing	Compact	The machine should be disassembled in packing but allows the user to self-assemble easily	Determine the level of disassembly use data from previous products and market research
Quantity	Medium	For domestic use, around 5000 per year	
Manufacturing facility	Ensure ready supply of components	Use stock items where possible and manufacturing customised components	Identify stock components and suppliers, determine lead time for self-manufactured components
Size	Small	Must be able to fit into traditional British kitchen shelf or drawers	Determine concept size from CAD model. Test concept use CAD model of shelf or drawers.
Weight	Low	Operational by average European adult use one hand, do not exceed 3 kg	Use CAD model to estimate weight. Weigh prototype components.
Aesthetics, appearance and finish	Attractive styling	Coloured labels	Expose CAD model and prototypes to focus groups

		Pleasing texture and shape	Expose CAD model and prototypes to focus groups
Materials	Strong	Blade should be washable, high resistance to wear	Test to national standards
	Light	Body should use light weight material	Test to national standards
Product life span	Medium	Remain in product for 5 years	
Standards and specifications	International standard	ISO	Test to ISO
Ergonomics	Maximise	Intuitive shape, natural grip and each to reach switch	Expose CAD models and prototypes to focus groups

Aspect	**Objective**	**Criteria**	**Test conditions**
Quality and reliability	High	Stable speed with rare fail	Test model
		ISO9704050, small kitchen appliances	Test to ISO
Processes	Normal	Normal manufacturing processes	Identify manufacturing process use focus groups
Time-scales	Minimise	Detail design should take less than 2 month	Use standard project management methods to track progress
Safety	High	Sharp edges should be avoided	Identify potential safety concerns use CAD models and prototypes, Bench test
		Hand protection during operation	Identify potential safety concerns use CAD models and prototypes, Bench test
Patents, literature and product data	Approved	No possible patent clashing	Expose CAD models and prototypes to focus groups
Installation	Easy to assemble	Should be able to assemble and disassemble easily by one average adult under instruction	Expose CAD models and prototypes to focus groups to determine the level of easy assembly
Documentation	Appropriate	Should have a written instruction for users	Use focus groups to conduct a detailed instructions for users
Disposal	High	All parts should be fully recyclable	Identify component materials in CAD model and expose to focus groups

2.4.2 **Quality Function Deployment**

Quality Function Deployment (QFD) was first introduced in Japan in 1966, published in Japanese in 1978 and then translated to English in 1994 (Mizuno, 1978; 1994). It was originally developed as an approach to Total Quality Control (Feigenbaum, 1983) and then evolved into QFD today which are also called House of Quality (Hauser and Clausing, 1988) in a wide range of Europe and American countries. QFD is a systematic product development method that capable of translating customer requirements into iterative sequential activities to develop products. Akao (1990) concluded that QFD is "a method for developing a design quality aimed at satisfying the consumer and then translating the consumer's demand into design targets and major quality assurance points to be used throughout the production phase. …QFD is a way to assure the design quality while the product is still in the design stage." AUT University (2008) summarized the three main goals of implementing QFD: Prioritize spoken and unspoken customer wants and needs, translate these needs into technical characteristics and specifications, build and deliver a quality product or service by focusing everybody toward customer satisfaction.

QFD contains four basic phases which can guide engineers and designers through the product development process using matrix representation: Product Planning, Design Deployment, Process Planning and Production Planning, shown in Figure 2.1.

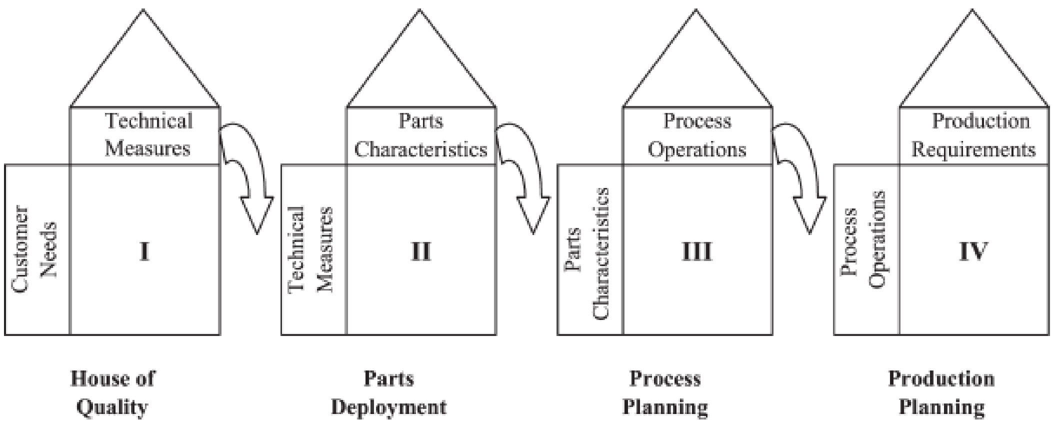


Figure 2.1 QFD flow process (Adapted from Chan and Wu, 2002)

Phase 1 - Product planning:

- Capture the voice of the customer
- Interpret and prioritize customer needs

- Production of PDS
- Translate customer needs into engineering requirements

Phase 2 - Design deployment:

- Identification of designs which fulfil engineering requirements
- Determination of significant design characteristics, e.g. size, dimensions, weight and material
- Verification of designs, make sure the fulfilment of PDS, e.g. calculations, simulations and tests

Phase 3 - Process planning:

- Selection of manufacturing methods and processes
- Identification of significant process operations and parameter, e.g. temperatures, cut rates, assemble steps

Phase 4 - Production planning:

- Development of the process control requirement, e.g. factory layout, tooling and machine maintenance.

The basic procedure of employing QFD (QFD1 as an example) is described below referring to (Breyfolge, 1999), where these primary steps can be carried out in subsequent QFDs since they have the same work principles:

> *1. Make a list of customer attributes. This list is usually identified through customer interviews and/or surveys.*
>
> *2. Identify the importance of each customer attribute. This information is also determined from customer surveys.*
>
> *3. Obtain customer ratings on existing design and competitor design.*
>
> *4. Designers compile a list of technical attributes to meet the customer attributes. These attributes should be scientifically measurable terms that can be assigned target values and designers should avoid concept specific terms.*
>
> *5. Relationships should be identified in the relationship matrix and assigned qualitative value (weak, medium, strong). These qualitative relationships are later replaced by a quantitative three number scale.*

6. Technical tests should be performed on existing design and competitor designs to gauge objective measures of difference.

7. The importance of each technical attribute should be calculated in either absolute values or relative weights.

8. The difficulty of engineering each technical attribute should be assessed.

9. The correlation matrix should be filled out.

10. Target values for each technical attribute should be set. This may be based on customer ratings from step 3.

Although some research has stated that the QFD approach is potentially flawed regarding quantitative assessment (For example, see Carnevalli and Miguel, 2008; Olewnik, 2005; Olewnik and Lewis, 2005; Hazelrigg, 2003), it is broadly employed in various industries with modifications depending on specific areas including transportation and communication, electronics and electrical utilities, software systems, manufacturing, services, and also in education and research fields (For example, see Chan and Wu, 2002; Sweet, 2010; He, 2009). Akao (1997) and Yoshizawa (1997) have summarized two arguments highlighting the significance of QFD deployment in industry:

1. QFD has changed what we have known as quality control in manufacturing processes, and established quality control for development and design. In other words, QFD has established quality management in product development and design. QFD has played a significant role when the focus of TQC shifted from process-oriented QA to design-oriented QA and creation of a new product development system.

2. QFD has provided a communication tool to designers. Engineers, positioned midway between the market and production, need to lead new product development. QFD renders a powerful arm to engineers as they build a system for product development.

The benefits of using QFD have been addressed by Chan (2002) and Carnevalli and Miguel (2008) from three main aspects: enhanced customer-orientation, effective product development and improved communications and teamwork.

Figure 2.2 and Figure 2.3 show the first two examples of QFD 1 and 2 of the cordless hand-held potato slicer design introduced in Section 2.4.1.

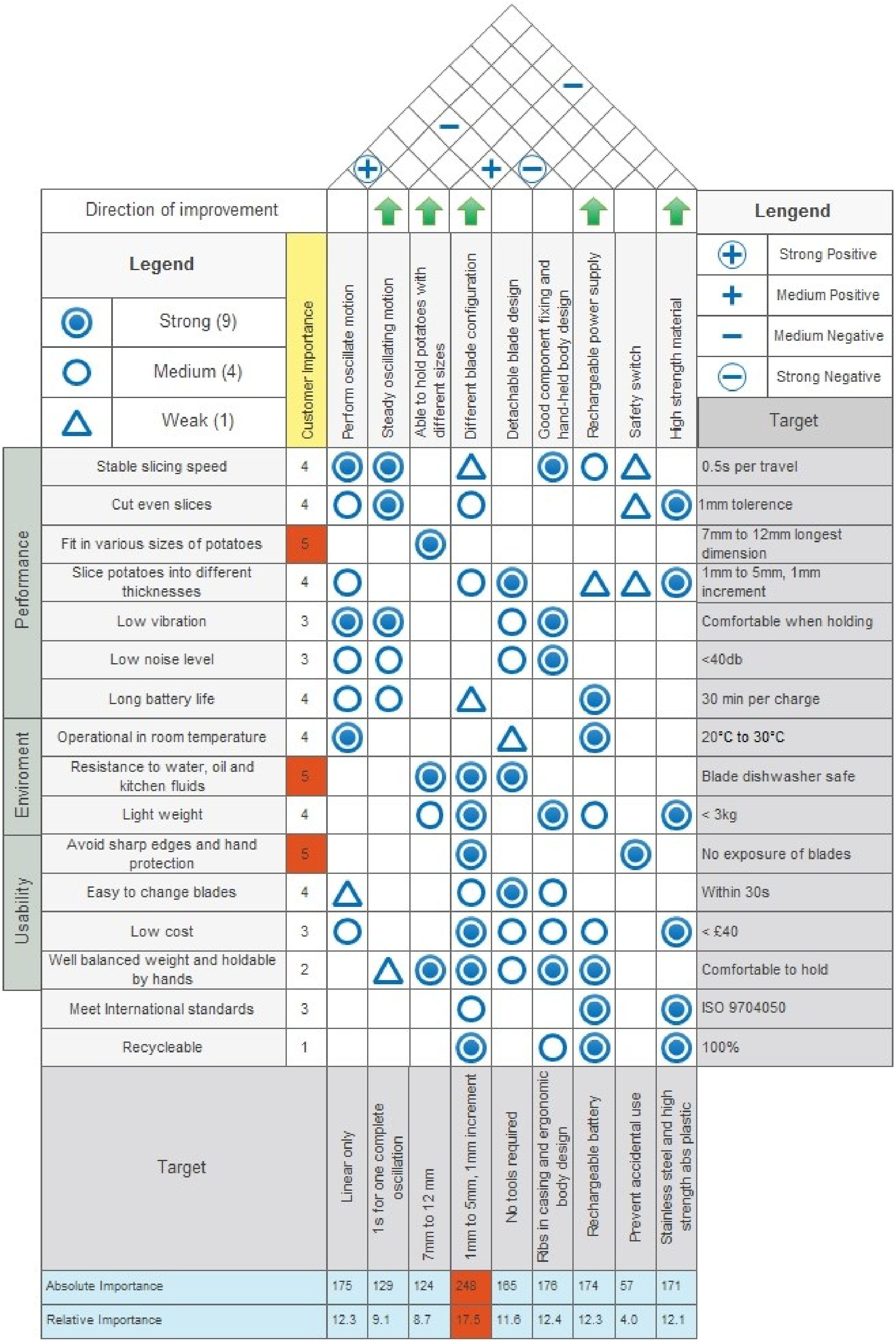


Figure 2.2 QFD1 of a cordless hand-held potato slicer

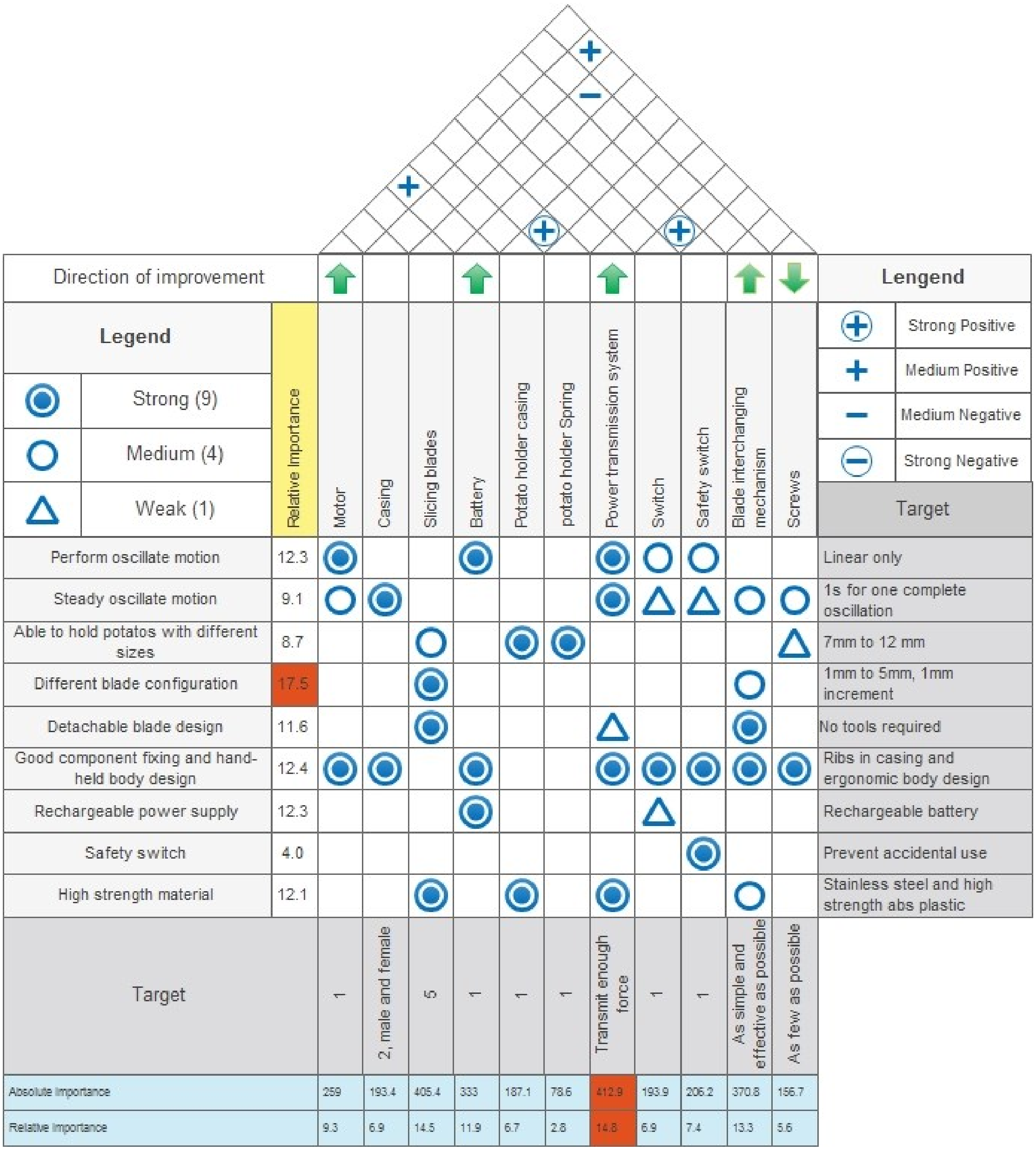


Figure 2.3 QFD2 of an automated potato slicer design

QFD 3 and 4 are more focused on the manufacture aspect of the product to ensure the feasibility of designs. Therefore they were not illustrated here since the focus of this thesis's research is on the conceptual design of engineering products. However, for the interest of readers, a complete QFD 1 to 4 example of the design of a toothpaste container can be found in Bahil's research (1993).

The Significance of PDS and QFD in engineering design can be found through their clarifications and examples, indicated that PDS and QFD are able to provide clear guidance on identification of system functional requirements. These two approaches can be employed prior to the utilisation of the new conceptual design tool, providing a starting point where key functional requirements of the product being design are defined at this stage.

2.5 Functional Analysis and Function Analysis Diagram

After functions of each component within the mechanism conceptual design is configured it is essential for engineers and designer to understand the relationships between this components in order to ensure no fatal risk exists especially with the increasing demand of complexity of products, which was also indicated in Chapter 1. Functional analysis is able to provide engineers and designers a systematic approach to study and develop products, reveal critical points in design and identify useful, useless and harmful functions within the product (Aurisicchio, 2010).

2.5.1 Functional Analysis

Functional analysis approaches have been implemented into various types of domains successfully such as medical, engineering and architecture. (For example, see Morris, 2011; Yordanov, 2013; Younju, 2005; Lechecalier, 1998), assisting people decomposing, describing and relating the functions a system must be performed in order to achieve end product success (Morris, 2011). Lechevalier (1998) indicated the difficulty when performing functional analysis of a complex system which often contains several aspects of knowledge from diverse disciplines, which may require experience in several technological areas when obtaining a functional formalism. This issue is expected to be solved by applying Function Basis introduced earlier in this chapter to describe functions, assisting engineers to model functions in a common universal language.

A few functional analysis representations were reviewed by Aurisicchio (2011; 2013) including Function Analysis System Technique (FAST), The Data Flow Diagram, Concept Map and Function Structure. FAST (1993) suggested that a matrix can be used to link functions and product parts or features, which seems to be a challenging task since the naming of the functions is difficult and requires precise thinking. Some research has proposed using a graphical approach to represent functions such as circles and blocks connected by arrows (For example, see VAI, 1993; Pahl and Beitz, 1991; Yourdon, 1989). Novak (1990) recommended an approach called Concept Map that uses the colours green and red to represent useful and harmful functions. Founded on these previous researches, a comprehensive functional analysis tool called Function Analysis Diagram (Aurisicchio, 2012) was proposed and well developed to present functional analysis.

2.5.2 **Function Analysis Diagram (FAD)**

First published as a part of patent claimed by the TRIZ vendor Invention Machine Corporation (Aurisicchio, 2012; 2013; Devoino et al, 2000), Function Analysis Diagram is able to combine the advantages of FAST, Function structure and Concept Map that represent functional analysis results by blocks, coloured arrows and labels. The blocks represent artefacts, users and other resources. They are linked by actions in the form of two arrows and a label. Two types of action can be defined as useful and harmful connected by green and red coloured arrows respectively (shown in Figure 2.4). There is a selection of mapping software can be used for FAD modelling such as Compendium, DRed and designVUE. In this research, Compendium and designVUE was mainly used to perform functional analysis and represent FADs.

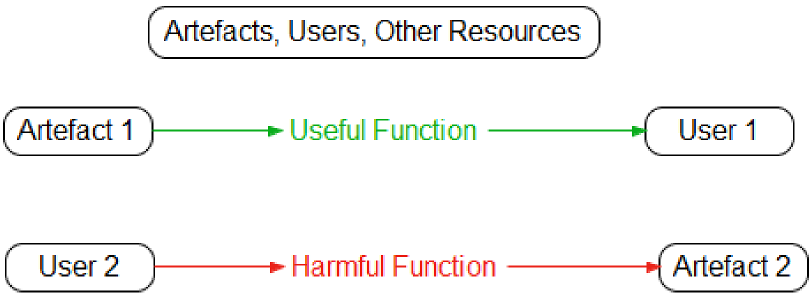


Figure 2.4 Function Analysis Diagram representations in designVUE

Hierarchical FAD is one of the FAD applications used to represent system breakdown for complex products. This enables the visualisation of system deconstruction through blocks and links, helping engineers and designers understand the product via a hierarchical approach such as sub-system 1, sub-sub-system 1 and component 1. Thus the function interactions between sub-systems or components in the same level can be analysed. In addition to represent product structures and the relationship between components and sub-systems, FAD can also be used to analyse the product system as a whole with relation to external factors such as human, temperature and humidity, called External FAD. Figure 2.5 to Figure 2.8 illustrate functional analysis examples of a lawn mower belt transmission system.

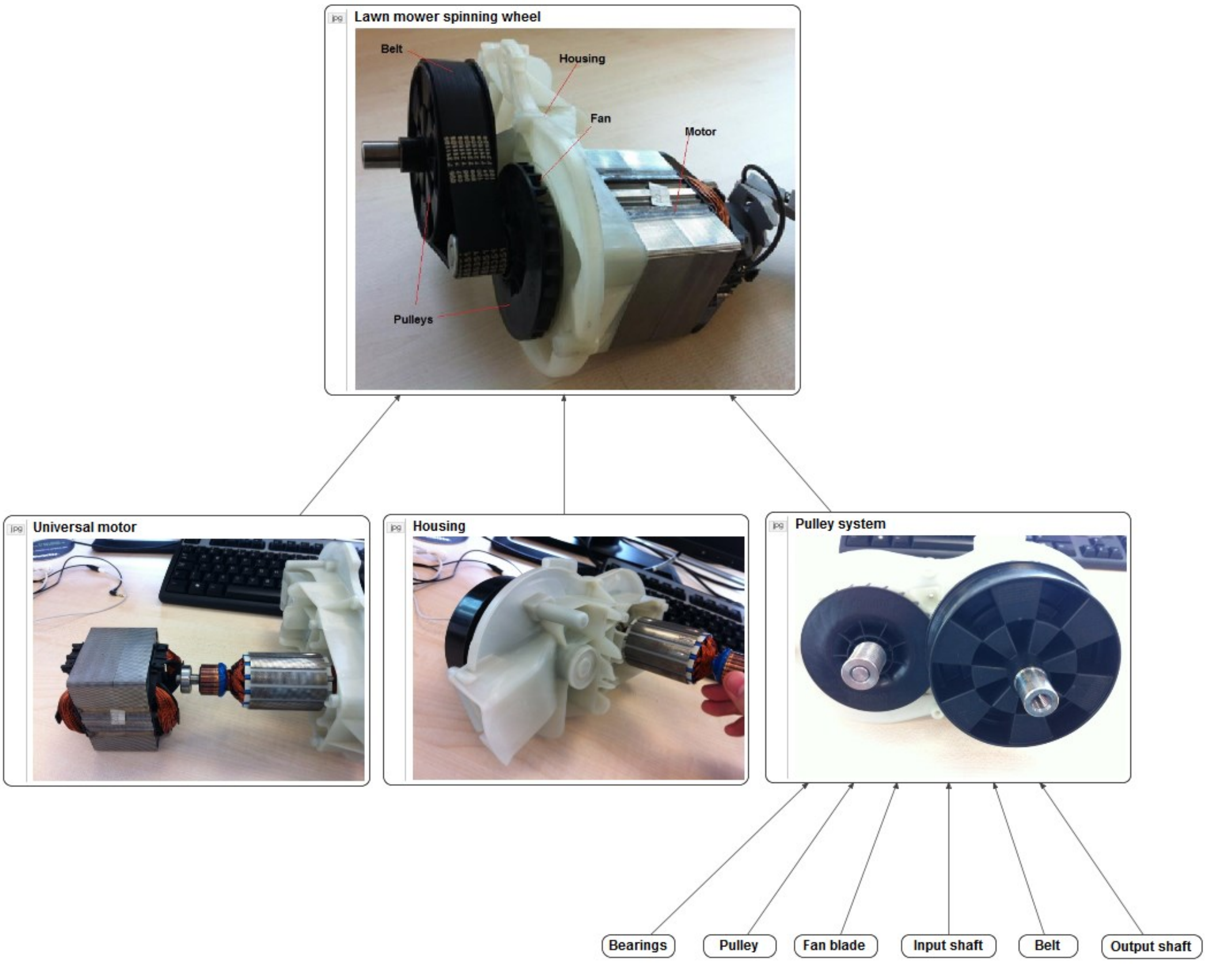


Figure 2.5 Belt transmission functional analysis

Pictures are integrated into the breakdown structure, providing a clearer view of the product structure and isolated sub-systems. Theoretically, pictures and figures can be added into every block to describe specific components or systems. However it may result in too much information contained in one diagram, becoming more difficult to read. The appropriate level of detail that should be added depends on the complexity of the system or team's preference.

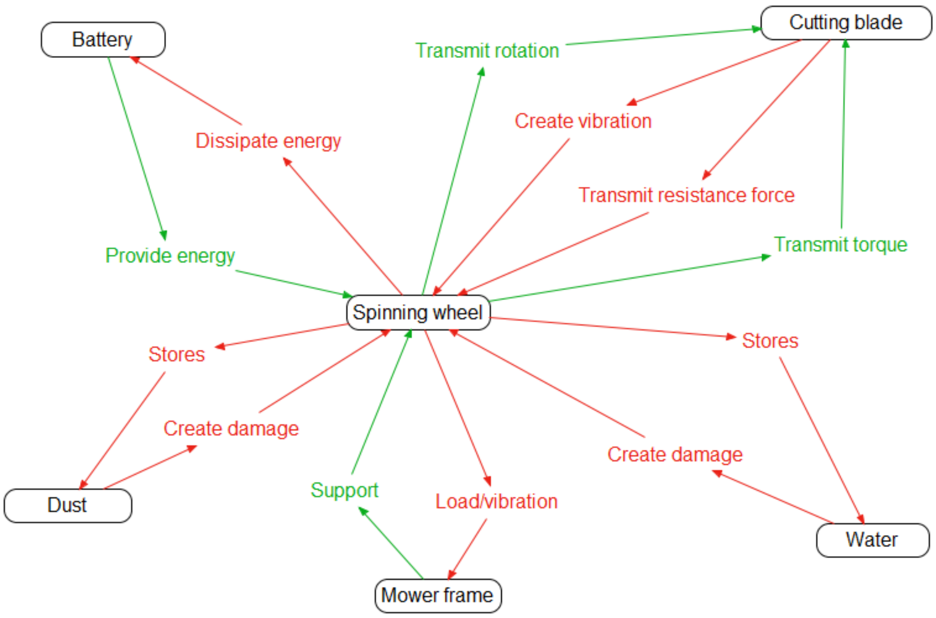


Figure 2.6 External FAD of the wheel system

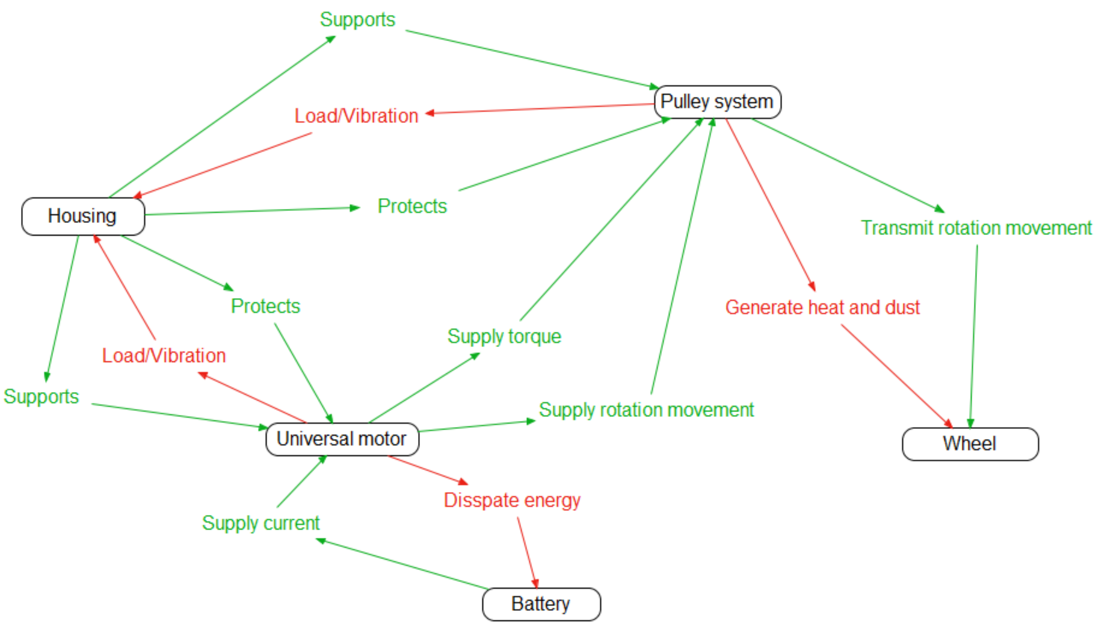


Figure 2.7 FAD of sub-systems in the lawn mower belt transmission

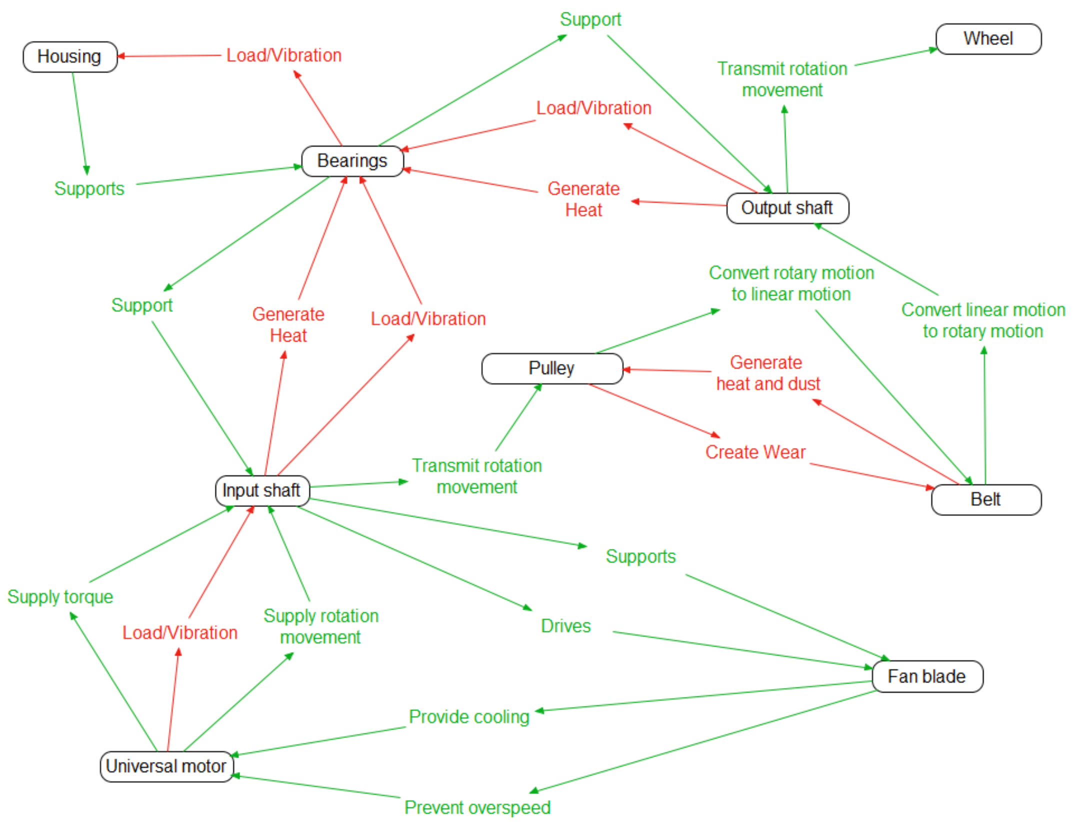


Figure 2.8 FAD of the pulley system

By employing FAD, engineers and designers are able to gain insights and understanding of the product, reveal critical points in the design, and identify useful, harmful and redundant functions, based on which further development and optimization of the product can be enabled. There are seven intended benefits of using FAD approach indicated by Aurisicchio (2013):

- *The notation is simple and unobtrusive and in a sense intuitively obvious. This means that FAD modelling hardly needs to be explained because one can simply look at the diagram and understand it. This is an extremely important aspect to enable a wider diffusion of functional analysis.*
- *The presence of the product structure makes the method easy to use.*
- *The mesh representation with high internode connectivity allows a more complete description of functional relationships.*
- *The layout of the diagram can be used to express additional meaning. The components of an assembly can be laid out following their actual positions. This is expected to be especially useful for design activities where space and position are relevant.*

- *The diagram is useful to analyse an engineering system, capturing the rationale for why something is designed the way it is.*
- *The diagram is a useful starting point for design improvement. Modelling functions together with product structure makes it suited to variant and adaptive design, unlike traditional approaches.*
- *The representation of hierarchies of schematic function structures is feasible and practical (For example, see Aurisicchio, 2012).*

Auriscchio (2013) suggested that modelled functions in FAD should be expressed in a natural language instead of Function Basis in order to align with the natural way of thinking of engineers and designers. However, the main focus of this thesis's research is to develop a database which can assist engineers and designers with their designs by addressing functional requirements collaborating with FAD approach. Therefore it is essential to formalise the functional modelling languages in the database and FAD for the convenience of locating components and data. The detail of the database development will be introduced in Chapter 5. In addition, by structuring product functions using FAD would complement Issue-Based Information System structures (For detail, see Chapter 4, Section 4.4.3) which focuses on finding alternatives solution of design problems. The combination of these two approaches has the potential to address flaws in existing designs, providing support for improvements and assisting the development of new designs. Examples will be given in later chapters.

2.6 **Chapter Summary, Findings & Learnings**

In this chapter the term 'function' has been defined and seven function types have been introduced. Two approaches, PDS and QFD which are capable of providing design activity frameworks based on functions have been introduced in order to obtain in-depth understanding on product functions. They are broadly adopted in industrial design processes aiming to determine functional requirements of products being developed, providing a sophisticated view of determining the boundaries of design activities, helping the functions that product need to fulfil to be explored.

FAD was introduced as an approach to analyse function inter-relationships within a product and between the product and environment. FAD is a powerful tool which can be used to analyse existing products and propose improvements by addressing harmful functions and finding alternatives. FAD is an important element of the Tool where conceptual designs of components required within a system with regard to functional requirements can be drafted for review and future development.

This chapter highlighted the significance of understanding product functions and standardised function expression which leads to the adoption of Functional Basis terminology in this thesis. This chapter also stated that PDS and QFD can provide assistance in understanding and identifying product functional requirements and offer guidelines for design activities. It was found that FAD can be applied to deconstruct, analyse and validate product designs, which makes it an important and powerful element of the developed conceptual design tool. The next stage of applying the conceptual design tool would be the generation of ideas with regards to functional requirements identified in PDS or QFD. There are plenty of creativity tools that can be adopted to stimulate creative thinking and help engineers and designers generate creative ideas, for example, Brainstorming, SCAMPER and TRIZ. In Chapter 3 these commonly seen idea generation and problem solving tools are introduced and their significance in design stated.

Chapter 3 Idea Generation and Evaluation in Conceptual Design

3.1 Chapter Introductory Statement

In this chapter creativity is introduced to provide context information of its application in idea generation. Three commonly used creativity tools are reviewed to gain insights on their application in idea generation. Three idea evaluation approaches are introduced with a focus on IBIS as a result of its capability on providing argumentation behind decisions. At the end of the chapter an industrial case study is introduced to demonstrate the benefits of employing creativity tools and IBIS solving real industrial problems and their potential application in the conceptual design tool.

3.2 Introduction

Engineering design is basically a problem solving process which resolves customer's specific requirements. According to the Systematic Design Approach and Total Design, ideas and concepts are developed in the conceptual design phase based on product specifications determined in the previous stage. Idea generation is an important step in design process since it explores the proposition and prototyping of feasible ideas which may become key solutions to the problem.

Goel and Singh (1998) have indicated that product design relies heavily on human experience, creative thinking and related knowledge that can be achieved by integrating creativity and innovation tools with axiomatic design methodology. "Creativity affects a wide spectrum of the business portfolio and is crucial for designing products (Sarkar and Chakrabarti, 2011)." Specifically to new product development, it involves idea generation, strategy, management, research and development, production, marketing and decision-making (Hsiao, 2004). Therefore it is essential for engineers and designers to understand creativity and its significance in idea generation.

In an engineering product design process, creativity tools can be adopted to enhance engineers' and designers' creative thinking and assist them to understand problems better and devise broader range of solutions. Creativity tools can be applied in different design stages including problem definition, idea generation and evaluation. In this chapter the idea generation phase is focused on with illustration of commonly used creativity tools such as Brainstorming, SCAMPER and TRIZ.

During a design process it is crucial to engineers and designers to understand the way a product is designed, reasons behind each design decision and the justifications for them. Design rationale enables the recording of design process and decision making, providing references and alternatives for future improvements. There are other approaches which can assist engineers and designers in the decision making process such as using a screening matrix and an evaluation matrix.

3.3 **Creativity**

Research on creativity began over a hundred years ago, with early examples including Poincaré (1913) and Wallas (1926), and it has become more commonplace now because of people's diverse thinking styles and economic globalisation. In this rapid changing world, creativity and its implementation has become extremely important to people working in business, industry, education and other professions. Many engineering companies are trying to introduce new products, designs and services into the market in order to increase their market share and competitiveness. However, a new product does not come from nowhere. Designers need creativity, creativity thinking and methods to develop their existing products or to design new ones. Therefore, appropriate use of these techniques will help people carry out high quality designs, leading to success in the market. There have been a many definitions proposed for creativity including:

- *"Creativity can be defined as the ability to imagine or invent something new of value (Childs, 2011)."*
- *"Creativity is a useful and effective response to evolution changes (Summers, 2004)."*
- *"Creativity is a response to the continual innovation and resourcefulness that have become necessary for economic survival (Craft, 2003)."*

- *"Creativity is the ability to challenge assumptions, break boundaries, recognise patterns, see in new ways, make new connections, take risks, and seize upon chance when dealing with a problem (Herrmann, 1996)."*
- *"Creativity can be described as the act of making new relationships from old ideas (Schlesinger, 1980)."*
- *"Creativity occurs through a process by which an agent uses its ability to generate ideas, solutions or products that are novel and valuable (Sarkar, 2008)."*

People see creativity based on their own understanding and context. Therefore, the definition of creativity is elusive and it can be interpreted and applied based on each area (Robinson, 2010). In engineering design field, creativity can be seen as the ability and capability to understand a problem from various perspectives and think outside the box in order to devise innovative solutions.

Creativity was identified by Boden (1996; 2004) into two types, one is called personal creativity (P-creativity) and another one called historical creativity (H-creativity). If an idea has not been had before by the person him/herself, even if other people have had the same idea before, this means a valuable P-creativity. H-creativity concerns an idea that has never been thought of in all human history. It can be seen obviously that H-creativity is more difficult to achieve.

In order to help individuals or teams become more creative, Amabile (1983) proposed a framework which determined the preconditions for creativity:

- *Domain-relevant skills: The necessity of domain-relevant skills and factual knowledge in a given domain.*
- *Creativity-relevant skills: Individual's or team's ability to become creative by using innate creativity or to invoke creativity producing processes.*
- *Task motivation: Motivational variables which determine the willingness of individual or teams using creative thinking to perform processes.*

Based on this framework, the 4-Ps model (For example, see Cougar et al., 1993; Rhodes, 1961) was developed for the application of creativity, providing a clearer structure for the understanding of creativity and its application: The Creative Person, The Creative Process, The Creative Product and The Creative Press/Environment.

- **The Creative Person**

When talking about people being creative, people may think that they must have higher IQ than others. However, the disconnection between IQ and creativity has been widely explored (Kaufman et al., 2008). IQ is representative of convergent thinking while creativity is representative of divergent thinking (Childs, 2011). A general list of the characteristics of a creative person includes fluency, flexibility, originality, elaboration, openness, capacity to make order from chaos, risk taking, curiosity, complexity, imagination, independence and tolerance of ambiguity as proposed by Isaksen (1987).

Kirton (1989) examined the style of creativity into two, adaptive and innovative. The adaptive style can be seen as a development or improvement of existing solutions while innovative style is doing things in a complete different way. In other words, adaptive creativity embodies on doing things better and innovative creativity reflects on doing thing differently. Based on this, he devised an instrument to measure the style creativity, which is called the Kirton innovator – adaptor (KAI) inventory. However, the test result has shown that these two styles are not related to the level of creativity. Another widely used instrument is Myers – Briggs type indicator (MBTI) (Myers et al., 1980), which determines that each person's type can be categorised as a combination of four preferences, which are thinking or perceiving, extroversion or introversion, sensing or feeling, and judging or perceiving.

The creative person can be seen as the most significant factor in 4-Ps model since fundamentally it is people who carry out creative solutions to problems using their knowledge, experience and creative thinking skills.

- **The Creative Process**

Creative abilities and results can be enhanced by utilizing approaches that facilitate the creative process (Cougar et al., 1993). Parnes's (1967) research also indicated that creative abilities can be developed by adopting deliberate programs and methods. Below two examples are introduced to provide a better understanding on creative process.

    - **Parameter analysis**

This process was originally used in the conceptual design stage but they also showed the relevance to embodiment design as a method for systematically incorporating design principles (Condoor, 2008). It consists of the motion between three processes and two spaces. Kroll (2009) described the procedure as follows (See Figure 3.1 for graphical representation):

> *The configuration space consists of description of hardware, shapes and forms. The result of any design process is certainly a member of configuration space and so is all the element of design artefacts that appear, and sometimes also disappear, as the design process unfolds.*
>
> *The concept space deals with "parameters", which in this context are functions, ideas or concepts that provide the basis for anything that happens in configuration space.*
>
> *Repeatedly moving between concept and configuration spaces is carried out by breaking the process into three steps: parameter identification, creative synthesis and evaluation. The three steps are applied time and again during Parameter Analysis, dealing with contingent, constantly evolving information associated with the design artefact. At each cycle of this process, the critical issues identified are different, as are the changing configurations and the results of the evaluations.*

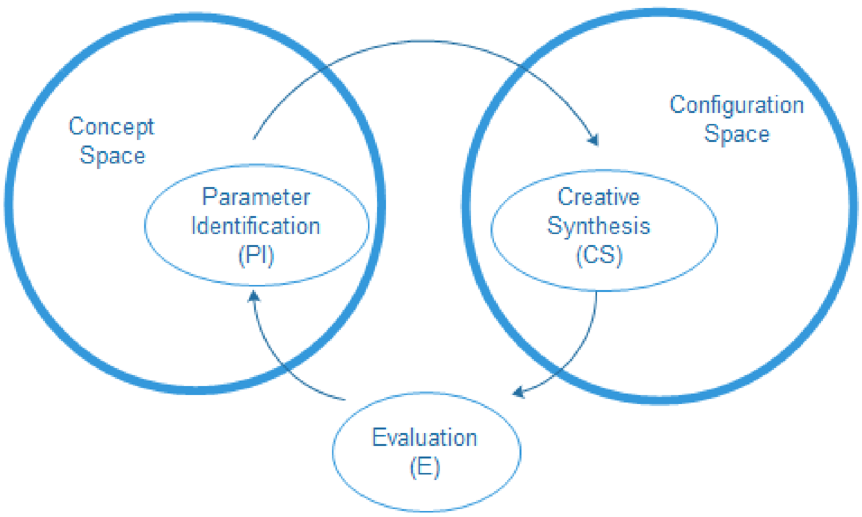


Figure 3.1 Schematic view of parameter analysis

At the start of the analysis, the most dominant issue is addressed. As the process moving forward, with the configuration results, through evaluation, more creative parameter/conceptual ideas will be inspired. This approach does not require designers to specify the functional requirement when starting with concept design. Its transitory configuration at each cycle helps a designer have better understanding and facilitates the discovery of innate conceptual relationships governing the design. As a result, the problem definition evolves from each cycle and the likelihood of innovation increases.

- **Osborn-Parnes' five-stage creative process model**

This creative process was proposed by Osborn (1953) and Parnes (1967) and developed by Guilford (1956), as illustrated in Figure 3.2.

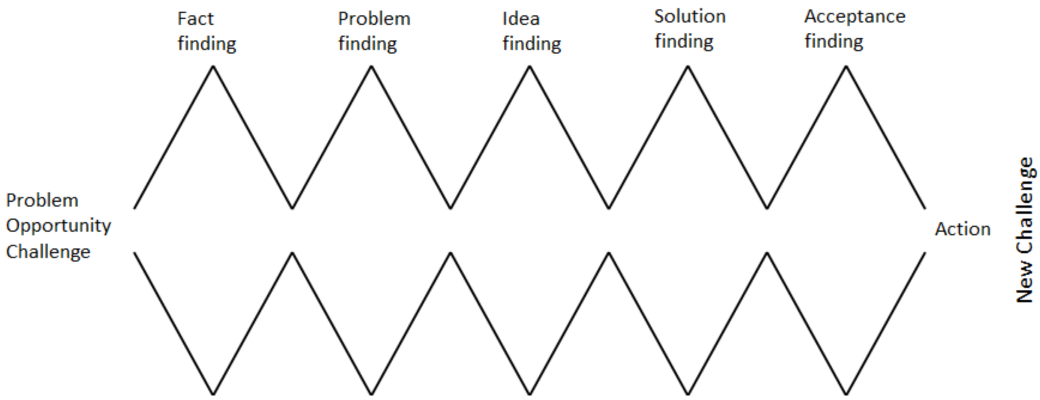


Figure 3.2 The Osborn-Parnes five-stage creative process model

The diamond shaped profile stands for the divergent-convergent thinking process. Divergent thinking includes the generation of ideas, and convergent thinking includes idea evaluations and solution selection.

The research and development of creative problem solving (CPS) process has been carried out over five decades, and now it has become more natural, flexible and dynamic (Treffinger, 2005). The CPS process attempts to separate idea generation and idea evaluation, to prevent the criticism of some ideas before they are evaluated. It has become a powerful tool in companies and industries. Based on the research by Hequet (1992), about 32% of USA companies have the some form of training program for over 100 people, which is twice as much as four years before. Another study by Basadur et al. (1982) has shown that 16 engineers who took the CPS training showed significantly higher performance on ideation in problem finding and solving. It appears to be an effective approach to improve people's creative thinking ability and work performance.

- **The Creative Product**

A product is a device or system designed to satisfy people's need with its specific functions. It usually consists of individual elements and simple links and the relationship between them. In some engineering applications and physical gadgets these elements and links may represent machine elements and mechanisms respectively. Each element and mechanism has its own feature and function. A new product can be produced either by invention or innovation, but they all require creative thinking. Mackinnon (1975) proposed three criteria for the determination of creative product: The product must be novel and original, the product must solve a problem or fit a certain need and the product must be produced, developed and communicated to others. The creative product can be understood as the outcome of utilising creative thinking and processes in both new and existing product development.

- **The Creative Environment**

The environment can affect the creativity of people or vice versa. However, this factor is rarely considered in design process models except a few (For examples, see Hequet, 1992; Thompson, 1999; Hales, 1987). Burnside et al. (1988) categorized environmental factors which affect creativity into stimulants and obstacles, some examples of which are shown in Table 3.1:

Table 3.1 Stimulants and obstacles to creative environment (Reproduced from Burnside et al., 1988)

Stimulants	Obstacles
Freedom	Inappropriate rewards, lack of co-operation, overly bureaucratic
Good project management	Constraint
Sufficient resource	Organisational disinterest
Collaborative atmosphere	External and critical evaluation
Recognition	Insufficient resources
Sufficient time	Time pressure
Challenge	Emphasis on status quo

Based on consistent identification in research studies, the 4-Ps model appears to be significant driving force for the occurrence of creativity. There have been a broad range of methods and tools developed aiming to encourage creativity from diverse perspectives and assisting people devise a wider range of novel ideas. In the next section of this chapter examples of creativity tools are provided, indicating the significance of employing creativity tools in idea generation.

3.4 **Creativity Tools**

Research on creativity tools is generally divided into two approaches, one is based on cognitive psychology and another is "Inventive problem solving" which is based on evolutionary engineering principles (Li, 2007). The first approach emphasises on individuals' thinking style, pushing them to consider problems from different perspectives, exploring and generating diverse and novel ideas, for example, Brainstorming, Six Thinking Hats and SCAMPER. Another approach is based on previous successful principles and aiming to understand and solve problems by learning from other disciplines, for instance, Altshuller's theory of inventive problem solving (TRIZ). In the following sub-sections Brainstorming, SCAMPER and TRIZ are explained in some detail, as these provide insight to understanding creativity tools and their application in engineering design.

3.4.1 **Brainstorming**

The business use of Brainstorming was originated by Alex Osborn, aiming to generate ideas to solve a specific problem (Osborn, 1963). Defined by the Webster Dictionary (2014), Brainstorming is "*a group problem-solving technique that involves the spontaneous contribution of ideas from all members of the group… also: the mulling over of ideas by one or more individuals in an attempt to devise or find a solution to a problem.*" It focuses on maximizing the productivity of idea generation of groups, i.e. quantity of ideas rather than quality.

In order to ensure a brainstorming session to be conducted successfully, a number of rules have been developed by Furnham (2000):

- *Group size should be about five to seven people. If there are too few, not enough suggestions are generated, if too many, the session becomes uncontrolled and uncontrollable.*
- *No criticism is allowed. All suggestions should be welcome, and it is particularly important not to use derisive laughter or disapproving non-verbal behaviour.*
- *Freewheeling is encouraged. The more outlandish (even impractical, off-the-wall) the idea, the better. It is always easier to moderate an idea than to dream it up.*
- *Quantity and variety are very important. The more ideas out forth, the more likely is a breakthrough idea. The aim is to generate a long list of ideas.*
- *Combination and improvements are encouraged. Building on the ideas of others, including combining them, is very productive. "Hitchhiking" and "piggy-backing" are essential parts of cooperation in brainstorming.*
- *Notes must be taken during the sessions, either manually or with an electronic recording device.*
- *The alternatives generated during the first part of the session should later be edited for duplication and categorizations. At some point the best ideas can be set aside for possible implementation.*
- *The session should not be over-structured by following any of the preceding seven rules too rigidly. Brainstorming is a spontaneous small-group process and is meant to be fun.*

Generally methods of brainstorming can be divided into three groups (Holt, 1996): classical brainstorming, brainwriting and computer-aided brainstorming (CAB).

Classical brainstorming starts with the central topic questions or issue written down, followed by idea generation and evaluation within the group. There have been research studies and arguments doubting whether interactive brainstorming would help groups generate more ideas than groups' members working alone (For example, see Rickards, 1999; Litchfield, 2008; Wegge, 2005; Nijstad, 1999; Bolin, 2006; Furnham, 2000; Zainol, 2012; Pinsonneault, 1999; Diehl and Stroebe, 1987), which has indicated three perspectives that may reduce the effectiveness of brainstorming: Social loafing, Evaluation apprehension and Production blocking. Social loafing can be defined as the reduction of personal effort with group work context. Evaluation apprehension is basically the fear of being judged by others, resulting in criticism of the ideas before telling other group members. Production blocking is the disturbance of individuals' thinking by others when presenting ideas to the group. Regarding these three pitfalls of brainstorming, both theory and evidence suggests that nominal groups (Group member generate ideas individually and then pool them together) have superior performance than interactive groups in the absence of interventions to deal with the pitfalls identified. In addition recent work by Yan, Y (2014) has identified the importance of trait in the selection and effectiveness of creativity tools to enhance the outcome of creative thinking.

Brainwriting can be seen as the writing form of brainstorming. Each group member writes down their ideas and circulates within the group. Different from classical flipchart brainstorming, brainwriting enables group member record down their ideas simultaneously instead of presenting one at a time. This can be achieved using post-its and then place them onto a whiteboard or in the centre of a table. Figure 3.3 shows a typical brainwriting session using post-its.

Figure 3.3 Brainwriting using Post-its

A typical brainwriting session normally contains more than one brainwriting stage. First each group member records down their ideas and then posts them onto the whiteboard without communicating with other groups members, called silent brainwriting. Then another silent brainwriting stage continues after the discussion within the group about previous generated ideas for inspiration of their own ideas. By conducting more than one stage of brainwriting everyone in the group is free to explore and generate more ideas based on others' ideas.

Another brainwriting approach called grid brainstorming can be employed when a few ideas are chosen to be further developed. Generally 3 or 4 ideas are chosen and then drawn on the first row of a grid by one of the group member then circulate within the group, each member is required to draw their own understanding or development of the chosen idea in the next row. By the end of this session every member should not have their own idea developed twice, therefore, each idea in each block could be a potential solution to the problem. Figure 3.4 illustrates a template of grid brainstorming.

Group member a	Idea A	Idea B	Idea C
Group member b	Idea A+ (develop from Idea A)	Idea B+ (develop from Idea B)	Idea C+ (develop from Idea C)
Group member c	Idea A++ (develop from Idea A+)	Idea B++ (develop from Idea B+)	Idea C++ (develop from Idea C+)

Figure 3.4 Grid brainstorming template

Computer-aided brainstorming (CAB) uses the advantages of modern technologies such as emails, video chat and other online communication tools that can organise brainstorming across different geographic locations, background. CAB is more flexible in time and space comparing the traditional face-face brainstorming methods. A good example of CAB is electronic brainstorming (For example, see Pinsonneault, 1999).

As a creative problem solving technique, brainstorming is popular among industries even though it may not be the most effective way to generate ideas. This may because people feel comfortable working in groups, with interactions between group members, and individuals may perceive their own productivity more favourable compare to working alone (Pinsonneault, 1999). Brainstorming is able to increase decision acceptance, pooling resources together in a relative short time period and specialisation of labour (Furnham, 2000). In conclusion, with intervention to deal with the pitfalls and appropriate facilitation, both group and individual brainstorming can be a powerful tool to boost the generation of creative and innovative solutions.

3.4.2 **SCAMPER**

Different from brainstorming techniques, SCAMPER is more widely employed in idea generation in developing existing products and designs via a checklist. SCAMPER is the short for (De Bono, 1992; Mycoted, 2015; Mindtools, 2015):

- S - Substitute – components, materials, people
- C – Combine – mix, combine with other assemblies or services, integrate
- A – Adapt – alter, change function, use part of another element
- M – Modify – increase of reduce in scale, change shape, modify attributes (e.g. colour)
- P – Put – put to another use
- E – Eliminate – remove elements, simplify, reduce to core functionality
- R - Reverse – turn inside out or upside down

Ideas may be generated by asking a series of questions regarding to each letter. Below some example questions are listed that could be asked during the SCAMPER process (Mindtools, 2014):

- Substitute:
    - Can I replace or change any parts?
    - Can I change its shape?
    - Can I use other processes or procedures?
- Combine:
    - What ideas or parts can be combined?
    - What material could be combined?

- Adapt:
    - Is there something similar to it, but in a different context?
    - What could I copy, borrow or steal?
    - What ideas outside my field can I incorporate?
- Modify:
    - What can be magnified or made larger or smaller?
    - Can I add extra features or somehow add extra value?
- Put:
    - What else can it be used for?
    - Are there new ways to use it in its current shape or form?
    - Can I use this idea in other markets or industries?
- Eliminate:
    - How can I simplify it?
    - What parts can be removed without altering its functions?
    - Should I split it into different parts?
- Reverse:
    - Can I interchange components?
    - Should I turn it around? Upside down? Inside out?
    - What if I consider it backwards?

SCAMPER is able to help identifying possible opportunities for product improvement, although many ideas may seem unfeasible, some of them could be a starting point for future discussion and development. Research and experiments (For example, see Chulvi, 2012; Lopez- Mesa, 2011; Poon et al., 2014) have shown the effectiveness of SCAMPER in stimulating creative thinking and potentiality in generating more feasible ideas than normal brainstorming techniques.

3.4.3 TRIZ – Theory of Inventive Problem Solving

TRIZ is a problem solving methodology primarily proposed by Genrich Altshuller (1956), aiming to explore creative and innovative solutions by drawing from previous successful problem solving techniques in various fields based on their regularities. TRIZ is short for Teoriya Resheniya Izobretatelskikh Zadatch, which stands for Theory of Inventive Problem Solving (TIPS). TRIZ is a unique, rigorous and powerful toolkit which is able to guide engineers and designers to understand and solve specific problems by analysing over 400,000 patents from various fields of engineering and revealing the trends of engineering system evaluations. It is able to deliver systematic guaranteed innovation and creativity, help people understand the problem and all its solutions, simplify systems to maximise benefits and minimize costs and harms and help overcoming psychological inertia (Gadd, 2011; Sushkov et al., 1995).

After formulating the basic principle of TRIZ, Altshuller and his team further elaborated it into three problem solving techniques (Sushkov, 1995):

- Inventive principles for elimination of engineering conflicts, e.g. 39 parameters and 40 principles.
- Inventive standards, which means there are common ways of problem solving for similar pattern of problems even though they may not be in the same engineering domain, e.g. 76 standard solutions.
- Scientific – engineering effects. This means using natural and physical knowledge rather than completed mechanical ones, e.g. effect database.

In TRIZ a specific problem is abstracted into general issues, enabling the feasibility to search for solutions for similar problems. Then general solutions are transformed back into the specific problem using analogy that answers the original problem (See Figure 3.5). Inventive principles were mainly reviewed in author's research for exploring problem solutions, i.e. focused on eliminating engineering conflicts.

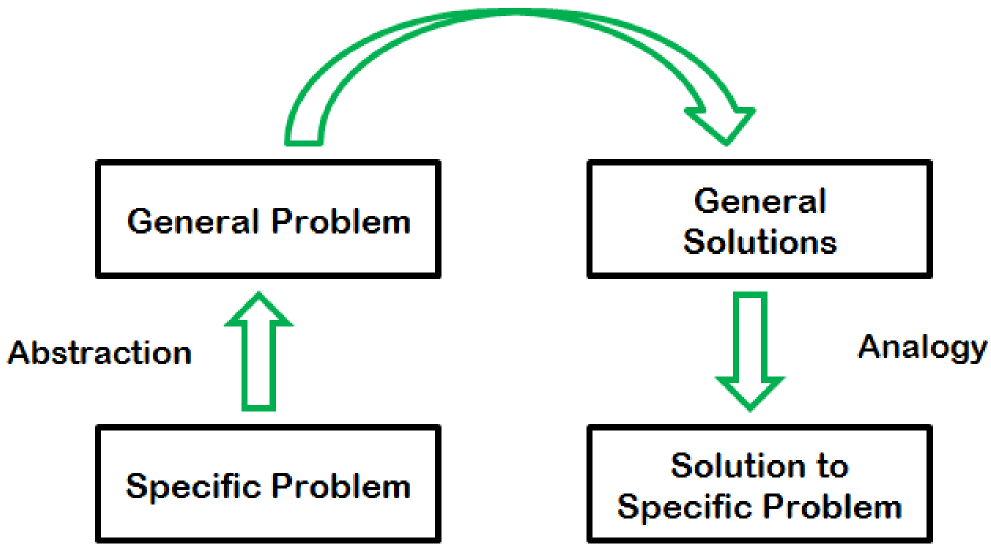


Figure 3.5 TRIZ systematic approaches to problem solving (Reproduced from Childs, 2011)

Engineering conflicts, also called contradiction in this case, are simply a clash of solutions. They are generally divided into technical contradiction and physical contradiction.

Technical contradiction means with the improvement of one parameter in a system, something else in the system gets worse. For example, improvement on material strength by adding more materials makes weight worse. It seems that it is not possible to have both improved. However, "The basis for TRIZ is not to compromise, or optimize contradictions, but fundamentally solve them – to not try and choose between two good things but systematically locate solutions that will give us both (Gadd, 2011)." Figure 3.6 shows a technical contradiction between two parameters and how TRIZ is used to find the good solutions for all. This is achieved by applying the 40 principles associated with 39 parameters and the contradiction matrix. Detail information of 39 parameters, 40 principles and the contradiction matrix can be found in Gadd (2011).

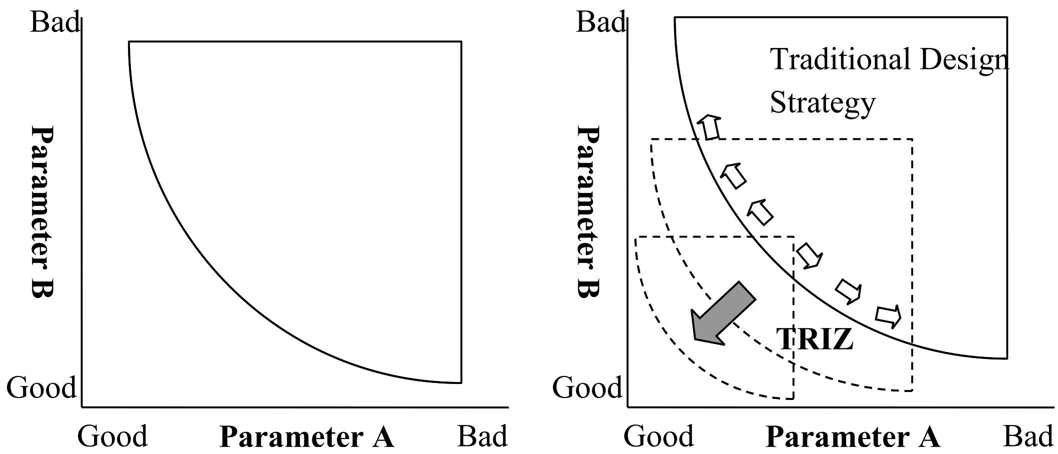


Figure 3.6 TRIZ application in solving technical contradictions (Mann, 2002)

In the contradiction matrix each box has a selection of 40 principles which gives guidance to solve a specific technical conflict. For physical contradictions the box shows blank. Suggested by Childs (2011), there are four steps recommended for contradiction matrix employment. First, use the 39 parameters to identify critical features in the problem. Second, identify the contradiction between the parameters where one causes problems with another. Then use the contradiction matrix to locate principles that can be used to resolve the conflicts. Finally use the numbers from the matrix to look up resolution principles and use these principles to find solutions to the problem. For example, when designing a conventional axe, if the blade is made heavier, it would have more power, but the quantity of material used would go up, and the axe would become more difficult to operate. The improving feature here is the force and the worsening feature is the quantity of the material. The features are 10 and 26 respectively regarding 39 parameters.

Table 3.2 Conventional axe example

	Worsening Feature Improving Feature	**25**	**26**	**27**
9	Speed	all	10 19 29 38	11 35 27 28
10	Force	10 37 36	14 29 18 36	3 35 13 21

From the matrix it is known that the selection of 40 principles recommended are 14, 29, 18 and 36 (indicated in the red circle in Table 3.2), which are curvature, pneumatics and hydraulics, mechanical vibration and phase transition respectively. Using curvature and pneumatics as inspiration, the handle could be hollow moving the centre of gravity of the axe forward to provide more power when operating without adding to the material used.

Physical contradiction basically refers to opposite solutions. A parameter was improved and got worse in the same time. For example, people want an umbrella to be big enough to cover the body but small enough to carry around. This type of conflicts can be solved by separating the solutions in different ways such as time, space, scale and alternative ways (For example, see Gadd, 2011; Mann, 2002; Tsai, 2008). Separate in time means having one solution at one time and the opposite solution at another time. Similar principles apply for separate in space and scale. Four alternative solution thinking methods were indicated if the time, space and scale do not apply to the problem: transition to sub-system, super-system, alternative system and inverse system (For example, see Mann, 2002).

TRIZ is able to offer engineers assistance with concept-solution locating and problem solving. In theory the toolkit can be applied for each stage in the problem solving process, as shown in Table 3.3. However, the most valuable application of TRIZ is in the conceptual stage of design. Its principle advantage over other methods in the early stage design process is that it contains high level knowledge about the regularities of engineering systems developments based on many years of analysing world's patent collection in various engineering domains (For example, see Sushkov, 1995; Ikovenko and Bradley, 2004), and is a short-cut to experience (Childs, 2013). TRIZ tools have been employed into industries indicating its value in increasing design efficiency, innovative ability and proposing better solutions (For examples see Chen et al., 2008; Cernigila et al, 2008; Cho and Kim, 2010).

Table 3.3 TRIZ application on each stage of problem solving (Gadd, 2011)

Before - Preparation for problem solving	**During - Problem solving**	**After - Solution Selection and Development**
TRIZ and other tool-kits for Requirements/needs capture System analysis Find any root causes of problem etc.	Brainwave ideas Brainstorming Creativity tools and/or TRIZ TRIZ Conceptual Solutions 40 Principles 76 Standard Solutions 8 Trends all used with relevant world's Knowledge and TRIZ Creativity Tools including - Ideal Solutions Smart little people Size - Time - Cost etc.	TRIZ and other Tool-kits For Concept development Concept selection process (such as Pugh Matrix) Successful Innovation and new technologies etc.

The advantages of TRIZ are quite obvious. It can help people who use it become more innovative and creative in problem finding and solving, and it can be applied to various kind of problems in different engineering fields. However, there are some criticisms of TRIZ. Gadd (2011) indicated that TRIZ cannot solve all the problems. An example given by Sushkov (1995) stated that if a difficult problem is only analysed in terms of conflicts between parameters, the solution may not be found. Another criticism both indicated Gadd (2011) and Sushkov (1995) is that although TRIZ is useful and powerful for problem solving, it does not tell you which TRIZ tools to use and when. Therefore, the proper use of TRIZ requires understanding of the Tool and high degree of expertise in engineering design. In spite of these drawbacks, TRIZ still represents a valuable tool to use when solving engineering design problems.

There are hundreds of creativity tools can be adopted to encourage creative thinking in the design process. Brainstorming, SCAMPER and TRIZ are just a tip of an iceberg. But they do have one common purpose, to devise more and better solutions. All these creativity tools are able to offer assistance to designers and engineers in their engineering conceptual design stage, which can be employed into the conceptual design process developed by this thesis's author to enhance its efficiency, effectiveness and robustness.

3.5 Idea Evaluation

After ideas and concepts are proposed, they need to be evaluated in order to find the most promising solution to the problem. In this section three commonly used idea evaluation approaches are introduced: Evaluation matrix, Screening matrix and IBIS represented design rationale.

3.5.1 Evaluation Matrix

An evaluation matrix is mainly used to evaluate a number of options against prioritised criteria. Before the evaluation of ideas, the team are required to establish evaluation criteria that approved by the whole team. These criteria need to be prioritised first with numeric representations, for example, 5 = high, 3 = medium, 1 = low. Then each idea is scored according to each criterion, e.g. 10 = Excellent, 7 = Good, 4 = Pass, 1 = fail. The score of each idea can be obtained by multiplying its score against each criterion and the criterion priority. The idea with highest score should be the best solution regarding the assessment criteria. A standard form of evaluation matrix is shown in Table 3.4.

Table 3.4 Evaluation matrix example

	Criterion 1	**Criterion 2**	**Criterion 3**	**Criterion 4**	**Total Score**		**Priority**
Idea 1	10	7	1	7	69	Criterion 1	1
Idea 2	4	4	4	4	48	Criterion 2	5
Idea 3	1	10	7	1	**75**	Criterion 3	3
Idea 4	1	1	7	7	48	Criterion 4	3

3.5.2 **Screening matrix**

Suggested by M. Joly (1992), a screening matrix provides a list of assessment criteria which include:

- **Advantages** – benefits deriving from the idea, e.g. "What are the advantages?"
- **Feasibility** – practicability of the idea, e.g. "Does it break any fundamental principles?"
- **Resources** – the resource required to realise the idea, e.g. "How many hours of labour are necessary?"
- **Adequacy** – whether the idea is suitable for the current organisation/system, e.g. "Is the idea coherent with current system design?"
- **Vital and fatal factors** – factors that determines the survival and death of the idea, e.g. "Profit, pollution"
- **Flexibility** – suitability of the idea for uncertain future conditions.
- **Risk** – Uncertainty of the idea.

This technique is suggested for application in groups with experts in the topic, which allows the team to assess the ideas according to different pre-defined criteria (Screening matrix, 2014). A similar approach is used to weight each concept and then the sum of the weights attributed to every criterion giving the definitive value of each solution. Detail information regarding each term can be found in Appendix 3.

3.5.3 **IBIS Represented Design Rationale**

Design Rationale is an explicit approach which allows engineers and designers to describe why an artefact is designed the way it is (Maclean, 1989). In engineering design, it is essential for designers and engineers to understand the reason behind a decision. Design Rationale is capable of recording design processes including considerations and trade-offs in the design process, justification for design decisions, record of design alternative considerations, decisions and reasoning behind them (Zhang, 2013).

Stated by Lee (1997), the design process can benefit from Design Rationale in four major ways: design support, maintenance support, learning support and documentation support. Well-structured Design Rationale cannot only assist designers in issue tracking and alternative exploration and their evaluations, but also help maintaining the design.

Design Rationale is also able to help people and systems learn mutually and interactively, as well as generating documentation of design process. Design Rationale is able to provide traceability in the event of issues, as well as a record to explore if opportunities for new markets and products emerge. It can include not only the reason behind a design decision but also the justification for it, other alternatives considered, the compromise made and the argumentation leading to a decision. There have been several approaches developed for Design Rationale representation (For example, see Conklin, 1991; Lee and Lai, 1991; Zhang, 2013, Bracewell, 2009). IBIS was selected for the research presented in this thesis, based on expertise within the group as well as evidence for its effectiveness.

IBIS is short for Issue Based Information System which was first proposed to support coordination and planning of political decision processes (Kunz and Rittel, 1970). It has three main types of elements: issues, positions and arguments. In this approach ideas are placed around issues, linked by arrows. Argumentation for each idea is positioned around the idea, providing records of thinking. In the IBIS approach everything is organised by questions with a structure allowing the diagrammatic representation to grow indefinitely if necessary (Conklin, 1991). It has been widely used in data and information management (For example, see Cao, 1999; Kim, 1993) and providing record of design and decision making processes. Design Rationale can be represented by the IBIS approach using simple and intuitive notation with clear structure and language. A range of software is available embodying IBIS principles including QuestMap, REMAP, DRed, designVUE and Compendium. designVUE was mainly used in the research.

designVUE is a branch of VUE (Visual Understanding Environment) originally developed by Tufts University. In desigVUE the element Position are referred as answer. Figure 3.7 illustrates the notations in designVUE.

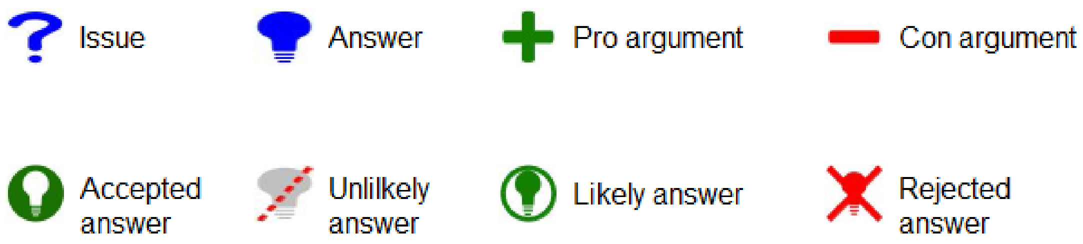


Figure 3.7 designVUE design rationale notations

In designVUE different layers of diagrams can be linked and accessed through wormholes in order to keep the diagram more organised. Some commonly seen file types such as pictures, videos and document files are supported and can be inserted into designVUE to support arguments and provide detailed information. IBIS represented Design Rationale using designVUE represents a powerful decision making support tool for idea evaluation providing a record of justification behind each decision. In the following section an industrial project was introduced to demonstrate the value of creativity tools and idea evaluation tools.

3.6 Case Study - Chain Spill Analysis

This case study is conducted by a group of PhD students led by this thesis's author. The author mainly contributed in leading this project including propose different problem solving techniques, devise and improve designs. Purposes of this case study in the context of this thesis are: to understand the value and benefits of employing creativity tools in problem identification and idea generation. Second is to understand the value of benefits of employing IBIS approach in identifying root causes and capture design rationale. These tools are expected to be applicable to the conceptual design tool to help the user analyse the design problem, generating novel ideas and capture design activities and decisions.

3.6.1 Problem Statement and Identification

Lengths of slack chain from electric chain hoists used to support production equipment in Royal Albert Hall (RAH) can, on occasion, spill from collection bags posing risk of significant injury to those below. This issue is a potential problem across many venues and live music events. In general, chain spills happen very quickly and the sound of the chain running over trusses or other resistant materials is the only warning. Should a falling chain strike a person it could cause serious injury and even fatalities. If the chain were to strike luminaires or other production equipment, broken parts and debris could fall onto people below.

At the Hall there are in-house motors which are mainly in fixed positions above the inner roof of the auditorium with the hooks and chains coming through holes in the roof into the auditorium. Motors bought in by individual productions are either sub hung from these hooks or from truss suspended by these hooks. Motors may be rigged in different configurations (motor up and motor down, see Figure 3.8) depending on the mode of use or to gain additional height. The in house motors have very rarely given rise to chain spills (one occasion can be recalled in a decade). It is with production motors that most of the incidents have occurred. Some of this rigging is hugely complex and is carried out by production riggers in very limited time windows which obviously have the capacity to increase the risk of spills occurring due to poor rigging.

Based on the information provided by Royal Albert Hall it is known that in house motor are hanged in the motor down position, where the motor is much less likely to move during operation, the main spill occurs in motor up positions where the motor moves up during operation. Therefore in this project motor up position was focused and analysed.

Figure 3.8 Motor down and up configuration

The hoist rigging system was configured and approved by RAH experts in order to help the author and his team to identify the problem precisely:

- Motor up position is used
- The chain bag is hanged at one or two points on the hoist using eyebolts
- The smallest eye bolt used is 5mm wire with 50mm diameter
- The length of the chain is normally 20 to 30 meters
- There is a dead end of the slack chain, fixed on the hoist
- The chain link dimension is typically 25*50mm or 15*30mm

The hoist rigging system was labelled for the convenience of component identification, shown in Figure 3.9.

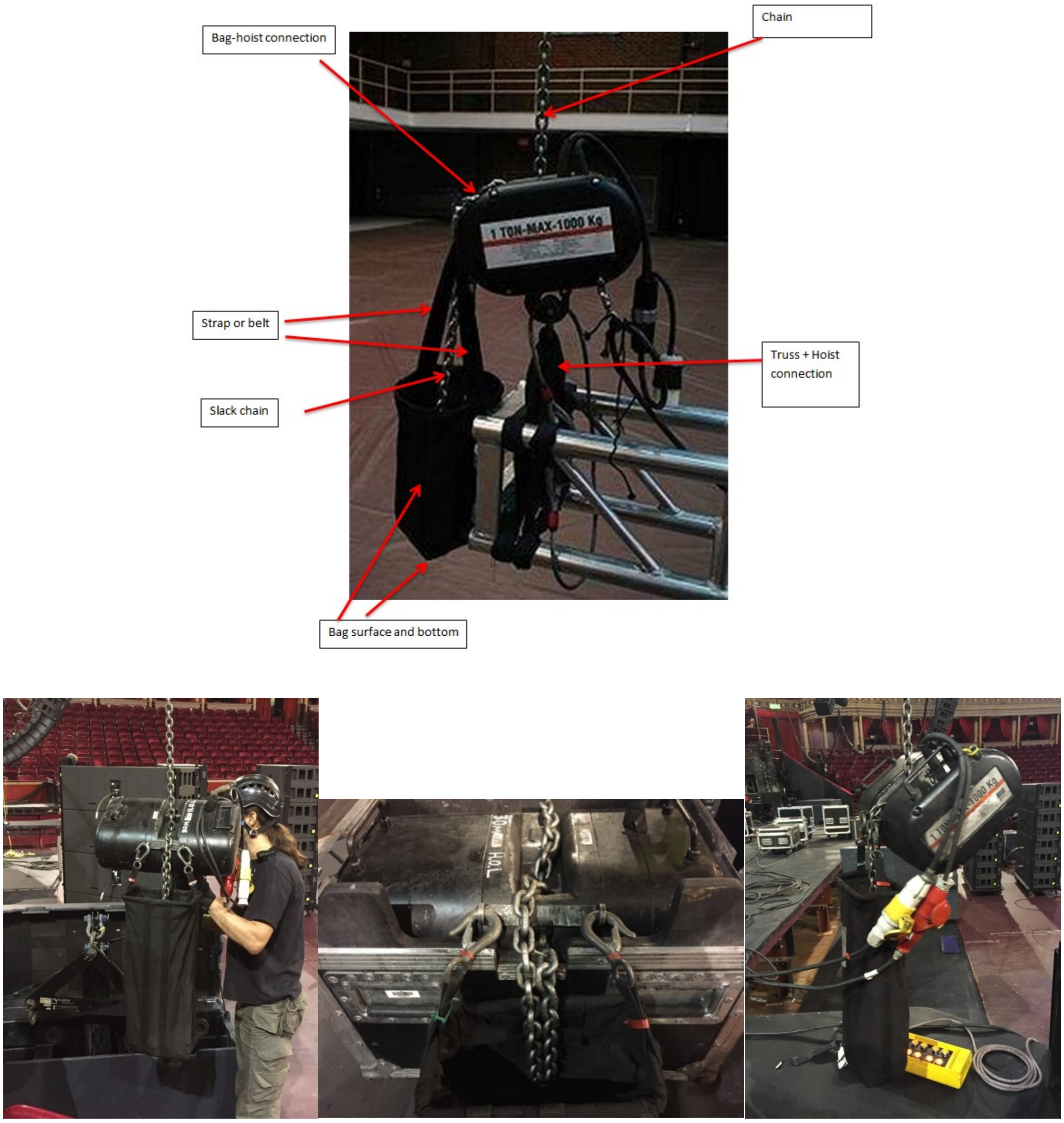


Figure 3.9 Hoist rigging system

Although several potential causes of the chain spill were suggested by RAH, IBIS approach was employed to identify root causes (see Figure 3.10). This enables the group to identify origins of this chain spill problem by investigating and analysing each element of the hoist rigging system, providing an organisable and clear view of the system composition and root causes. This diagram offered guideline and helped the group gain insights on solving this problem by focusing on each of these issues individually. These issues were then numbered and evaluated using risk assessment matrix agreed by both Imperial and RAH, shown in Table 3.5.

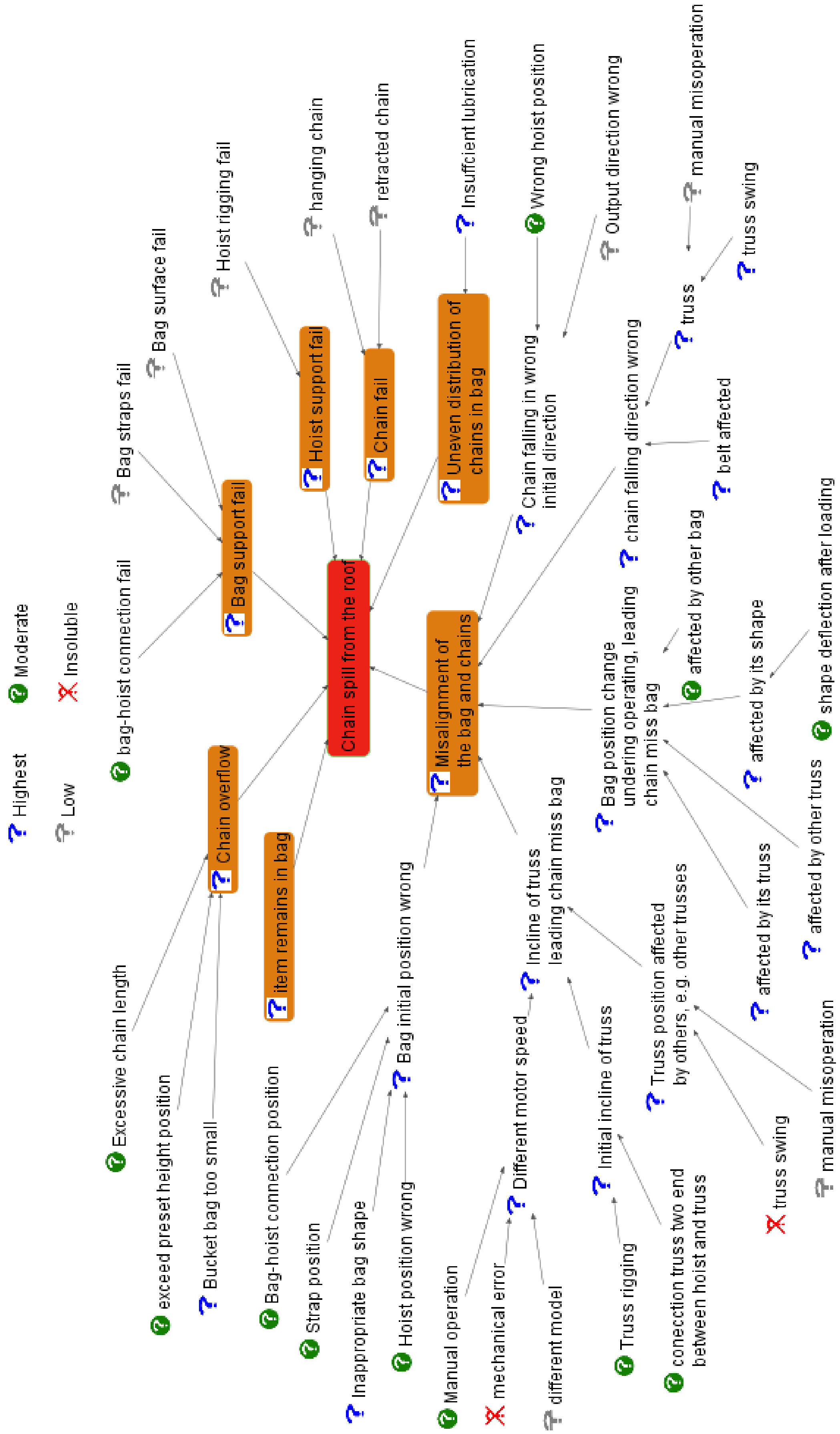


Figure 3.10 Chain spill analysis map

Table 3.5 Chain spill cause risk assessment

Chain Spill			Possible causes (DEG)	Likelihood of occurrence	Severity of Consequences	Number
Bag support fail			Bag-hoist connection break apart	C	4	1
			Bag strap break apart	B	4	2
			Bag Surface broken	A	2	3
Hoist support fail			Hoist rigging fail	D	4	4
Chain fail			Retracted chain break apart	D	1	5
Uneven distribution of chains in bag			Insufficient lubrication	C	2	6
Misalignment between bag and chain	**Bag initial position wrong**		Bag-hoist connection position(bag does not hang in a proper position)	D	2	7
			Bag strap get into the way that chain default falling route	A	2	8
			Inappropriate bag shape	D	2	9
			Hoist position wrong	A	2	10
	Incline of truss leading misalignment	**Different motor speed**	Manual operation	D	2	11
			Mechanical error (motor speed)	D	2	12
			Different hoist model(although with same specification)	D	1	13
		Initial incline of truss	Length differences of Hoist rigging at each end of truss	B	2	14
			Length differences of Connection between hoist and truss	B	2	15

		Truss position affected by other truss	Truss swing	C	3	16
			Manual operation caused truss collision	B	4	17
	Bag position changing under operating		Affected by its own truss	C	1	18
			Affected by other trusses	B	2	19
			shape deflection after loading the chain	C	1	20
			Affected by other bags	C	1	21
	Chain falling direction wrong		Belt affected chain falling during operation	A	3	22
			Truss swing	C	1	23
			Manual operation	D	2	24
	Chain falling wrong initial direction		Wrong hoist position	D	2	25
			Wrong chain exit direction	D	1	26
Chain overflow			Actual retracted chain length exceeds default value. (e.g. to hang the truss at pre-set position, the default retracting length is 25m, but actually 27m chain is retracted)	D	3	27
			Exceed pre-set height position (the pre-set height of the truss position is 30m, but it reaches 32m)	D	3	28
			Bucket bag too small	C	3	29
			Other items remains in bag (initially)	D	2	30
			Chain has been loaded in to bag incorrectly	B	2	31

According to the risk assessment table these issues were prioritized and tabulated. Issues were focused on in the order of their risk level, i.e. from top-right corner to bottom-left in Table 3.6. Table 3.7 provides more detail information regarding high priority problem causes.

Table 3.6 Chain spill cause risk matrix

	1	2	3	4
A		**3, 8, 10**	**22**	
B		**14, 15, 19, 31**		**2, 17**
C	**18, 20, 21, 23**	**6**	**16, 29**	**1**
D	**5, 13, 26**	**7, 9, 11, 12, 24, 25, 30**	**27, 28**	**4**

Table 3.7 Chain spill cause problem reformulation

Issue No.	Possible causes	Chain spill scenarios	Likelihood of occurrences	Impact
22	Bag affected chain falling during operation	Wrong chain falling direction	High	Serious
2	Bag strap broke apart	Collection bag support failure	Moderate	Critical
17	Manual operation caused truss collision	Truss incline causing misalignment of bag and chain	Moderate	Critical
3	Bag surface broken	Collection bag support failure	High	Moderate
8	Bag strap got in the way of chain default falling route	Wrong bag initial position	High	Moderate
10	Wrong hoist position	Wrong bag initial position	High	Moderate
1	Bag-hoist connection broke apart	Bag support failure	Low	Critical

3.6.2 **Idea Generation and Evaluation**

Different types of creativity tools were suggested according to research conducted by Yan (2014), include TRIZ, Smart Little People and SCAMPER. Focusing on issues stated in Table 3.7 ideas were generated by the team and then evaluated using Screening Matrix (For detail see Table 3.8).

Table 3.8 Screening Matrix criterion

Advantage	**Feasibility**	**Resources**	**Adequacy**
• Efficiency of the mechanism • Application novelty/originality • Space saving	• Complexity (Idea itself) • Level of realisation • Level of adaption to the existing system	• Cost • Time • Man power	• Appearance in accordance with RAH style • Operation procedure accordance with workers • Budget
Vital factors	**Fatal factors**	**Flexibility**	**Risk**
• Idea focus	• Pollution caused • IP violation	• Tolerance with any future changes • Compatibility with other components	• Cause any other problems? • Damage to other parts of system? • Generate waste

Figure 3.11 shows a selection of initial concepts selected by the group regarding the issues identified above. The author was recommended to use SCAMPER in idea generation.

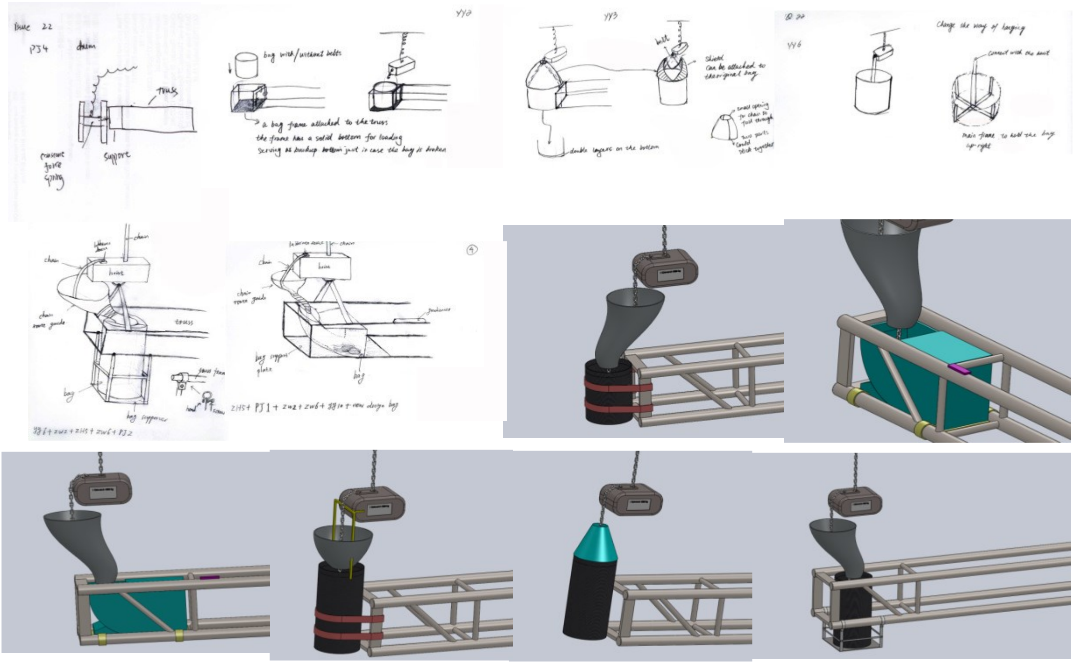


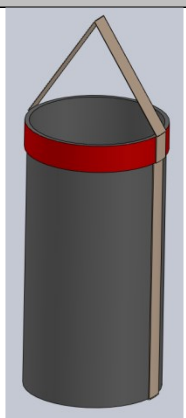
Figure 3.11 Hoist rigging system initial concepts

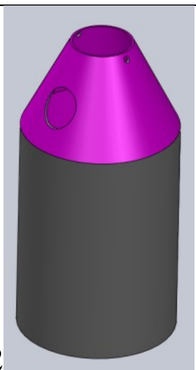
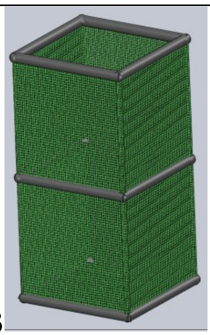
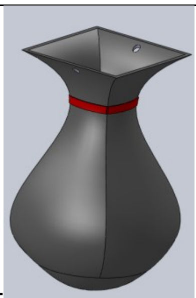
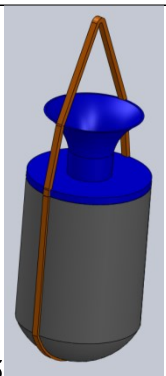
From the feedback it was known that the electric hoists are normally brought by the parties who hold the event, which indicates that any changes to the hoist should be eliminated. Therefore two areas of design focuses were determined using SCAMPER:

- Substitute - new types of chain spill proof bag design.
- Combine and Adapt- an accessory design act as a chain guide which can be installed onto the existing system.

3.6.3 Chain Bag Designs

Table 3.9 New chain bag designs

Bag Design	Brief	Comments from RAH
 1	A development of existing bag with extended height, aiming to reduce the gap between the bag opening and chain exit.	Not feasible since there is no extra space allowed. Still no prevention of spilling. A shorten belt with same bag size will help.

 2	A side entrance for the chain dead end was designed to prevent lumps during operation. The cone shaped cover was designed aim to make sure that the chain will not spill out once fell into the bag.	When pulling up the chain going through the side entrance could life the whole bag and cause collision.
 3	Inspired by tennis racquet, textured design enables the deformation of the bag surface under loading, and therefore create a larger volume. The bag is separated into segments by rigid metal frames, enables a compensation of the leaning of the bag, ensure the bag opening stays horizontal.	Concept is good but the material used needs to be determined, e.g. frame, string material. Better shape may be used to increase reliability.
 4	Rigid material is used above the red frame to maintain the shape of bag opening, punch bag shape with soft material is used for the remainder of bag.	Punch bag design is good but bag opening is too wide. Chain guide may be used to ensure the chain will not spill when leaned.
 5	A trumpet cover is used to reduce the gap as well as guiding the chain into bag. The cover stitched prevents the chain from spilling even the bag is leaned.	Bag opening too wide, reverse the trumpet may reduce the spill risk but require more precise proposition.

Bag design 3 was RAH staff's favourite with regard to its novelty. In accordance to comments and feedback provided, this design was further developed, shown in Figure 3.12. In the improved design, circular rim is used instead since it has less stress concentration and easy to manufacture. More bag segments are designed to ensure at least one section of the bag remains vertical even it was caught (by, for example, trusses). Belts are used to enhance strength and reliability.

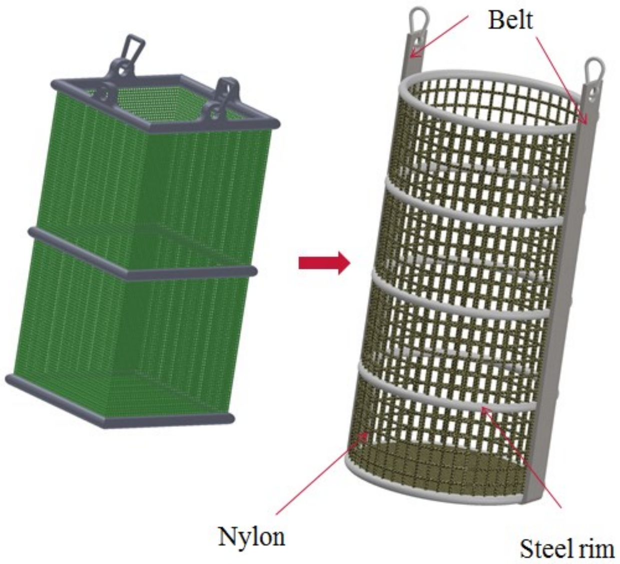
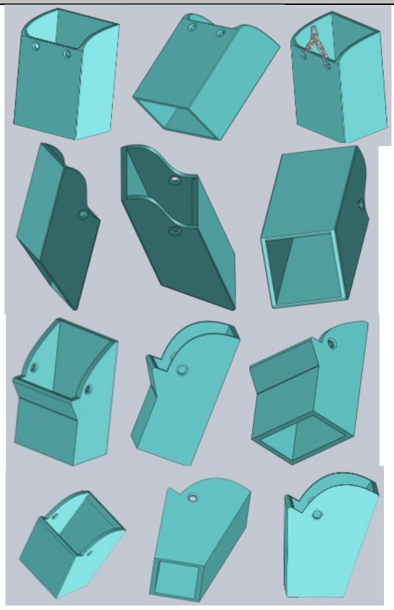
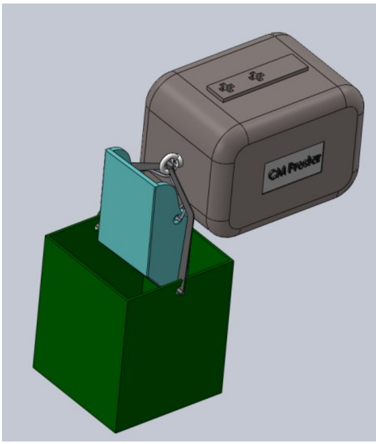


Figure 3.12 Improved texture bag design

3.6.4 **Chain Bag Accessory Design**

The most significant benefit of using an accessory is that no changes are required to the existing system which will reduce the cost and has a much broader range of application. Table 3.10 shows several chain guidance designs proposed.

Table 3.10 Chain bag accessory designs

Accessory Design	Brief	Comments
 	These designs have curvatures buffers which are able to reduce the gap between chain exit and the accessory ensure that chain will fall through the guide safely.	There is a good chance the chain could spill out from the space outside the guide if the bag is leaned to 90 degree. Therefore a design that is big enough to guide the chain into the bag but also small enough to prevent the chain from spilling is recommended.

In accordance with the feedbacks from RAH, a new chain bag accessory design was proposed, shown in Figure 3.13.

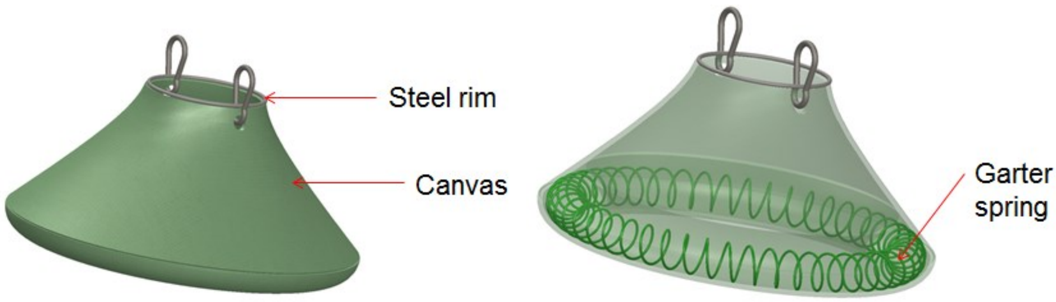


Figure 3.13 Improved chain guide

The steel rim ensures that the guide opening remains rigid during operation. One option for the surface material is canvas, strong but flexible, can be bent and twisted if necessary. The garter spring is placed inside the exit of the guide covered by bag surface material which will be placed into the collection bag, i.e. below the bag rigid opening. The size of the spring (the outer diameter) is designed to be slightly bigger than bag opening to ensure it operates as interference fit. An illustration of the assembly is shown in Figure 3.14.

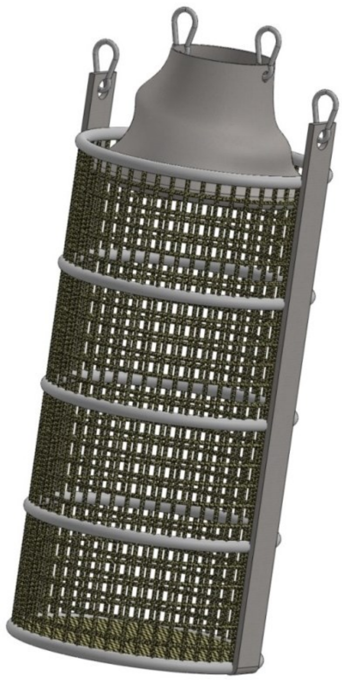


Figure 3.14 Chain guide and chain bag assembly

This design enables robust installation and use of the chain guide with no necessary change of the existing system. The chain guide is also collapsible for the convenience of transportation. However, a potential risk has been identified that can the garter spring withstand the load when the 20kg's chain is leaned. Therefore, prototyping and experiments are suggested to simulate different scenarios to see the feasibility of this design. Currently this project is at prototyping stage, future work will be identified depends on outcome of the prototype performance. Figure 3.15 shows the Design rationale of this project.

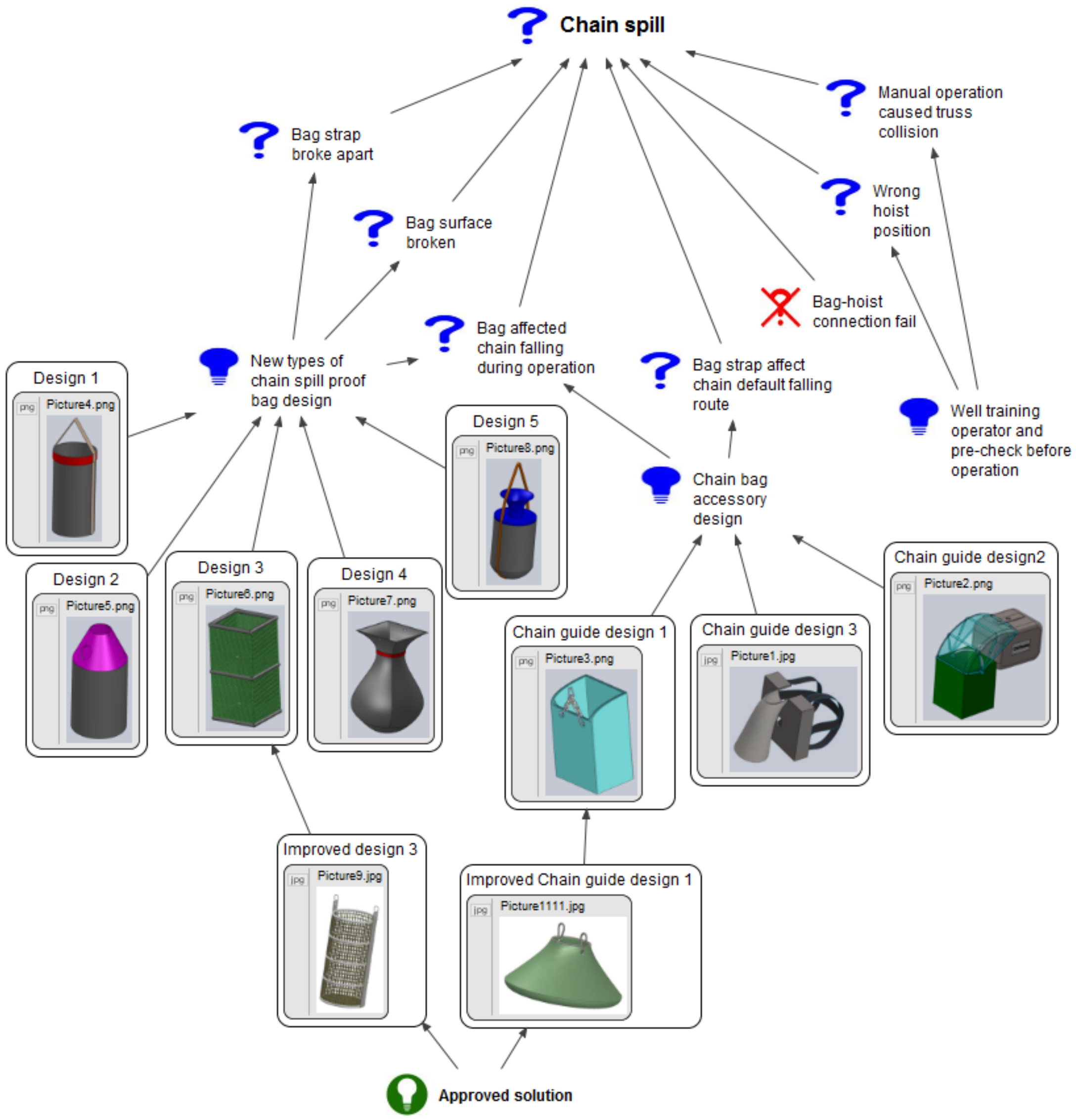


Figure 3.15 Chain spill analysis design rationale

From the review of creativity tools and their applications in the chain spill case study, it was found through personal experience and positive feedback from Royal Albert Hall experts that appropriate employment of creativity tools can provide assistance on analysis of the design problem and solution seeking from different perspectives, providing a structural but effective idea generation process. Although most of the ideas generated are at conceptual stage and may be eliminated eventually, it is still beneficial to use creativity tools in idea generation process. Idea generation can be seen as the most important stage in engineering design since it has the most significant impact on the design outcome. Quality ideas are able to create a good kick-start for future design activities. In-depth understanding on and appropriate employment of creativity and creativity tools can not only help engineers and designers to understand design problems better but also help them devise broader range of solutions. The case study outcome also suggests the value of IBIS approach in deconstructing complex problems and identifying root causes. IBIS's structural approach is able to help the user analyse the problem and devising solutions from different perspectives and recording them with argumentations. With the support of IBIS map engineers and designers are able to see alternatives and track any changes of solutions. IBIS is also able to provide the rationale of every idea for the convenience of the board. This case study also indicated the benefit of using system breakdown in problem analysis and idea generation, i.e. it is able to help engineers and designers formulate a complex core problem into puzzles and solve them individually incorporate with creativity tools. This provides an effective and efficient start for devising conceptual solutions which can be further developed.

3.7 Chapter Summary, Findings & Learnings

In this chapter creativity and three commonly seen creativity tools were introduced, whose aim is to help engineers and designers to understand the problem better and devise creative solutions in ideation in general as well as product conceptual design. IBIS has been highlighted as an effective mean to evaluate ideas and capture design rationale. A chain spill analysis case study was demonstrated to show the value of IBIS and creativity tools in problem formulation, root cause analysis, idea generation and concept selection.

The benefits of employing creativity tools in idea generation and IBIS approach in problem analysis and idea evaluation were demonstrated in the review and the industrial case study. The implementation of creativity tools and IBIS approach also forms an important part of the conceptual design tool in terms of problem reformulation, idea generation and evaluation. As introduced in the research structure, the other route of research is the necessity to help engineers and designers understand commonly used machine elements and mechanisms and their appropriate use in order to conduct successful mechanism conceptual designs. In Chapter 4, the most important element of the conceptual design tool, MMET and an initial design approach built on it are introduced.

Chapter 4 Mechanism and Machine Elements Taxonomy (MMET)

4.1 Chapter Introductory Statement

In this chapter the establishment of MMET is introduced, including its data collection, database setting up and software support development. A conceptual design tool built on MMET is then introduced and validated through a surgical platform design case study, providing insights and feedback on the database and the design approach and offer opportunities for database and design approach improvement.

4.2 Introduction

According to the research problems stated in Chapter 1, the need for a tool that is capable of helping engineers and designers gain in-depth understanding on commonly used mechanism and machine elements' functions, extend their knowledge scope on these components has led to the development of the mechanism and machine elements taxonomy (MMET). MMET in principle is a classification of commonly used machine elements and mechanisms (e.g. gears, bearings, linkages and electric motors) in mechanical engineering industries. Different from similar work conducted regarding mechanism conceptual design (For example, see Szykman and Sriram, 2002; Vogwell and Cully, 1991), MMET contains no complete products but fundamental components which can be purchased from manufacturers as stock items (Lee, 2013). Instead of providing commonly seen component data such as sizes, dimensions and stock numbers, MMET focuses on providing in-depth information of these components such as functional attributes, movement attributes and merit analysis, aiming to offer assistance to the user regarding the application and benefits/drawbacks of using them. In the mechanical engineering industry there are numerous types of mechanisms and machine elements, and therefore it is difficult to include all of them into the database. The main scope of MMET is to cover mechanisms and machine elements that are commonly used in mechanical industries. The data recorded in the database was based initially on items sourced from the Mechanical Engineering Design Handbook (Childs, 2013), the

Mechanism and mechanical device sourcebook (Sclater and Chironis, 2001) and IHS GlobalSpec (GlobalSpec, 2014).

The main purpose of MMET is to assist engineers and designers to have an in-depth understanding on mechanisms and machine elements with details including functional and movement attributes and merit analysis. By providing this information the database is able to expand engineers' and designers' knowledge scope on mechanisms and machine elements that can fulfil certain design requirements and offer assistance on the selection of mechanisms and machine elements in engineering product design. Analysis of movement attributes can also provide support for kinematic considerations. MMET act as a crucial part of the conceptual design tool in respect of helping engineers and designers to carry out conceptual designs by providing suggestions and options in component selection. It is able to provide assistance in idea generation in mechanism conceptual design when functions of the system are defined and deconstructd. The development of MMET is an original contribution to the field of mechanism design in terms of its focus on functional attributes and other types of information of machine elements and mechanisms that are practical in solving mechanism conceptual design problems. As mentioned in Chapter 1 conceptual design stage has a significant impact on the quality of the design, in which creative thinking and process are encouraged to help engineers and designers understand the problem from various perspectives and delivering broader range of ideas and solutions, for example using methods and tools introduced in Chapter 4.

4.3 **MMET Data Collection**

The data collected were presented in mapping style using designVUE, the same tool employed to draw Function Analysis Diagrams. In designVUE coloured and shaped blocks were used to represent different types of information, shown in Figure 4.1.

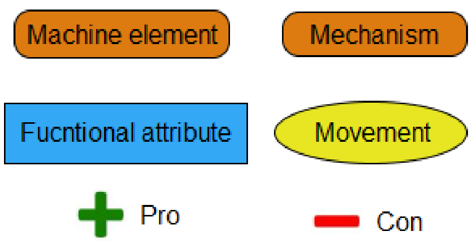


Figure 4.1 MMET notations

Figure 4.2, Figure 4.3 and Figure 4.4 show examples of functional attributes, movement attributes and pros and cons of elements respectively.

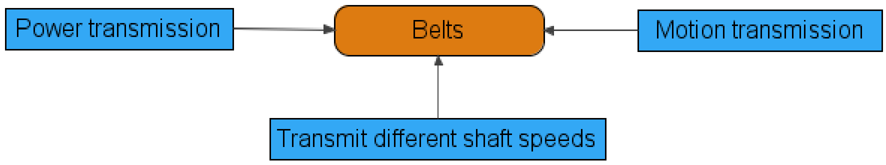


Figure 4.2 Belt functional attributes

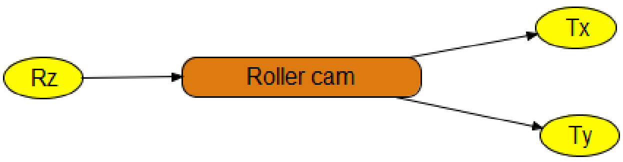


Figure 4.3 Roller cam movement attributes

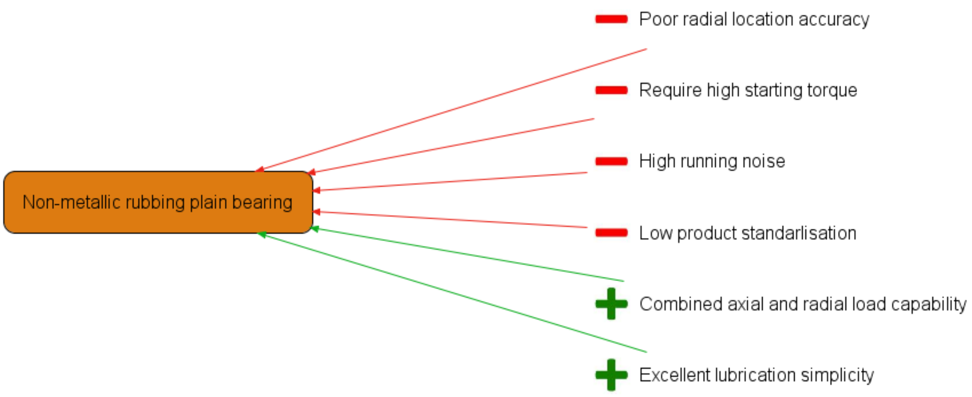


Figure 4.4 Advantages and disadvantages of using non-metallic rubbing plain bearing

Components were constructed and presented in a hierarchical structure with regard to their categories for the convenience of locating data (For example, see Figure 4.5).

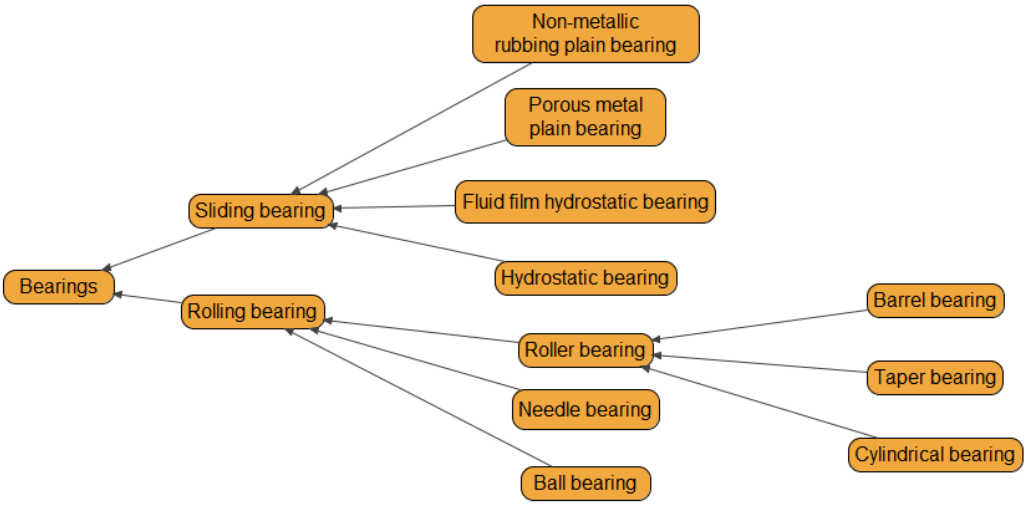


Figure 4.5 Bearing options in MMET map

A test run was conducted in a group of Innovation Design Engineering master students from the Royal College of Art, in which they were asked to find suitable machine elements and mechanisms from the database to solve three simple mechanical problems. Results and comments from most of the students have indicated that the database is helpful but difficult to use to find information due to the mapping-style layout. Therefore, a software version of MMET was developed to enable efficient and effective location of components, aiming to help engineers and designers in more convenient way. The user then should be able to search MMET using the programmed interface by simply typing in their requirements plus a few mouse clicks. Three approaches were proposed to inquire MMET for assistance to engineers and designers, which are:

- **Component Oriented** – the user can gain access to component information by component category and name.
- **Function Oriented** – the user can obtain recommendations with regard to functional requirements specified by the user, for example, gears and belts will be provided when the user is looking for components that can transmit rotary motions or torque.
- **Movement Oriented** – the user can obtain suggestions regarding movement input and output, for example, gears and belts will be also listed when the user are looking for components that has rotation as input and output. It is worth noting that there are six degrees of freedom in the universal axis (See Figure 4.7), and each combination needs to be specified to obtain suitable components.

4.4 **MMET Software Support Development**

Figure 4.6 demonstrates the basic structure of MMET. It has five main areas of focuses:

- **Element illustration** – provides a visual impression of each element by illustrating an example photo or picture.
- **Element linking regarding category**
    - Other elements belong to the same category, provide alternatives.
    - Possible connecting elements according to their classifications. For instance, bearings, gears, couplings and clutches are provided in shaft information page since in general they are connected with shafts.
- **Functional attributes**
    - Technical functions of each element.
    - Other elements that carry the same functions as the displayed component are listed, provide alternatives.
- **Movement attributes** – the universal coordinate system and six degrees of freedom (see Figure 4.7) are used to identify precise movement input and output behaviours. Some other types of input and output were stated separately for elements which do not have an exact translational or rotational movement input/output. Examples include electric motor, springs, certain types of cam mechanisms and Geneva mechanisms. Therefore inputs and outputs such as force, electricity, oscillate movements are recorded in the movement attributes independently.
    - Other elements that have the same movement behaviours are listed to provide alternatives.
    - Since each element has an input and output, elements can be connected together theoretically if their inputs and output match with each other. For example, a shaft can be connected with spur gear since a shaft has rotational output while a spur gear has rotational input.
- **Advantages and disadvantages** – pros and cons of using each element are stated to provide engineers and designers references for decision making.

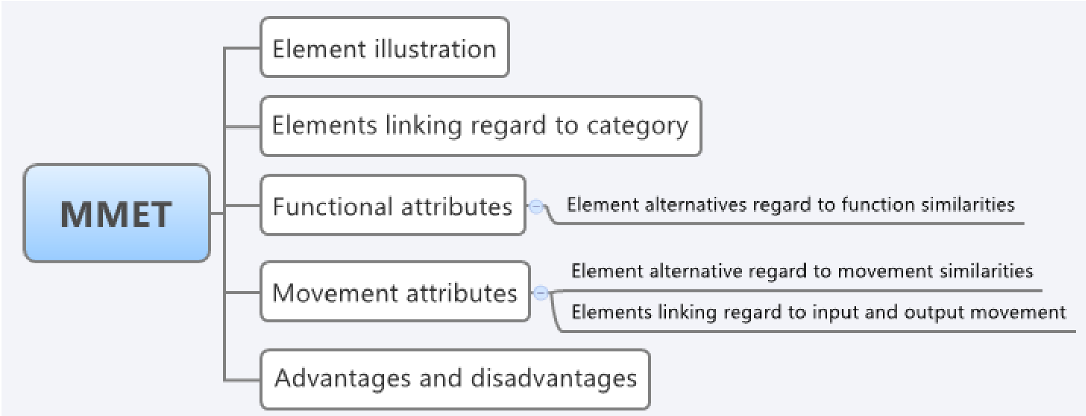


Figure 4.6 MMET structure

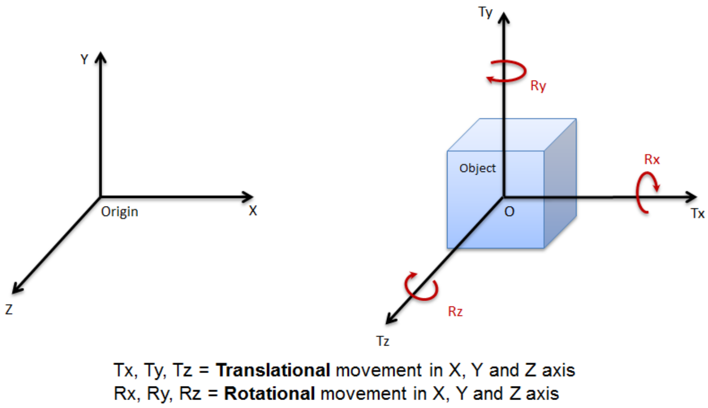


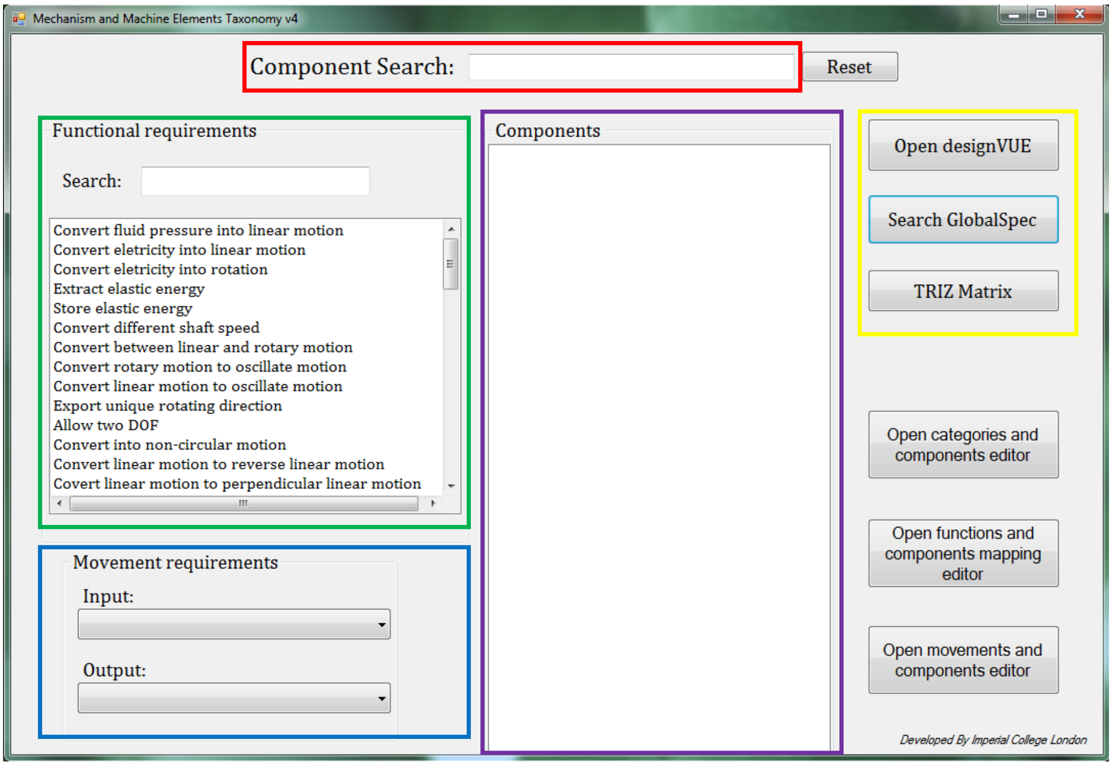
Figure 4.7 Universal Coordinate system and the six degrees of freedom

4.4.1 Main interface

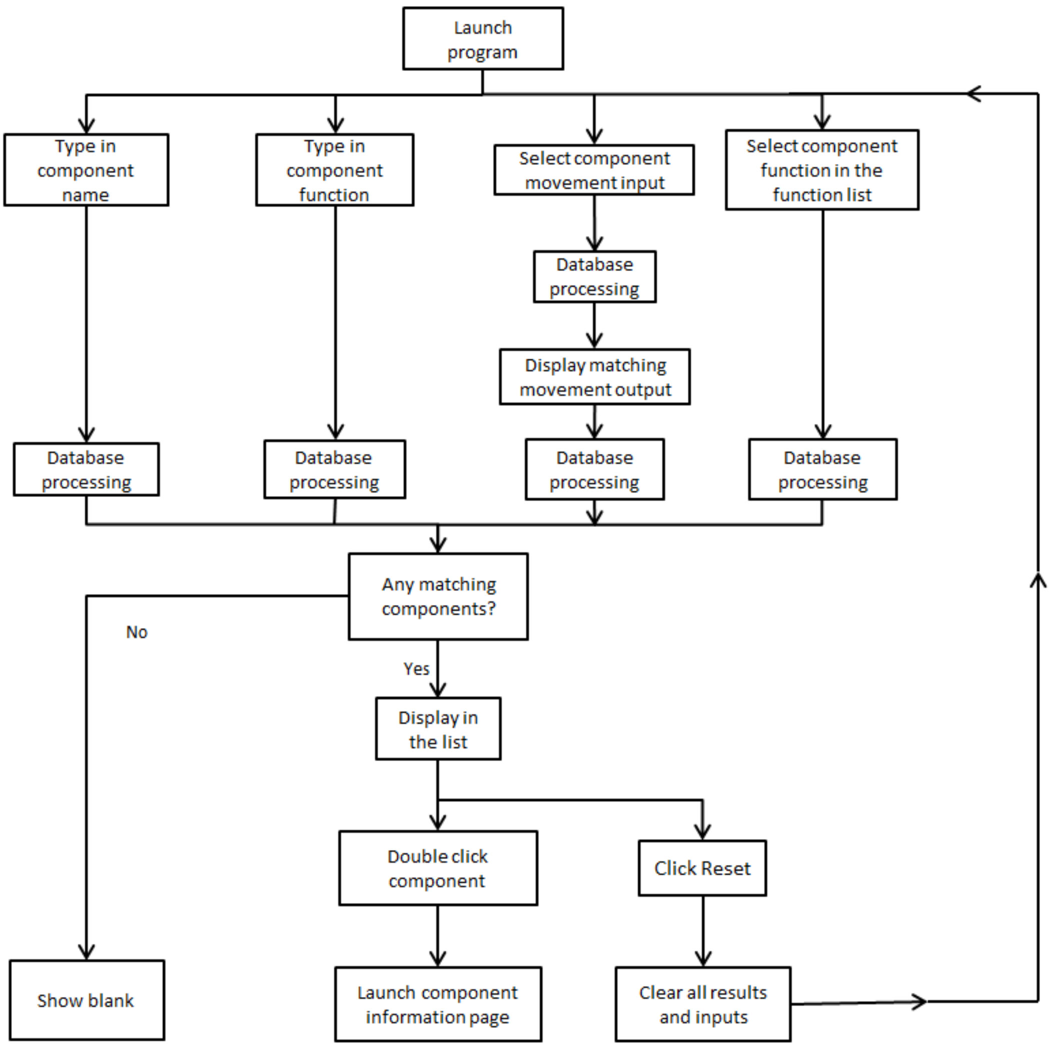
The software was written in Microsoft Visual Studio in the format of an exe file.

Figure 4.8 illustrates the main user interface of MMET software and its text based searching algorithm. In the start page there are five main sections displayed:

- **Components list** (Circled in **Purple**) – in this section all components matching with the searching criteria will be shown.



a. MMET start page



b. MMET text based searching algorithm

Figure 4.8 MMET's main user interface and algorithm

- **Component search box** (Circled in **Red**) – in this section the user can locate a component by typing in its name directly, for example, plain bearing, helical gear or DC motor (For an example, see Figure 4.9).

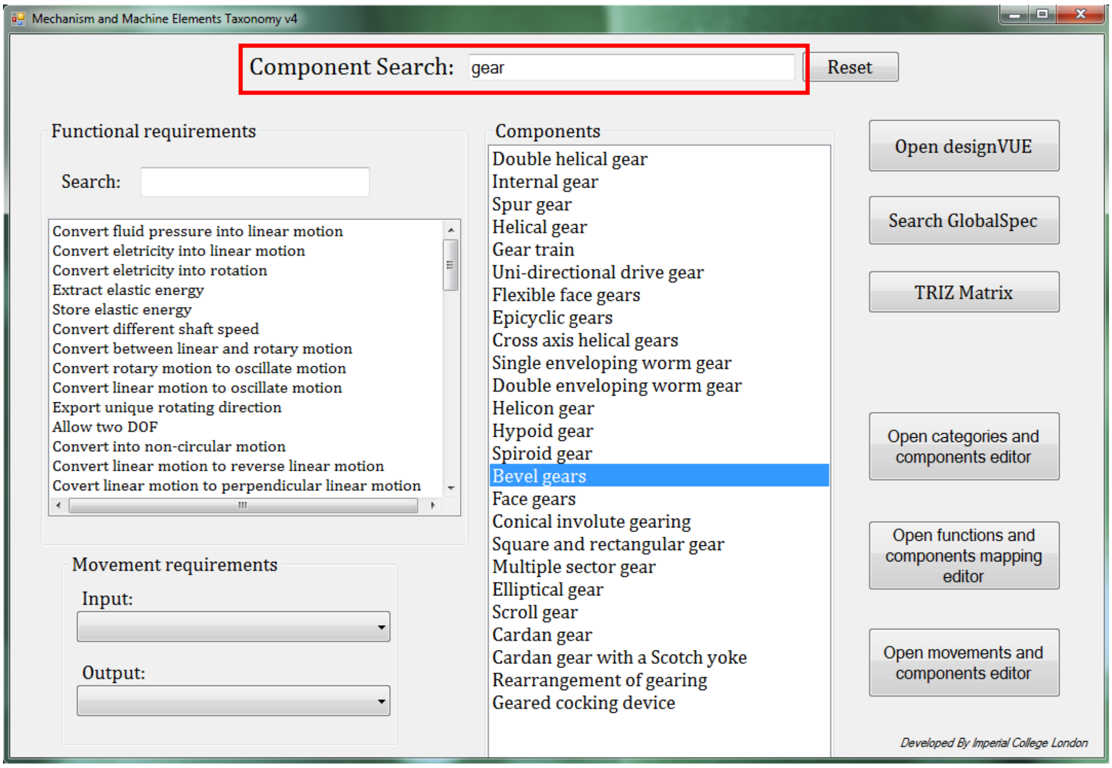


Figure 4.9 MMET component search

- **Functional requirements** (Circled in **Green**) – in this section the user can search MMET according to a specific function, e.g. stop reverse rotation, support compression load or convert linear motion to oscillate motion (For example, see Figure 4.10). A text based searching algorithm is used (See Figure 4.8b). The user can also scroll down the list and then find the most suitable function to locate components.

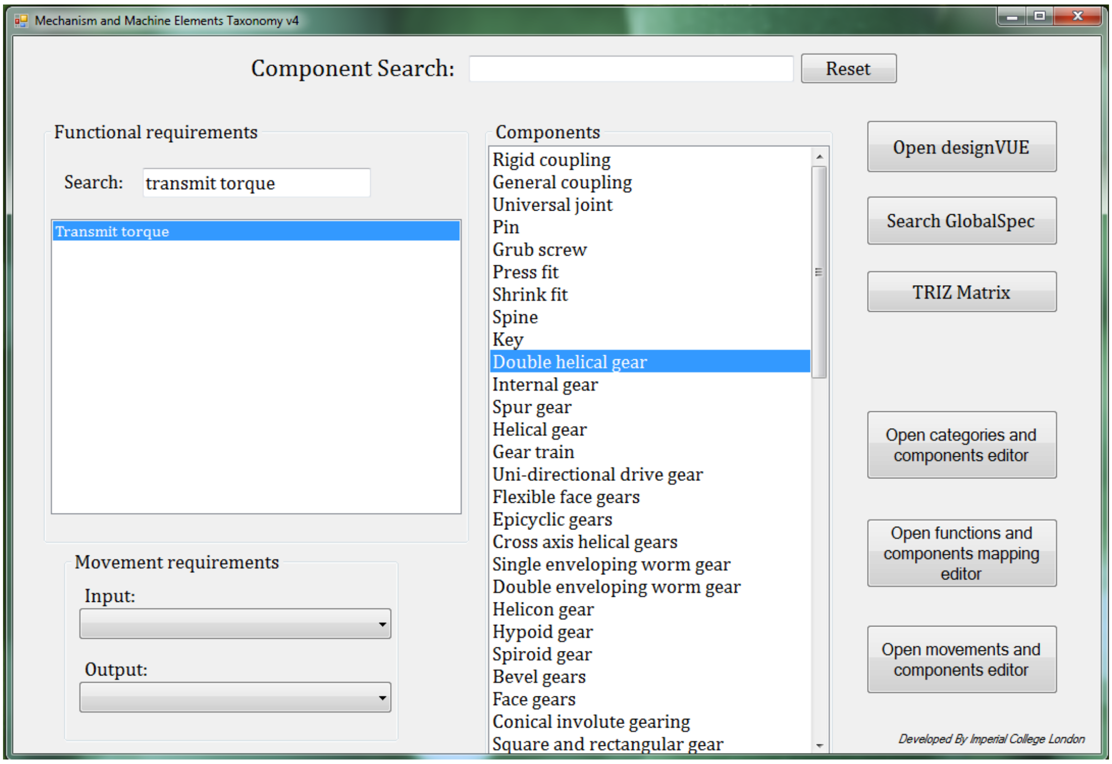


Figure 4.10 MMET function search

- **Movement requirements** (Circled in **Blue**) – the user can select a pair of input and output criteria to locate components in the database. Different types of input and output other than six degrees of freedom are also shown in the drop down list (For example, see Figure 4.11).

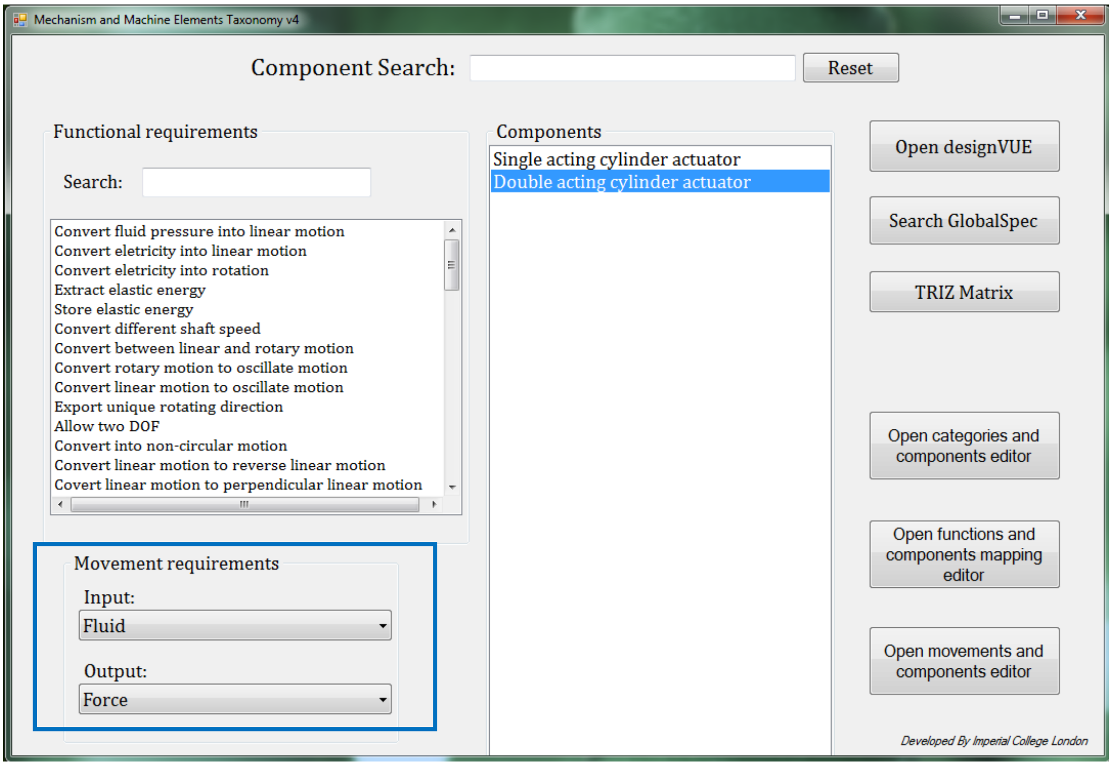


Figure 4.11 MMET movement input and output search

- **Supplementary features** (Circled in Yellow) – in this section three supplementary tools are linked to the software providing extra support for the user. FAD represented using designVUE can help engineers and designers define system functional requirements, analyse functional relationships between components and assist them to devise broader range of solutions. The GlobalSpec website provides detailed component information such as dimensions, stock numbers and suppliers. The TRIZ contradiction matrix can be applied to the development of an existing product associated with MMET and FAD by identifying harmful functions, eliminating redundant parts and finding design alternatives. More detail of the utilisation of MMET associated with these tools will be provided later in this chapter and Chapters 6 and 7.

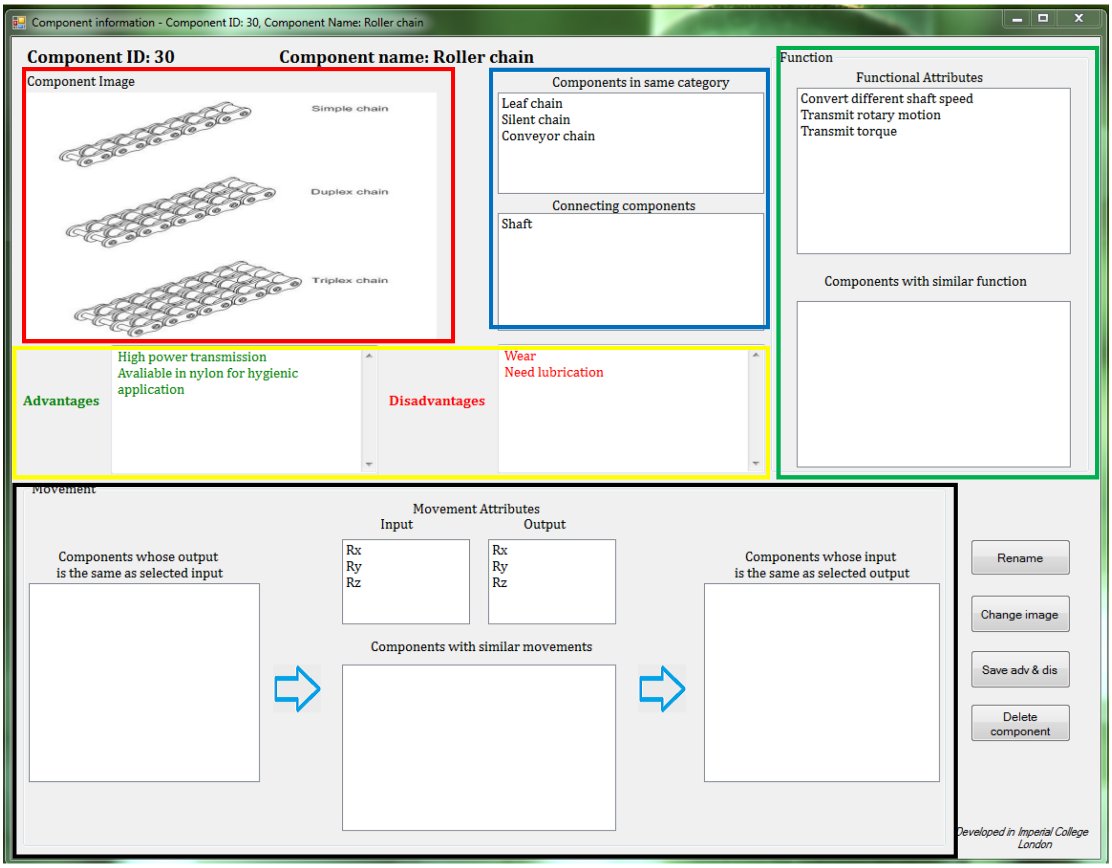
A new component search can be started by clicking on the reset button next to the component search field. Three editing buttons at the bottom right corner of the interface enable the editing of the database, including adding new components, adding or removing component functional and movement attributes. More information of these editing features can be found in Appendix 5.

4.4.2 **Component Information Interface**

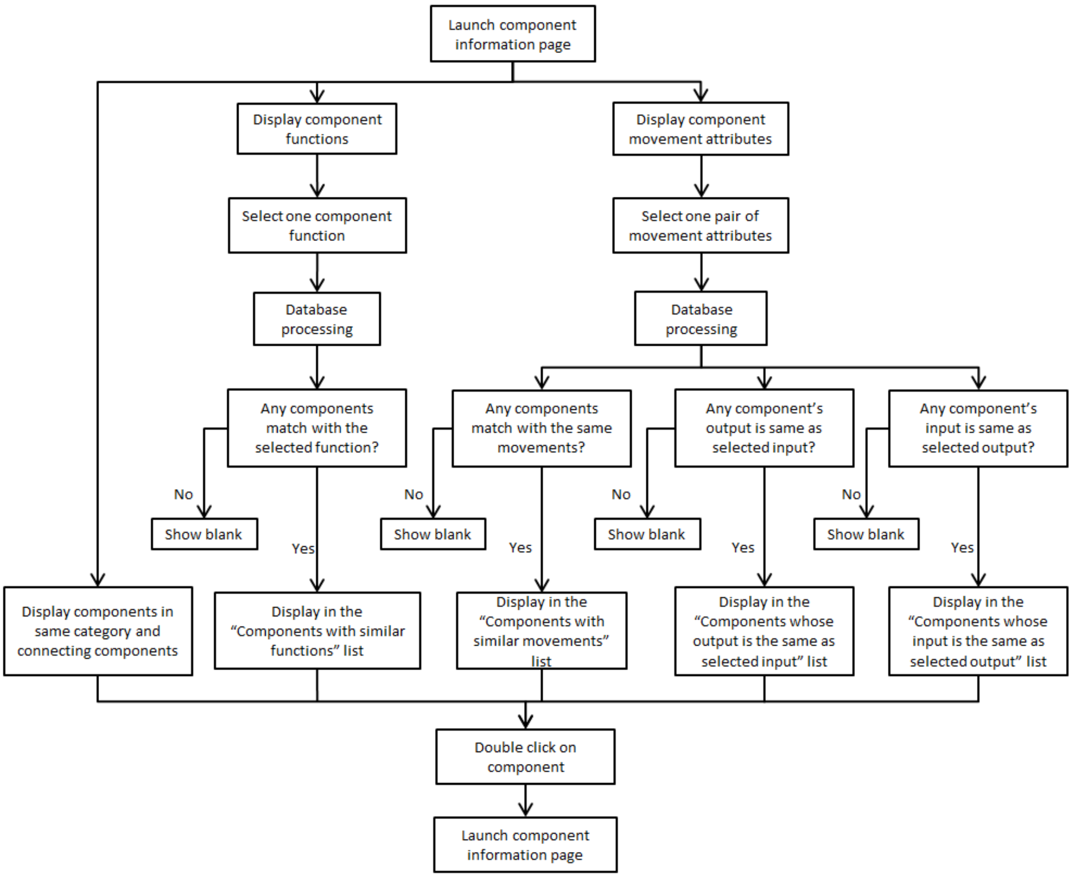
The component information interface can be accessed by double clicking on a component.

In the interface (See Figure 4.12a) five segments are presented:

- **Component image** (Circled in **Red**) – in this section photos or drawings are shown, to provide a visual impression of the component. Full sized images can be accessed by double clicking on the image.



a. MMET component information interface



b. MMET component information searching algorithm

Figure 4.12 MMET's component information page and algorithm

- **Components in same category** (Circled in **Blue**) – in this section components that belong to the same category are listed, and components that can connect to this category are listed.
- **Component functional attributes** (Circled in **Green**) – the most important feature in this interface, in which technical functions of the displayed component are shown in this section. This list allows the user to select one of the functional attributes to bring up a selection of components that fulfil the same function. Figure 4.13 provides an example where function "*convert different shaft speed*" was selected. In the box below all components in the database that satisfy this function are listed. Components displayed in the list can be opened by double clicking on them, providing detailed component information and enable comparison.

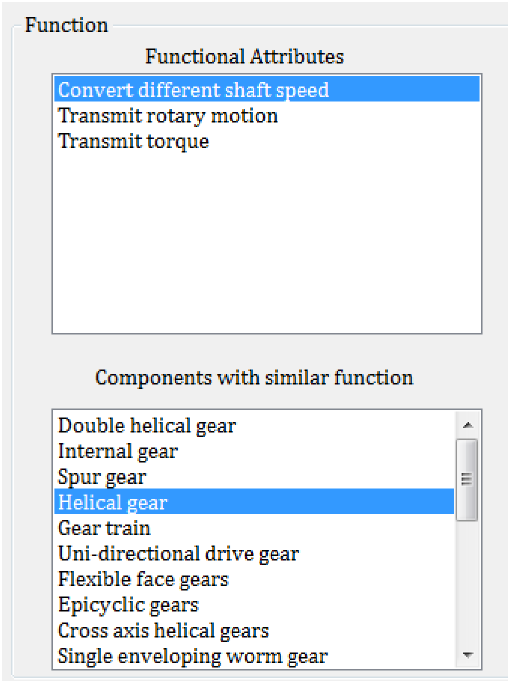


Figure 4.13 Components regarding the same function

- **Component advantages and disadvantages** (Circled in Yellow) – in this section pros and cons of using the component are stated, providing support and assistance for component comparison and selection.
- **Component movement attributes** (Circled in **Black**) – in this section movement attributes of the component are shown. By selecting a pair of movement attributes three groups of components can be located (For example, see Figure 4.14). In this example component that have the same movement input and output as a roller chain are shown in Box1, providing alternatives with regard to movement attributes. Box2 and 3 list components that can be linked to a roller chain with regard to their movement attributes. Component movement attributes can be represented with the FAD approach to identify a possible series of components that can satisfy a mechanism movement requirement, called Kinematic FAD (For example, see Lee, et.al, 2013). Figure 4.15 illustrates an example KFAD for a roller chain. KFAD can be seen as a derived application of FAD approach that can be used in mechanism design process associated with MMET when movement attributes of a system are focused.

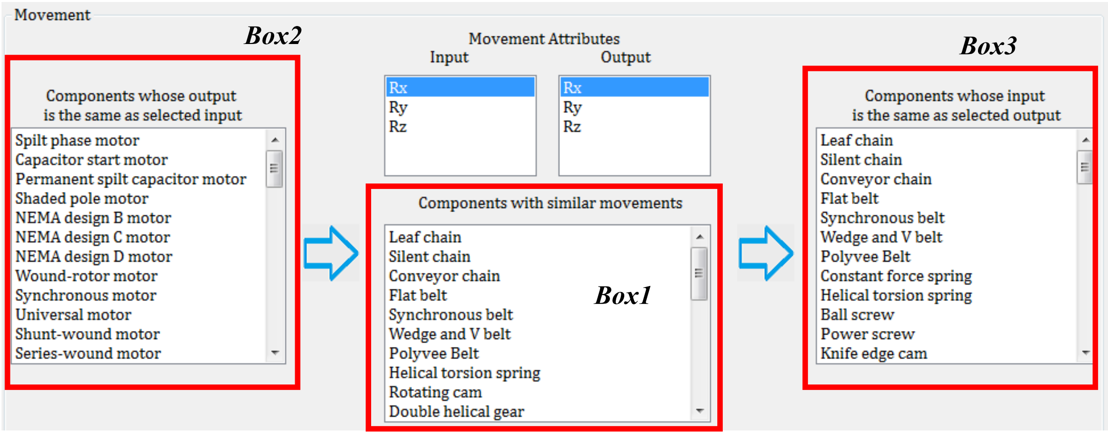


Figure 4.14 Component movement attributes and connections

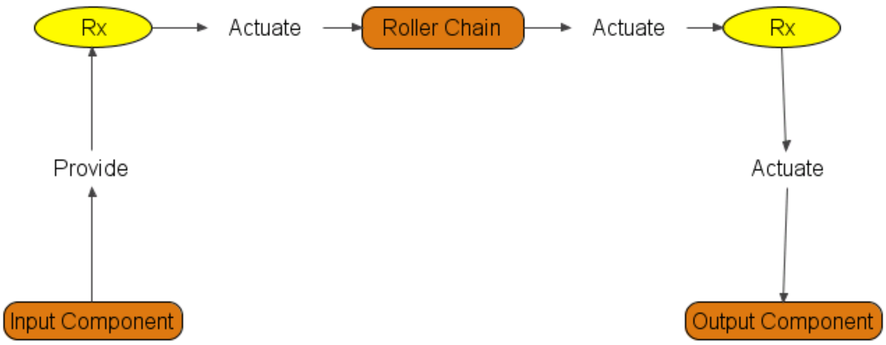


Figure 4.15 KFAD for a roller chain

The component information can be edited by the user too, including changing the image, editing pros and cons.

4.5 MMET Based Conceptual design tool

MMET allows exploration of components options in which engineers and designers can assemble them together using permutation and combination approach, compose various types of potential solutions to the design problem. Different methods of exploring components in MMET led to three different approaches of conducting mechanism conceptual designs: Function Oriented, Movement Oriented and Combination of both. In these design approaches FAD is employed to perform system deconstruction with regards to functions or movements.

- **Function Oriented Application of MMET**

This approach focuses on exploration of components that satisfy specific functional requirements (See Figure 4.16), i.e. functional requirements are used as searching criteria. In order to employ this approach function deconstruction of the system into fundamental functions is recommended prior to using MMET since at current stage only functions expressed in Functional Basis format are recorded in the database and higher level functions are normally abstracted, system related and expressed in natural language. Therefore for complex designs sub-systems can be further broken down into lower levels if necessary. MMET is able to provide component options with regard to each function required within the system, merit analysis and alternatives, providing support and argumentation in decision making.

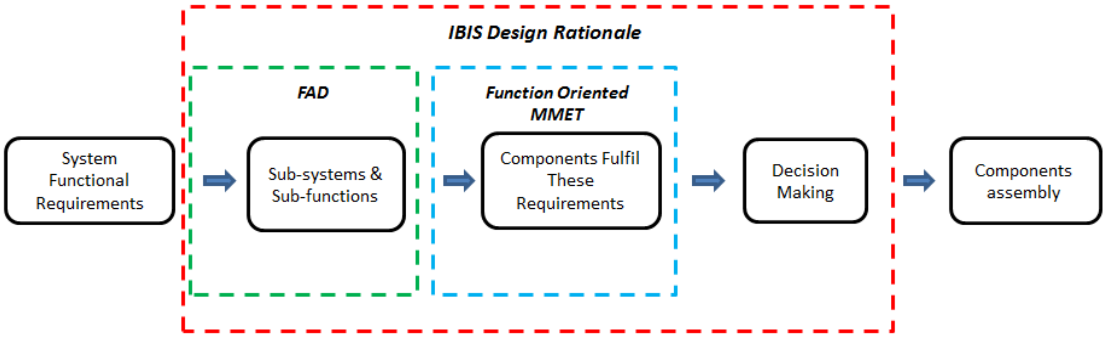


Figure 4.16 Function oriented MMET design approach

FAD structure is used to break down the system into sub-systems with sub-functions identified according to its PDS. Further breakdown can be conducted for complex product designs. With regard to each sub-function requirement MMET can provide a selection of components, along with each option's pros and cons and alternatives. Once components that can satisfy every sub-function are decided then they can be assembled together, and composed to form a complete design. During the conceptual design process IBIS represented design rationale in designVUE can be employed to record design activities and decisions made for future development.

- **Movement Oriented Application of MMET**

This approach was developed based upon the dynamic nature of many mechanisms and machine elements. This can be employed as a supplementary tool to assist a Function oriented application of MMET. This approach focuses on the kinematic perspective of mechanisms, aiming to provide options that fulfil combination of movements. Similar to a Function oriented design approach it starts with the definition of system movement requirements, and then uses the FAD approach to break down the system into sub-systems with movement types defined. Then MMET would be able to provide options for each pair of movement requirements for engineers and designers to choose. Once all components have been selected they can be assembled together to form a complete conceptual design. The working principle of movement-oriented MMET is shown in Figure 4.17.

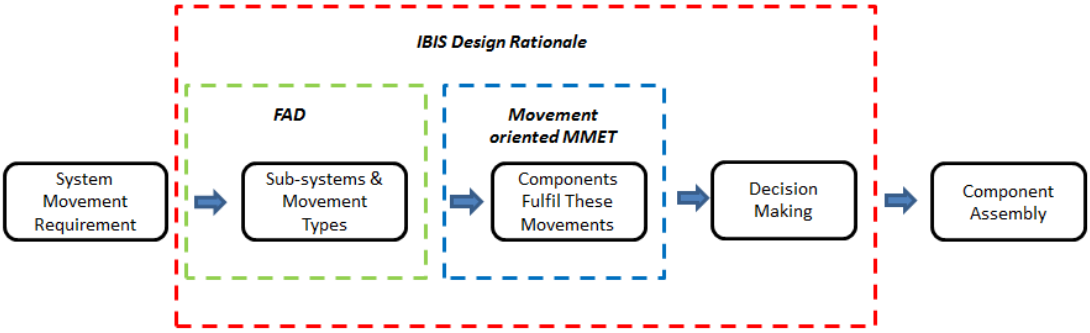


Figure 4.17 Movement oriented MMET design approach

Although kinematic consideration is important in mechanism design it is not enough to devise a complete design. Components such as bushings, casings and clamps do not have any exact movement behaviours but they do have important functions in mechanism design. Similarly, in some component functional attributes they do not specify the exact movement direction in universal coordinates which may cause misunderstanding in design. For example, bevel gears and spur gears both carry the function *Transmit rotation* but according to movement type analysis the output axis of bevel gear is perpendicular to the input axis whereas spur gears' input and output are coaxial. It can be seen that a movement oriented design approach is able to compensate for the lack of precise movement type determination in a function oriented design approach. Therefore a comprehensive conceptual design tool was proposed by combining function oriented and movement oriented MMET.

- **MMET Based Conceptual Design Approach**

This design approach starts from the identification of the design problem and design specification, including what types of functions and movement the system needs to achieve. For simple product designs, MMET is able to provide robust solutions in a short time with function or movement requirements stated. For more complex design problems, the system can be broken down into lower level systems using FAD approach carrying sub-functions and movements. Then both function and movement oriented MMET are used to explore components that can satisfy specified requirements. After obtaining all the components they can be integrated into sub-systems which can be then composed to a complete design for the engineer or designer to evaluate. The MMET conceptual design process is shown in Figure 4.18.

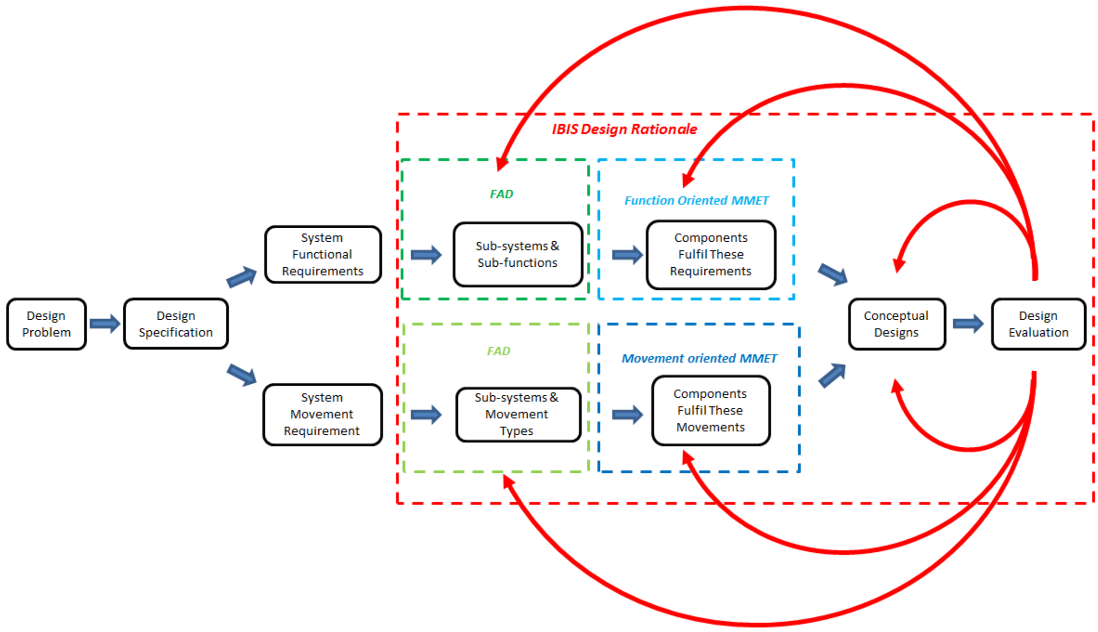


Figure 4.18 MMET conceptual design tool

This design approach enables the generation of a broad range of ideas and concepts. For example, different sub-system layouts will affect system function deconstruction and therefore result in a diversity of ideas and combinations. Function and movement oriented MMET do not necessarily need to be conducted at the initial stage of design. They can be employed at any stage where system/lower level system requirements are defined. For instance, when designing a system that mainly contains kinematic movements, Movement oriented MMET can be used first to allocate movement types for sub-systems and then Function oriented MMET used to explore solutions where specific functions of a sub-system are defined.

This design approach performs as an iterative process for the purpose of achieving better design outcomes. With the aid of IBIS represented Design Rationale recording the design process, activities and judgments, engineers and designers are able to go back to previous stages, and improve the design if new insights or technologies emerge in later stages of design or the final concept fail to meet the specification.

The aim of developing this conceptual design tool based on MMET is to provide a guideline for engineering product design, assisting engineers and designers in idea generation and component selection. Similar to Creative Problem Solving (CPS) process, the MMET design approach follows a divergent-convergent design process but focuses more on divergent thinking. The working principle of the MMET design approach is shown in Figure 4.19. The diamond shape represents the flow of idea generation process. From the system deconstruction to component selection, each unique combination could be a potential solution to the problem. Some of them may seem impractical at the time but as more ideas generated, more likely a better solution will be arrived at. Furthermore, as technology evolves some concepts may become a better solution in the future. Concepts generated can then be evaluated through design rationale or other idea evaluation tools such as an Evaluation Matrix or a Screening Matrix to find the best solution to the design problem.

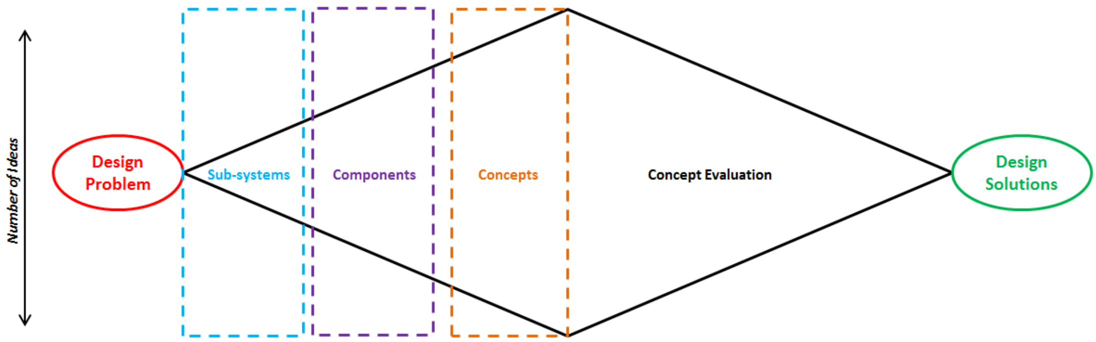


Figure 4.19 MMET conceptual design working principle

This approach will provide numerous ideas for evaluation which may be time-consuming. In order to increase the time efficiency of employing this design process evaluation is allowed to be conducted after every stage of idea generation. As a result, MMET conceptual design tool allows the evaluation to be conducted at any stage of idea generation, creating a more flexible design approach for engineers and designers that is highly customisable according to their preferences, shown in Figure 4.20.

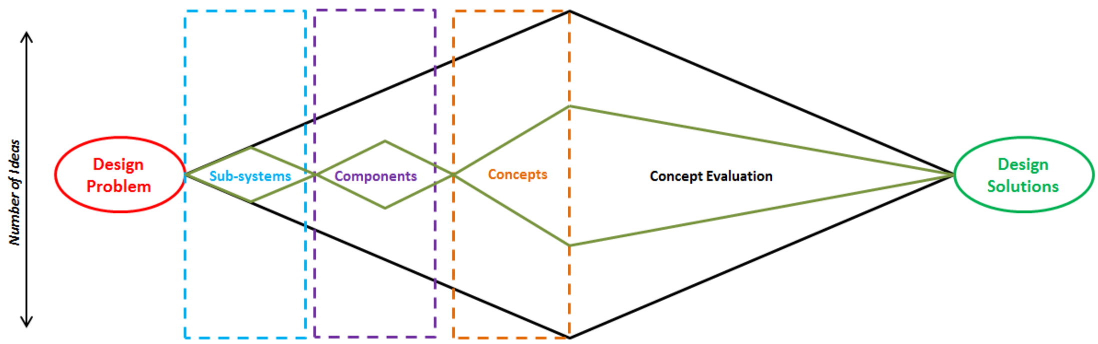


Figure 4.20 Developed MMET conceptual design working principle

This conceptual design tool encourages the creative thinking throughout the process to explore a broad range of possible solutions. By choosing a favoured working process, engineers and designers are able to develop suitable design concepts based on their experience or prompts provided by MMET. An iterative process can be conducted if necessary to achieve better design outcomes. In Section 4.6 a surgical platform design project using the MMET based conceptual design tool is presented.

4.6 Case Study - Surgical Platform Design

This project was with Eschmann Equipment, a company that designs and manufacture general and specific surgery tables and other medical devices. The project concerned a possible new strategy to target the market in third-world countries by introducing a brand new low cost electrical surgical operating table, capable of performing general surgeries and some specific surgeries with the aid of accessories. The table is targeted to be electrically driven with some manual operating movements. The objective of the project described here is to develop conceptual designs of an operation table/surgical platform. Figure 4.21 shows the design process adopted based on MMET.

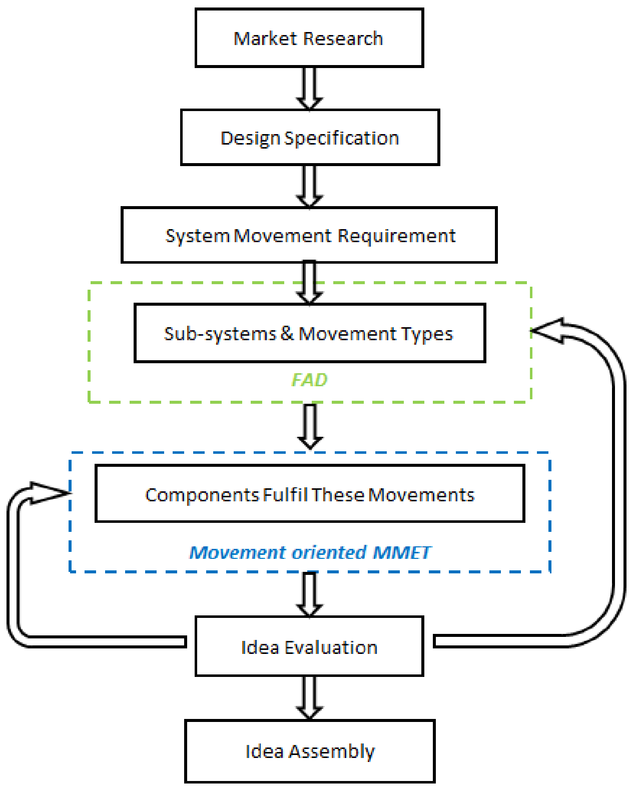


Figure 4.21 Surgical platform design process

4.6.1 Market research

Eschmann Equipment currently provides a range of surgical platforms containing the T10, T20, T30 and T50 series products. The T10 series was selected as a basis for design development given its lowest price among Eschmann's product range and most basic functionality. A competitor analysis was conducted to help the team to have a basic understanding on general surgical table designs. Table 4.1 and

Table 4.2 show a list of competitors from different regions across the globe and their table models compared to the Eschmann T10 series.

Table 4.1 Competitors from different regions providing operation tables

Company	Web link	Location
Eschmann	http://www.eschmann.co.uk/	UK
Schmitz u. Söhne	http://www.schmitz-soehne.com/	Germany
Üzümcü	http://www.uzumcu.com.tr/en/	Turkey
ALVO MEDICAL	http://17191.pl.all.biz/en/	Poland
Brumaba	http://www.brumaba.com/	Germany
Gubbemed	http://www.gubbemed.de/	Germany
Lojer OY	http://www.lojer.com/english	Finland
Medical Illumination International	http://www.medillum.com/	US
Mediland Enterprise	http://www.mediland.com.tw/mediland/	TW
Merivaara	http://www.merivaara.com/	Finland
Schaerer Medical	http://www.schaerermedical.ch/	Swiss
Skytron	http://www.skytron.us/index.htm	US
Sturdy Industrial	http://www.sturdy.com.tw/	TW
Üzümcü Tıbbi Cihaz ve Medikal Gaz Sis. A.Ş.	http://www.uzumcu.com.tr/en/	Turkey
Medimark	http://www.medimark.co.za/	South Africa
SMS	http://www.smsmedical.com/	Turkey
Al-er	http://www.ar-el.com/Default.asp	Turkey
Eryigit	http://www.eryigit.com.tr/en/index.php	Turkey
Farafan UK	http://www.farafan-uk.com/operating_table.html	UK
Swift Medical Trolleys	http://www.swiftmedicaltrolleys.co.uk/index.html	UK
Steris	http://www.steris.com/healthcare/	US

Table 4.2 Table model comparison

	T10	**OT-125A**	**Practico II**	**SMS electrical-hydraulic**	**SMS electrical-mechanical**	**Ar-el 2074**	**Ar-el 2079**	**STR 2000**	**Farafan OT-931E**	**Opmaster 531**	**Cmax**
Max weight capacity (kg)	250	not specified	225	300	300	150	150	350	200	not speicified	270
Main use	general and specialist	general	general	general	general	general	general	general and specialist	general	general	general and specific
Length (mm)	2102	1900	2090	not specified	not specified	1980	1920	2038	1995	1925	2025
Width (mm)	600	500	540,594	600	600	500	550	500	510	500	520
Min height (mm)	703	750	595,665	740	780	740	650	740	730	800	680
Max height (mm)	1003	1000	895,965	1200	1080	1040	1020	1070	1130	1100	1143

Table break up (degree)	80	90	70	90	55	110	100	80	70	no	90
Table break down (degree)	35	0	40	90	90	0	0	40	35	no	90
Lateral tilt (degree)	15	20	20	30	25	0	0	30	20	15	25
Trendelenburg and Reverse Trendelenburg (degree)	30	30	26	30	30,25	22	0	30	35,25	35	45,30
Head flap (degree)	45	30	45	90	55,90	90	90	90,80	50,45	31.5 (up and down)	not specified
Leg flap up (degree)	55	0	20	90	30	90	90	30	30	0	60
Leg flap down (degree)	100	90	90	90	90	0	0	90	75	90	80
Override control	N	N/A	Y	N	Y		N	N	N	N	Y

4.6.2 **Design Specification and Requirement**

A product design specification was defined according to the market analysis and then explored and elaborated on in collaboration with Eschmann. The range of movements was derived from the T10 model. Different table positions are shown in Figure 4.22.

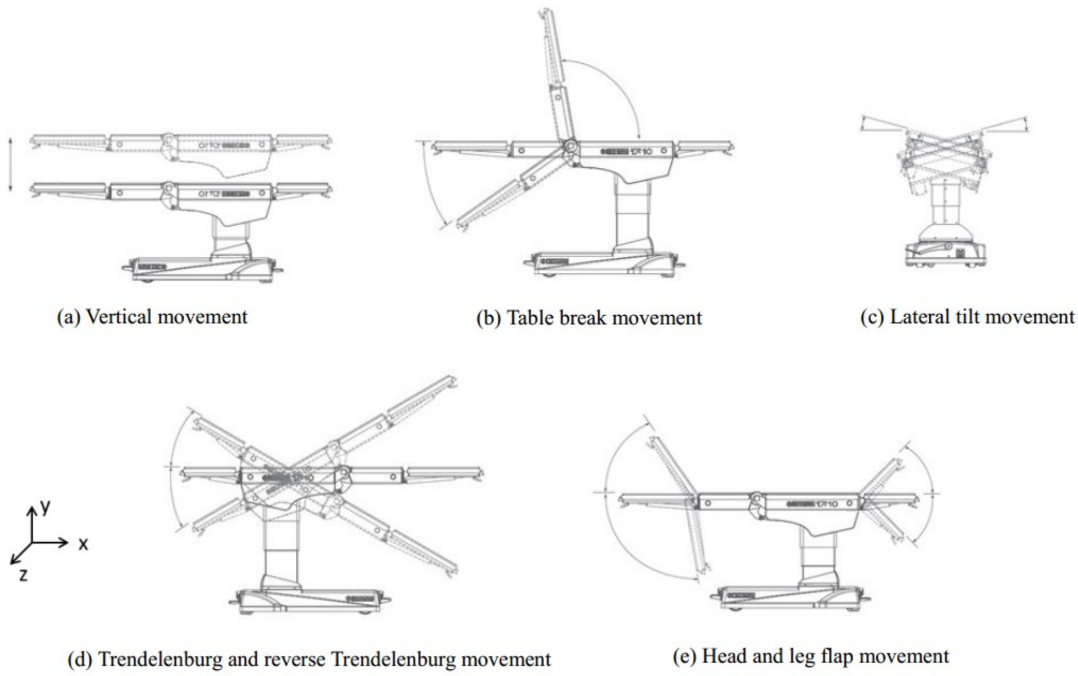


Figure 4.22 General surgical table positions

Table 4.3 shows the design specification defined mainly regarding movement positions, with the range of articulation derived from the T10 series.

Table 4.3 Surgical platform movement specification

Main use	General and specialist surgery
Safety factor	4
Standard	BS
Driven power	Electrical or manual
Weight capacity	150kg at every position
Length (without extension)	2102mm
Height	Adjustable between 703mm to 1003mm
Table break angles	80 degree up, 35 degree down
Lateral tilt angle	15 degree
Trendelenburg and reverse Trendelenburg position angle	30 degree
Head flap angle	45 degree
Leg flap angle	55 degree up, 100 degree down
Fluid resistance	Need to have fluid draining design
Accessories capability	Armband, Light-weight leg section, Foot extension, Head rest, Width extender, Divided leg section, Leg holders

4.6.3 System Deconstruction and Component Identification

In an early review, Eschmann stated that they were not interested in ideas based on the existing table designs such as the T10 series, but instead what they expected were brand new ideas based on basic design requirements. A few novel concepts of the table design structure were proposed in the beginning as Figure 4.23 shows, however these concepts were eliminated due to design constraints such as mobility and technical limitations. As a consequence a traditional table structure was mainly considered while the design focus was moved to the mechanism designs that articulate the table.

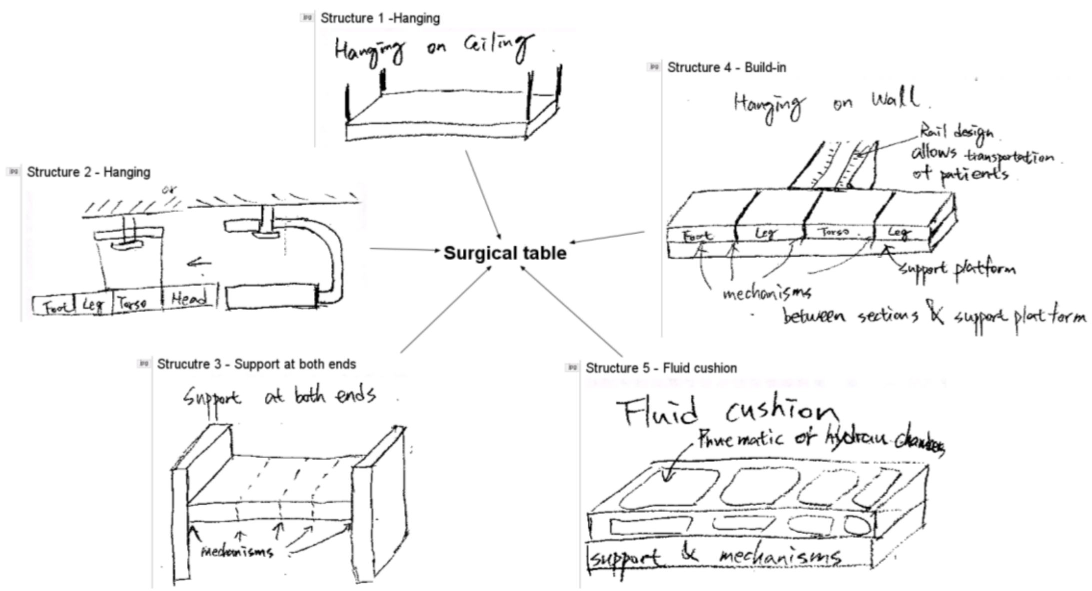


Figure 4.23 Some sketches from table structure concept brainstorming

According the market analysis a surgical platform generally contains six sections in order to enable different body positions: Head, Trunk, Leg, Foot, Column and Base. The conceptual design process started with the arrangement and combination of these sections, i.e. different section layouts. System breakdown was able to help the author to identify movement requirements for each sub-system. Additionally, different breakdown structures and layouts will result in different design constraints and consideration, especially for joint B, C and D (See Figure 4.24). Whether these joints are detachable to the main table section or not will have significant impact on the component selection when using MMET. It is better to design table sections that require heavy load closer to power source to maximise power efficiency. Table sections that do not have much articulation requirements can be designed relative complicated. Table 4.4 shows the design consideration of table sections regarding distance from power source, load supporting strength, complicity and others.

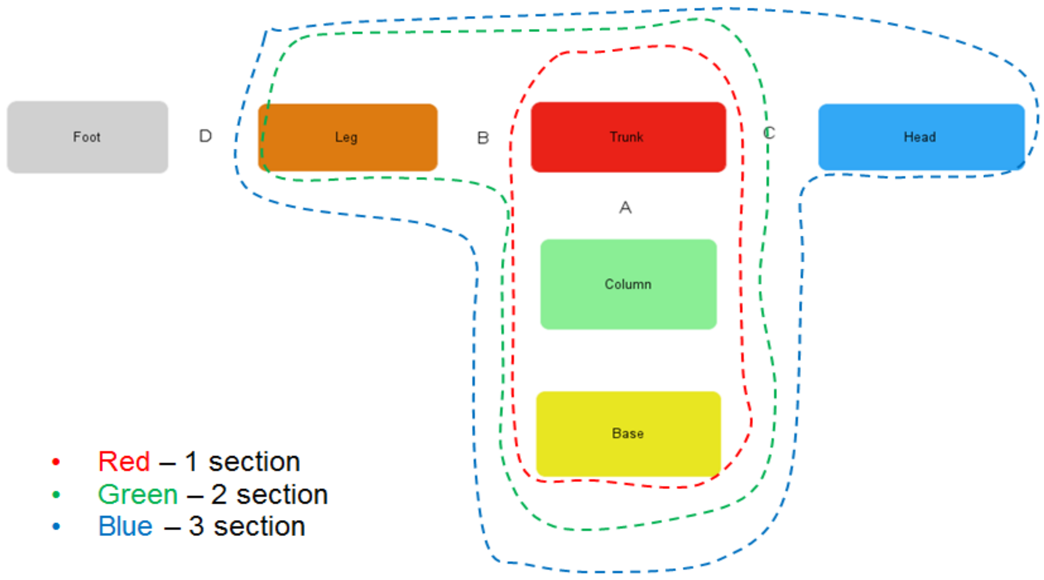
Table 4.4 Table section design considerations

	Distance from power source	Strength in terms of load supporting	Complicity	Others
Base	Close to power source	Strong for static loading	Can be relatively complicated	Can have large footprint
Column	Close to power source	Strong for static loading	As simple as possible	
Head	Far	Light load	As simple as possible	Can be designed either detachable or fixed

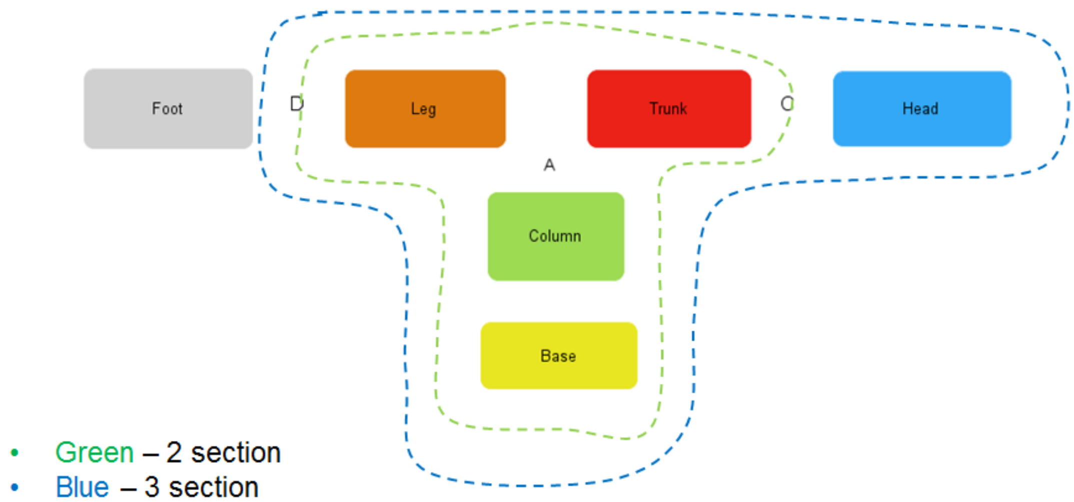
Torso	Close to power source	Strong for different body position	Can be relatively complicated	Can be the largest section, Main patient contact area
Leg	Can be designed close to power source	Heavy duty	Can be designed to be divided leg section	Main patient contact area
Foot	Far	Moderate duty	As simple as possible	

Figure 4.24 illustrates the design considerations on table section layouts. The column section can be designed to support the truck section only or to support leg and truck section in the same time. The number of sections stated in the figure stands for the un-detachable section designs for the table. The letter A, B, C and D represent the connection joints between sections. The main difference between these two layouts is that the design of an A joint in Layout 2 is required to have the ability to perform relative rotation between Leg and Trunk section whereas in Layout 1 the A joint is only required to perform single rotational movements.

In Figure 4.24 each closed coloured contour forms into a complete table design. Different table section layouts will require different section designs and table accessories. For example, if only one trunk section is designed, accessories including a leg extension and head extension are required in order to perform different surgery positions. All detachable sections were designed to have the same attaching method as the existing T10 series design which uses spigots and pin holes to secure table section positions. By reducing the number of sections in table layout without affecting its functions, it was considered that it was more likely that a low cost table design can be achieved since less material and components are used. However, for less table sections used more accessories will be required which will also increase the overall table system cost. Therefore it was still worthy to consider all possible table layout designs. Figure 4.25 shows the IBIS structured design argumentations on different table section designs considered. It is worth noticing that the number of table sections stated here means the number of un-detachable sections.



a. Layout 1



b. Layout 2

Figure 4.24 Table layout arrangement types

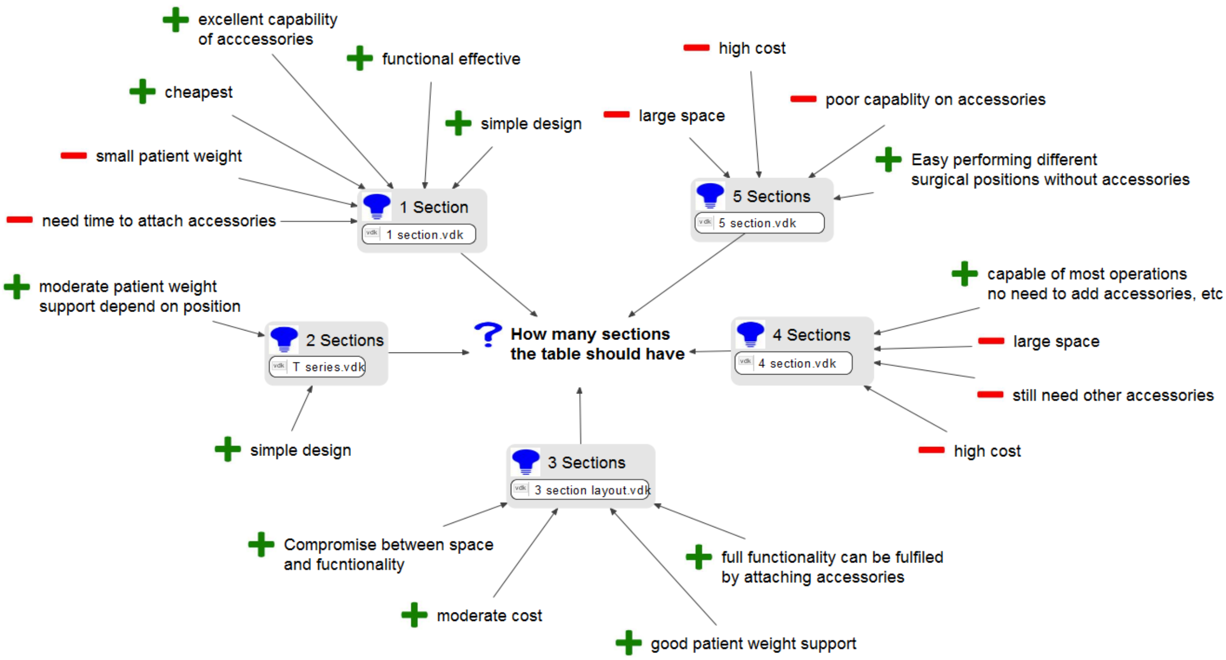
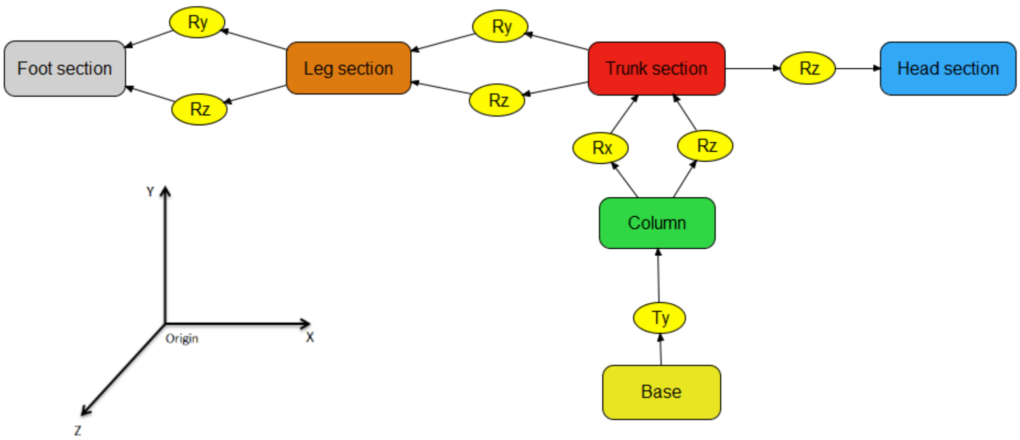
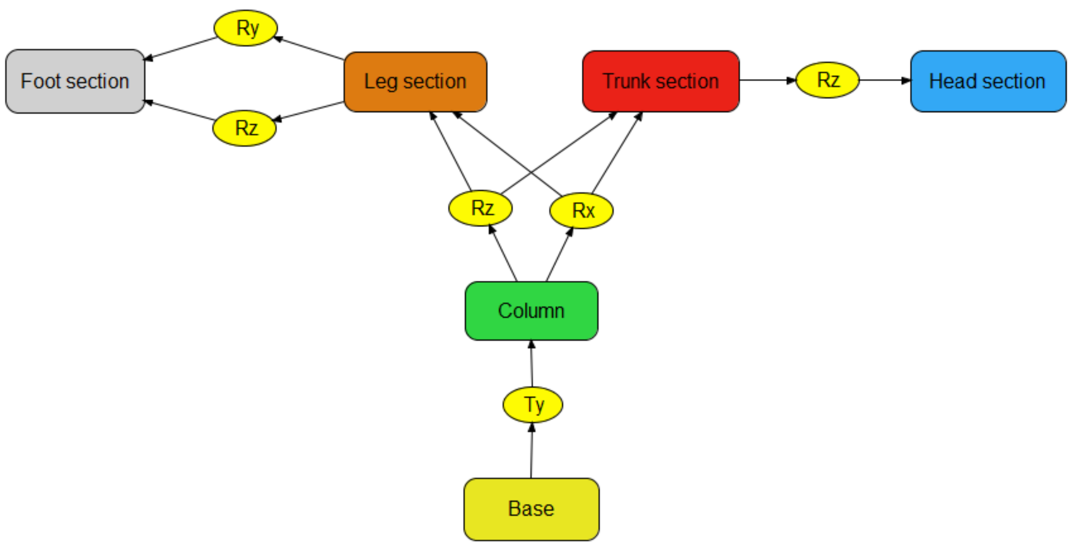


Figure 4.25 Table section design rationale

The movement requirements of each joint were defined with regard to different table positions, which are shown in Figure 4.26. The movement requirement indicated stands for the movement output in this case.



a. Layout 1



b. Layout 2

Figure 4.26 Movement requirements of each connection joint

Under some specific circumstances the transverse movement (Tx) of the table platform might be needed without moving the table base. A simple design was devised based on the suggestions provided by MMET (See Table 4.5) which uses a combination of ball screw and worm gear. The column bottom was designed to be moveable relative to the base. Figure 4.27 shows the conceptual design for the table transverse movement. The column bottom is sat on a pair of parallel rails which enables the sliding movement of the column. A ball screw is attached to the column base, driven by worm gear pair which is driven by an electric motor. This is just an illustration of the concept where no detail design is specified. This extra feature increases the design complexity and cost of the table, and therefore it was chosen to be a customisable feature that can be selected by the customer if required.

Table 4.5 Partial list of components that satisfy Tx movement output

a. Components that have Tx as output

	Input Rx	**Input Ry/Rz**	**Other types of inputs**
Output Tx	**Ball screw** Power screw End cam Barrel cam	Roller cam Valve drive Slider-crank linkage Rotary-linear Linkage Groove cam Rack and pinion	Gas spring Wire rope Class 1/2/3 lever Pulley system Drawbar spring

b. Components that have Rx as output

	Input Rx	Input Ry/Rz	Other types of inputs
Output Rx	Roller chain Flat belt Helical gear Double-rocker linkage **Gear train** Spur gear	Rotating cam Cross axis helical gear Helicon gear Bevel gear Spherical Geneva drive	Rack and pinion Servo motor Universal motor Brushless motor

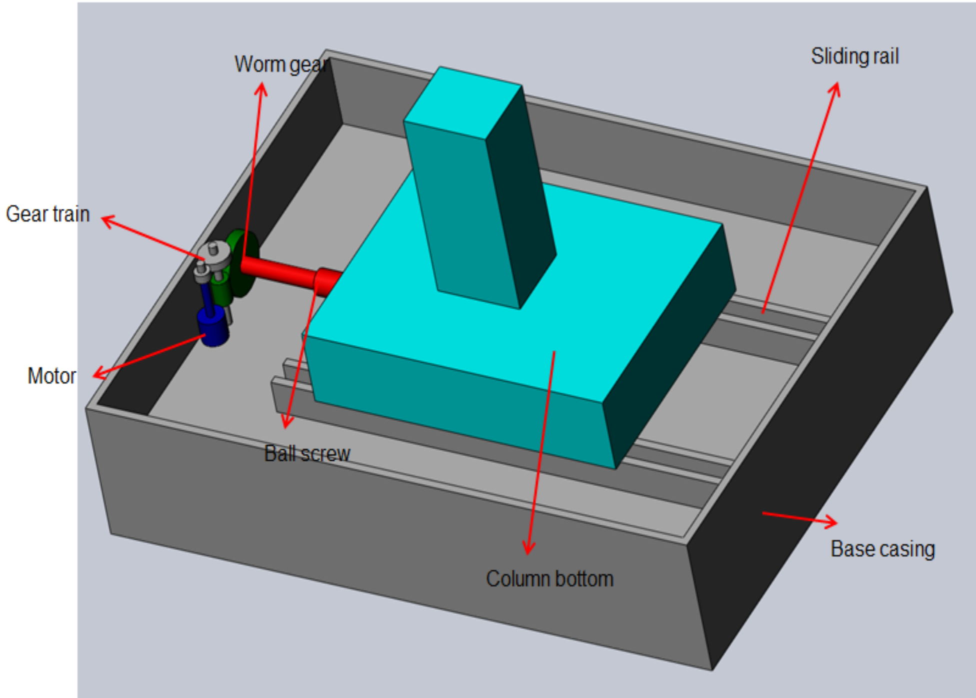


Figure 4.27 Table transverse movement mechanism design (Not to scale)

According to each movement requirement identified in Figure 4.26, MMET was used to explore possible solutions. Table 4.6 shows a partial list of components that fulfil the movement requirements provided by MMET.

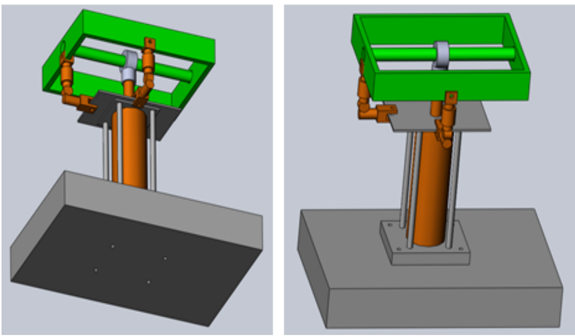
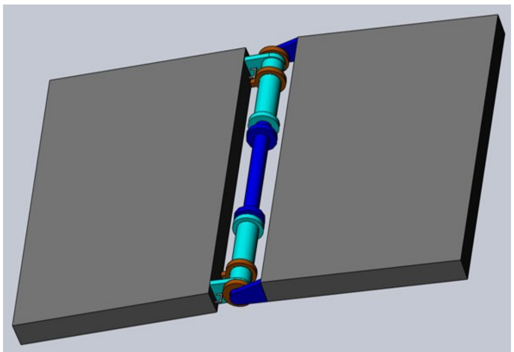
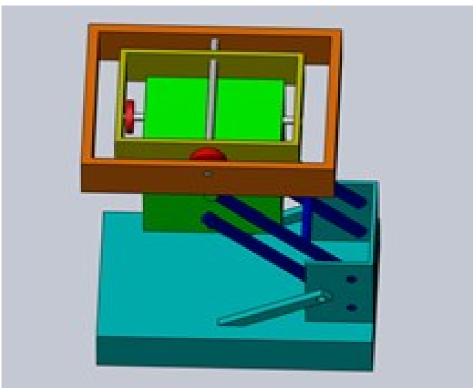
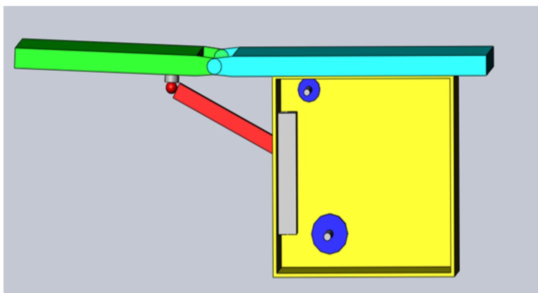
Table 4.6 Partial list of components that satisfy table section movements

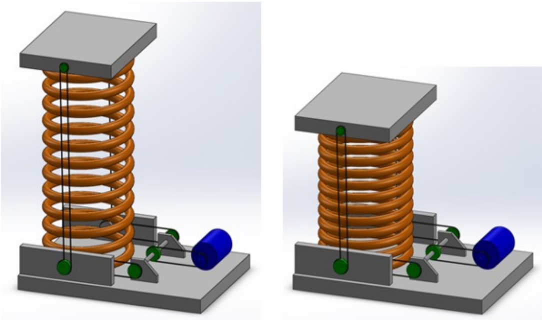
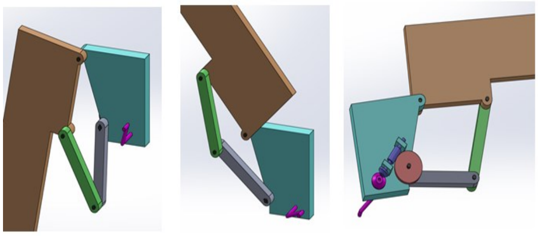
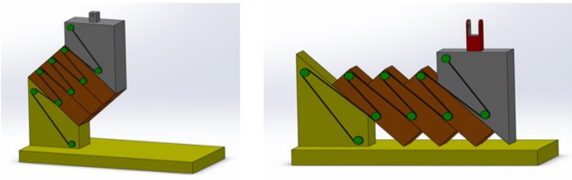
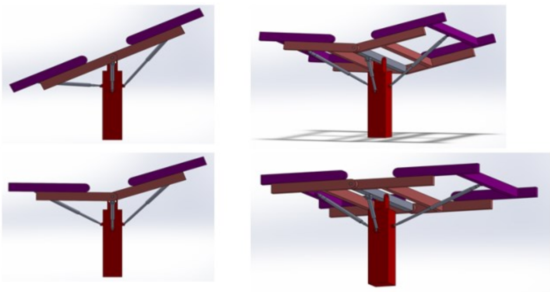
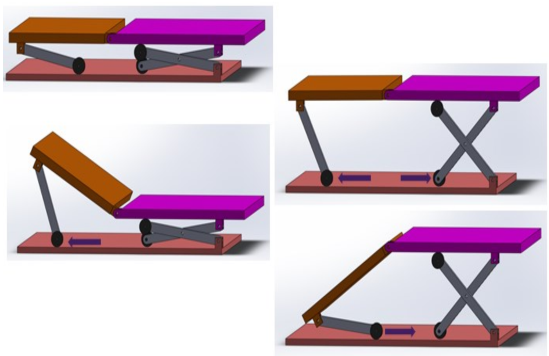
Sections	Movement requirements (output)	Components
Base to Column	Ty	Ball screw
		Hydraulic cylinder
		Linkages
		Rack & pinion
		Linear actuator
		Hydraulic jack

A/B/C /D	Rz/Ry/Rx	Bevel gear
		Linkages
		Helical gear
		Chain and sprocket
		Combination of linear actuators
		Worm gear
		Gear train

Components suggested by the database were evaluated through their mechanical effectiveness, cost, ease of operating and cleanness and then their design embodiment considered to make sure they will work as a part of surgical table referring to table design layout in the beginning. A collection of ideas are illustrated in Table 5.7 with schematic 3D drawings.

Table 4.7 Selected mechanisms for different section designs (Not to scale)

Base to Column + A	**B/C/D**
 A1 – Hydraulic actuators	 B/C/D1 – Kickstart ratchet
 A2 – Hydraulic jack and dual frame	 B/C/D2 – Slider

 A3 – Spring	 B/C/D3 – Linkages
 A4 – Sliding blocks	
 A5 – Linear actuators	
 A6 – Sliding platform	

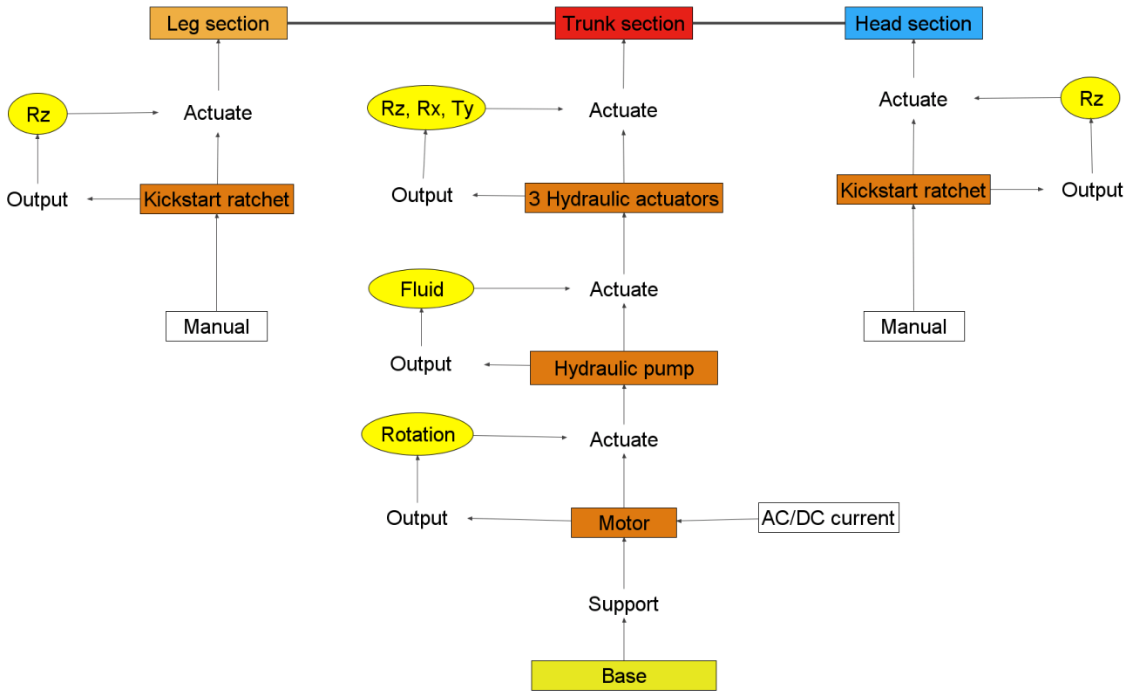
4.6.4 **Conceptual Design Embodiment**

Different section designs can be assembled together composing complete table designs, as Table 4.8 shows. In theory, combination of any idea from each joint will compose to a complete table design that is able to perform required articulations. Figures 5.31 – 5.33 illustrate three examples of assembled table conceptual designs using KFAD and their corresponding 3D models.

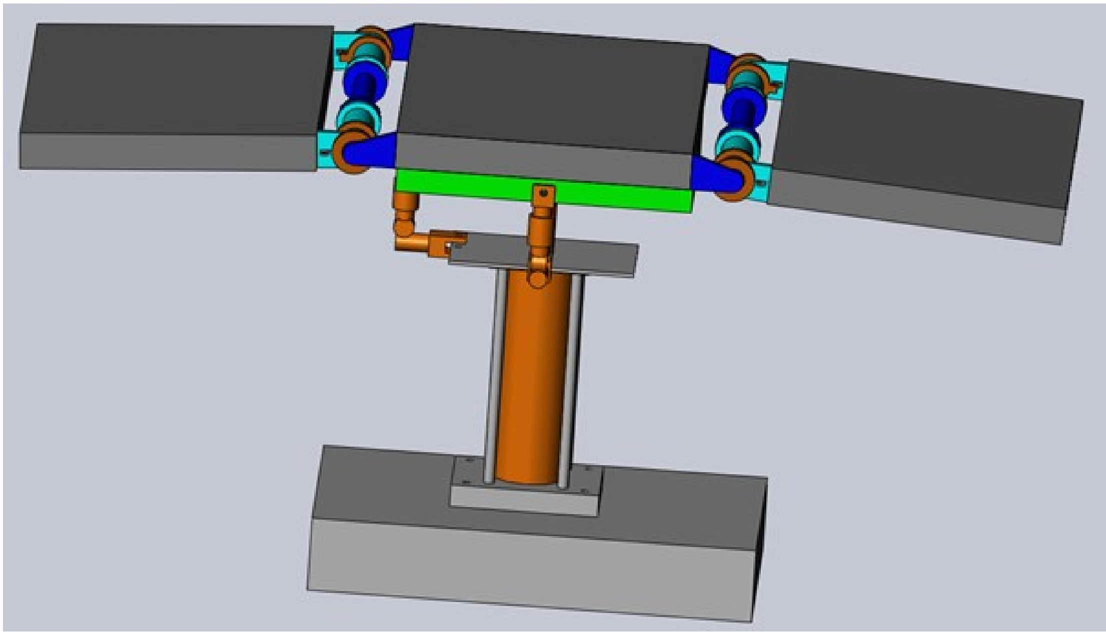
Table 4.8 Table design assembly matrix

Note: Idea 5 and 6 for A joint are designed for table layout 2 therefore no B joint design is required.

	Idea 1	**Idea 2**	**Idea 3**	**Idea 4**	**Idea 5**	**Idea 6**
A	A1	A2	A3	A4	A5 (without B)	A6 (without B)
B	BCD1	BCD2	BCD3		N/A	N/A
C	BCD1	BCD2	BCD3			
D	BCD1	BCD2	BCD3			

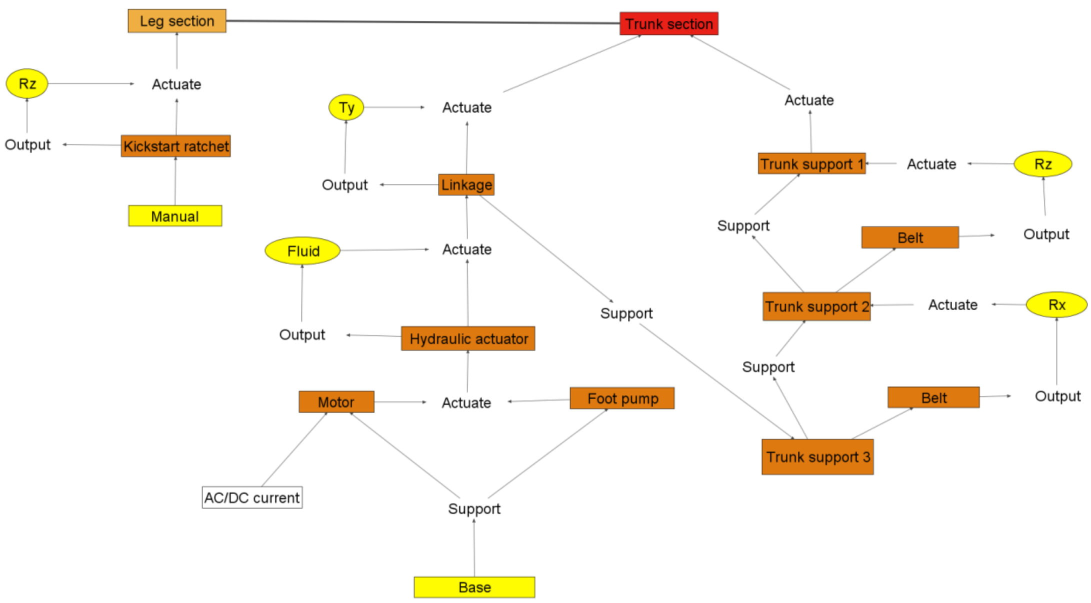


a. KFAD for table design Concept 1

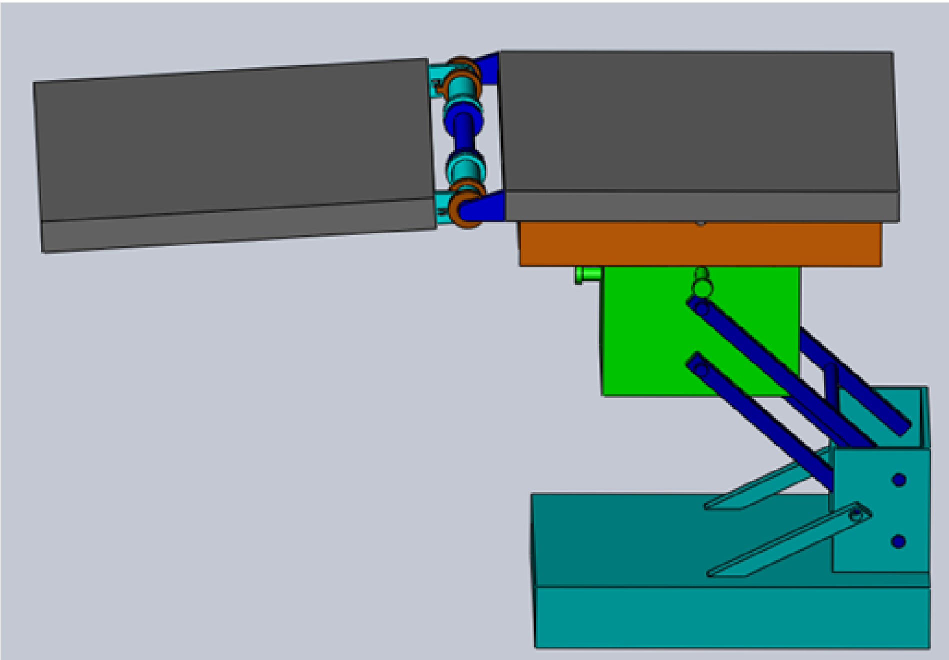


b. Concept 1 idea illustration

Figure 4.28 Table design Concept 1

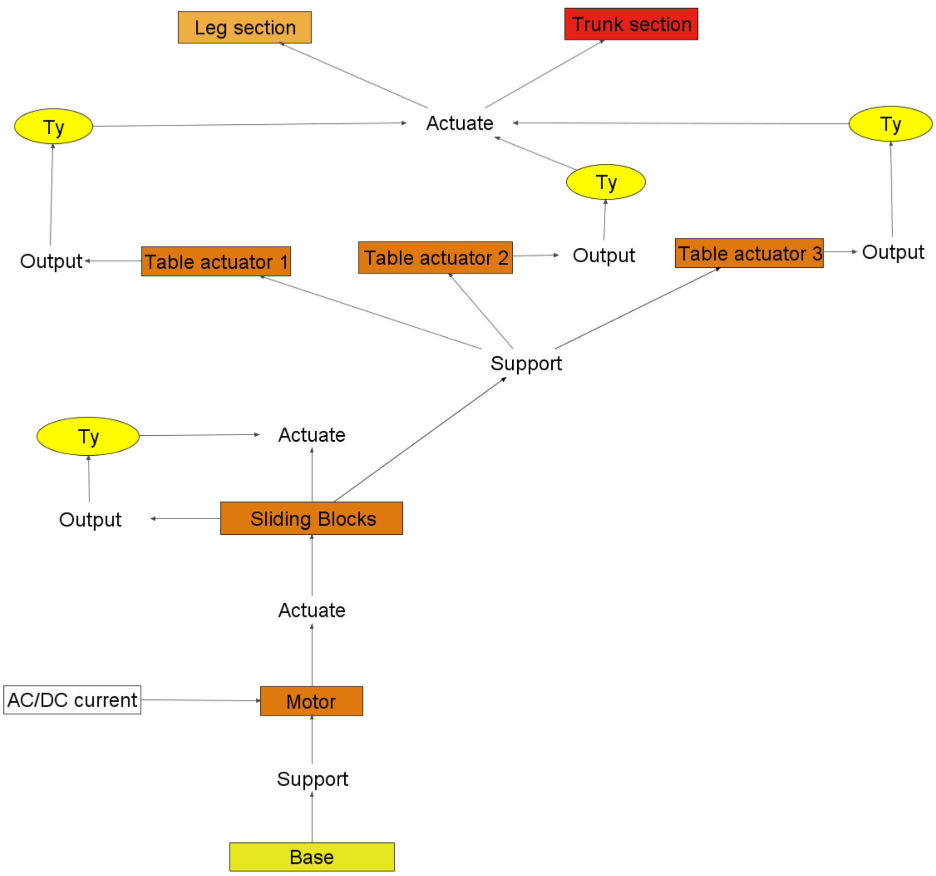


a. KFAD for table design Concept 2

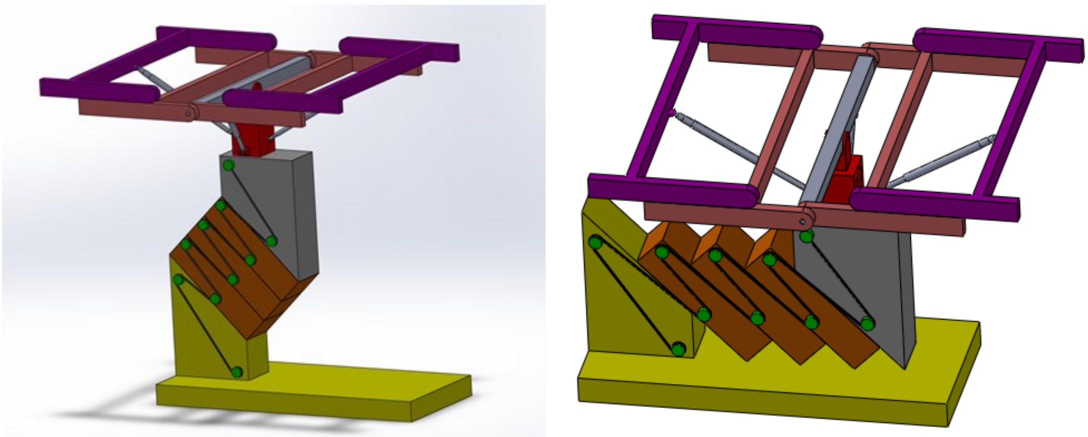


b. Concept 2 idea illustration

Figure 4.29 Table design Concept 2



a. KFAD for table design Concept 3



b. Concept 3 idea illustration

Figure 4.30 Table design Concept 3

These three concepts are examples that demonstrate the idea assembly using the matrix. With the addition of new section designs, more design assemblies will be able to be achieved. These conceptual designs can then be evaluated and assessed again by designers and engineers to decide whether they are worth to be developed further. Although no detailed designs came out from the employment of this design approach in this case study, it is still be able to provide a broad range of options for engineers and designers to choose from.

4.7 Discussion

One of the main purposes of MMET as originally implemented was to help novice engineers and designers to gain in-depth understanding on commonly used mechanisms and machine elements. MMET enables component identification with regard to functions and movement types. Due to increasing demand of complex engineering product designs, experienced engineers and designers are also facing challenges in design and problem solving that are not in their domain. MMET can also offer guidance help to experienced engineers and designers with component information which may not in their expertise as well as possibly domain experts, although this has not been explored as part of this research programme.

The essence of MMET is to provide assistance and recommendations on the selection of mechanical components based on their functional or movement requirements. The majority of engineers and designers have their own approach for design which may unwittingly eliminate some solutions that are not within their expertise. MMET is able to overcome this drawback and provide new insights for component selection and alternative exploration. By conducting deconstruction of the system the database is able to provide a broad range of suggestions with regard to each function, and offer engineers and designers a broad range of potential solutions.

The three table concepts presented provide a demonstration of the design outcomes by employing an MMET based design approach. This design process is able to provide conceptual ideas suggestions which can be further developed into design solutions. From the design outcome it can be seen that the shortcoming of considering only movement oriented MMET is obvious. The lack of functional requirement identification led to incomplete design of table components that do not have exact movement attributes, for example, width extension and hand rest only accomplish functions rather than movements. Therefore both functional and movement oriented search are recommended to make sure that all design requirements are satisfied.

The function oriented search feature in MMET allows the user to identify components through a text based search algorithm. This may become a challenge when practically used since designers and engineers generally tend to describe functions in different forms using natural language, and it will be difficult to contain all possible ways of expressing one specific function. Therefore the Function Basis for design introduced in Chapter 3 was adopted to define functions in the database. The user will be required to describe the function in Function Basis format before he/she uses it as searching criteria.

Currently the database mainly contains commonly used mechanisms and machine elements found in mechanical engineering industry including bearings, gears, springs and motors since it is challenging to include all components used in industry. However, as technology evolves new types of mechanism and machine elements will be created with new functions or movement types. Therefore in order to maintain MMET's effectiveness and value it needs to be expanded and updated through time. This can be achieved by using web crawler technology to obtain information from the internet and expand and update with the newest inventions and technology and then add this into the database. Some information relating to the use of web crawler technology to update a database can be found in Wang (2013).

Research has shown that experienced designers and engineers sometimes have a tendency to overlook areas that they are not familiar with, which may result in the lack of creative solutions. MMET enables the idea exploration of a wide range of components that satisfy system requirements regardless of design expertise. These ideas then can be evaluated according to design constraints and considerations to achieve optimised solutions. MMET is only capable of providing components which fulfil specific functional or movement requirements, not a complete design. It can be seen as a design tool that offers assistance to engineers and designers to select components and design mechanisms.

The design approach associated with MMET focuses on the development of conceptual designs in terms of exploring components that fulfil product design requirements. By decomposing the system and functions using a FAD approach a wide range of components suggested by MMET allows engineers and designers to make an informed selection. The next step is that the components chosen need to be assembled to compose complete conceptual designs, which might be a challenge and requires experience for engineers and designers. In this surgical platform design case study presented in this chapter, only key components that perform different table positions were considered, i.e. how these table sections were assembled together was not considered in detail and detailed designs were not developed. MMET does not offer this capability. Therefore it can be seen that this design approach aid described is mainly applicable at the conceptual design stage where components' design functions and movements are identified. For emergent functions during the product design process MMET is not able to identify solutions. In this situation FAD can be employed to analyse functional relationships between these components, reveal critical design flaws and emergent functions in order to carry out additional design features and improvements. Functional analysis of these components within the system is able to help engineers and designers to avoiding missing important design features.

4.8 Chapter Summary, Findings & Learnings

In this chapter MMET and a conceptual design tool built on it were introduced. MMET is a classification of commonly used mechanisms and machine elements in mechanical engineering industry, providing detail information with purpose of helping engineers and designers in three perspectives:

- Help both experienced and novice designers and engineers to understand components with regard to their functions, movement types, pros and cons.
- The function and movement oriented search enables the identification of components within the database by simple manipulation, in the meantime providing alternatives with regard to specific function or movement requirements, expanding the scope of possible solutions.
- The movement connection feature in MMET is able to assist designers and engineers with the assembly of ideas.

Literature review of work related to mechanism conceptual design suggests MMET is an original contribution to this field in terms of establishing links between system functional requirements and actual mechanical component selection. Along with the design approach developed which focuses on divergent thinking in idea exploration, MMET base conceptual design approach aims to assist designers and engineers to devise a broad range of components options in mechanism conceptual design regardless of their expertise through system function and movement deconstruction. The surgical table case study design project provided a tangible opportunity to validate MMET and the result provided promising indications of future design development.

Features within MMET software allow the user to explore commonly seen mechanisms and machine elements through different approaches, assist them to gain in-depth understanding on these components. Outcomes of the surgical platform design were presented to company experts, provided evidence and support for the effectiveness of MMET. Flaws of the initial conceptual design tool have been spotted through feedbacks from the case study, suggested structural system breakdown and solution validation should be integrated into the conceptual design tool. The detail of the improved design tool is shown in Chapter 5.

Chapter 5 The Conceptual Design Tool

5.1 Chapter Introductory Statement

In this chapter the initial conceptual design tool is improved with respect to the feedback and insights gained in the surgical platform design case study. FM tree and FAD are integrated into the design approach, which contributes to the completion of the Tool. Another industrial case study is conducted for the purpose of validating the Tool and providing insightful information regarding its application in solving real industrial problems.

5.2 Design Approach Improvement

In accordance with the outcomes of the surgical platform design project, an improved conceptual design tool was developed by introducing Function Means tree (FM tree) structure to represent system deconstruction. This approach aims to establish a clearer and more organisable view of representing how an engineering product is designed with regard to its functional requirements as well as helping engineers and designers to devise a broader range of solutions with the aid of MMET.

A Function Means tree is an approach to model the composition of a product from two perspectives: functions and means. It has a hierarchical structure of functions and means at different levels connected by causal relations (A.J. Robotham, 2010). In order to establish an FM tree product deconstruction is required containing a search for the means to realise a function, identification of functions to realise the chosen means and a decision making process to select the best solutions (Hansen, 1995). Figure 5.1 shows a typical FM tree structure. In an FM tree an elbow line represents options while straight line represents all necessary parts. In general, means are attached to a function by elbow lines since they represent different methods of achieving that function and functions are attached to a mean via straight lines since a mean may have more than one functional requirement.

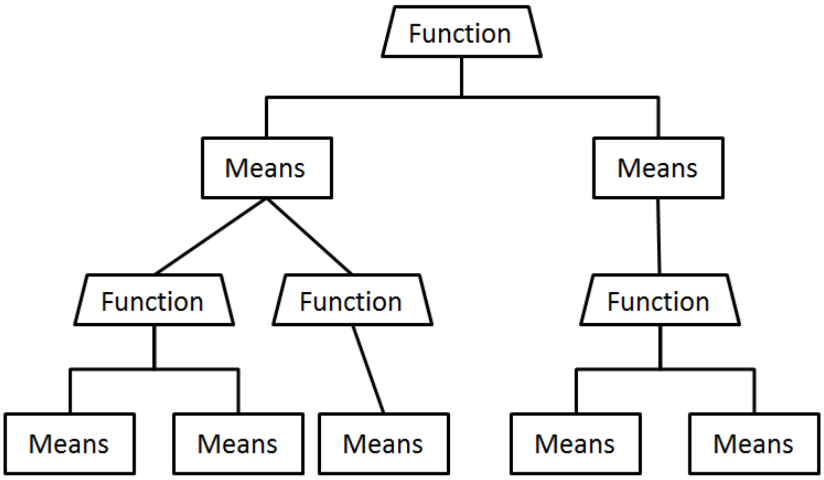


Figure 5.1 Typical Function means tree structure

The working principle and format of an FM tree fit into the conceptual design tool developed in Chapter 4 well in terms of functional breakdown of the product system and components search for individual functions. In order to adapt the traditional FM tree into the design approach, it was modified by adding a layer of product sub-systems for composite designs, represented using designVUE. Figure 5.2 shows the modified FM tree in association with the MMET based conceptual design tool where the database can be employed to search for components that can satisfy defined fundamental functions. Only straight lines are used to connect functions and means since an elbow line cannot be created in the current implementation of designVUE. Blocks with different shapes are used to represent different objects.

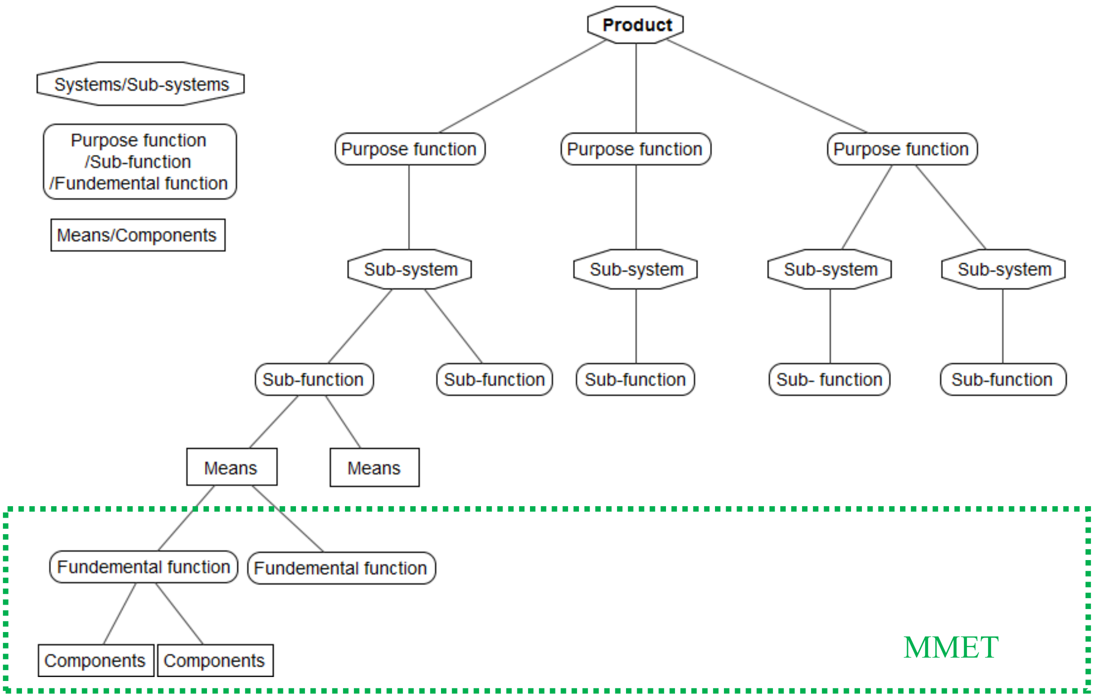


Figure 5.2 Modified FM tree associated with MMET

This structure allows the user to deconstruct the system with regard to its functions, and identify sub-systems that can fulfil these functions. Each sub-system carries their lower level functions which can be used as searching criteria for the database. MMET is able to provide components options for explicit fundamental functional requirements defined by the user. For complex product designs further breakdown on sub-system functions may be required to reach the level where fundamental functions are defined, i.e. more layers of Function Means tree are required to be constructed. In the FM tree structure shown in Figure 5.2 the lowest level 'Components' are basic mechanisms and machine elements that can be located in MMET or from other sources. The expression of functions other than 'fundamental function' in this approach is not limited to a Function Basis format in order to avoid distraction. The reason for this is that the user may spend too much time concentrating on trying to express functions in the Function Basis format which may result in the interruption of their thoughts on actual system deconstruction. The adoption of Function Basis terminology is only recommended when defining fundamental functions, which will help the user to identify components using MMET quickly.

In a Function Means tree different methods to achieve one specific function are listed in a hierarchical structure, which enables the user to view different options at the same time. By providing this information the approach is able to offer the user design alternatives with regard to the same functional requirement, and help engineers and designers to explore broader range of conceptual solutions by preforming different combinations of ideas. Furthermore, this approach is able to help the user to understand product systems with regard to functional requirements, and enables the compensation on lacking of idea generation that are not in the user's expertise.

From the working principle of an FM tree it can be seen that this structure is mainly capable of identifying explicit functions that are generated in system deconstruction. However in general mechanism designs there will be functions that emerge from interactions between components and sub-systems which result in the requirement of additional design features or components. Furthermore, this approach is mainly applicable on the identification of useful functions within the system, i.e. functional requirements of the system. Thus for harmful actions that may be caused between components an FM tree is not able to identify them and suggest solutions. In order to compensate for this drawback functional analysis of the system using FAD approach is recommended after the components selection, aiming to analyse the function relationship between these components, identify functions that emerged from the composing/assembling process, after which MMET can be used again to help the user to identify solutions to these emergent functions. Another benefit of employing FAD after the construction of a FM tree is that it is capable of revealing harmful functions generated among the components and identifying redundant functions and components, and provide a start point for design improvement by eliminating these harmful functions and components.

5.3 The Conceptual Design Tool

Essential procedures of applying the Tool contain design specification identification, system breakdown using FM tree, component exploration using MMET, concept evaluation using FAD and design improvement. The Tool should be able to fit into conventional engineering design models including the Total Design and Systematic Design Approach, aiming to help engineers and designers to conceive a broad range of conceptual designs which can be then evaluated and developed further into detail designs.

Figure 5.3 illustrates the core of the Tool built on MMET, FM tree and FAD. The process is performed in an iterative manner in order to obtain optimised solutions. Engineers and designers can go back to any stage in case of the emerging of new insights and unsatisfactory results. The iterative process between FAD and MMET is capable of helping the user to identify emergent functions generated in component assembly and devise solutions (For example, see the following potato slicer design example). FAD is able to help the user to identify functional relationships between components, verify the feasibility of component assemblies. In the design evaluation stage generated conceptual designs can be evaluated for further development using decision making tools such as Screening Matrix and IBIS.

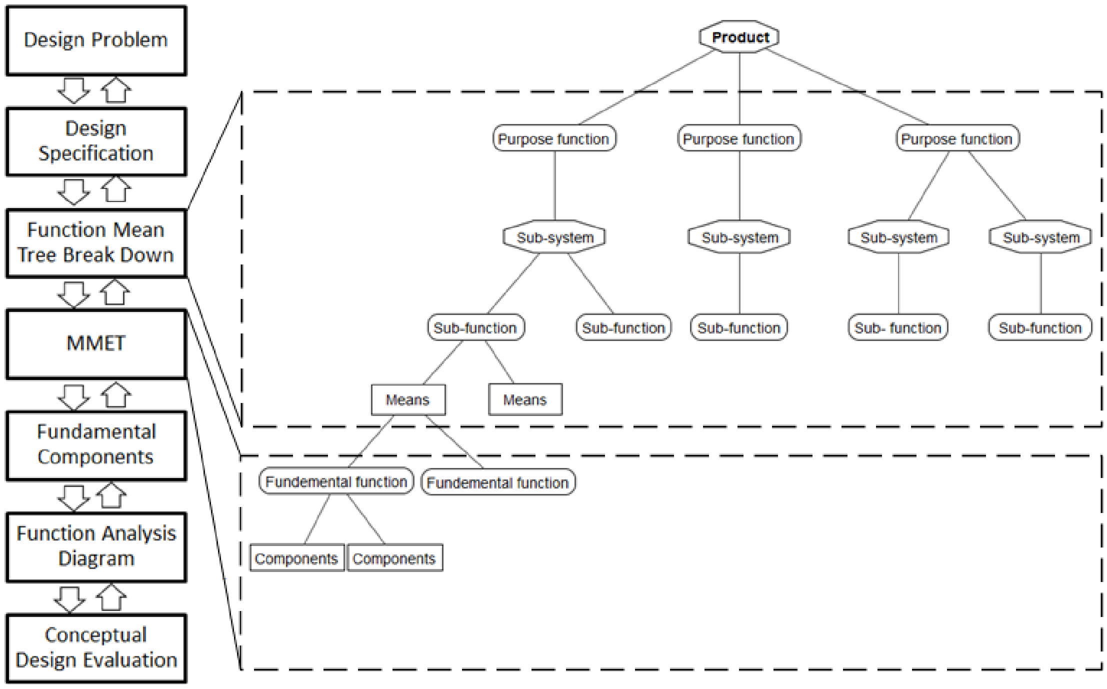


Figure 5.3 MMET based conceptual design tool associates with FM tree and FAD

Figure 5.4 illustrates a FM tree of the cordless hand-held potato slicer example mentioned in Chapter 3. The purpose functions of the potato slicer were defined as ‘hand-held’, ‘automated potato slicing’ and ‘cordless power supplying’. Based on these three functions four sub-systems were identified: Power supply, Slicing mechanism, Body and Power Transmission. They were then further broken down according to their sub-functional requirements.

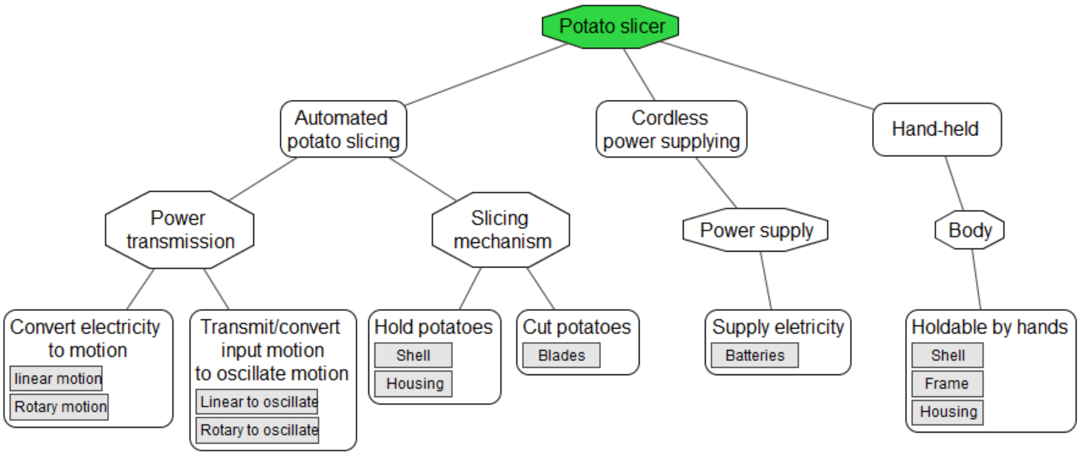


Figure 5.4 Potato slicer Function Means tree

With functions identified for each sub-system MMET can be used to explore potential, generalized means that may fulfil these functions. For a tidier and clearer view the means at this level were listed within the function block (See Figure 5.4), represented in rectangular blocks. Then fundamental functional requirements regarding these means can then be identified, where MMET can be used to explore potential design components. For example, see Figure 5.5 that illustrates further breakdown of the means 'Rotary motion' and 'Rotary to Oscillate' in the Power transmission system.

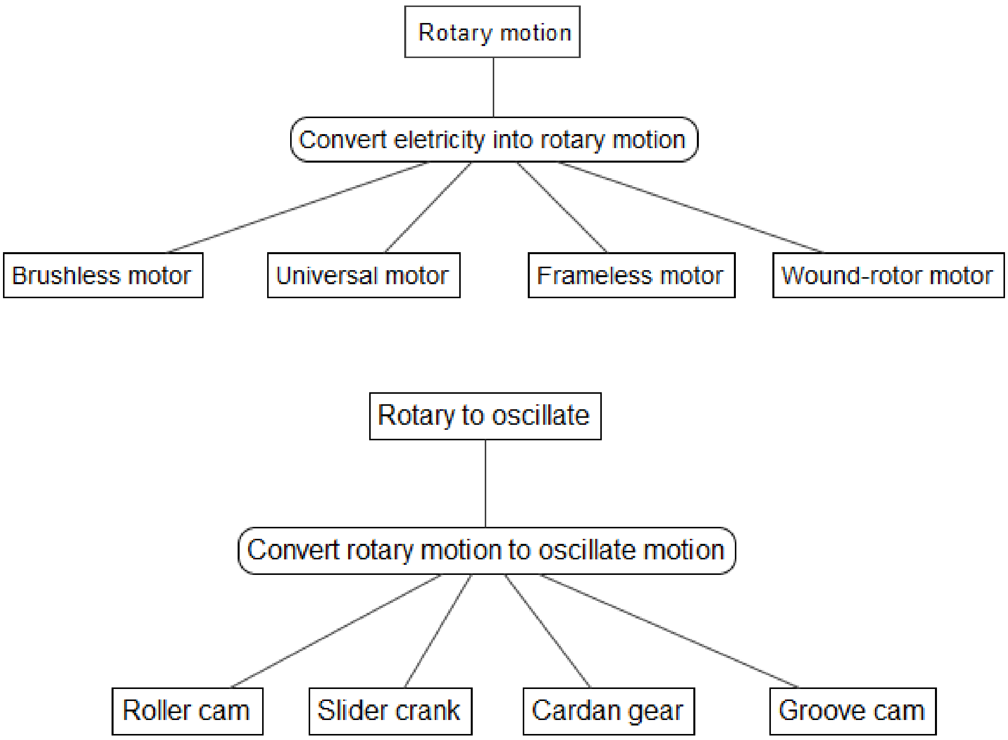


Figure 5.5 Function Means trees for means generated in the primary Function Means tree

Figure 5.5 indicated defined fundamental functions of the two means in the power transmission system: *Convert electricity into rotary motion* and *Convert rotary motion to oscillate motion.* According to these functions MMET was employed to explore components that can satisfy these functions. Different options were presented using rectangular blocks in the FM tree for the user to choose from. Engineers and designers would subsequently be able to make judgments and decisions based on information provided in MMET and their experience.

Components identified under each fundamental function should be able to be composed to produce a complete design which can fulfil all system functional requirements. For instance, in principle, in this case an assembly of a frameless motor and a slider crank could become a potential solution to the power transmission system and the same principle applies for the rest of sub-system defined. However, as mentioned in Section 5.2, system deconstruction using FM tree at the current stage is only capable of identifying explicit functions generated, thus system analysis using FAD was conducted to ensure the composition of components works and no important design features are missing. FAD was conducted to analyse the relationship between example components within the whole system, shown in Figure 5.6.

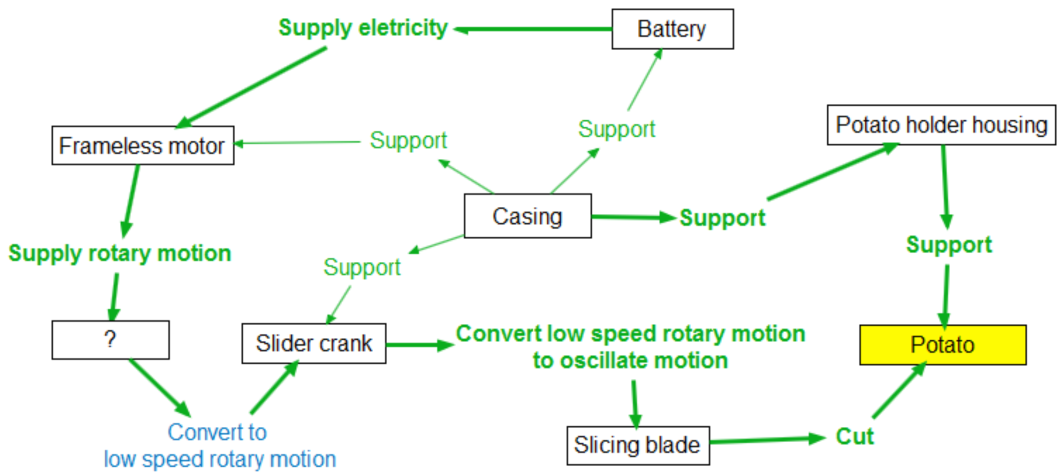


Figure 5.6 FAD of the potato slicer system

From the FAD the functional relationships between selected components with key functions indicated by bold arrows can be seen. However, an emergent function was identified indicated in blue in Figure 5.6, which requires an additional design feature to fulfil this function. In this case, this emergent function can be used as searching criteria for MMET. The database then is able to provide options regarding this emergent function, e.g. gear trains, helical gears and belts. Using this approach the completion of a comprehensive FAD for the automated hand-held potato slicer can be achieved with useful functions identified, shown in Figure 5.7.

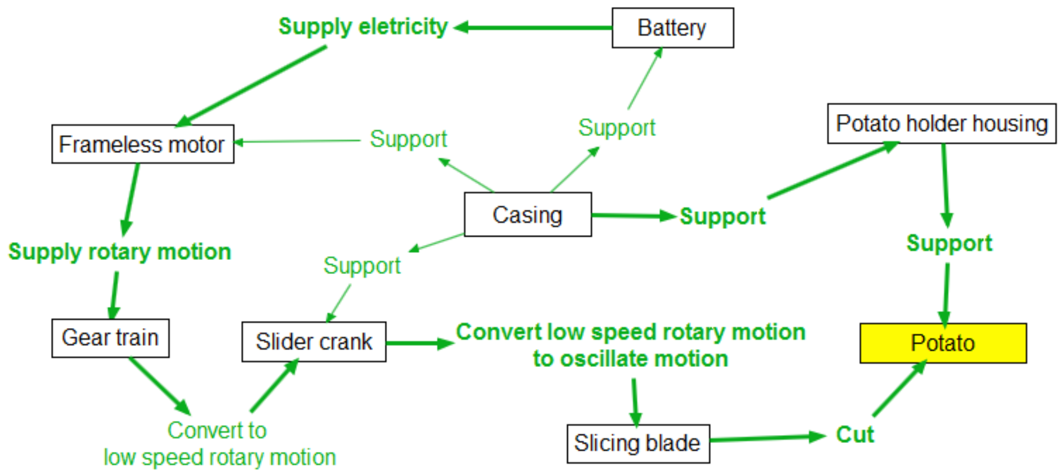


Figure 5.7 FAD for the air propulsion system with all components identified

Sometimes emergent functions are generated with the identification of components that satisfy original emergent functions. Thus an iterative process can be conducted if necessary, to ensure all emergent functions are satisfied.

The potato slicer example has indicated the benefits of using an FM tree, for the case of a ‘me too vernacular design example’, to represent system deconstruction in product design and the significance of employing FAD to validate components compatibility to make sure all necessary designs and components are covered. It is asserted here that an FM tree enables a clearer and more structural approach to devise conceptual ideas compared to the MMET based approach stated in Chapter 5. It is capable of decomposing the system with regard to functions and movements, capturing what system functions and movements need to be achieved and how, as well as providing alternatives.

This approach can also be applied to the improvement of existing product designs. An FM tree can be employed to conduct product breakdown into fundamental components, helping engineers and designers to understand the way the product being designed. An FM tree approach also enables the capture of different designs with regard to their functions, providing alternatives. Therefore, by decomposing the existing product alternatives can be explored regarding system functions. With alternative designs configured functional analysis of the new system is useful to evaluate the improvements.

In new FADs containing the alternative designs more harmful functions may be spotted, in which case the user can decide either to keep improving the design by eliminating emergent harmful functions or to find other alternatives.

In Section 5.4 an under floor insulation spraying robot system design case study conducted using the improved MMET based conceptual design tool is described.

5.4 **Case Study - Under Floor Insulation Spraying Robot System**

5.4.1 **Design Brief**

A company, q-bot Ltd, is aiming to design an autonomous or semi-autonomous robot system for spraying under floor insulation. The process is achieved by delivering the polyurethane foam to the bottom surface of the suspended floor. This robot system is aiming to access the under floor cavity with minimum disruption, for example, entering from the outside by removing bricks or from an air vent brick. The robot system will need to carry or drag payload, and be operational under different under floor environments such as humid, damp, dusty and obstacle strewn conditions. Figure 5.8 illustrate the working conditions of the robot, where the pink shading stands for the foam being sprayed.

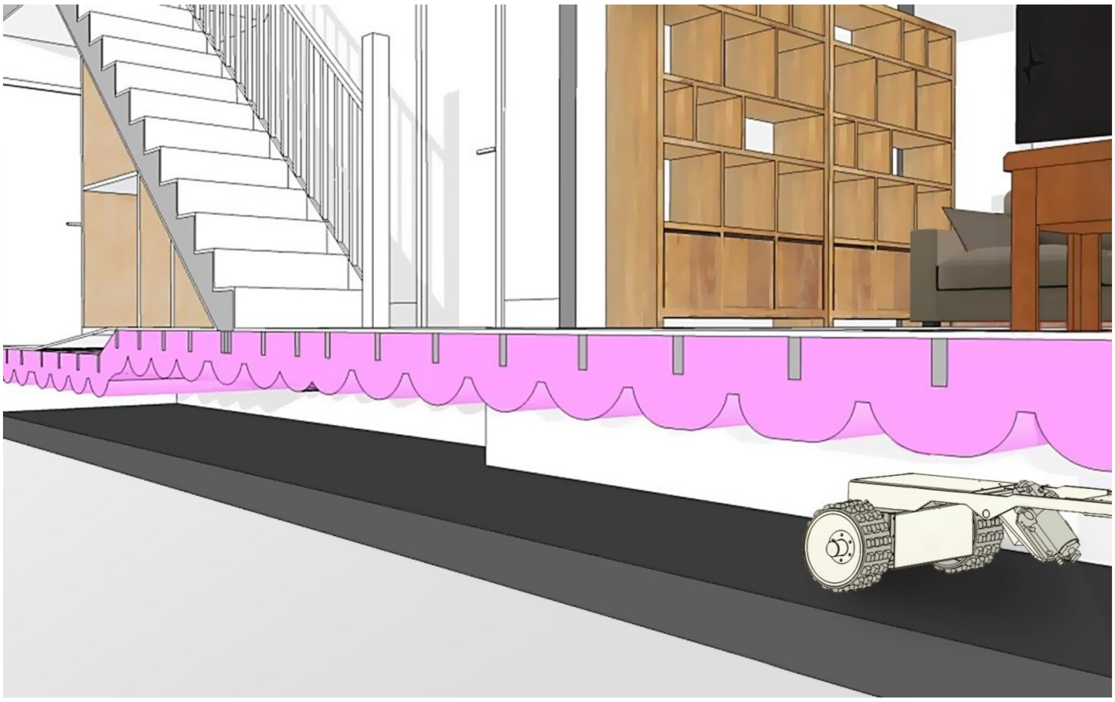


Figure 5.8 Spraying robot working environment

In this project the author was asked to focus on the development of three areas of the robot system: Foam application, Movement traction and Accessibility. The main objective of this project case study is to explore potential ideas for the design of the robot system with regard to these three fields. The MMET based conceptual design tool associated with FM tree and FAD was employed to help the author to carry out design solutions.

5.4.2 **Design Process**

The robot design procedures followed the process introduced in Figure 5.3. Design specification was provided by the company, help the author to understand the main functions this robot system needs to achieve and its design constraints. But the design constraints of the robot was not applied in the idea generation stage since the main purpose of this project was to devise as many designs for the robot system as possible. Similarly, since the viability of the concept is not the main focus in this project, FAD was not conducted after finding means to the functions, which becomes the company's decision whether to perform functional analysis on their favoured concepts devised through the FM tree and MMET database. Therefore, the design was simplified to a linear process starting with system deconstruction using FM tree, followed by component identification in MMET, finding possible concepts for the robot system (Foam application, Movement traction and Accessibility).

5.4.3 FM Tree Construction and Idea Exploration

Three sub-systems of the robot system can be identified in accordance with the three areas of focus. Other sub-systems required within the robot system were not included since they are not the focus in this project. Functional requirements of these three sub-systems can be then defined followed by possible means to achieve them generated by brainstorming by the author and the company team. At this level current version of MMET was not able to help the team explore ideas since the functions defined at this level are normally vague, highly abstracted and system-related comparing to fundamental functions, thus there would be no matching results from the database. Therefore each function at this level requires further deconstruction where fundamental functions can be defined and MMET can be employed to search for suitable components. Further Function-Means analysis may be required for complex systems in order to reach to fundamental function identification. For example, the functional requirement of the movement traction system is to drive the robot forward, and there are several methods to achieve this specific function such as using legs, wheels or peristaltic movements. Each mean has an independent map indicating a more detailed FM tree containing lower level functions and means. More layers of maps can be added and linked if necessary. Figure 5.9 and Figure 5.10 show examples of existing designs regarding Foam application, Movement traction and Accessibility from the robot prototypes, providing a visual impression of the robot system.

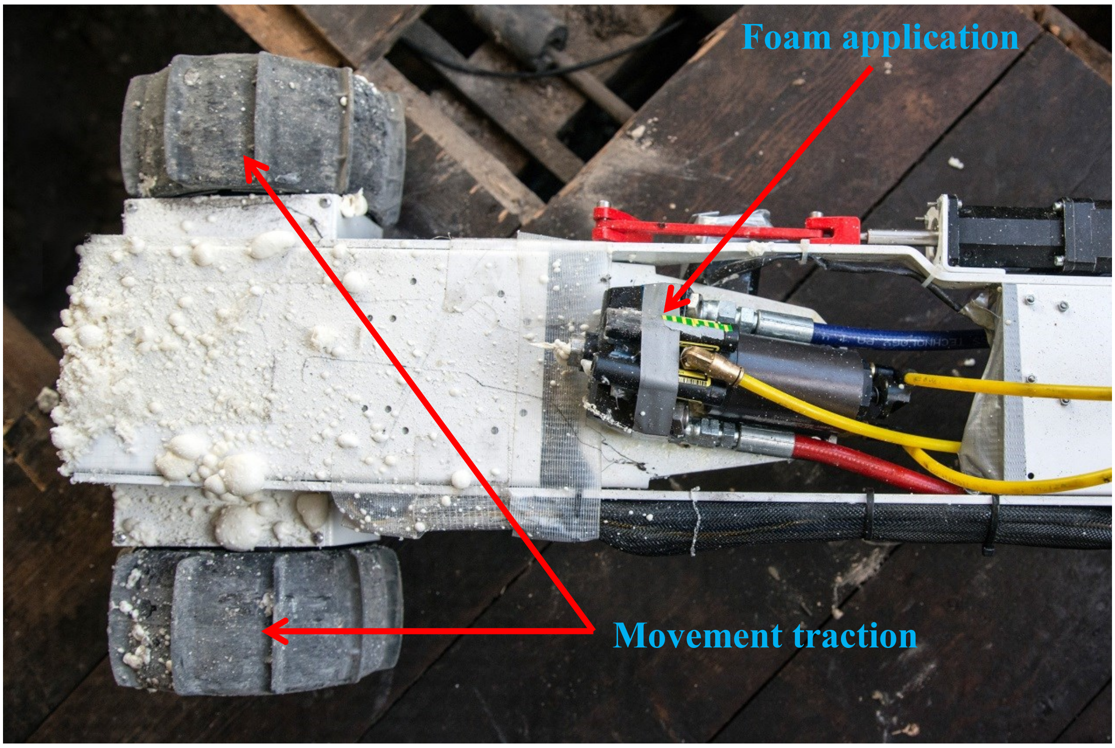


Figure 5.9 Robot prototype containing foam application and movement traction system

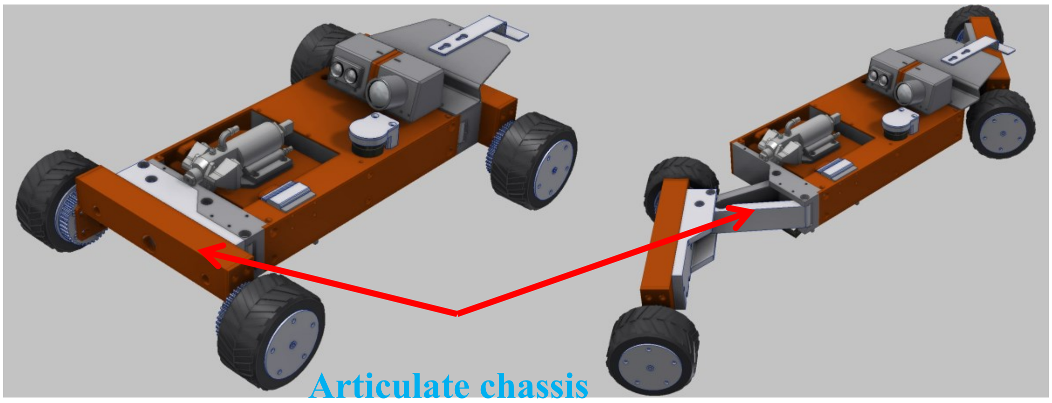


Figure 5.10 Robot design with accessibility system (folding design)

Figure 5.11 demonstrates an FM tree of ‘Folding’, one of means enabling accessibility of the robot system.

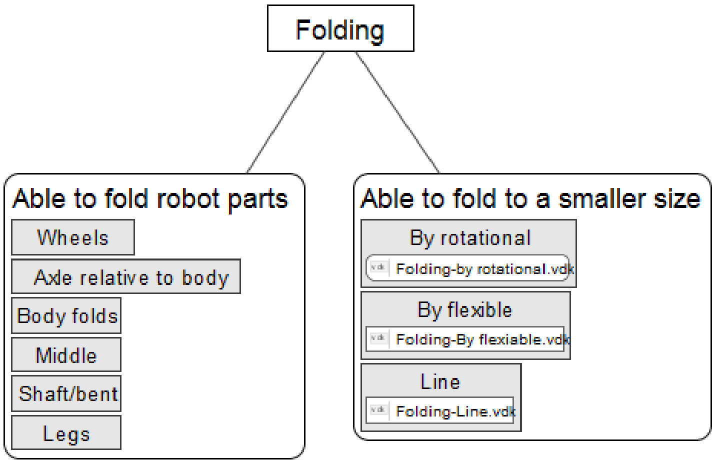


Figure 5.11 Function means tree for 'Folding'

In order to accomplish the mean 'Folding' the system needs to be able to fold the robot into a smaller size. MMET is not capable of offering options for function 'able to fold into smaller size' since it is too vague to be a fundamental function. Therefore, means to achieve this function were identified by the author and the company team by brainstorming. For each mean identified another layer of FM tree was established. For example, mean 'By rotational' is shown in Figure 5.12, in which fundamental functions were able to be defined and MMET can be employed. Function 'Able to rotate robot parts' is a specific function relate to the robot system, in which MMET is incapable of providing any suggestions. Therefore the options listed were generated by the author himself and the company team according to the parts a robot system may have such as shaft and wheels.

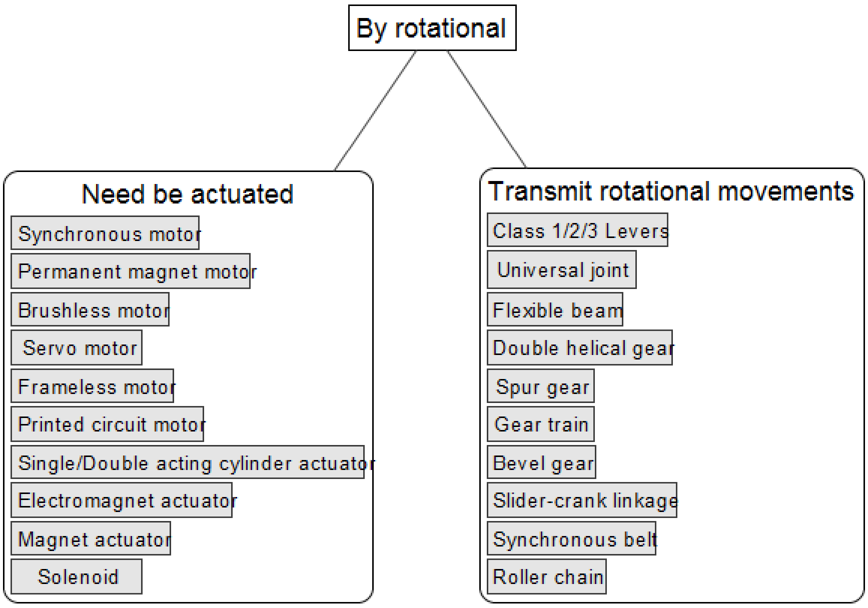


Figure 5.12 Function means tree for mean 'By rotational'

For function 'Transmit rotational movements' MMET is able to provide component options such as class 1/2/3 levers and universal joint through two approaches: function oriented search with regard to function *'transmit rotary movement'* and *'convert X motion in to rotary motion'* where X stands for other types of movement such as linear or oscillated, and movement oriented search with regard to movement output *'Rx/Ry/Rz'*.

The same approach applied to another two means to achieve 'Folding', shown in Figure 5.13 and Figure 5.14. Both of these means need to be actuated in order to provide power to drive the folding mechanism, therefore MMET was used, provided components options such as different types motors and linear actuators. 'By flexible' the design will need to have flexible joints so the robot can be folded up. With regard to the function *'Contain flexible joints'* MMET mainly offered different types of linkages, levers, latches and clamps. In this case a few types of linkages were chosen and listed in the FM tree as a result of design simplicity. 'By line' basically means the robot needs to be able to extend/retract its length when necessary. MMET provided options such as hydraulic cylinders and solenoid with regard to function *'Transmit linear motion'*.

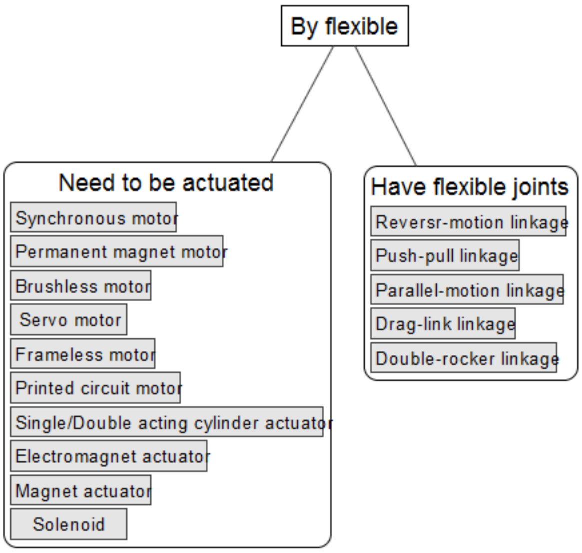


Figure 5.13 Function means tree for means 'By flexible'

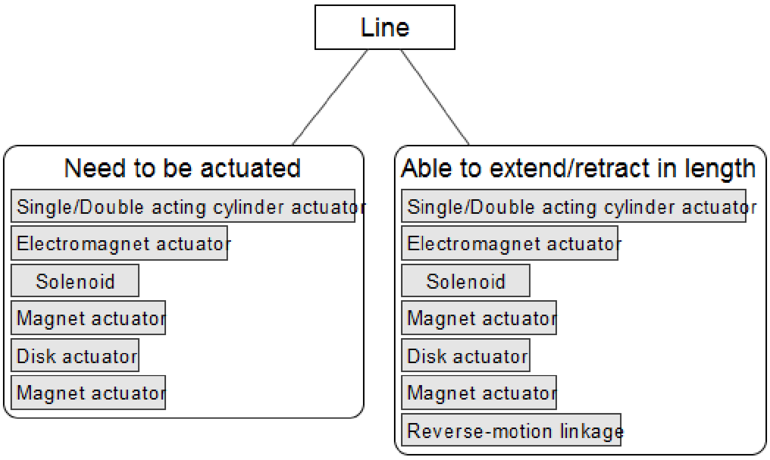


Figure 5.14 Function means tree for means 'By line'

Some other examples are shown below, providing more detail regarding the conceptual design development process.

- **Movement traction system – mean 'Legs' and 'Wheels'**

FM tree for the mean 'Legs' for the movement traction system is shown in Figure 5.15.

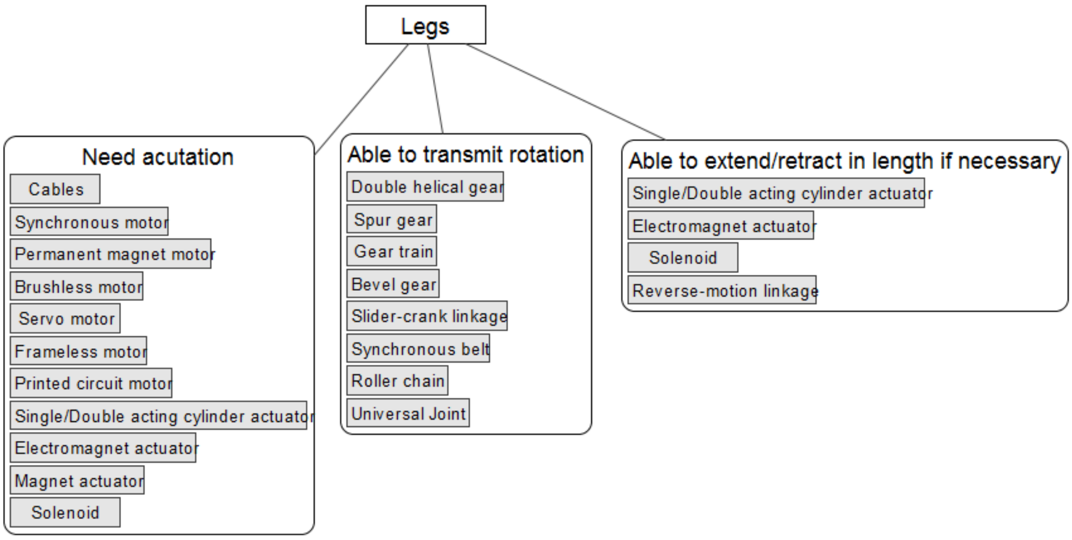


Figure 5.15 Function means tree for movement traction means 'Legs'

Three fundamental functions were identified based on the analogical analysis on human and animal legs. First the legs need to be actuated by the power supplied that normally is electricity or fluid. In order to drive the robot forward the legs need to have rotatable joints and multiple joints may be required in each leg. An optional function was defined at last to enhance the functionality of the movement traction system, in which the leg may become extendable in length. For the first functional requirement components that can provide power to the legs are listed such as motors and actuators. Similar to the 'By rotational' means in 'Folding', components like linkages, levers and gears can be used to perform rotary motion. The last functional requirement is same as 'By line' where MMET provided options like linear solenoid and hydraulic/pneumatic actuators.

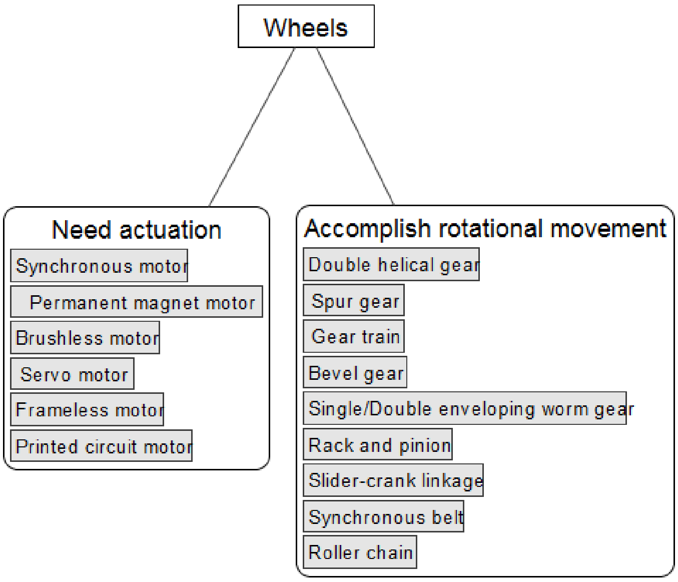


Figure 5.16 Function means tree for movement traction 'Wheels'

Figure 5.16 shows the FM tree for the mean 'Wheels' for the movement traction system. The actuation methods were mainly focused on different types of motors since the working principle of wheels is use rotational movement and friction between wheels and the ground to drive the robot. Slider crank linkage is an exception in the list since it requires linear oscillated movement to accomplish rotational movements. According to MMET, none of these motors listed can satisfy to drive slider crank linkage. Hence it will require other type of components that have linear movement output such as fluid actuators or rack and pinion.

- **Spray foam – 'Gun'**

Figure 5.17 illustrates the FM tree for the mean 'Gun' for the foam application system. Three functional requirements were defined. Means for mixing the foam were supplied by the company team and then added into MMET with function definition *'Mixing'* since they were not covered in the database beforehand. For triggering the spraying system the means simply need to perform a slight amount of linear movement to activate the gun. Therefore, MMET provided options such as solenoid and fluid cylinders regarding function *'Transmit linear movement'*. A few movement types were devised to move the gun by the author and the company team, including a novel concept that fixing the gun, reaching all the spraying angles by the movement of the robot body instead. For different movement types another layer of FM trees were constructed to analyse each mean in more detail, shown in Figure 5.18.

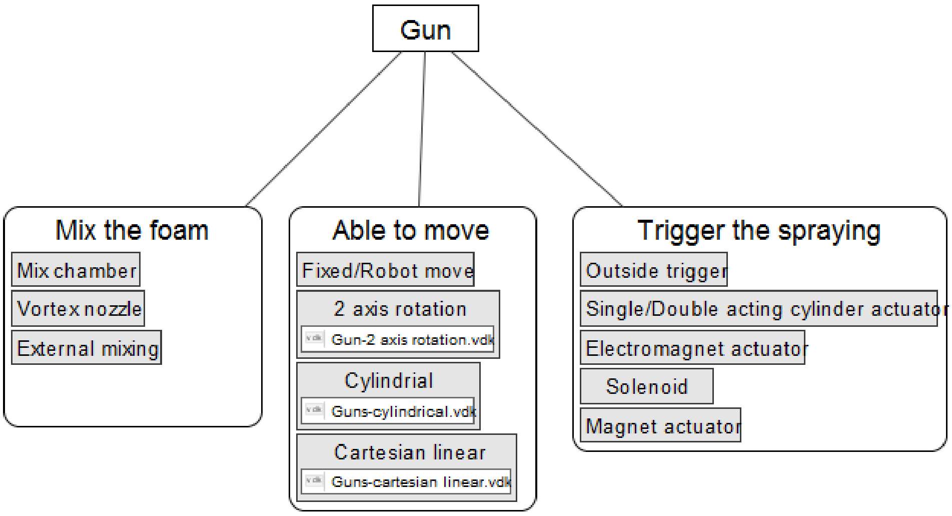


Figure 5.17 Function means tree for spraying foam using 'Gun'

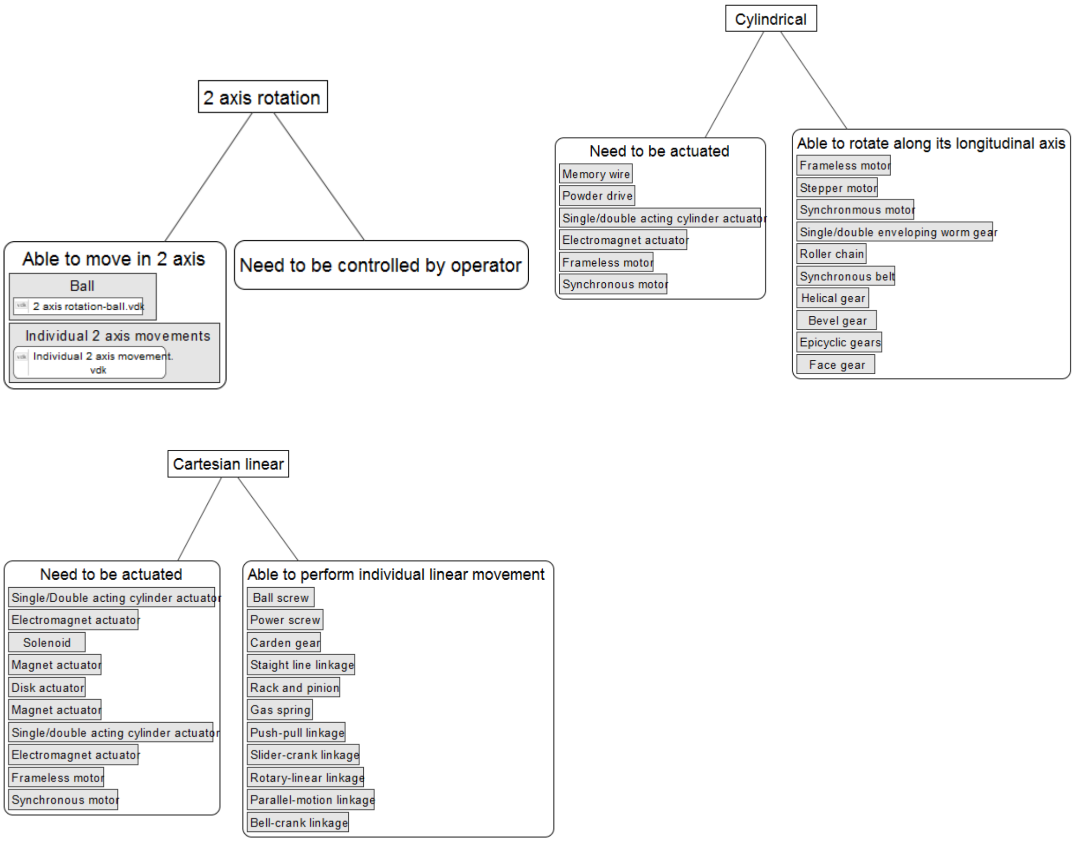


Figure 5.18 Function means tree for different types of Gun movements

'Able to rotate in 2 axis' was further broken down into two 2 means, ball movement and 2 individual axis rotation. An additional layer of FM tree was constructed for these two means, shown in Figure 5.19. Ball movement system and individual 2 axis rotation system need to be actuated and be able to perform spherical motion and individual rotation respectively. A selection of components suggested by MMET is listed in the

FM tree. Similar to other types of means, 'Cylindrical' and 'Cartesian linear' will require actuation and different types of movement transmission or conversion. The FM trees of these two means are shown in Figure 5.18 with options suggested by MMET.

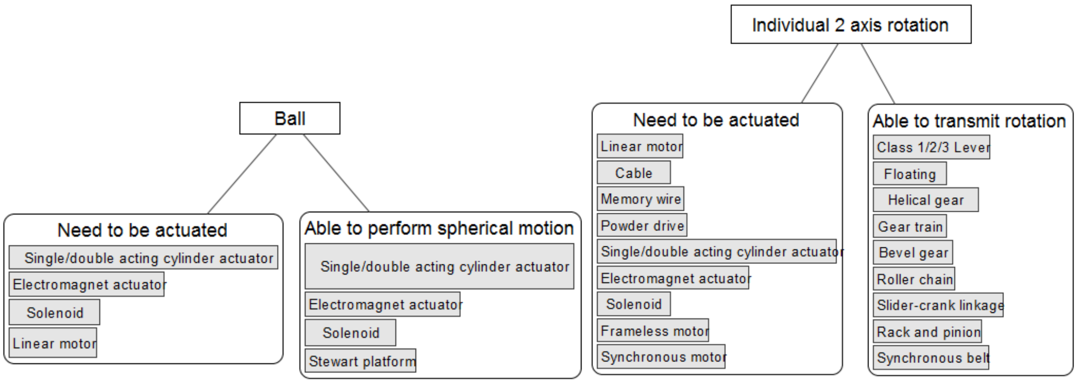


Figure 5.19 Function means tree for 'Ball' and 'Individual 2 axis rotation'

Figure 5.11 to Figure 5.19 have shown examples of the robot system FM tree containing different levels of Function-means. It can be seen that the benefits of constructing the system FM tree into different layers of maps are obvious, helping the user organise large amount of information and be able to locate data quickly through wormholes. It may be noticed that even for the same function, means listed are different from each other under different system design constraints and limitations. For example, with regard to the same function *'need to be actuated'* options for wheels and legs are different. This is affected by design constraints set by the upper level mean. Wheels mainly perform rotational movement where legs mainly perform as linkage systems that contain rotations. However, MMET is not capable of recognising the difference in design preconditions, and it provides all possible options to satisfy the defined function from the database. Therefore, it may need the user's effort and intervention to identify practical options and screen insensible ones out. It can be seen from these examples that FM tree approach is able to help the author to identify fundamental functional requirements for lower level sub-systems and explore possible component options with regard to these functions. Each mean devised should be able to achieve the identified function and then be composed into a complete design solution. Not all the FM trees for the robot system design are shown in this thesis, the working principle are demonstrated instead.

The next step, albeit beyond this project's scope, would be the functional analysis of the chosen components. This will enables the validation of the chosen designs, making sure they can work as a whole system by analysing the functional relationships between those components. FAD is recommended to perform these analyses for each unique combination of ideas. The user will be able evaluate the concepts and decide the best ones to be further developed.

5.5 Discussion

The insulation robot system design project can be seen as a validation of employing FM tree and MMET in engineering product design in terms of function deconstruction and finding suitable components. From the robot system breakdown the benefits of using FM tree are obvious. It represents the system deconstruction in a structural format along with function identification of each lower level sub-system defined. It is able to help designers and engineers to understand the system they are designing with regard to the system deconstruction into sub-systems carrying different functions without losing the whole picture. The FM tree allows them to focus one specific function/mean and devise means/functions without interruption from consideration on other functions/means. For example, when designing movement traction system using wheels its adaptability on other systems and designs such as whether wheels designs are compatible with the folding mechanism was not considered. Compatibility of selected components as complete designs will be assessed later through functional analysis using FAD. This encourages the divergent thinking on idea exploration regardless of other design constraints, only on design requirements.

The FM tree approach is also able to provide assistance to engineers and designers on the organization of ideas regardless of the method and time they were generated. Sometimes ideas generated are like scattered seeds or a shot gun blast when using creative tools such as brainstorming and SCAMPER. But with the representation using FM tree ideas can be fitted into the structure under appropriate definition. In other words, those diverse ideas can be noted down first and then added into the FM tree. By doing this engineers and designers are looking at a clearer and tidier view of the generated ideas.

According to the design process MMET is mainly applied when fundamental functions were identified in the system deconstruction, i.e. the definition of lower level systems, purpose functions and sub-functions still require engineers' and designers' thinking effort. Until then creative thinking is encouraged where creative and innovative means can be devised. For example, in the robot movement traction system design, the means including wheels, legs and peristaltic were generated by brainstorming within the group formed by the author and the company designing team. If new means at this level are founded they can be added into the FM tree for further analysis and development. Moreover, with the hierarchical structure different tasks can be assigned to different groups of engineers and designers to work on at the same time to improve the time efficiency and design outcome. For example, one group can focus on the idea generation on movement traction system while another group working on the foam spraying design and then swap. Therefore before fundamental functions are defined creative thinking and employment of creativity tools are encouraged to assist engineers and designers to devise innovative and creative ideas.

As mentioned before, FM tree and MMET are only capable of identifying fundamental components to fulfil explicit functions defined in the system deconstruction. Designers and engineers need to make sure that the components they select can be composed into a complete design without any critical issues, even in conceptual design stage. Analysis of conceptualised components and their assembly prior to detail design and testing enables pre-examination of the solution, provide opportunities for time and resource saving in eliminating impractical design at conceptual design stage. Under such situation FAD is able to offer assistance on functional analysis of the system composed of selected components, identifying useful and harmful functions as well as revealing flaws in design such as missing components or emergent functions. By performing FAD engineers and designers are able to verify the design in terms of its feasibility and explore potential opportunities for improvement.

The current version of MMET is mainly capable of providing component options with regard to fundamental functions. For complex system designs, it will require several levels of function deconstruction to reach the definition of fundamental functions. Until then it will require the user to define lower level functions and come up with means before MMET can be applied, which may require experience and knowledge to do so. For example, it took three levels of deconstruction in the robot accessibility system design to finally configure what types of the components can be used. This will require time and patience from the user to identify basic components that can adopted into the design. Another shortcoming of employing this design approach is the difficulty in function definition when establishing the FM tree. Fundamental functional requirements need to be defined precisely by the user before the database can be used. Imprecise definition of fundamental functions may lead to unsuitable components that can neither achieve target functions nor fit into the whole design. Therefore, in order to achieve the best design outcome when using this conceptual design tool a certain level of experience of the user is recommended mainly embodied on the understanding on product technical functions. With the precise definition of fundamental functional requirements the database can be powerful to use to provide a wide range of options for the user to choose from.

It is worth noticing that this improved design approach is aiming to help engineers and designers to devise conceptual designs base on system functional or movement requirements by providing potential components that can fulfil these requirements. Verification of components compatibility is limited to functional perspective. Detail design of the components and the system need to be conducted in a detailed design stage. With a wide range of component options provided by this design approach and database it is more likely an optimised solution would be achieved. Furthermore, the FM tree approach allows engineers and designers to record their options and choices along with argumentation if necessary in case the final design fails and modifications are needed. Table 5.1 shows a SWOT analysis, undertaken by the author, of the original and improved conceptual design tool, indicating their values in general mechanism conceptual design.

Table 5.1 SWOT analysis of the original and improved conceptual design tool

Strengths	
MMET Based Conceptual design tool	**Improved Approach Associated with FM Tree and FAD**
• Generation of a broad range of mechanism components options regardless of design expertise • Iterative process enables optimised design outcome	• Generation of a broad range of mechanism components options regardless of design expertise • Structural approach to system deconstruction and idea generation using FM tree • Iterative process enables optimised design outcome • Conceptual design validation using FAD

Weaknesses	
MMET Based Conceptual design tool	**Improved Approach Associated with FM Tree and FAD**
• Not able to identify solutions for emergent functions • Not able to validate components compatibility as a whole design • Mainly capable of providing component options for fundamental functions	• Mainly capable of providing component options for fundamental functions • Time consuming
Opportunities	
MMET Based Conceptual design tool	**Improved Approach Associated with FM Tree and FAD**
• Compatible with commonly seen design processes • Applicable for general and specific engineering designs • Suitable for both experience and novice engineers and designers	• Compatible with commonly seen design processes • Encourage creative thinking and employment of creativity tools in idea generation • Suitable for both new and existing product development • Applicable for general and specific engineering designs
Threats	
MMET Based Conceptual design tool	**Improved Approach Associated with FM Tree and FAD**
• Requires the user to have experience using Function Basis to express function instead of natural language • There are specific conceptual design models available for specific design contexts	• Requires the user to have experience on function deconstruction and definition • There are specific conceptual design models available for specific design contexts

5.6 Chapter Summary, Findings & Learnings

In this chapter the initial MMET based design approach evolved into the Tool by integrating FM tree and FAD. It is asserted that the Tool is able to help the user to deconstruct the system with regard to functions and means, in which MMET can be used to explore component options once fundamental functions of means are identified. FAD can then help engineers and designers to validate the component selection in terms of functional relationships at conceptual design stage, ensure all functions can be satisfied and prevent critical issues.

From the two applications explored, the potato slicer example and the insulation robot system design case study demonstrated that the Tool is useful in generating and organising ideas as well as encouraging creative thinking in devising means to achieve non-fundamental functional requirements. It is also able to provide traceability of decisions that allows engineers and designers to go back if the final design fails or requires modification. However, the case study has revealed that this conceptual design tool requires the user to have an in-depth understanding of product technical functions in order to achieve best design outcomes.

Through the case studies introduced in this chapter benefits of employing FM tree to conduct system deconstruction were indicated, embodied on its structural representation, creative thinking encouragement and capability of organising ideas and providing alternatives. This chapter also indicated the limitation of applying the Tool in mechanism conceptual designs including knowledge requirement in system deconstruction, function identification and idea generation. In Chapter 6 another industrial case study conducted by this thesis's author adopting the Tool is introduced, providing further support with respect to the benefits of using the Tool in mechanism conceptual design.

Chapter 6 Case Study - Mechanical Discriminator Design

6.1 Chapter Introductory Statement

Development of a novel mechanical discriminator design is shown in this chapter. The conceptual design tool is applied along with the employment of brainstorming in initial ideation stage. The purpose of this chapter is to demonstrate the application of MMET and the Tool in mechanism conceptual designs in terms of system deconstruction, idea generation, component exploration, alternative finding and conceptual design improvement.

6.2 Mechanical Discriminator Project Brief

An organisation is developing a small mechanism that is able to prevent inadvertent movement of a rotor until a sequence of electrical signals is mechanically interpreted. The core concept of this mechanism is similar to mechanical switches or conventional combination safe locks but works on a smaller scale with several functional requirements and design constraints defined by the organisation. Comparing to electrical switches, mechanical switches are noted for their quality, reliability and longevity. Mechanical switches also have visible operation, high repeatability and more importantly, high resistance to ambient conditions such as power cut, moisture and vibration. These advantages have made mechanical type switch favourable for the organisation, and became the main inspiration of this discriminator design. A few conceptual designs have already been conducted by the organisation but they are looking for novel concepts in comparison to traditional discriminators that may have potential for further development. The main purpose of this project is to devise conceptual designs for the small mechanism with regard to design requirements and constraints defined. The conceptual design tool was applied in this project to help the author to explore ideas and devise designs, as well as explore the effectiveness of the Tool.

This mechanical discriminator design represents a typical and complex industrial mechanism design problem as it contains various functional requirements and design constraints that are critical to the success of the concept. This makes this case study a credible opportunity to validate the conceptual design tool and its application in solving industrial problems. The outcome of this case study will have significant impact on determining the usefulness of the Tool.

6.3 Design Specification

Design requirements and constraints were concluded from the design brief provided by the organisation. This mechanism, performs as a mechanical discriminator, is also required to be safe during it dormant life and reliable when called upon to operate.

Table 6.1 Design requirements and constraints

Input	24 sequential signal inputs: ABBA ABAB AABB BAAB BBBA AAAB
Operation time	2 seconds including the complete movement of the rotor.
Output	The discriminator must be able to rotate a rotor with inertia of 13,500 g mm^3 through an angle of 90 degrees.
Volume	20 mm x 20 mm x 20 mm (does not include prime movers and rotor)
Locking feature	If an incorrect event is received during the 24 sequential signal inputs the mechanism must lock up on that incorrect event, i.e. if an "A" signal is sent instead of the correct "B" signal or vice versa.
Other Design constraints	The rotor's initial and final position must be controlled All "A" events must have the same time duration, identical format and only allow one "A" event to occur and must prevent a simultaneous "B" event. (An event is the arrival of the electrical signal representing one step from the sequence). Same rules apply for "B" event.
	Only one mechanical step is permitted per event, even when an "A" and a "B" event are sent simultaneously.

	Only after all 24 bits have been successfully processes can the rotor be moved, i.e. there shall be no progression of the rotor during the 24 bit sequence.
	After successful rotation of the rotor the mechanism must be able to be electrically returned to its original state, using the same prime mover.
	After a lock up has occurred, the mechanism must not be able to unlock electrically, only by human intervention.

6.4 Design Process

A brainstorming session was conducted at the beginning of this case study to generate multiple concepts, followed by a focused conceptual design development process on a selected concept. Figure 6.1 shows the core conceptual design process of this project, which was built on the conceptual design tool.

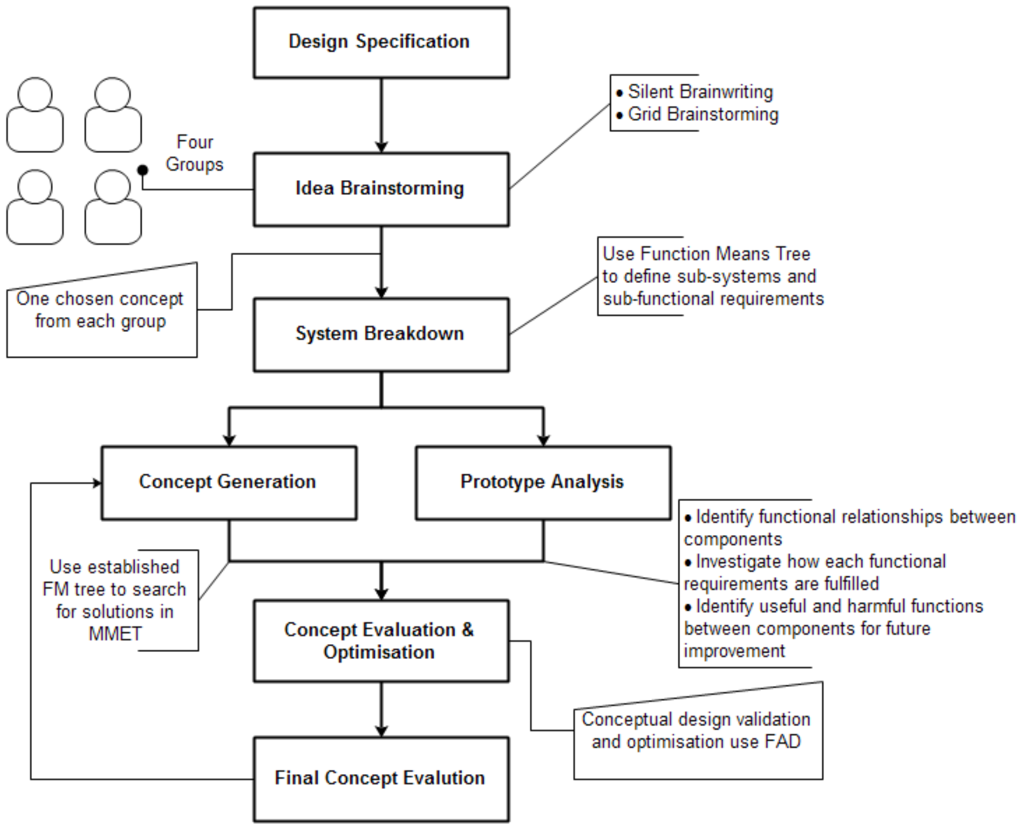


Figure 6.1 Discriminator design process overview

In order to help the author to gain in-depth understanding on mechanical discriminators a 3D printed prototype of one of company's designs was provided for demonstration and analysis. A scale model analysis conducted was able to help the author to understand the working principle of the current design including how it converts electrical signal into prime movement, interprets 24 sequential inputs and how the mechanism locks under incorrect signals and unlocked by human intervention. The analysis with regard to system functions is able to provide a framework for Function-Means breakdown, helping the author with the FM tree construction.

6.5 Brainstorming

A one day brainstorming workshop (See Figure 6.2 for the brainstorming workshop schedule) was held at Imperial College London attended by the main stakeholders, a group of PhD students and experts from different areas including physics, chemistry and design. The main aims for this activity were:

- To produce new ideas for an electro-mechanical device, capable of discriminating a sequence of binary events.
- To produce mechanisms that demonstrates a high level of novelty.
- Devise concepts which significantly vary in function and method.
- Employ mechanisms or concepts not previously considered by the company.

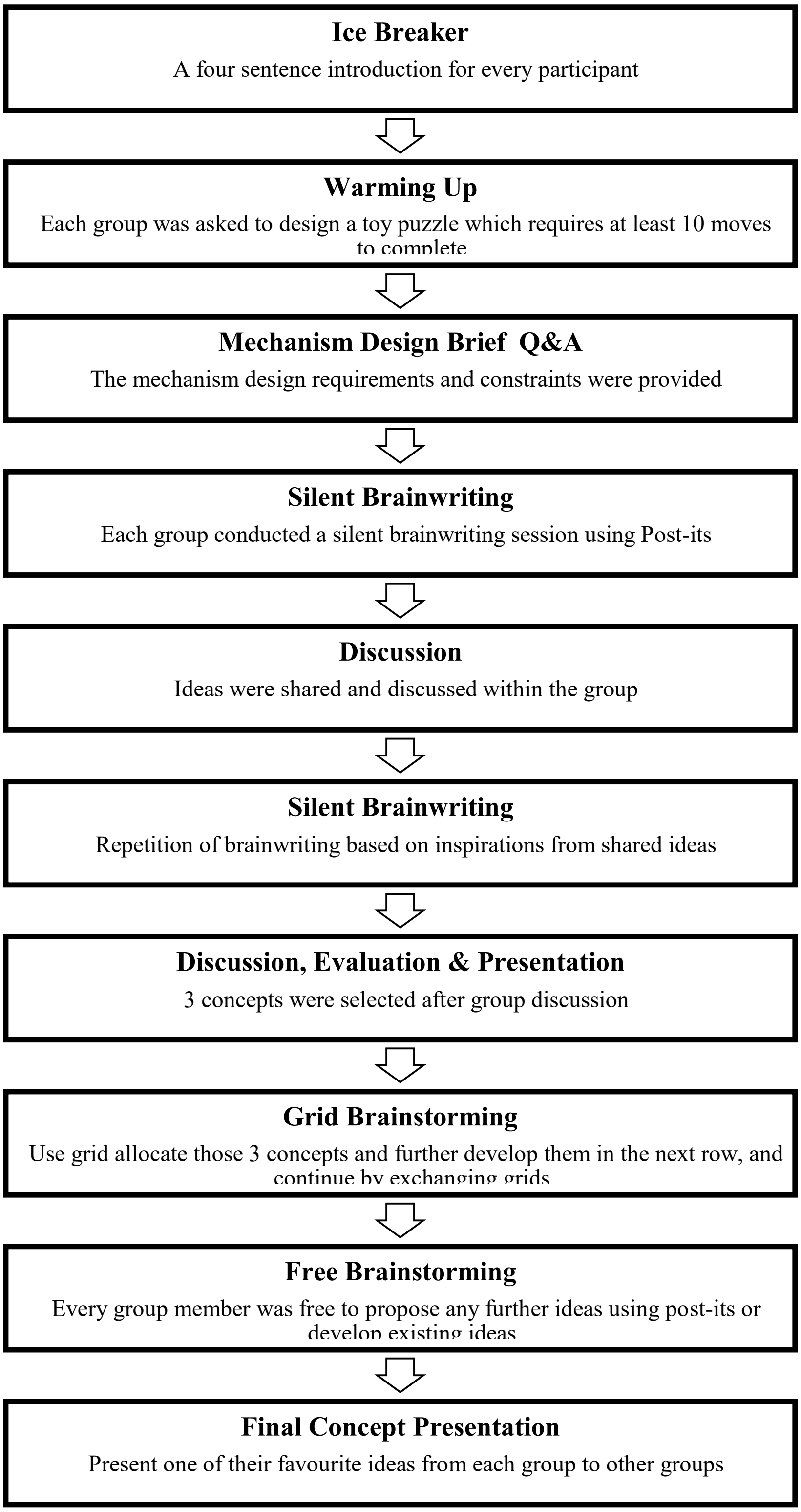


Figure 6.2 Brainstorming workshop schedule

Four groups of 5 or 6 people were formed. Attempts were made to balance skills and backgrounds among the groups. Members of the organisation, expert guests and Imperial College London were evenly spread between the groups. After the brief two ideation exercises were conducted: Brainwriting and Grid brainstorming. These were done to create a large volume of possible mechanism ideas. Each brainwriting exercise was followed by a review, undertaken to identify ideas or aspects of the concepts generated that have merit for further consideration. At the end of the brainwriting exercise three preferred concepts were selected by each group to conduct grid brainstorming. In grid brainstorming, three chosen concepts were drawn in the first row of 3 by 3 grids by each group member. These grids were then exchanged between group members and further developed in the next row. Then they were exchanged again to complete all the grids. Grid brainstorming offers a diverse range of concepts developed based on each group member's understanding on the chosen concepts. Table 6.2 shows a summary of ideas generated in the brainstorming session of each group.

Table 6.2 Brainstorming session summary for each group

Group	Post-its summary	Idea Highlights	Three ideas adopted in Grid Brainstorming
Group 1	58 Post-it ideas, around half of them used gears and maze designs	• Coded shaft with maze designed around it, having a pin passing through • Teethed wheel with escape mechanism • Having signal A and B rotate clockwise and anti-clockwise respectively • A planer maze design • A novel idea of using liquids • An idea of using light, mirrors and sensors, control the angle of light passing through	• Light, mirror and sensor design • Two valves used to control the flow of liquid • Teethed wheel and escape mechanism
Group 2	79 Post-its covered a diverse range of ideas includes using magnet, sound, biology, chemistry and liquid	• A group of ideas were developed using magnet and electromagnet to control pin positions • Designs using light were also proposed by this group • Coded shaft or wheel designs with escape mechanism • Some novel ideas were proposed containing: Adopting osmosis concept, use chemical reactions to trigger the rotation, 3D maze, sound transmission and Rubik cubes	• Light and disk design • Magnet control • Planer maze

Group 3	59 Post-it ideas, with majority of them focusing on maze and lock design	• Simple design with a pin passes through 24 layers of plates • A magnetised lock, spins when correct, lock when wrong • Having a ball drop through pairs of plates with the correct code input, otherwise ball get stuck in one layer • A traditional combinational lock, with 3 or 4 layers of rotating plates • A novel idea of pulling a tube out from 3 layers with 8 steps each layer, considered to be a unlock process rather than locking • Novel idea of using air pressure and airflow	• Linear movement of a rod through coded tubes/maze • Planar movement of an object moving through a gate with correct input codes • Ball dropping through different pairs of plates
Group 4	61 Post-it ideas, around half of them are related to gears and locks	• Tube maze design or planer maze design • A rotating key block passing through layers of blocks with correct signals • A jigsaw design, 24 signals control 24 pieces, with the correct order, engage with rotor • Two face gears, perfect mesh together with correct codes • A cylinder approach, a signal is given when two cylinders are aligned by a common ball, then the ball moves to the next layer	• Rotating block design • Cylinder and common ball design • Jigsaw design

Initially reviews were conducted internally to prevent 'idea contamination' between groups. This increases the likelihood that final device concepts, between groups, are significantly varied in function/method. To end the workshop each group was tasked with identifying their favourite idea generated by their group during the previous brainwriting and grid brainstorming exercises and presents the concept to everyone. In the brainstorming workshop over 250 ideas were produced, around half of them were designed with maze, gears and locks. However some novel approaches were also proposed such as using liquid, light and chemistry. Some of the ideas devised from the brainstorming workshop are illustrated in Figure 6.3 and Figure 6.4.

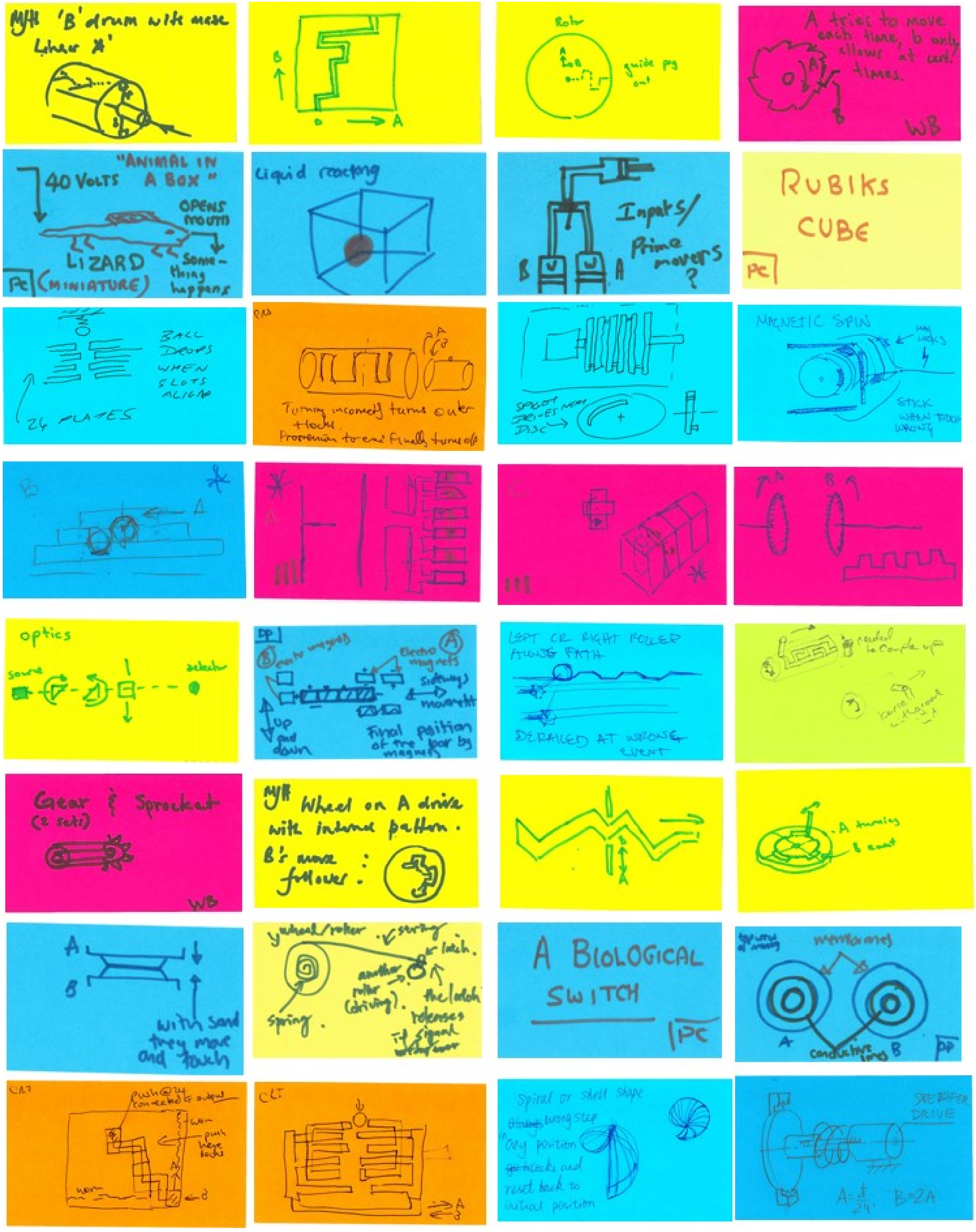


Figure 6.3 Brainstorming Post-its

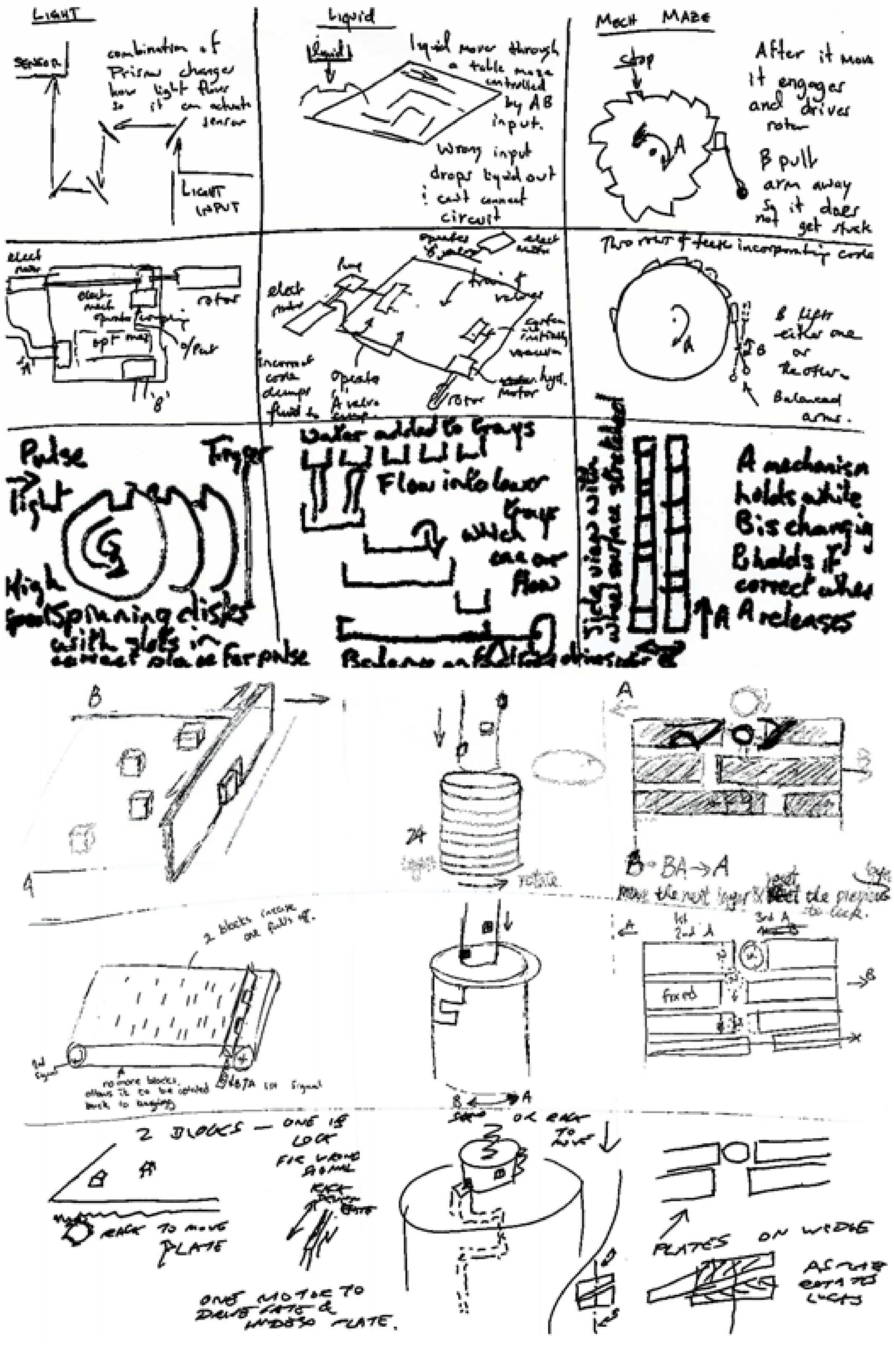
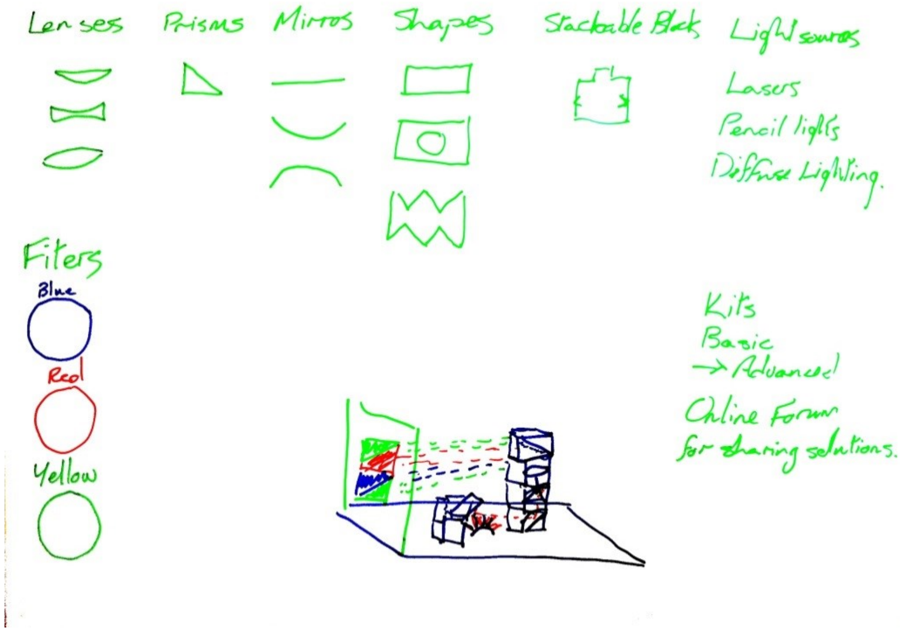


Figure 6.4 Grid brainstorming

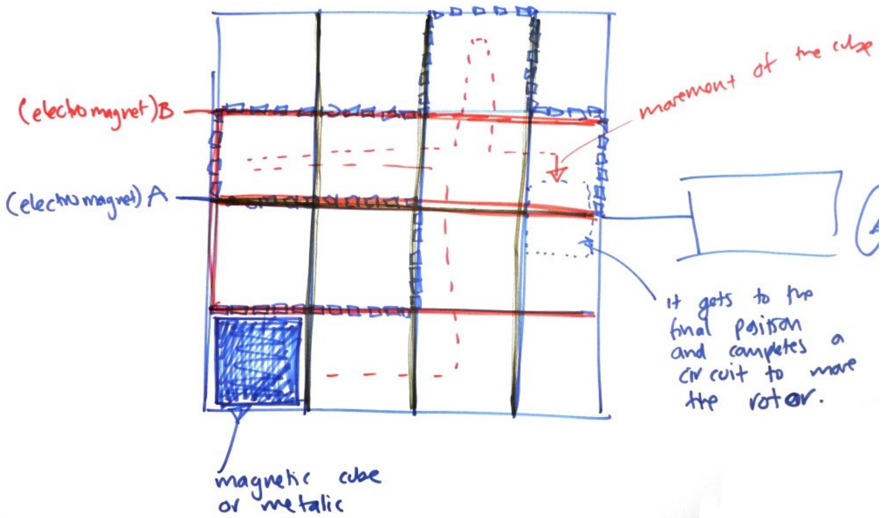
The workshop ended with four 'final' concepts with the potential for further development, shown in Table 6.3.

Table 6.3 Final chosen concepts from four groups

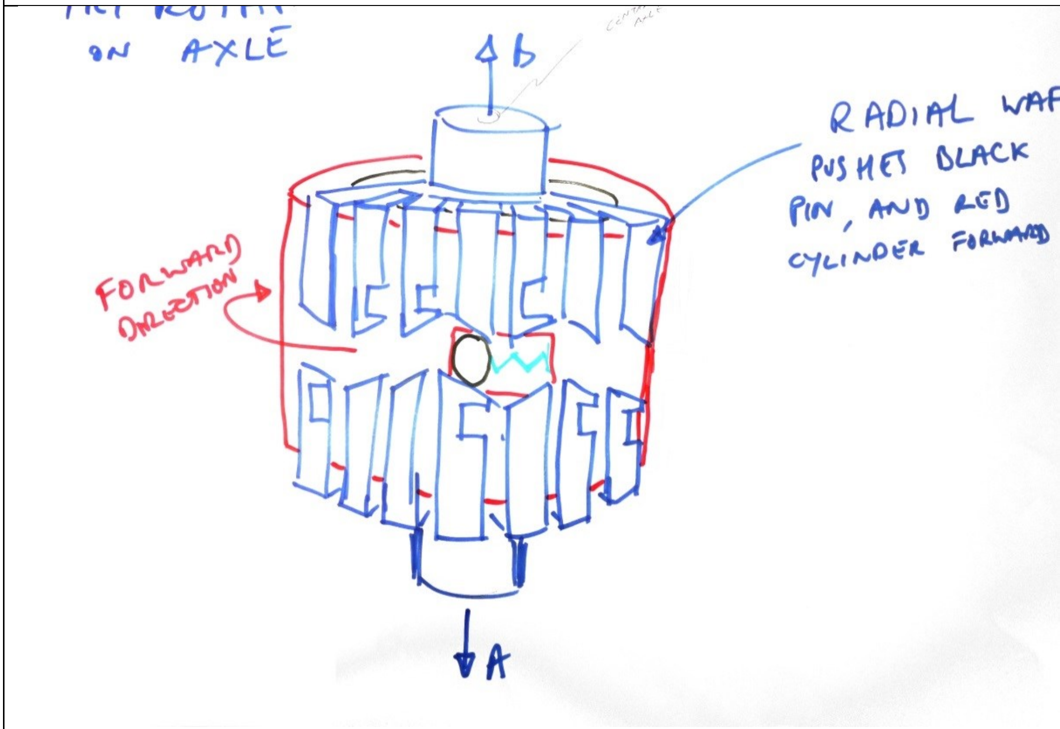
Group 1 - An optical mechanism which employed manipulated light beams to decode a signal



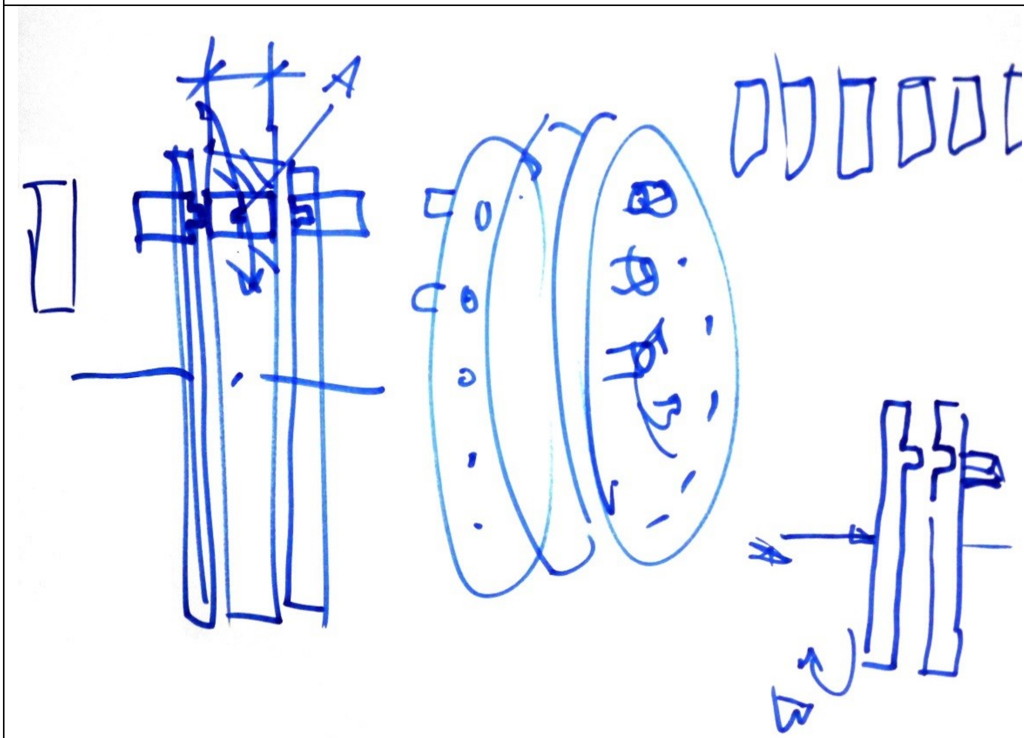
Group 2 - A simple maze which uses electro-magnetic fields to control the movement of a pin along a coded path



Group 3 - A cylindrical maze employing a series of interwoven cylindrical parts to read the code



Group 4 - A circular disc combination lock type mechanism



It can be seen that all four concepts vary significantly in discriminating methodology. In the workshop the design of signal interpretation and locking mechanism were mainly concentrated on by most of the group members since they are the most important features. Actuators that drive the discriminator and its eventual engagement mechanism were decided to be excluded until the configuration of interpretation concepts. The cylindrical maze design was preferred above the other design concepts from the workshop and decided to be further developed with regard to three perspectives:

- It was identified as the most complete concept.
- It showed potential to meet the brief requirements.
- Although not a completely novel discriminator mechanism (similar discriminator function to existing company designs) the cylindrical concept has shown the potential on dramatically reducing the volume, number of springs and actuators from current products.

6.6 **Cylindrical Maze Conceptual Design Development**

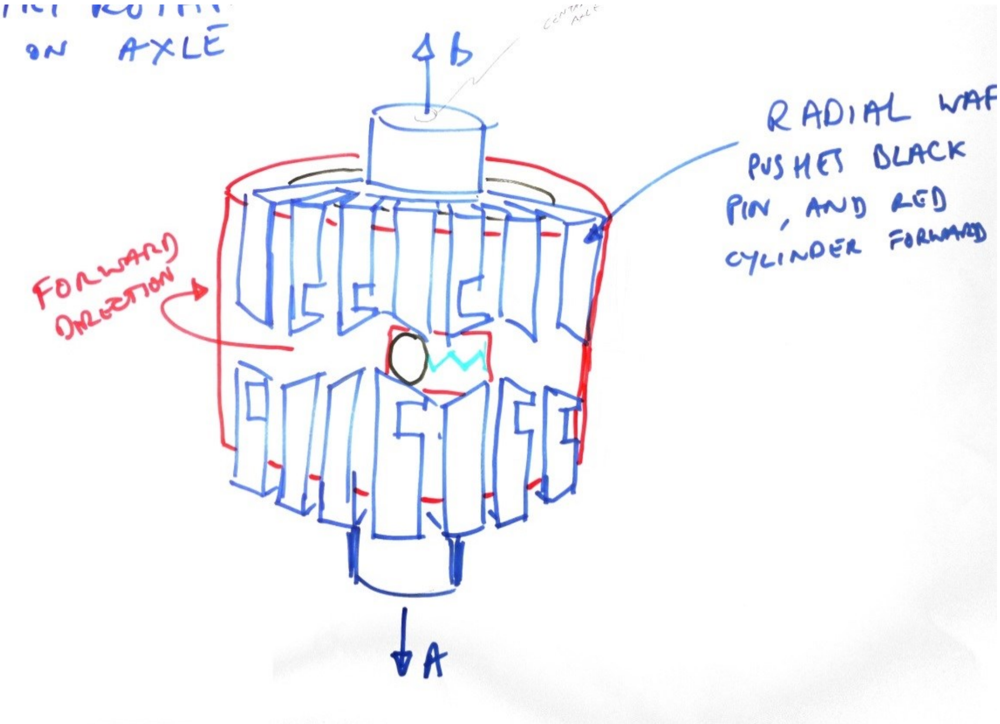


Figure 6.5 Cylindrical maze initial concept from the brainstorming workshop

In order to help the author to illustrate and understand the working principle of this concept in more detail it was modelled in 3D using Solidworks, shown in Figure 6.6.

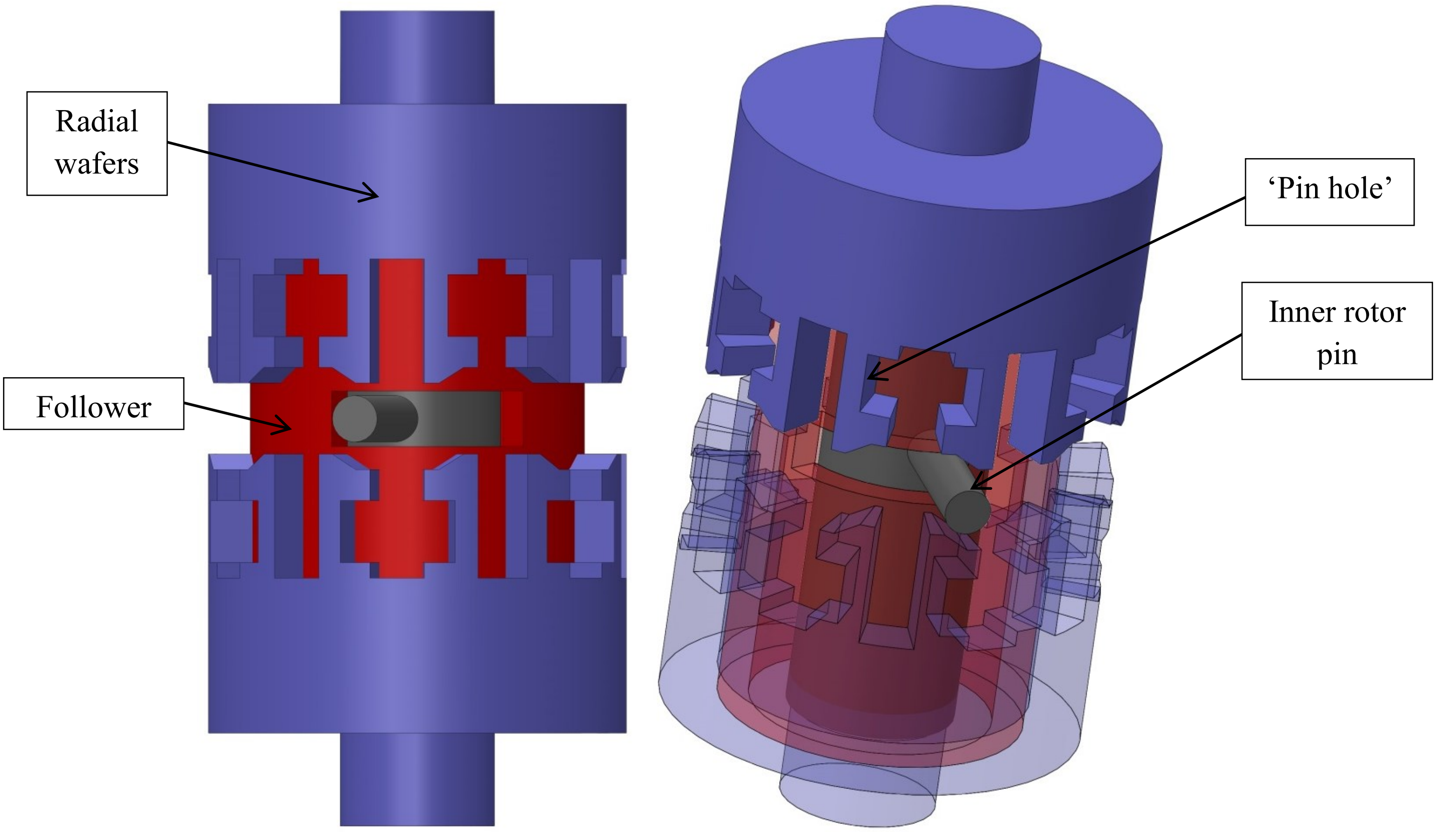


Figure 6.6 3D model of the initial cylindrical maze concept

This concept is comprised of three layers. The layer indicated in grey is an inner rotor pin which reads the code. It is sprung loaded and restricted to rotational motion around its central, longitudinal axis. The layer indicated in red acts as a follower which rotates around the central axis in one direction only, designed for rotor engagement. The outer layer indicated in blue provides rotation motion to other layers. Radial wafers (Blue layer) are restricted to linear motion along its longitudinal axis, and no rotational movement is allowed. In this concept, a correct signal input should be able to push the pin and follower in a clockwise direction while a wrong signal would only be able to push the pin in an anti-clockwise direction, allowing the pin to be captured by the 'pin hole' designed in the radial wafer and lock the entire device. A FAD was constructed to validate the feasibility of this design concept, as Figure 6.7 shows. From the FAD shown in Figure 6.7 it can be seen that this design is incapable of performing continuous signal interpretation because the pin is always one half step behind the desired position. Therefore, this concept fails with regard to interpreting sequential signals.

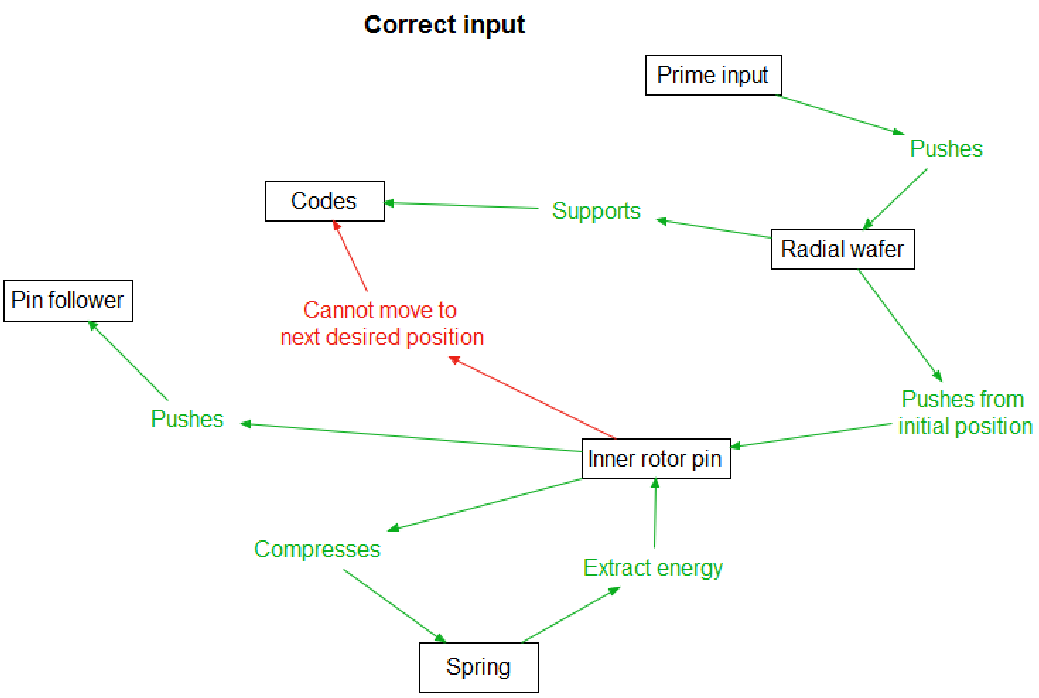


Figure 6.7 Initial concept FAD for correct signal input

From the FAD of the initial cylindrical maze concept it is can be seen that from the functional perspective the concept is only capable of satisfying functions 'interpret 24 sequential inputs' and 'lock the mechanism when wrong signal is inputted', but the design failed to do so due to a fatal design flaw (shown in Figure 6.7). Despite the failure in interpreting sequential signals, the cylindrical concept still shows great potential in terms of reducing the volume, numbers of the springs and actuators of the mechanism. Inspired by the firing and retracting mechanism of click point pens (shown in Figure 6.8), an improved design was carried out, shown in Figure 6.9.

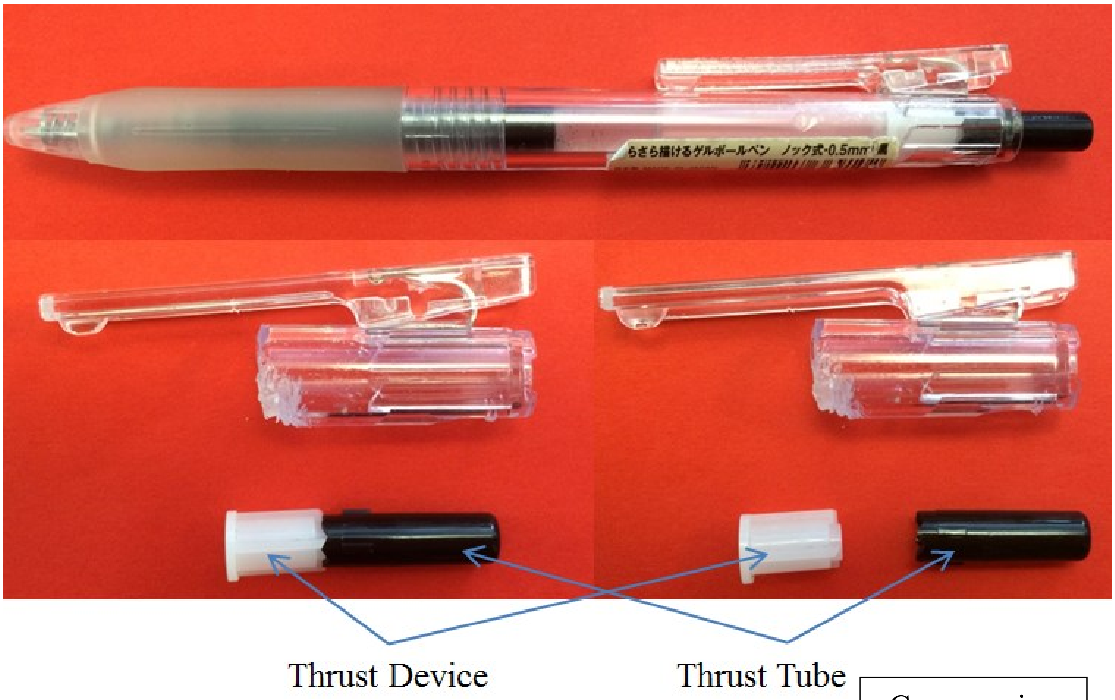


Figure 6.8 Retracting click point pen

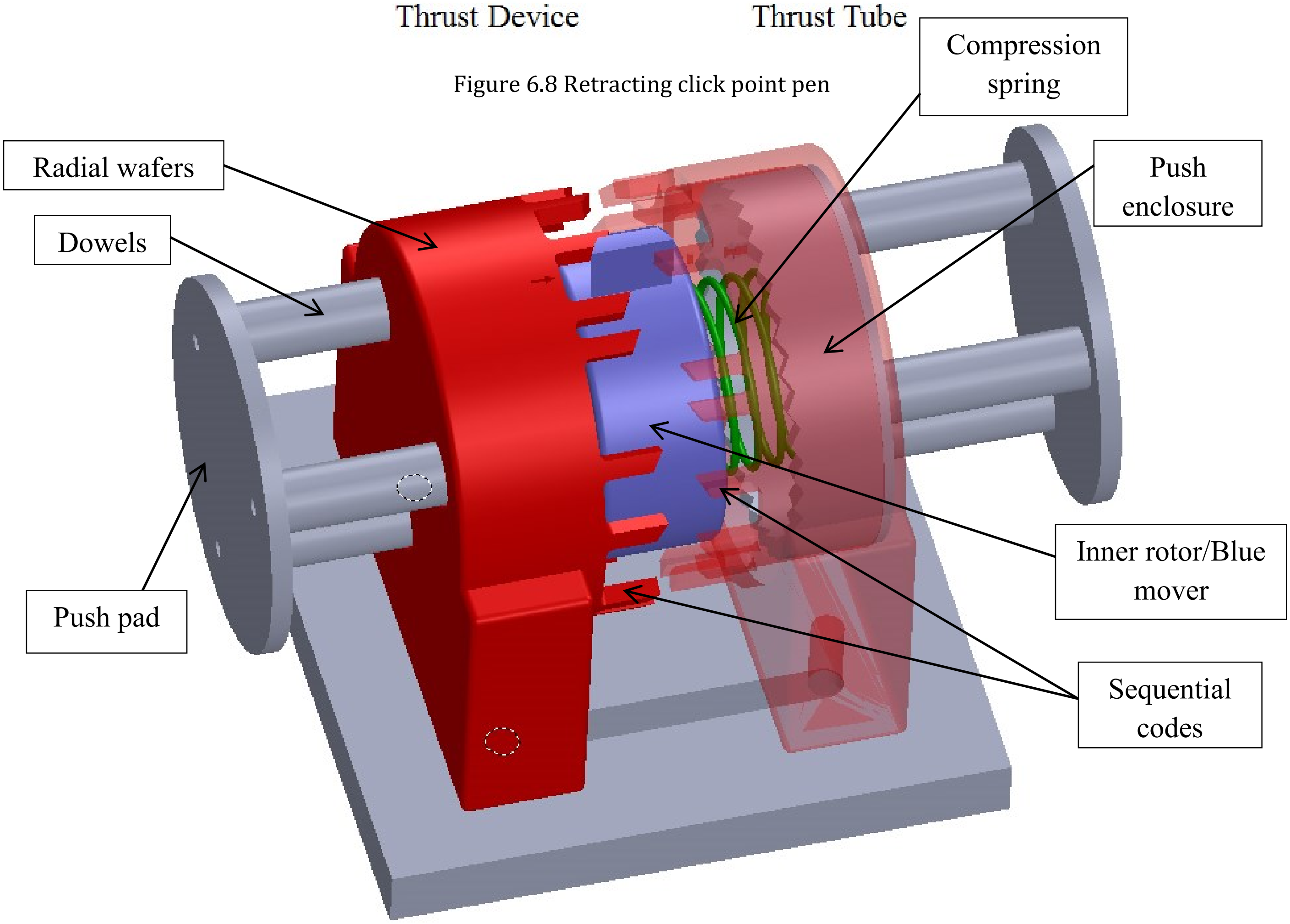
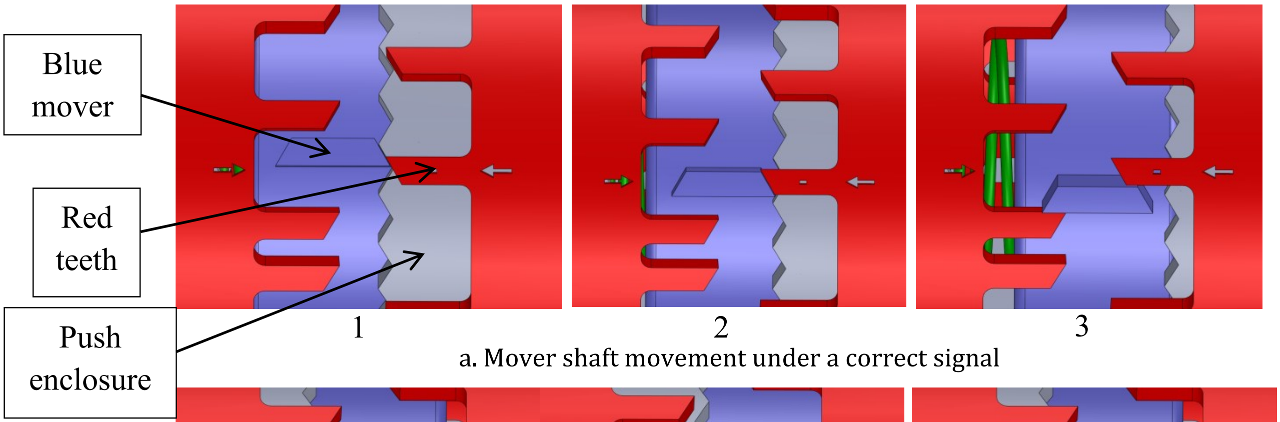
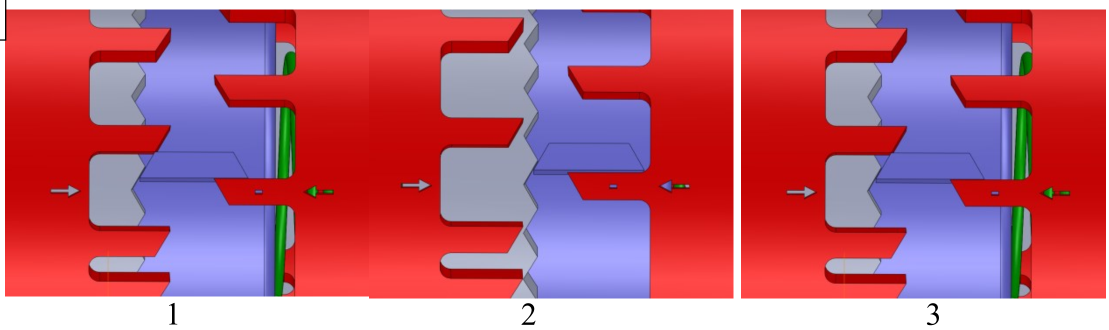


Figure 6.9 Improved signal interpreting system design

Two compression springs are attached to the blue mover shaft. Inside the red radial wafers two grey push enclosures are connected to push pads via dowels. From the enlarged top view of the design it can be seen that when the right hand side grey part is pushed via push pad, it makes contact with the blue mover, engages with one of the teeth and pushes it forward while the spring on the opposite side being compressed at the same time. The blue mover keeps being pushed away from its neutral position, engages with the red radial wafer and slides onto the red tooth, where a rotational force is applied. When the grey push enclosure is released, the blue mover keeps sliding along the red tooth surface driven by the spring force, advances to the neutral position of next step. If an incorrect signal is inputted, the left push pad being pushed in this case, the mover will keep moving rightwards but without any tooth to engage. When the push pad is released, the mover will return to its original position, resulting in no signal advancement. Figure 6.10 demonstrates the mechanism status under a correct signal and an incorrect signal.



a. Mover shaft movement under a correct signal



b. Mover shaft movement under an incorrect signal

Figure 6.10 Discriminator mover shaft position under correct and incorrect signals

There are 24 sequential signals before the engagement of the rotor and it needs to be rotated 90 degrees. In this 360 degree cylindrical maze the 24 signal inputs were designed to occupy three quarters of the circumference while the last quarter, 90 degrees, was designed for the rotor rotation. Therefore a total number of 32 signals inputs are required to complete a whole event after which the rotor returns to its initial position (indicated by the arrows on the radial wafer). In order to evaluate the feasibility of this 'click pen' design it was 3D printed, assembled and tested. The result looks promising in terms of interpreting sequential codes. The 3D printed prototype is shown in Figure 6.11. As identified in the brainstorming workshop, this concept shows a great potential to become a complete solution with appropriate improvements and modification. Therefore, in order to consider the interpretation design and other system requirements from a systematic approach, a FM tree was constructed to assist the author to deconstruct the system and devise solutions, shown in Figure 6.12. Four purpose functions of the mechanism were defined according to the design brief, followed by three sub-systems satisfying these requirements. Each sub-system carries more detailed, lower level functions that require means to achieve. The 3D printed model provided by the company was analysed in order to help the author to have an in-depth understanding on the prototype design containing the functions it is able to deliver and how. Figure 6.13 demonstrates the prototype and its component indications.

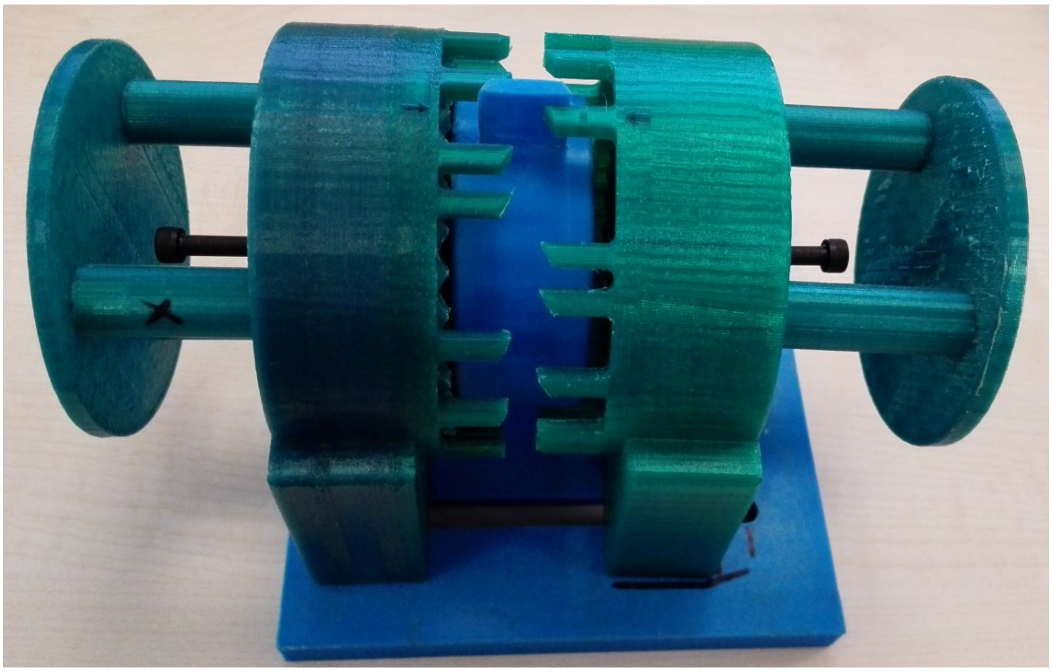


Figure 6.11 3D prototype of 'click pen' design

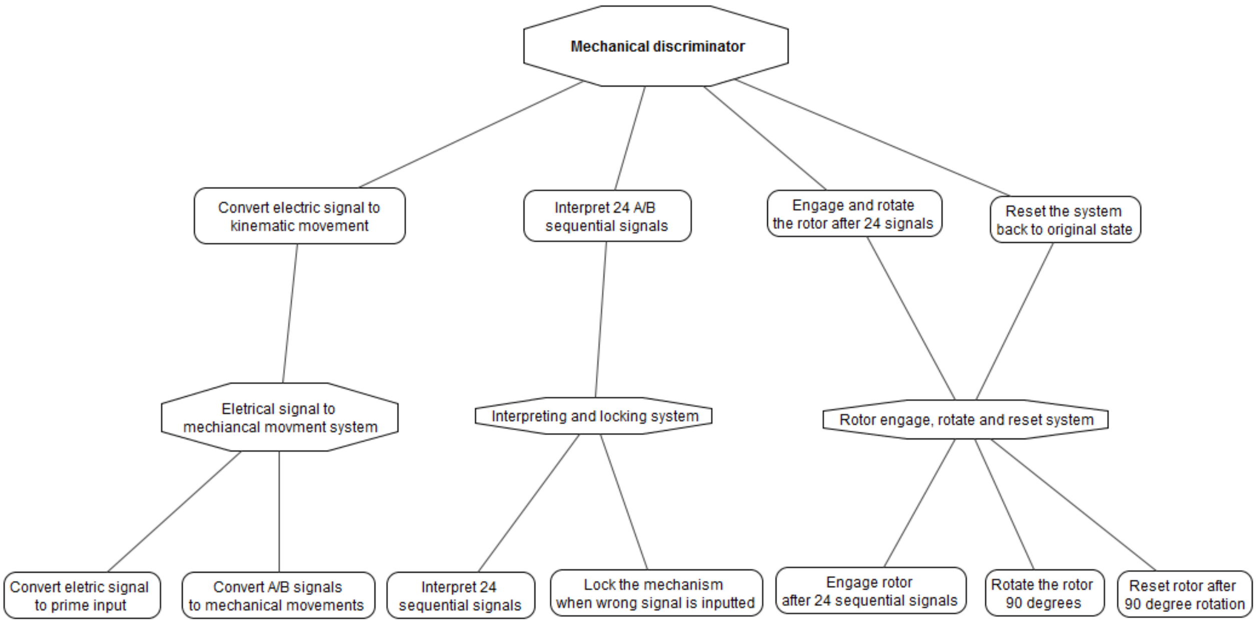
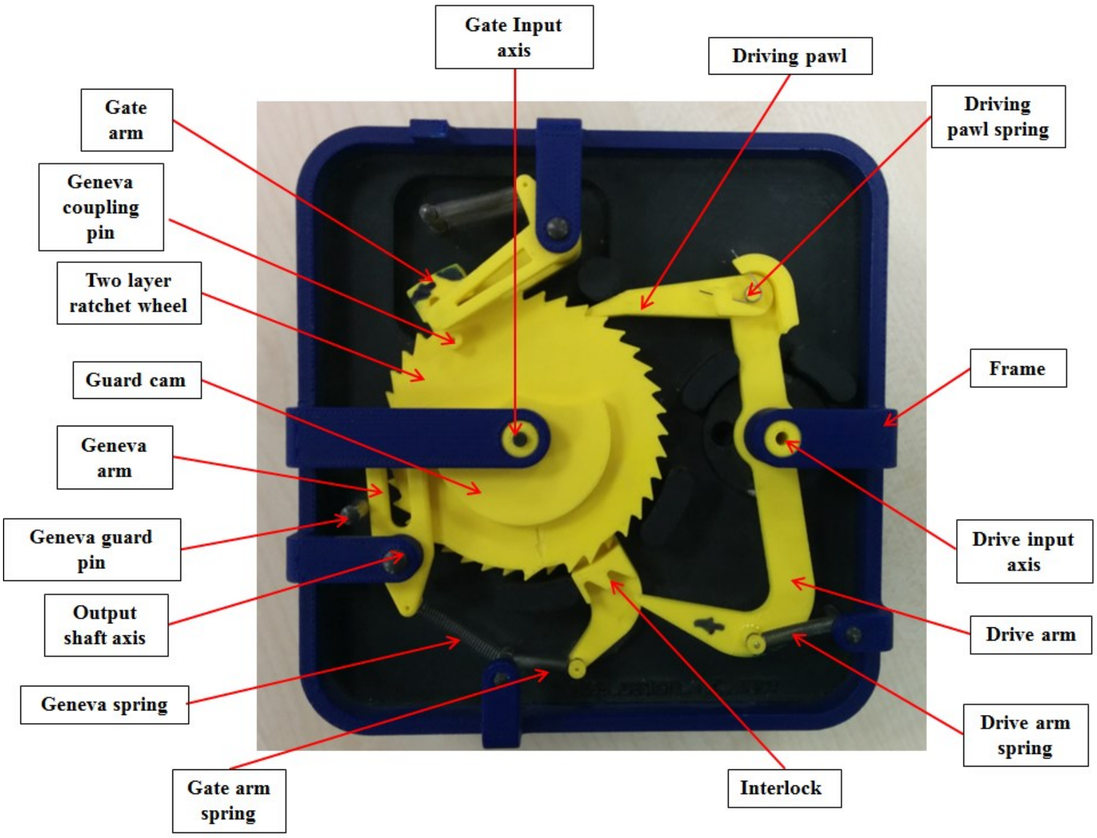
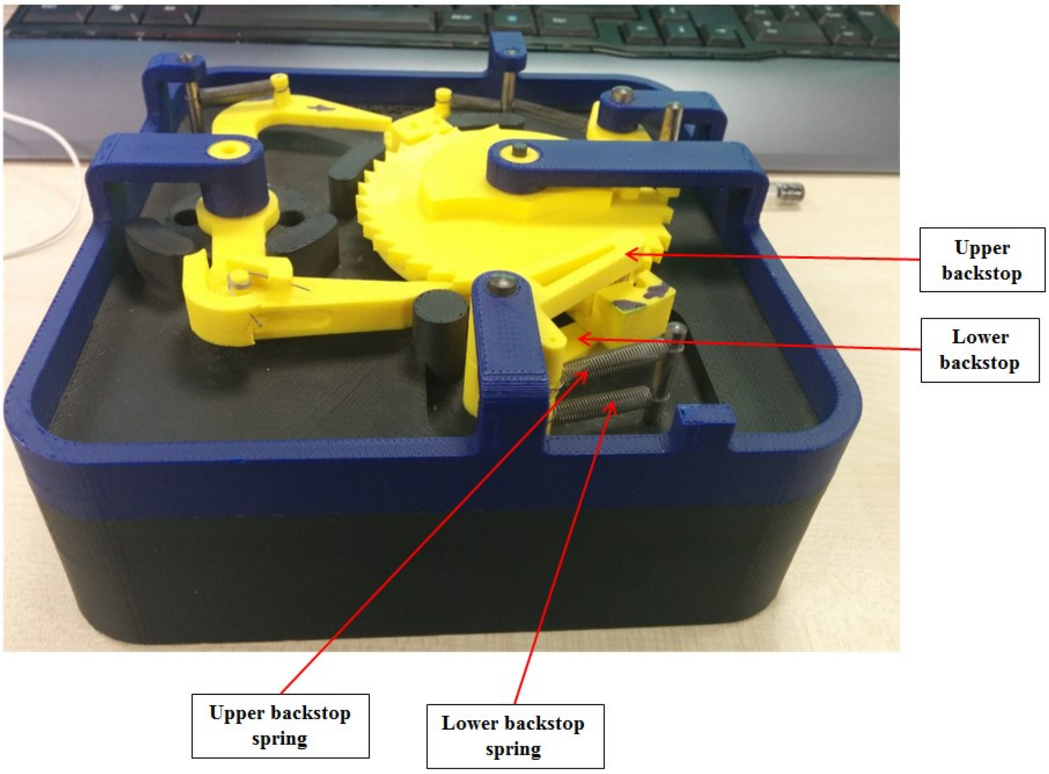


Figure 6.12 Mechanical discriminator Function Means tree





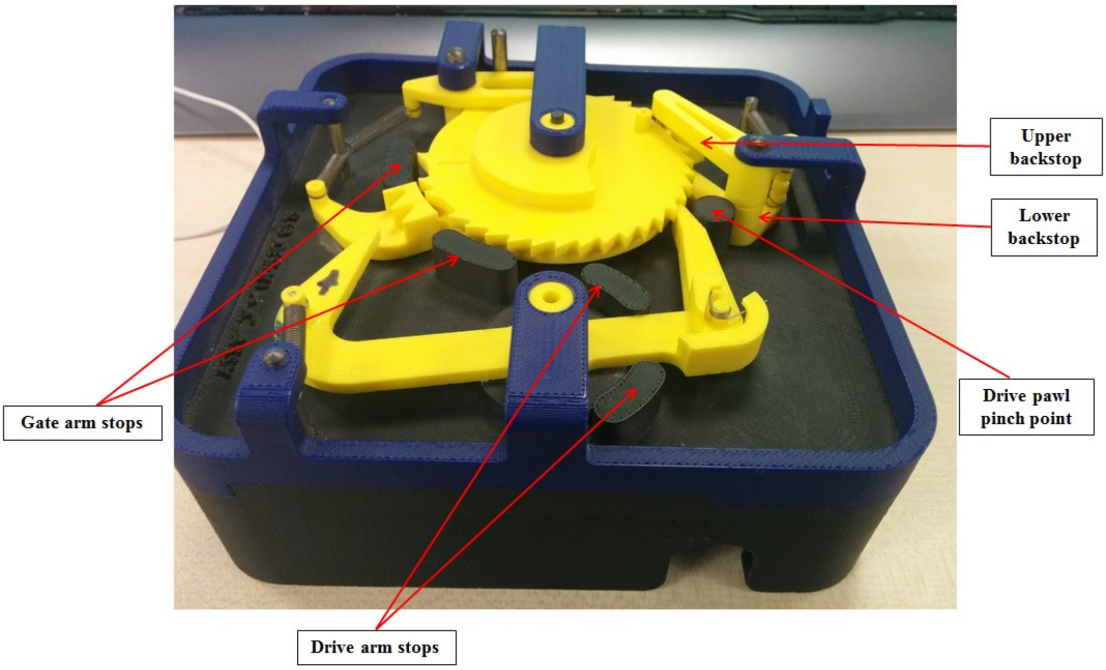


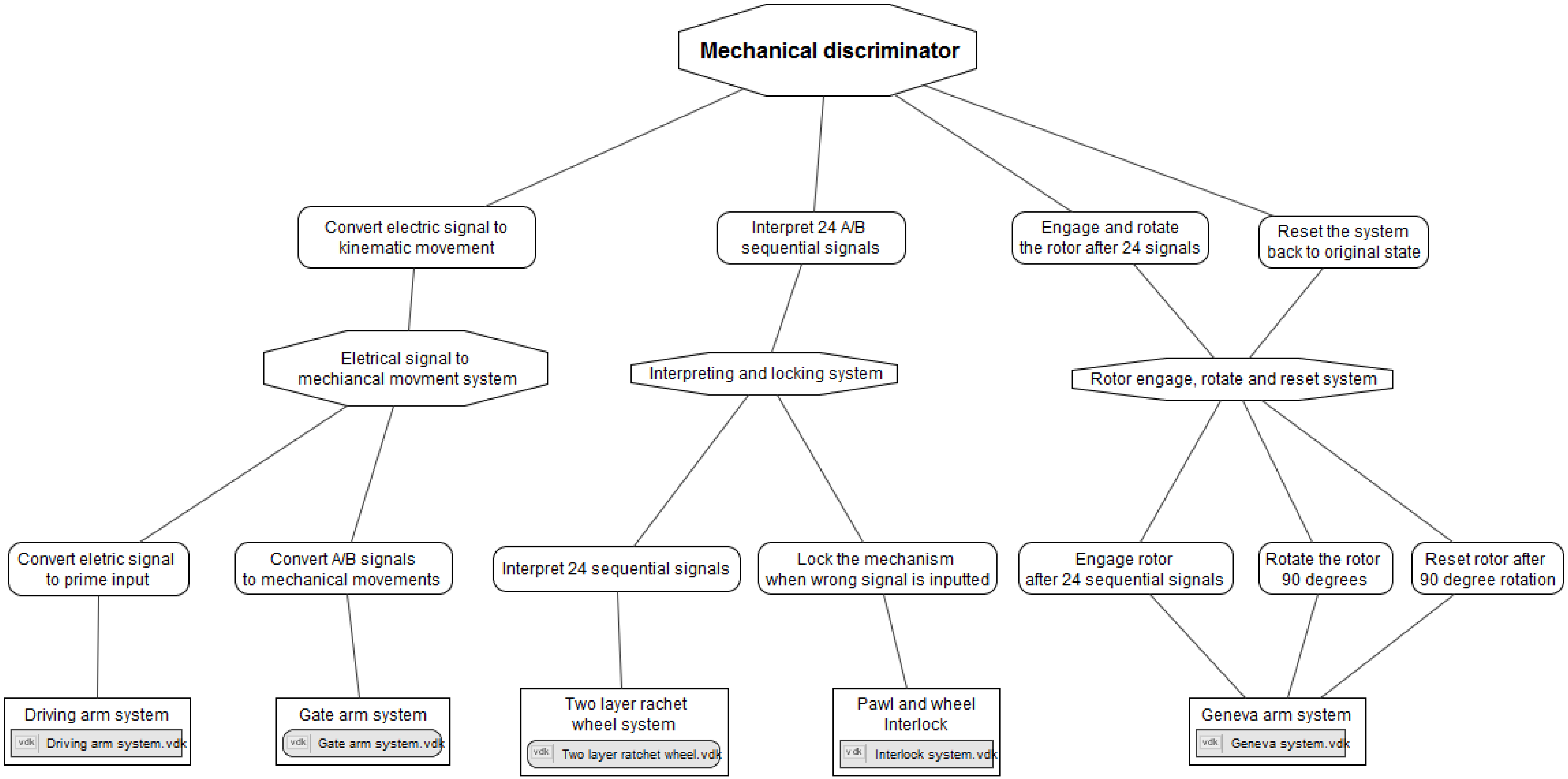
Figure 6.13 Prototype pictures and component indication

The model design features were analysed and established in the mechanical discriminator FM tree, shown in Figure 6.14a. FADs were then conducted to validate their design and to analyse the functional relationships with regard to different mechanism statuses since in this discriminator design components carry different functions under different circumstances. Therefore it is clearer to construct FADs regarding different system statuses. This approach applies to complex systems that have various statuses. In this case five statuses were defined:

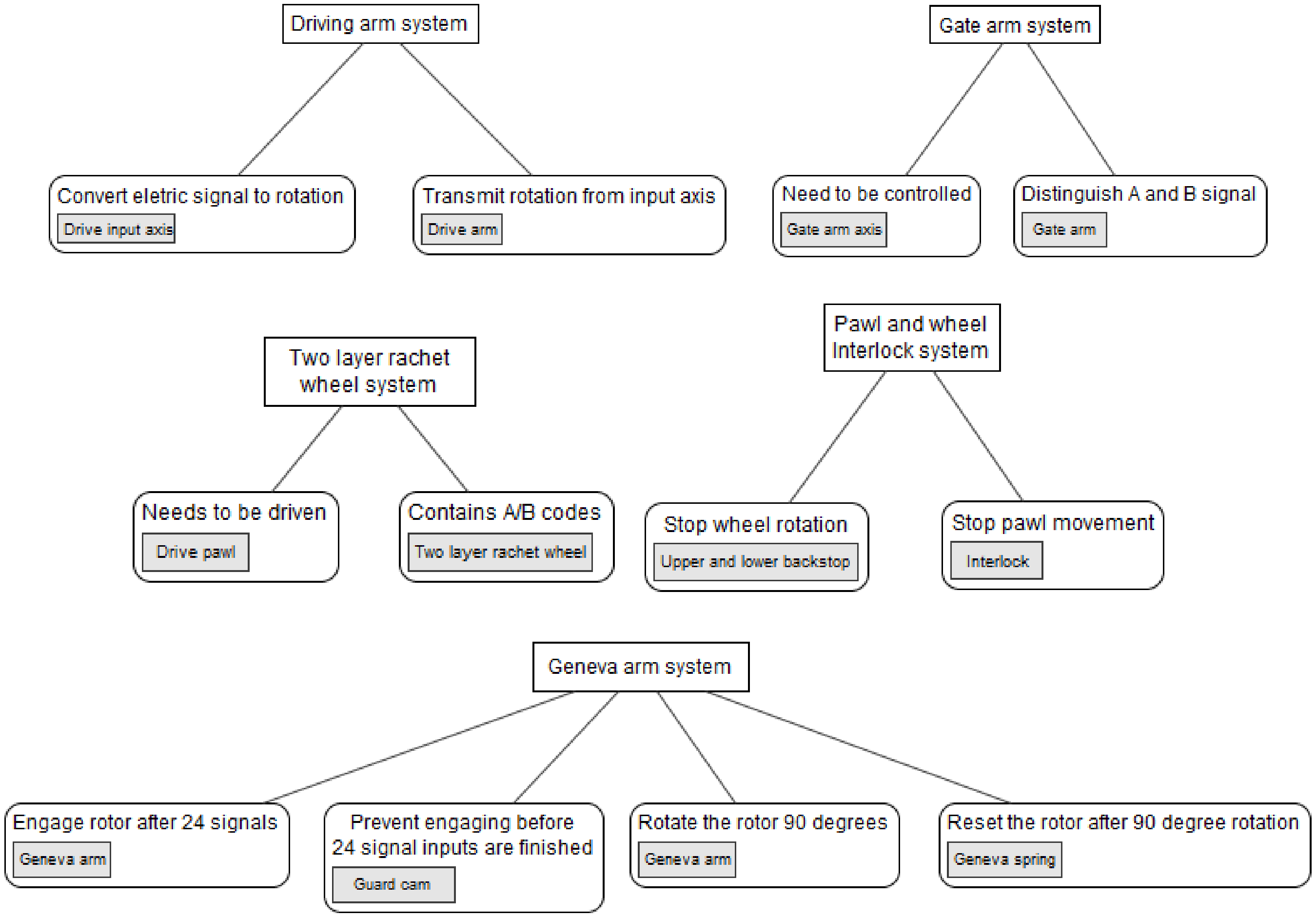
- Correct input in 24 sequential signals
- Incorrect input in 24 sequential signals, i.e. the locking of the device
- The unlocking of the mechanism
- Rotor engagement and 90 degree rotation
- Reset to original state

Figure 6.15 to Figure 6.19 demonstrate the FADs with regard to these five statuses. Key functions are indicated by black bold arrows while red and green dashed arrows indicating useful and harmful functions respectively. With harmful functions identified in FAD critical points in designs could be addressed, providing opportunities for further optimisation and improvement. From the figures the necessity to conduct FADs for different statuses can be seen since some of the components carry different functions under different conditions. For example, the drive arm transmits the movement under correct signal input but stops the movement of the drive pawl when the system is locked. Some of the components they only carry functions under certain situations, for example, the pin only engages with the rotor when 24 sequential signals are interpreted successfully, and other examples include the Geneva arm spring and the output shaft.

From the functional analysis with regard to different statuses of the mechanism the author was able to fully understand the design and working principle for this complex discriminator prototype. With the aid of component images FADs became easier to understand. From the organisation's perspective these FADs are able to help them to understand each component's functions under different statuses, for example, to see which component carries the most functions and what potential damage may occur to system components. Depending on these analyses they are able to perform developments on the design to improve its functionality and reliability.



a. Primary FM tree for the mechanical discriminator prototype



b. FM tree for lower level sub-systems

Figure 6.14 Function Means tree of the discriminator prototype

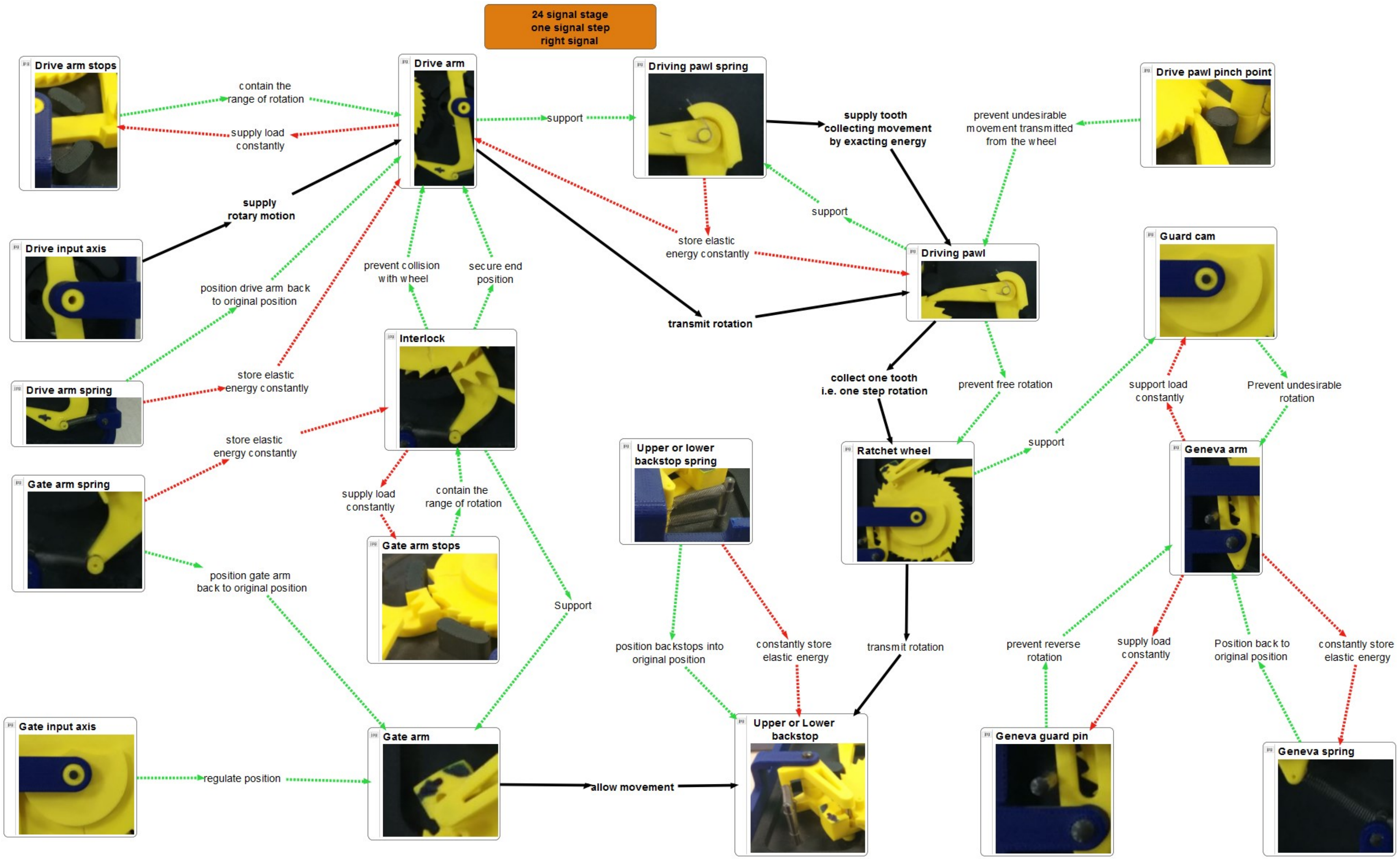


Figure 6.15 FAD of the prototype under one correct signal input

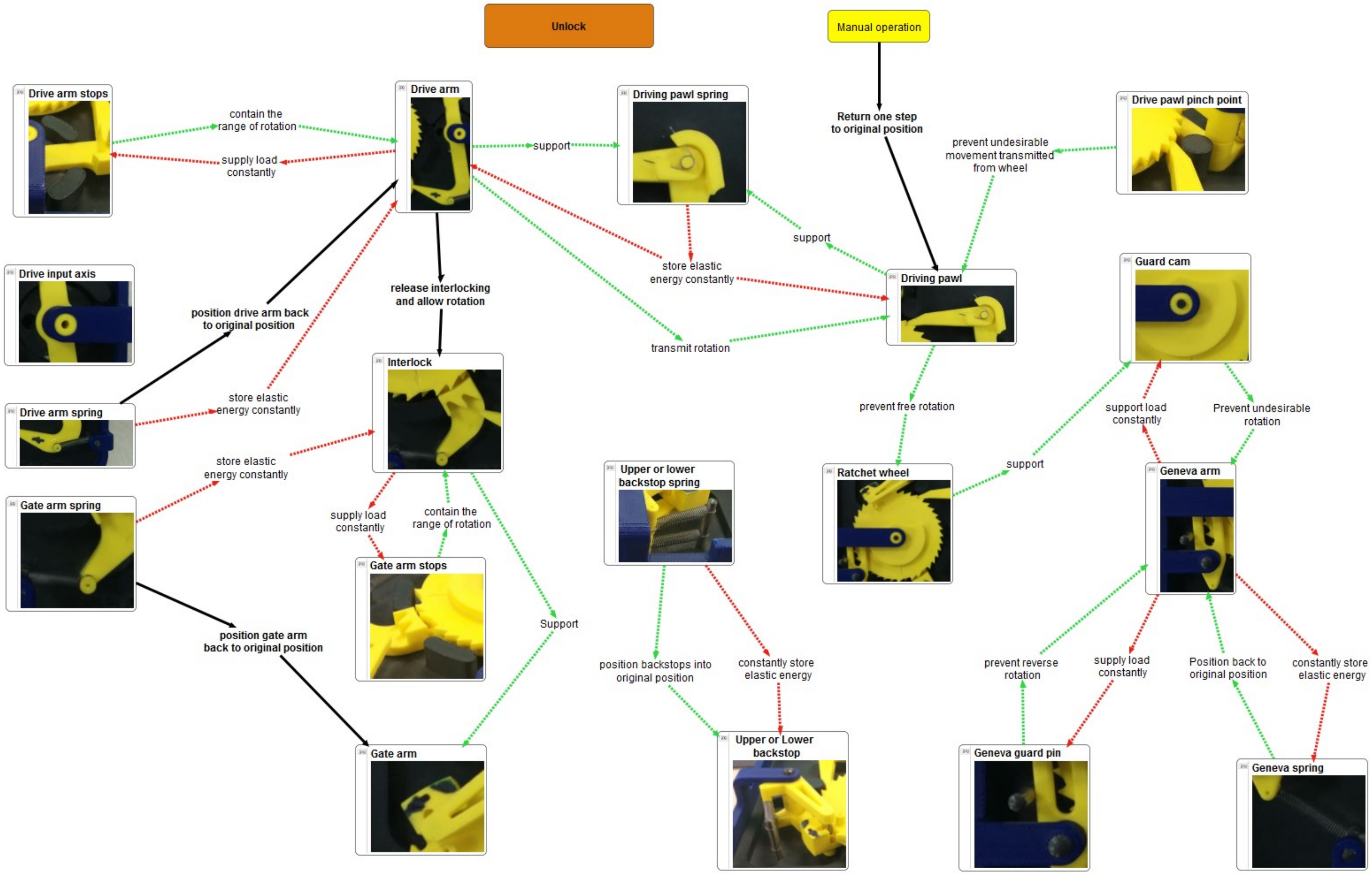


Figure 6.16 FAD of the prototype under one incorrect signal input

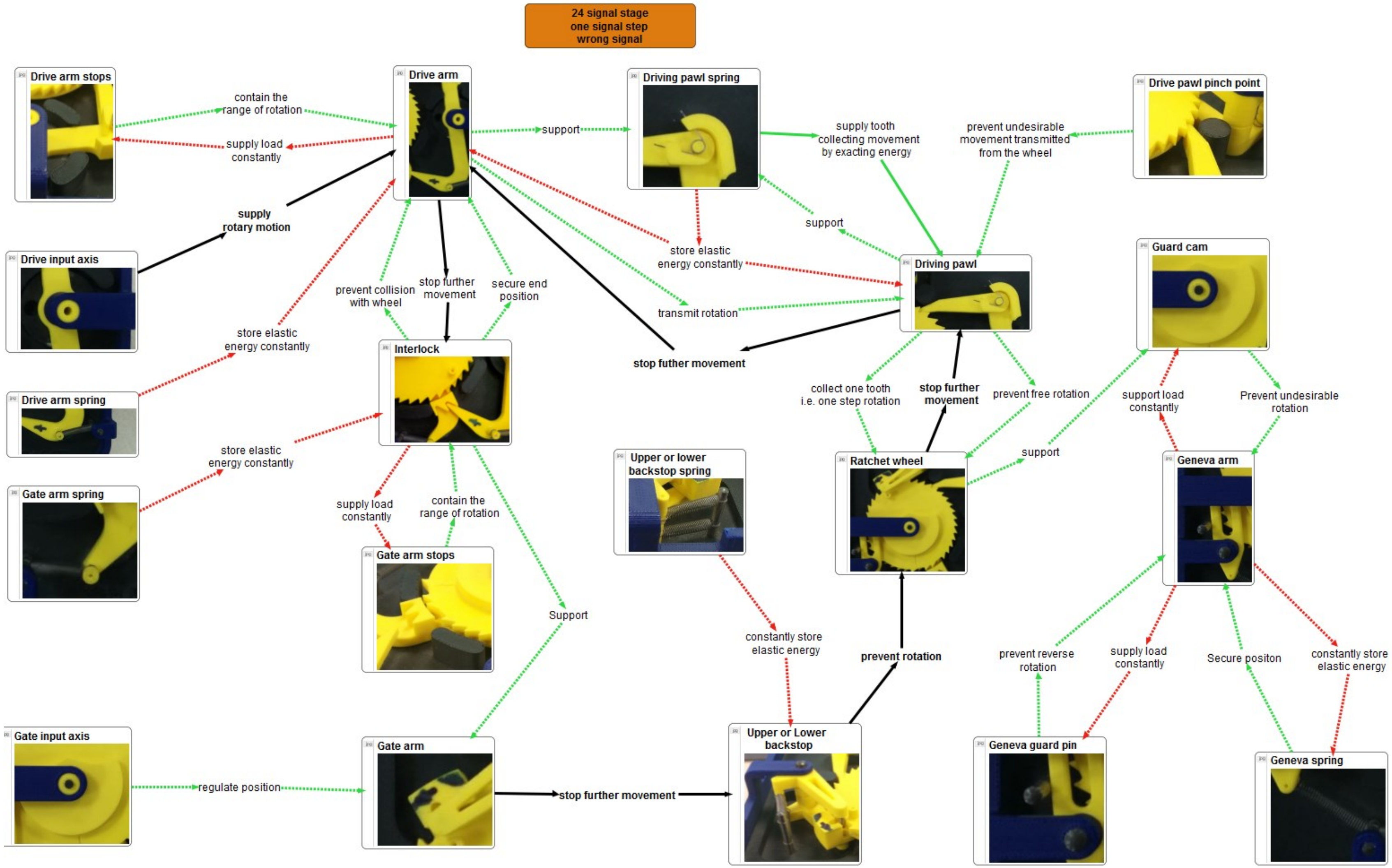


Figure 6.17 FAD of the prototype when unlocking

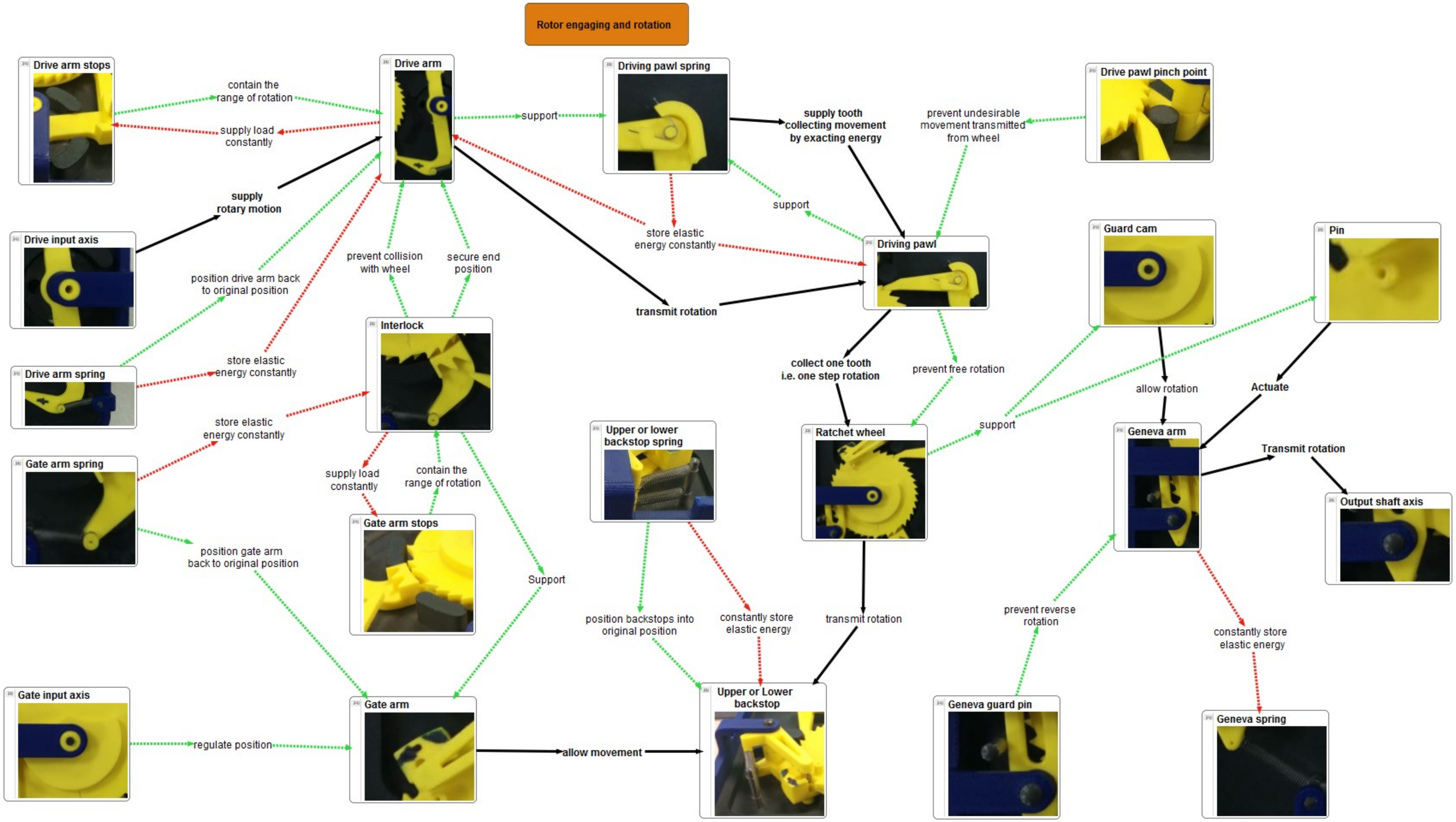


Figure 6.18 FAD of the prototype when engaging and rotating the rotor

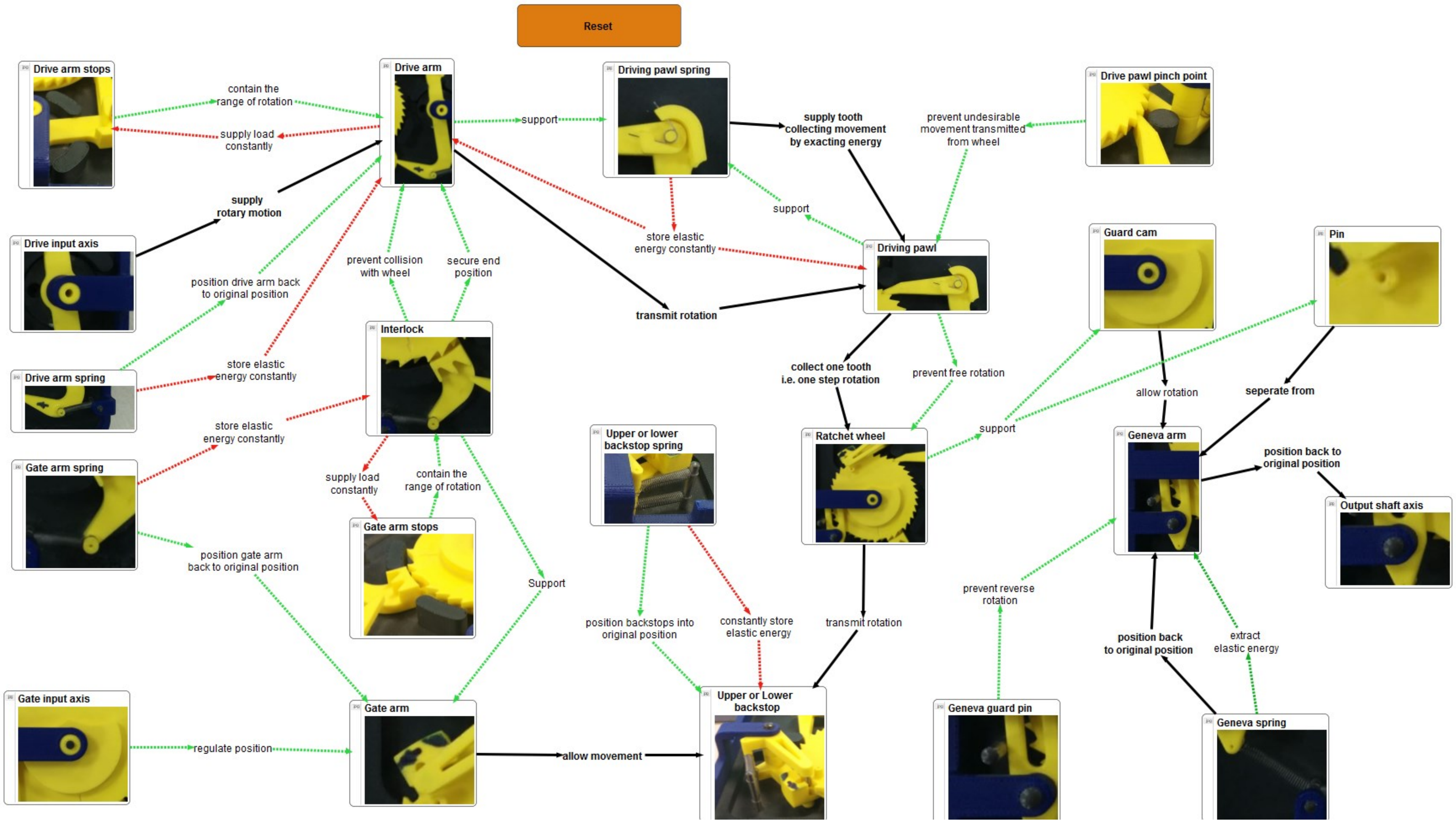


Figure 6.19 FAD of the prototype under reset stage

In accordance with the FM tree constructed and scale model analysis the author was able to continue to develop the cylindrical maze design regarding all functional requirements identified in system FM tree. From the improved signal interpretation design it can be seen that the actuation method enables the A/B signals to be inputted by the linear movement of each push pad to fulfil the function 'convert A/B signals to mechanical movements' identified in the system FM tree. In order to 'convert the electric signal to prime input', the mechanism needs to be able to *'convert electricity into linear motion'*. MMET suggested a few types of actuators including solenoid, electromagnet and disk actuators. After that linear motion needs to be transmitted to the push pads to drive the dowels. Function *'Transmit linear motion'* was used to search for components in the database. Options such as reverse-motion linkage, parallel-motion linkage and push-pull linkages were recommended by MMET. The Function-Means tree for this linear driving system is shown in Figure 6.20.

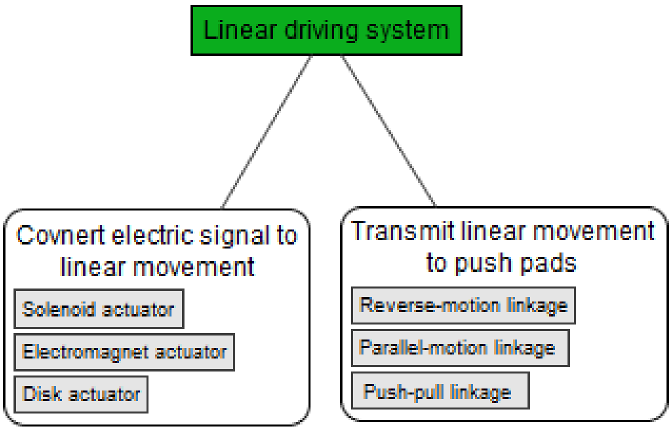


Figure 6.20 Function Means tree for cylindrical maze linear driving system

The merit analyses provided by MMET regarding these three actuators are shown in Figure 6.21. A solenoid actuator was chosen because in this discriminator design, the rotation of the rotor only requires a small amount of force and the two positions of the actuator can be used as A and B events.

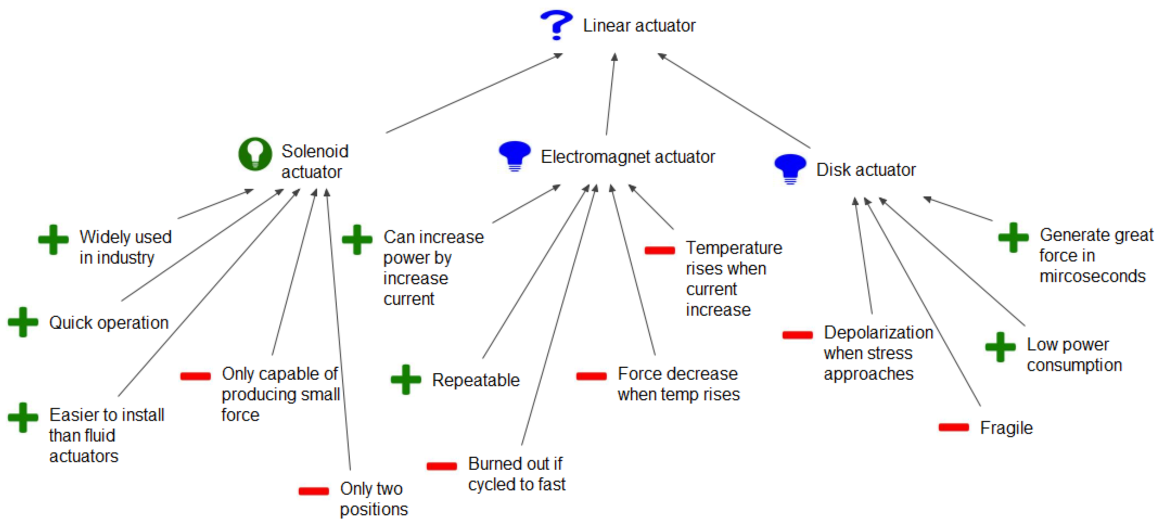


Figure 6.21 Linear actuator merit analysis

From the design shown in Figure 6.9 it can be seen that if the two push pads are actuated simultaneously with synchronised movement the system will be able to allow only one signal input at a time even if A and B signals are sent together. A push-pull linkage was chosen in this design as a result of its capability for transmitting linear motion in the same direction at end points. In order to validate the component selection a FAD was constructed for this linear driving system, identifying functional relationships between these components, shown in Figure 6.22.

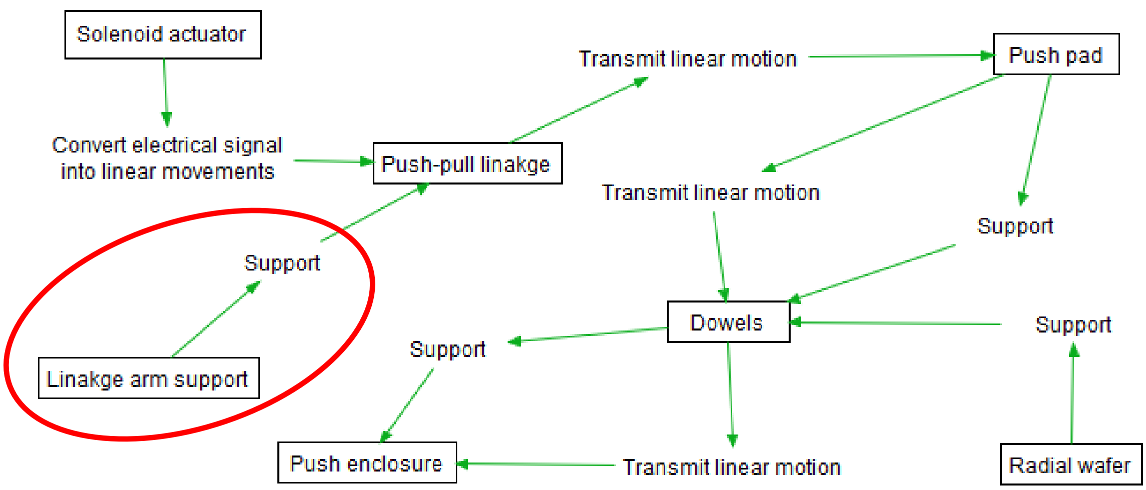


Figure 6.22 Cylindrical maze linear driving system FAD

The FAD has indicated the requirement of additional components to support the push-pull linkage and hence a linkage arm support was designed. Basic components for the driving system then can be configured, containing push-pull linkage arms, linkage arm support, push enclosures, dowels and push pads. Figure 6.23 shows the conceptual 3D drawing of the linkage arm system.

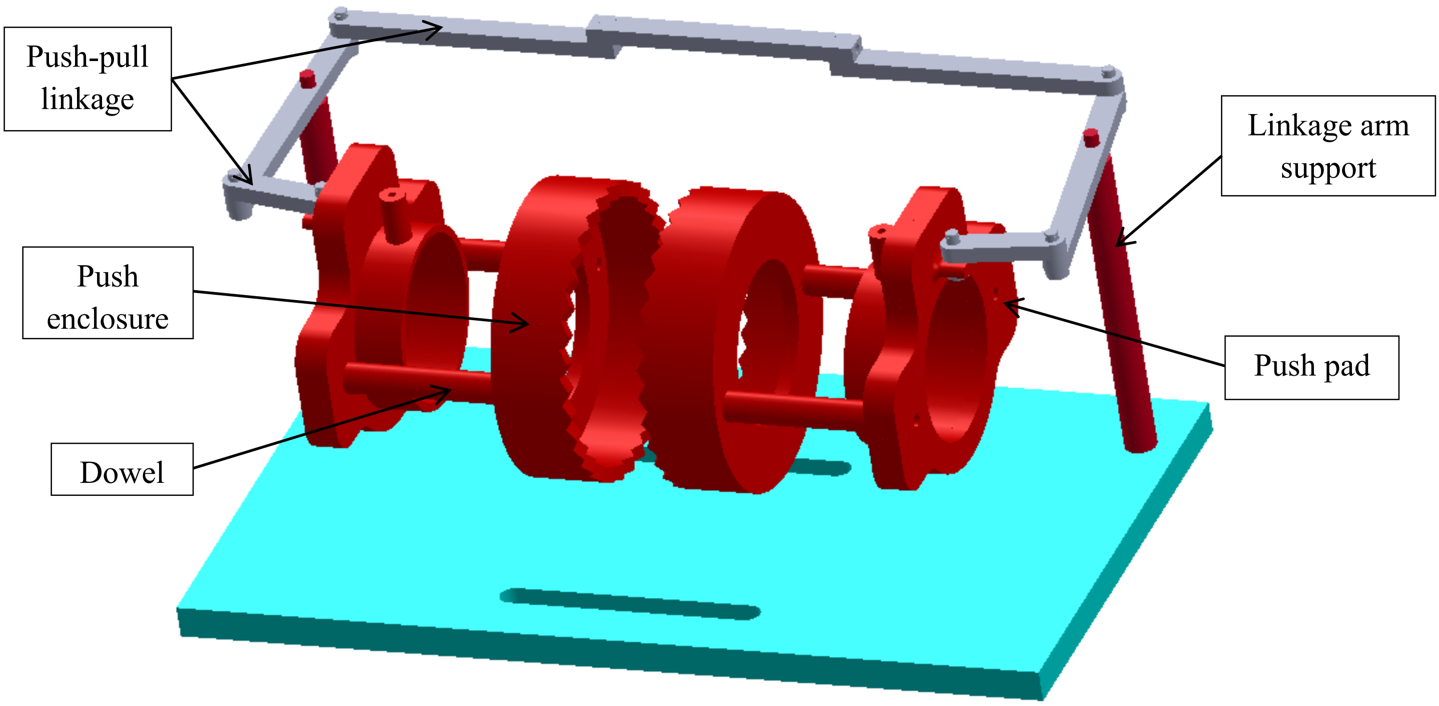


Figure 6.23 Linkage arm system 3D model

The same approach applied to the interpreting and locking system design where function 'interpret 24 sequential signals' has already been achieved by having a mover shaft rotating inside two layers of cylindrical codes (Radial wafers). For the function 'lock the mechanism when incorrect signal was inputted' MMET was used to explore solutions with regard to function *'secure position'*. The database offered a wide range of options including pin, key, various types of clamps and chucks. The pin was adopted in this design as a result of its high torque capacity, easy position adjustment and good fatigue resistance. Figure 6.24 illustrates the FM tree for the pin locking system, followed by its FAD (See Figure 6.25)

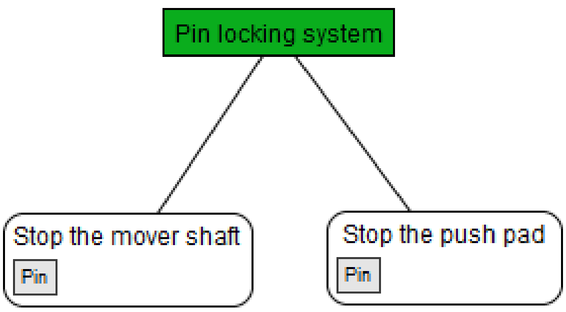


Figure 6.24 Function Means tree for locking system design

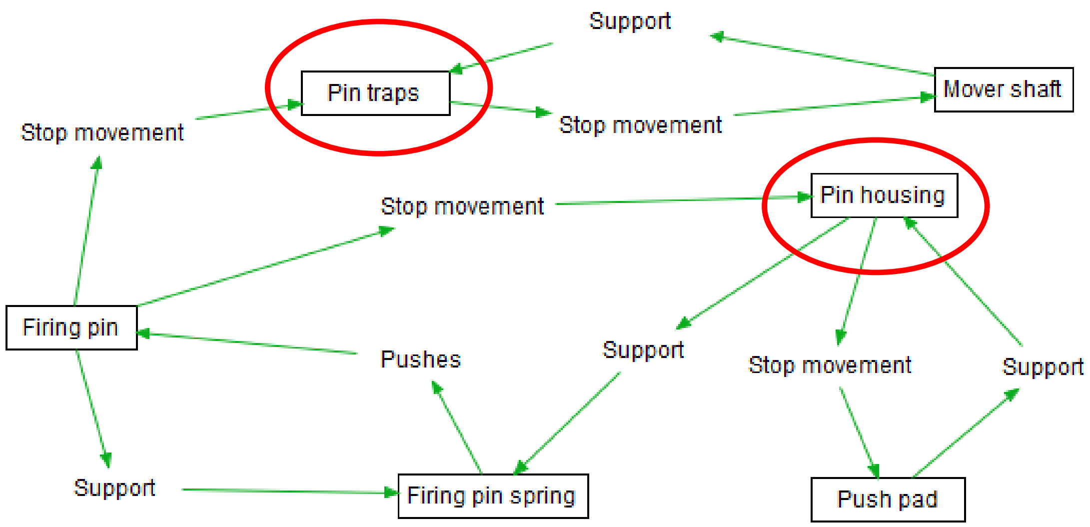


Figure 6.25 Cylindrical maze pin locking system FAD

From the functional analysis it can be seen that in order to secure the positions of both mover shaft and the push pads extra design features are needed. Therefore the design of pin traps and pin housing was carried out. The positions of the pin traps were designed according to the radial wafer teeth positions ensured that there is a pin locking hole for each mover position under each A or B signal input. In addition, the pin needs to be fired into the traps when an incorrect signal is inputted therefore a spring was used to actuate the pin. Hence all basic components required for the pin locking system can be configured according to the FAD, containing firing pin, pin trap and pin housing and spring. A conceptual design modelled in 3D is shown in Figure 6.26.

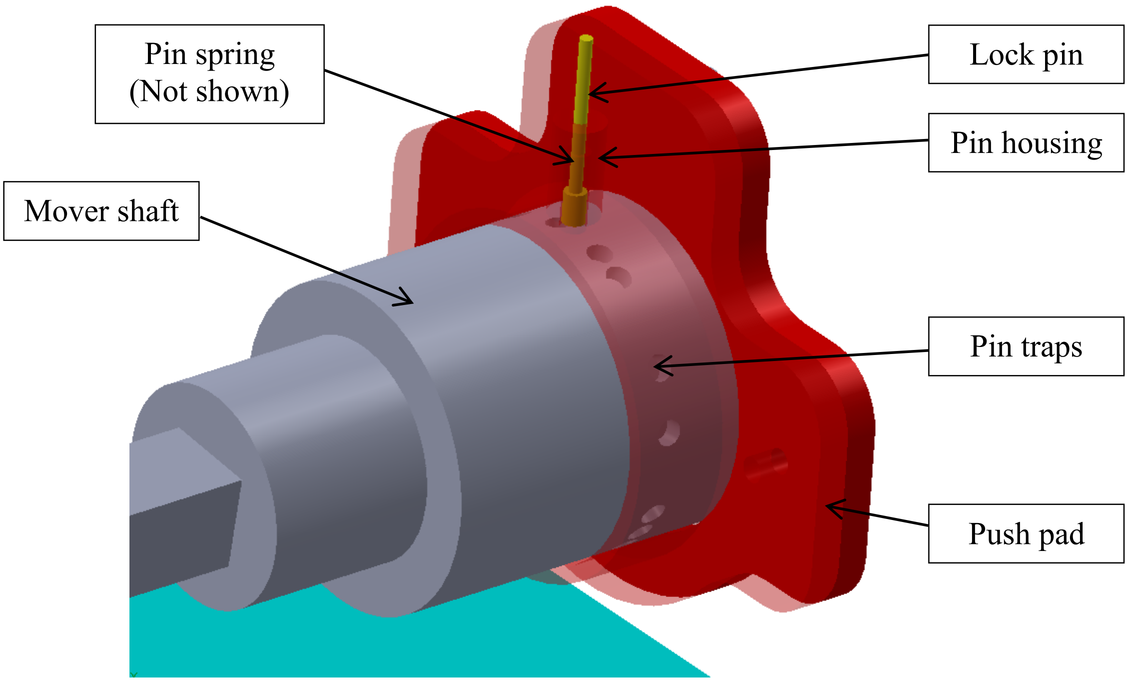


Figure 6.26 Locking feature 3d model (spring not shown)

For rotor engagement, rotation and reset of the cylindrical maze the design needs to fulfil function *'Convert continuous rotation into intermittent rotation'*. MMET provided component suggestions including External Geneva drive (Organisation's prototype), Internal Geneva drive, Spherical Geneva drive and Sector gears.

Based on the timing and practical purpose of the design case, same design, i.e. an External Geneva arm system was adopted, which attaches to each side face of the mover shaft. Due to time constraint and the complexity of 3D modelling this sub-system is not shown in the figures. The sector gear option also worth further exploration if time is allowed since it has an advantage of transmitting large torque.

Similar to the analysis on the prototype, FADs were conducted on the cylindrical maze design to validate its feasibility, evaluate whether it is able to fulfil the key design requirements and has the potential to be further developed. Figure 6.27 to Figure 6.29 FAD of the cylindrical maze under unlocking. Figure 6.29 shows the FADs for the cylindrical maze under three statuses: correct signal, incorrect signal and unlocking.

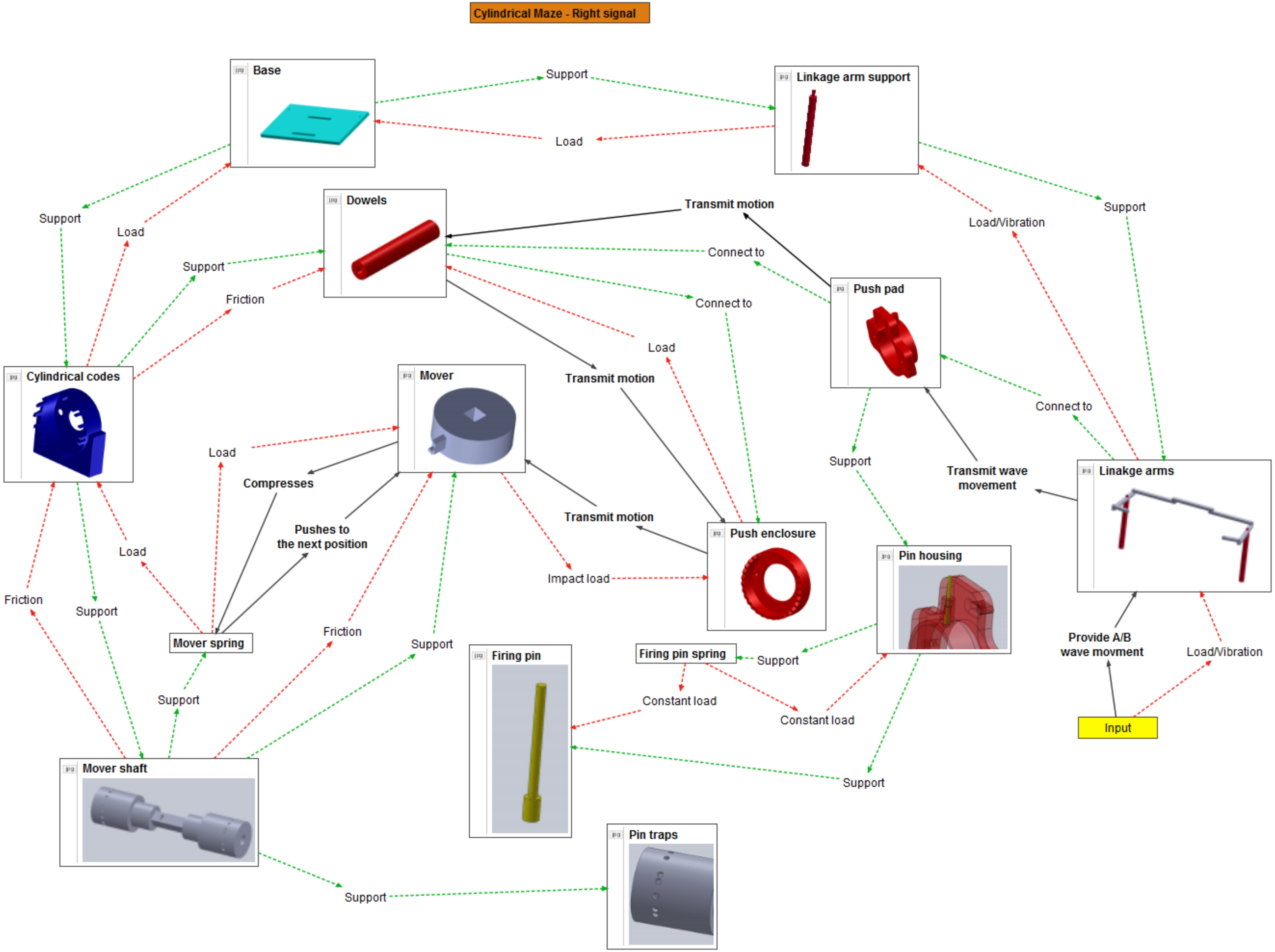


Figure 6.27 FAD of the cylindrical maze under one correct signal

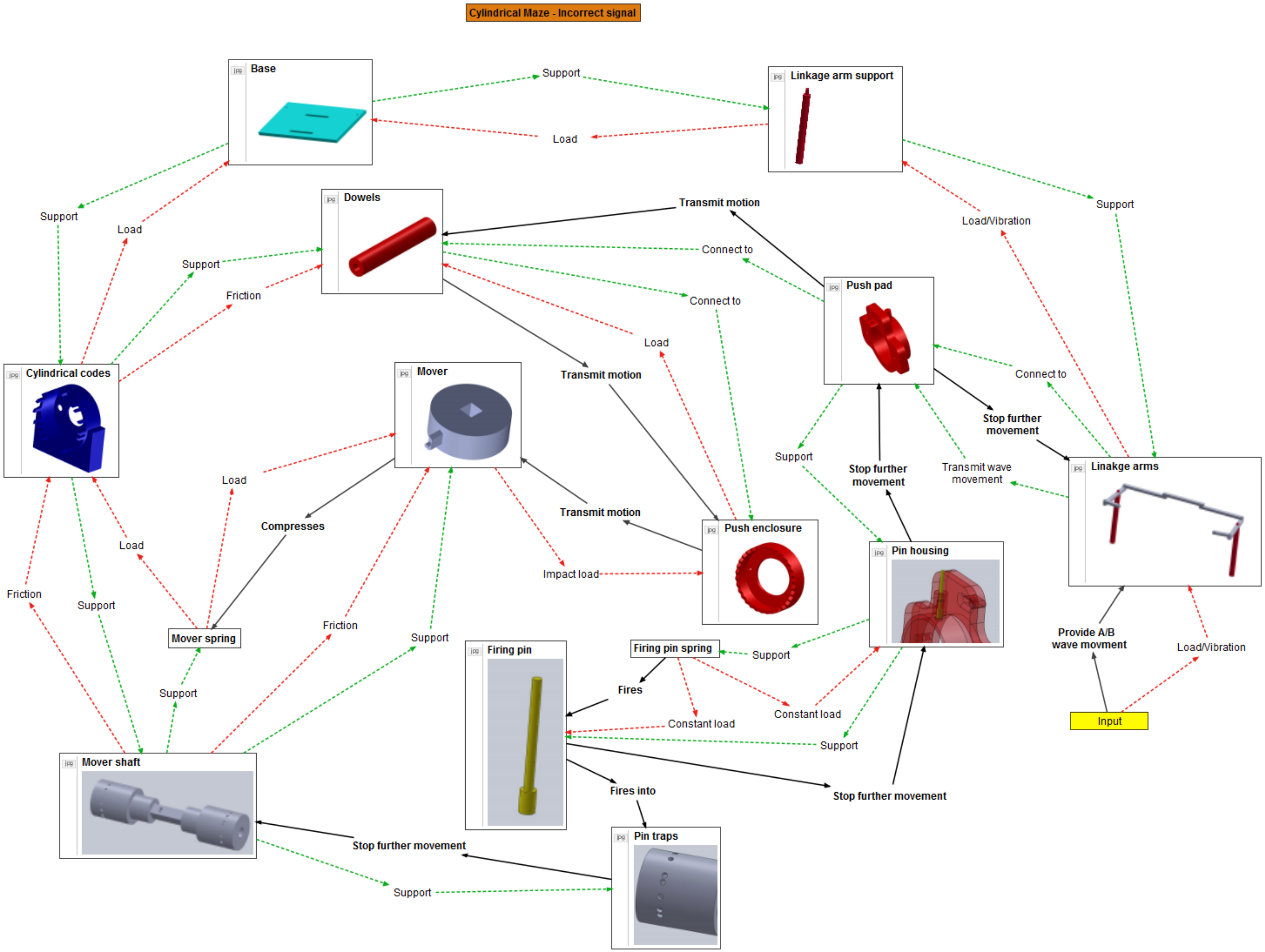


Figure 6.28 FAD of the cylindrical maze under one incorrect signal

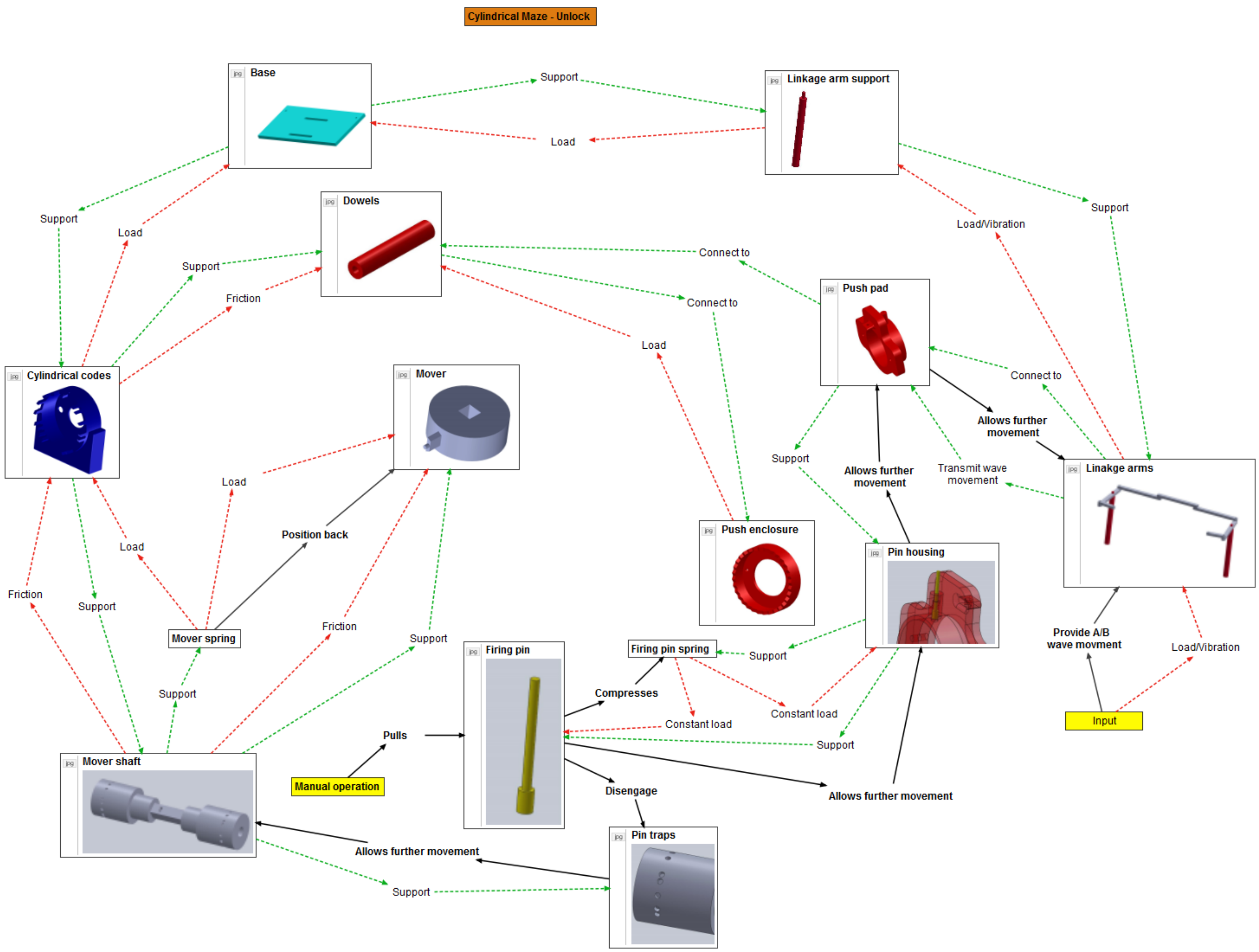


Figure 6.29 FAD of the cylindrical maze under unlocking

From the FADs key components and functions that perform signal advancement, system locking and unlocking can be identified and indicated in black bold arrows. The analysis has identified the functional relationships between components and verified the viability of this design. Harmful functions indicated by red arrows are able to reveal the flaws in design and provide opportunities for improvement. Despite those harmful functions FAD has provided evidence supporting that this cylindrical maze is viable in terms of satisfying system functional requirements and component compatibility. Figure 6.30 shows an assembled view of the mechanism. Note that the drawings shown were driven by a desire to make a rapid prototype, therefore dimensions, and in particular joints between parts, were chosen to give the best possible results for 3D printing of the device.

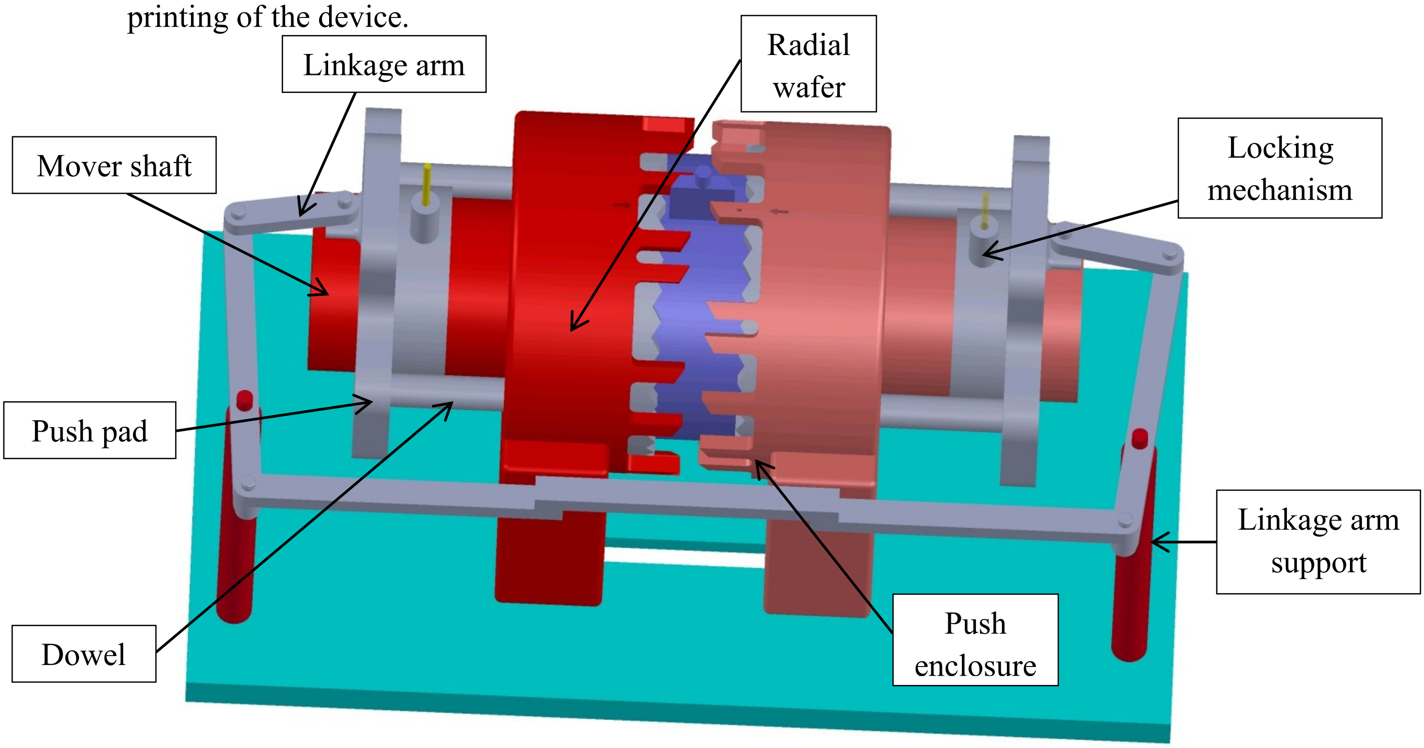


Figure 6.30 Assembled view of the cylindrical maze discriminator

In this design signals are converted and transmitted through the linkage system to the mover shaft (indicated in grey). The push pads carry the sprung load firing pin used for the locking of the mechanism. The linkage system design provides protection against vibration induced jumps and enables the locking mechanism to stop the entire system once incorrect signal is inputted. The radial wafer section has extended to attach to a base plate, which indicates that it is a completely stationary part. The grey mover shaft is allowed to rotate around its longitudinal axis with a relatively small amount of linear sliding permitted along this axis as well. Rotation is only induced from a corrected signal step. Once an incorrect step is inputted the mover shaft will slide into the buffer, where the locking mechanism is triggered to jam the entire device. After 24 correct signals are interpreted the mover shaft will engage with the rotor rotating mechanism (Not shown in figures), drives the rotor for 90 degrees and then returns to its original angular position, ready for next group of events, Figure 6.31 illustrates a 3D printed prototype of the cylindrical maze design.

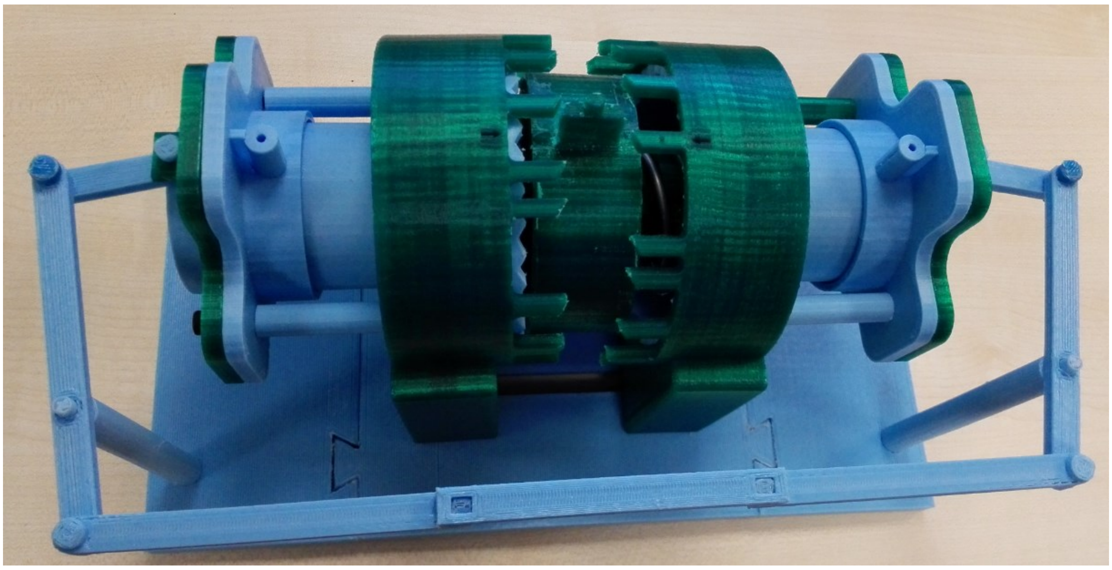


Figure 6.31 3D printed cylindrical maze prototype

Functional analysis for this cylindrical maze design suggested good potential in terms of design improvement. For example, the friction between components may result in un-smooth running of the system and the firing pin seems too small to stand large impact loading especially under great shock. Nevertheless this concept has provided a good opportunity for the organisation to look into further since it satisfied most of the design requirements with fewer components, actuators and springs. It also has a significant reduction in volume compared to the prototype. The next stage is an assessment of the conceptual design regarding the organisation's criteria provided.

6.7 **Cylindrical Maze Design Evaluation**

11 assessment criteria were provided by the organisation for the evaluation of every conceptual design. The cylindrical maze design undertook the same procedure to demonstrate its value and potential to be further developed.

- **24 sequential inputs – given sequence as exact as ABBA ABAB AABB BAAB BBBA AAAB**

YES - The sequence of 24 signals was achieved by using two coded disks. On each disc the codes are established by using the radial wafers. An A or B signal can be easily differentiated as the left or right hand side disc. There are 32 events in total on the disks, 24 pre-designed signals. The code on the prototype is ABBA ABAB AABB BAAB BBBA AAAB, followed by ABABABAB for rotor to rotate and reset.

- **Not unlockable by electrical pulses – once locked, it cannot be unlocked by any further A or B signals**

YES - The locking function is achieved by a sprung loaded firing pin and a set of traps that correspond to each signal. If a wrong event occurs, the pin will be fired in to one of the traps. Due to the linkage system design the entire device is locked once the pin enters a trap hence no further A or B signals will provide any movement to the discriminator. In this case electrical pulses will not be able to unlock the mechanism.

- **Abnormal electrical signals shall not allow advancement of discriminator – any other type of signal pulse will only advance 1 step (even if A & B are sent together)**

YES - The linkage system design will only allow one signal input at a time. Only one step input is permitted and if it is incorrect the entire system locks.

- **A shock must not cause a locked discriminator to unlock, or advance an event**

YES – The firing pin should be able to resist shocking since it is light-weighted and held by a spring under locked status. However in a 'rest' (un-locked) position a weakness of the current design has been spotted that a step 'jump' could occur from abnormal vibrations, for example, see Figure 6.32. A shock could cause the mover to vibrate along the mover shaft, in which case one of the springs could be compressed in the correct direction result in an advancement of an event. This issue can be solved with the addition of another linkage system which engages the pin mover between inputted step events.

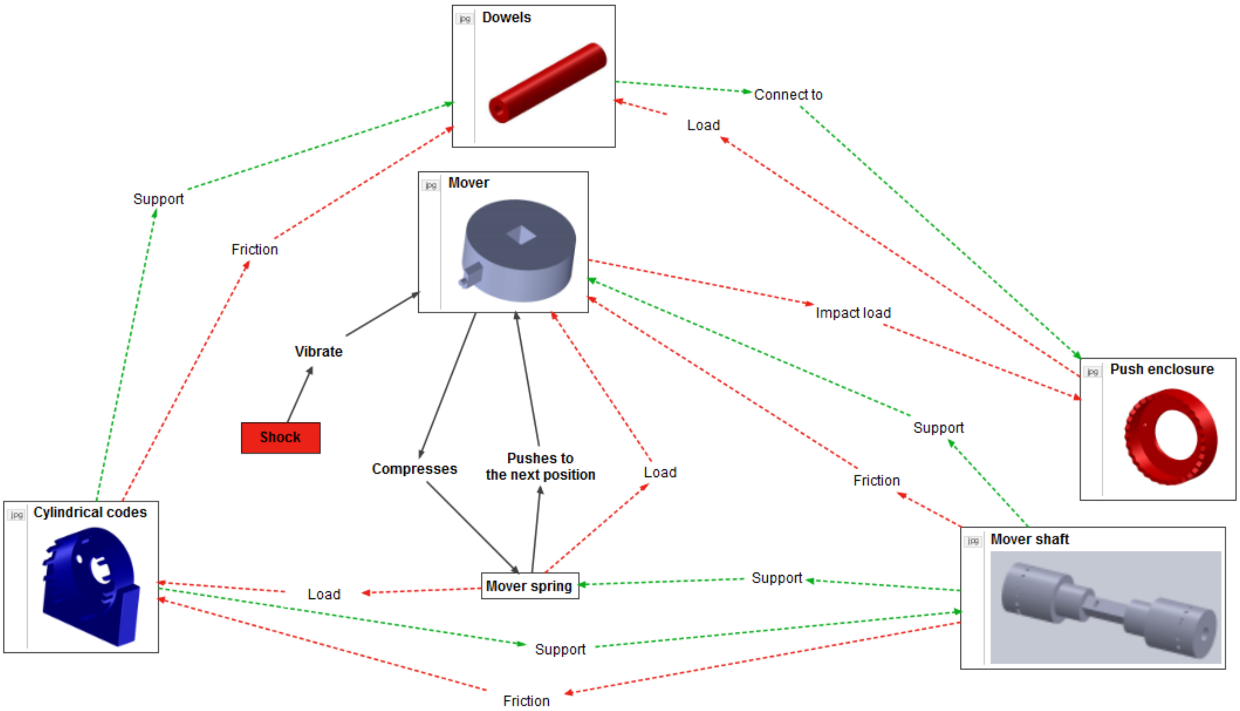


Figure 6.32 FAD for the mechanism under shock (Rest of parts are not shown)

- **No energy accumulation during discrimination**

NO – In current design springs are still used therefore there would be energy accumulation in the system.

- **Driving feature is also the locking feature – if the locking feature is lost, further electrical input will not drive the mechanism**

NO - If one locking pin is lost the discriminator could continue after every A or B incorrect input. If both are lost the discriminator could continue after every A and B incorrect input.

YES - If the linkage system is broken the discriminator is disconnected from the actuator so no A or B will provide any motion to the discriminator. However, now the discriminator is susceptible to vibrations.

- **Load limited locking features – Input energy to prime mover cannot over load the mechanism**

NO - In the current design further signal input will create impact load on the firing pins which may lead to failure of the locking mechanism. This could be overcome with the addition of a clutch or ratchet link between actuator and linkage system preventing the overloading to the mechanism.

- **Interference locking features – locking features need to be kinematic, does not depend on the planned spring-loaded motion.**

NO – In the current design the pin was held and actuated by a spring which means it fails to meet this requirement.

- **Coded mechanism is restrained – no free wheeling**

YES - In current design freewheeling is unlikely to happen since between events the mover will be at neutral position, held by the radial wafers preventing it from moving freely.

- **Human intervention for mechanical unlock will only permit a signal event for each actuation – no discrimination should be lost.**

YES - In this cylindrical maze design the mechanism can only be unlocked by lifting the firing pins and putting the linkage system into neutral position where the same step will be processed again.

- **Safety enhancement – non-inevitability.**

YES - In this design the rotor will be connected to the grey coded mover shaft, therefore no direct connection to the prime mover, if the discrimination part is lost the rotor will not be engaged.

The evaluation has indicated that this cylindrical maze design is able to satisfy 7 of out 11 criteria while the prototype provided by the company was only able to achieve 6. This is only a slight improvement but it has proven its potential to be further developed.

More advanced and detail design work could be conducted by the company design team to achieve better design outcomes.

6.8 Discussion

This project applied the conceptual design tool developed associated with brainstorming to explore novel ideas. The brainstorming session has achieved an excellent outcome in terms of the large amount of ideas generated as well as the diversion in methods and functions. The session followed a divergent-convergent thinking process of creative problem solving technique for the purpose of devising creative solutions. Although half of the concepts were focused on maze and lock designs, there were still a few novel and innovative concepts have been proposed, for example, using light and sensors, chemical reactions and jigsaws. These ideas may seem impracticable for the time being but it still has proven the value of using brainstorming in encourage creative thinking and creative idea generation.

The brainstorming session is considered to be valuable in the perspective of establishing a start point for the project since the author did not have experience on discriminator design before. Although only one out of 250 ideas was developed does not mean it is the best one. All the Post-its, sketches were scanned and sorted with regard to their types including lock/maze, gears and liquid, which enables the company to locate any specific idea in the document provided. The feedback from the one day brainstorming session has suggested that a more open brief to attendants may be better in order to maximise the brainstorming outcome. With less constraint participants may be able to devise more imaginative, innovative and creative concepts. More brainstorming workshop can be conducted with varied brief or specification to seek different outcomes.

Analysis regarding functions and system breakdown was conducted on the company's 3D printed prototype to provide the author a guideline on designing of a discriminator as well as improve the time efficiency on system deconstruction. After the construction of the FM tree for the prototype the structure of the mechanism became clearer in which different sub-systems carrying different functions. It can be seen that FM tree for an existing design can help the user:

- To understand core functional requirements of the system

- To perform system breakdown into sub-systems which fulfil core functions
- Identify lower level sub-systems and sub-functions
- To understand what components were used to fulfil each fundamental functions

Different from the robot system case study conducted in Chapter 5, this case study mainly focused on two perspectives: development of initial concepts based on system deconstruction and functional analysis and comparison between different designs.

In the brainstorming session the initial cylindrical concept selected was only capable of achieving one of the system requirements while others were not considered. The FM tree approach allows the user to analyse the system design in a hierarchical approach, identifying functions have been achieved and functions need to be achieved. For example, the initial cylindrical maze design was only able to interpret 24 sequential signals and no other system functions were satisfied at that point. Therefore, by adding this design concept into the FM tree other functional requirements that need to be accomplished can be identified. Designs with regard to these functions can then be devised incorporating with MMET which is able to provide a range of options for the user to choose from.

In this case study the MMET database was mainly used to explore component options when designing lower-level sub-systems instead of identifying fundamental system components at the bottom level of the FM tree. The reason for this is that in this particular discriminator design case nearly every single component within the system is customised due to specific functions therefore it is difficult for MMET to be employed since it is mainly for component identification of generalised fundamental functions. In this situation MMET is able to provide suggestions with regard to more generalised functional requirements such as *secure position* or *transmit linear movements*. It is able to provide the user more abstracted concepts to achieve desired functions which may need to be further developed to adapt into the system. For example, for the locking of the cylindrical maze, MMET offered to use pin as a solution, but the user had to design other components including pin housing, pin spring to complete the design. It can be seen that this requires certain level experience for the user to recognise where and when to employ MMET in the FM tree in order to reach the best the design outcome. Therefore training regarding the understanding on product technical functions and Function Basis terminology are recommended before adopting this design approach.

As mentioned before only key components that directly relate to the functional requirements can be identified in FM tree but generally there are emergent functions generated during the design process which may need additional components or design features. FAD can be used to validate component selections by assisting the user to identify system emergent functions generated from components composition, provide a start point for additional component exploration and identification. FAD is also able to reveal flaws in design and harmful functions and therefore provide potential opportunities for improvement. This provides opportunities for design improvement in the conceptual design stage. For example, the initial cylindrical maze design was spotted to be unsuccessful in FAD and hence the click ballpoint pen design was carried out. To conclude the employment of FAD acts as a validation and improvement process of conceptual design once the components from the FM tree are configured.

From this case study it can be seen that FM tree is also able to display and provide comparison between design alternatives. Regard to each function different designs that are able achieve it can be put into the Function-Means tree. This enables the comparison between different concepts regarding different ways to fulfil specific functions, which may encourage and inspire the generation of new concepts and combinations. A FM tree for both designs was constructed for comparison to help the author to understand how each system requirement is fulfilled by different designs (See Figure 6.33).

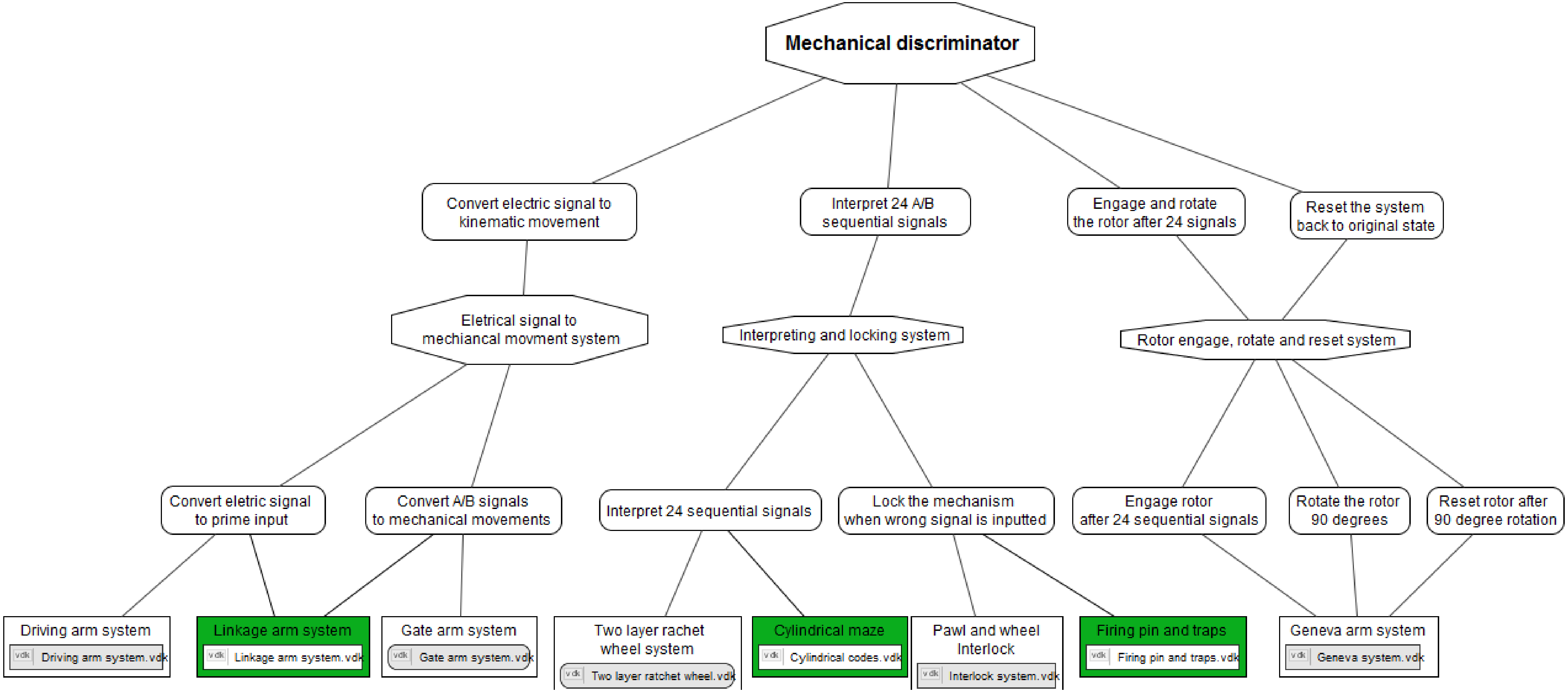


Figure 6.33 Function Means tree for both mechanical discriminator designs

Figure 6.34 shows a cyclic process within the conceptual design process, which focuses on design improvement base on FM tree and FAD. During the construction of a FM tree system functional requirements are defined and deconstructed, followed by component identification with regard to fundamental functions. An FM tree can also provide comparisons between different designs regarding a same function. FADs for the system and lower level systems are capable of identifying system design flaws and harmful functions, provide opportunities for improvement. Design improvement can be then performed according to functional analysis represented in FAD and design alternatives provided in FM tree, after which FM tree and FADs for the improved design can be constructed again to further develop the concept. This is a cyclic process between these three steps aiming to accomplish an optimised solution. The user can stop at any stage when they are confident that the conceptual design is good enough to satisfy the system requirements. Therefore the benefits of using FM tree and FAD to improve conceptual design are:

- Helping engineers and designers to understand product functions and how these functions are achieved
- Able to compare different designs with regard to their fulfilled functions
- Able to stimulate and inspire new design by comparing different designs
- Able to reveal design flaws and identify harmful functions, provide opportunities for future improvements.

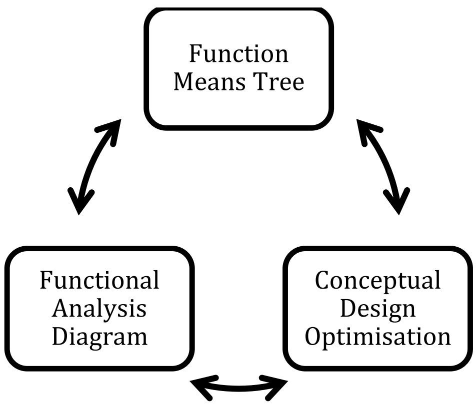


Figure 6.34 Conceptual design improvement process

The outcome of this mechanical discriminator design looks promising in terms of becoming a potential novel solution to the problem. FM tree construction of the prototype provided a framework of breaking down the discriminator system with regard to its purpose functions, helped the author to divide the core design task into smaller, more specific problems. Each problem was then further broken down to reach the definition of fundamental functional requirements which can be used as searching criteria for MMET database to exploring solutions. As mentioned above it might be challenging for novice engineers and designers to define functional requirements and devise means for the systems in the FM tree before reaching to its fundamental function level but this encourages the creative thinking in product deconstruction and finding means before fundamental components are identified. The user is required to devise different types of means to satisfy system functions. Here creative thinking and the aid of creative tools can be adopted to help the user conceive more creative and innovative concepts that may become solutions to the problem. These concepts can then be embodied on components by further Function-Means analysis.

This conceptual design tool can be adapted into product design processes in industries since it focuses on the conceptual design development, aiming to devise a broad range of solutions with regard to system functional requirements. In the meantime it encourages creative thinking and the generation of creative ideas to maximise the design outcome. The layout and arrangement of the components selected in the FM tree can be then configured in detail design. Each unique combination of components could be a potential solution to the problem. The comparison of different designs including existing ones enables engineers and designers to analyse existing designs in structural format regarding different sub-systems and functional requirements, exploring ways to improve the design by finding alternatives. FAD also enables the analysis on existing design, identify harmful functions and provide opportunities for improvement.

3D printing has played a significant role in this project since it helped the author to understand the company's design as well as verifying his new design. Sometimes ideas are better to be illustrated with hands-on experience. It can help people understand an idea thoroughly by touch it, playing with it and even break it. For the cylindrical maze signal interpreting design it was not certain that it works until it was printed out and operated successfully. By looking at and playing with the actual prototype design flaws and potential improvement become easier to be identified. However, there are limitations of current desktop 3d printing technology that it is not able to print too complex shapes especially with overhang structures. Another drawback of having the design 3d printed is that small components could be too weak to be assembled and operated. For example, the dimension of the firing pin is too small to be 3D printed and it breaks easily. However, this suggested the necessity of improvement of the locking system design by increasing the reliability of the firing pin.

The conceptual design tool also applies for new product development based on design specifications, in which case the FM tree needs to be constructed from scratch. Sub-systems carrying sub-functions need to be identified and then means to achieve these functions can be devised through the database or other methods including the employment of creative tools. Then these conceptual solutions can be validated through FADs and be further developed to become comprehensive designs. Supplementary tools provided in MMET are able to assist engineers and designer in establishing Function-Means tree and conducting functional analysis. designVUE can be used to establish FM trees and perform FAD of the systems. GlobalSpec is able to provide detail information about components' specification in the database. TRIZ contradiction matrix is able to provide assistance on design improvement focusing on finding best compromised solution between two technical conflicts, which is believed can be applied both in new product design and existing product design.

6.9 Chapter Summary, Findings & Learnings

In this chapter a mechanism discriminator design case study conducted by the author using the proposed conceptual design tool was presented. A new cylindrical maze discriminator design was developed with a significant reduced volume and number of actuators. The design has shown great potential with respect to the organisation's assessment criteria. In this case study by employing the Tool the author was able to explore component options focusing on the system functional requirements. However the design approach requires a knowledge base on product technical functions and Function Basis terminology in order to use MMET efficiently. Although MMET is able to help the user to explore components that satisfying system functions the design process still encourages creative thinking and the employment of creativity tools to devise novel and innovative concepts before fundamental functions are defined. FAD plays a significant role in this design process since it is able to validate component selections with regard to functional relationships as well as suggest design improvement by identifying harmful functions and components. MMET based conceptual design tool in association with FM tree and FAD is useful in both new product design and existing product improvement. It provides a clear and organisable structure to represent product design in the format of Functions-Means to help engineers and designers understand the way the product being designed and why. It provides a starting point for improvement of the design by finding alternatives and eliminating harmful functions and components.

Outcomes of the mechanical discriminator case study has indicated the value of the conceptual design tool, reflected on its capability on identifying system requirements, providing clear and structural system deconstruction, encouraging creative thinking in idea generation, offering component exploration, design comparison and finally conceptual design improvement. The results indicate the potential of this conceptual design tool in application of conducting mechanism conceptual designs in mechanical industry. In Chapter 7 the author’s research work will be concluded and original contributions to the research field will be highlighted.

Chapter 7 Conclusion

7.1 Chapter Introductory Statement

In this chapter research work conducted in this thesis is concluded chronologically to provide a holistic view of the research. Research contributions are then highlighted with respect to establishment of MMET and the development of the conceptual design tool containing MMET, FM tree and FAD. At the end of the chapter future work is recommended for the purpose of any potential further elaboration.

7.2 Research Summary

Engineering design can be seen as a problem solving process where engineers and designers use their knowledge and skills to conduct designs or devise solutions to satisfy market and customer's requirements. There have been different types of design models available for people to use in mechanism design, for example, Systematic Design approach, Total Design, Double Diamond design process and Concurrent Engineering. Total design and the Systematic design approach were mainly adopted as a research basis in the author's research due to their broad use in both educational and industrial contexts. Systematic engineering design processes such as these two commonly used design models normally contain a conceptual design stage where raw ideas and thoughts are embodied on conceptual designs. This stage is crucial and important in engineering product design since it determines the product's fundamental design features with regard to its design requirements. In conceptual design ideas are generated and then evaluated regarding their potentials and the promising ones can be selected and further developed into final solutions.

With the increasing demand on complex mechanism designs it becomes more important that engineers and designers are able to conceive high quality conceptual designs. In conceptual design idea generation creative thinking and appropriate employment of creativity tools can help engineers and designers to understand the design problem better and devise broader range of solutions. Furthermore, the capability of knowing commonly used machine elements and mechanisms among engineers and designer become vital especially for novice engineers and designers who may not familiar with the suitable use of mechanisms and machine elements and design processes. For experienced engineers and designers have the tendency to avoid areas they are not familiar with resulting in a limit range of solutions. Therefore, with the aim of helping both novice and experienced engineers and designers with mechanism conceptual design this thesis contains a series of researches:

- Reviewed nine commonly seen engineering design models emphasizing on Systematic Design Approach and Total Design since these two are widely used in both educational and industrial context. Total design was chosen to be author's research basis on design process since it has a clear framework of design activities and its iterative nature for the purpose of better requirement-meeting results during the design process. The review has indicated that a unified model of design process is unlikely to be seen in industry, instead are modified design processes according to specific areas.
- From the review on Total Design process it was found that this model requires the user to have related experiences in the field of working such as product design specification (PDS), functions of products, idea generation and evaluation. Therefore a research on functions of product was conducted, including function definition and types, Product Design Specification (PDS) and Quality Function Deployment (QFD). Function Analysis Diagram (FAD) was also introduced as a functional analysis tool which is able to help engineers and designers understand the product they are designing and exploring opportunities for improvement by reviewing design flaws.
- Reviewed definitions of creativity and the 4-Ps model for creativity (The Creative Person, The Creative Process, The Creative Product and The creative Environment) aiming to help the author and reader to understand creativity and its application. Creativity is significant to idea generation in conceptual design since it is able to help engineers and designers to develop innovative products and designs. There are hundreds of creativity tools available for people to use aiming to assist them in the generation of diverse and novel ideas and solutions. Brainstorming, SCAMPER and TRIZ contradiction tools were mainly introduced due to their broad application in idea generation and problem solving.

- After ideas were generated they need to be assessed regarding their potentials. Three decision making methods were introduced including a powerful approach – IBIS represented design rationale which not only able to support decision making, but also provide the justifications for it, other alternatives considered, the compromise made and the argumentation leading to a decision. IBIS represented decision making method are mainly adopted in author's research.
- The need for a conceptual design tool that can help novice engineers and designers conduct mechanism conceptual designs is well supported based on a report-based research on second year mechanical engineering undergraduates' design project. A database that contains commonly used machine elements and mechanisms (MMET) was established in order to help both novice and experienced engineers and designers to obtain a deeper understanding on these components by providing their technical functional attributes, movement attributes, pictures/drawings and merit analysis. A conceptual design tool based on MMET was then proposed aiming to help the user to explore a wide range of component selections regarding system functional/movement requirements. In order to validate the database and the design approach a surgical platform design was conducted providing support that MMET is capable of solving industrial-related mechanism design problems in the meanwhile the case study has indicated that the conceptual design tool is mainly capable of providing component options for explicit, defined function/movement requirements. For requirements that emerged during the design it is not able to provide solutions. In order to overcome this drawback Function-Means Tree and Function Analysis Diagram were employed to perform system deconstruction and validate component selection respectively, leading to the development of an improved MMET based conceptual design tool.
- With the purpose of validating this developed conceptual design tool two major design case studies were conducted regarding a robot system and a mechanical discriminator whose design outcomes have indicated its value in helping engineers and designers in mechanism conceptual design.

7.3 **Research Contributions**

There are two main contributions of this thesis:

- The establishment of MMET which can be seen as a classification of commonly used mechanisms and machine elements in mechanical engineering industry, providing detail information including their functional and movement attributes and merit analysis. Components information in the database can be fetched through text-based searching algorithms regarding component's name, functions and movement types. This enables the identification of component options through these three searching criteria, helping engineers and designers with component selection in mechanism design. MMET is also able to assist the user in finding alternatives by providing components regarding same functions and movement types in each component information page.
- The development of the MMET based conceptual design tool associated with FM tree and FAD. The design approach can be applied to general mechanism conceptual design stages, helping both novice and experienced engineers and designers to devise broader range of solutions by providing a clear structure defining and demonstrating product functional requirements, comparing different designs regarding same functions, stimulate creative thinking and finally validate conceptual design viability through functional analysis. This design approach can be adapted to general industrial mechanism design processes focusing on the idea generation in conceptual design phase, encouraging creative thinking and the generation of creative ideas to improve design quality. Each combination of component selections devised from this design approach could be a potential solution to the design problem. The approach also applies for comparison of different designs including existing ones enables engineers and designers to analyse existing designs in structural format regarding different sub-systems and functional requirements, exploring ways to improve the design by finding alternatives.

7.4 Chapter Summary, Findings and Learnings

Conceptual design phase is crucial for mechanism design especially with the increasing demand of more complex designs which requires engineers and designers to have in-depth understanding on the design process and suitable use of mechanism and machine elements. This thesis's author has developed a database that contains commonly seen mechanism and machine elements in mechanical industry and a conceptual design tool based this database incorporating with Function-Means Tree structure and Function Analysis Diagram. The Mechanism and Machine Element Taxonomy (MMET) is able to:

- Provide detail information of commonly seen mechanisms and machine element in mechanical industry, mainly including:
  - Image/Drawing of the component
  - Functional and movement attributes
  - Merit analysis
  - Components with similar functions/movement types
- Assist engineers and designers to identify component options with regard to functional/movement requirements.
- Assist engineers and designers in finding alternatives.

The conceptual design tool developed built on MMET, FM tree and FAD is able to help both novice and experienced engineers and designers in the following aspects:

- Helping engineers and designers to understand product functions and how these functions are achieved.
- Focusing on the idea generation and component selection process, aiming to devise a broad range of concepts regarding system functional requirements.
- Assist engineers and designer in exploring component options using MMET after defining fundamental functional requirements.
- Provide assistance in generating and organising ideas with regard to system functional requirements as well as encouraging creative thinking and the employment of creativity tools to conceive novel and innovative concepts.
- Able to compare different designs with regard to their fulfilled functions.
- Able to stimulate and inspire new design by comparing different designs
- Able to reveal design flaws and identify harmful functions, provide opportunities for future improvements.

From the feedback on the design case studies some future work has been suggested:

- MMET software programming

Since the author does not have sufficient experience on software programming the MMET software interface and algorithm may seems 'unprofessional'. Therefore programming of the MMET software can be further improved regarding following perspectives:

- Integrate the MMET search engine with web-based search engine, i.e. if a component cannot be located in the database, the software will perform a web-based search automatically through certain websites, for example, GlobalSpec, and then display component information to users in the software interface.
- Separate the movement input and output pairing since most of the time the user only look for components that have a desired output. Currently the software can only provide component options with defined movement input and output pairs.
- As technology evolves new components will be invented with new functions and merits, therefore it is important to ensure the database is up to date. Web-crawler technology can be used and programmed into the software, enabling the update of the database by searching for newly invented components in websites.

- MMET database

At present the database is mainly capable of providing component options for fundamental functions defined using Function Basis terminology which may become a challenge for the user when they are looking for components that can satisfy functions specified to a system. Therefore, an expansion on the component database with broader scope of functions and components is necessary, which means functions in the database will not only contain Function Basis terminology but also include more specific function expressed in nature language with corresponding components.

In conclusion this thesis's contributions to knowledge are:

- A database (MMET) offers detail information regarding commonly used mechanisms and machine elements in mechanical industry, aiming to provide assistance to novice and experienced engineers in component exploration and selection.

- A conceptual design tool composed by MMET, FM tree and FAD, which is applicable for commonly seen engineering design processes, aiming to assist novice and experienced engineers in conducting mechanism conceptual designs by focusing on structural system breakdown, creative thinking, idea generation, solution comparison and design improvement.
- Industrial case studies that offer support and evidence of the effectiveness and value of MMET and the developed conceptual design tool.

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Appendixes

Appendix 1: Flow Definitions

- Material
  - Human. All or part of a person who crosses the device boundary. Example: Most coffee makers require the flow of a human hand to actuate (or start) the electricity and thus heat the water.
    - b) Gas. Any collection of molecules characterized by random motion and the absence of
      bonds between the molecules. Example: An oscillating fan moves air by rotating blades.
      The air is transformed as gas flow.
    - c) Liquid. A readily flowing fluid, specifically having its molecules moving freely with
      respect to each other, but because of cohesive forces, not expanding indefinitely. Example: The flow of water through a coffee maker is a liquid.
    - d) Solid. Any object with mass having a definite, firm shape. Example: The flow of
      sandpaper into a hand sander is transformed into a solid entering the sander.
      24 i) Object. Material that can be seen or touched that occupies space. Example: The box
      of scrap paper for recycling is represented as the flow object. ii) Particulate. Substance containing minute separate particles. Example: Granular sugar and powdered paint are particulates. iii) Composite. Solid material composed of two or more substances having different physical characteristics and in which each substance retains its identity while contributing desirable properties to the whole unit. Any class of high-strength,
      lightweight engineering materials consisting of various combinations of alloys, plastics, and ceramics. Example: Materials such as wood, fiberglass combined with
      metals, ceramics, glasses, or polymers together are considered a composite.

Kevlar
cloth combined with paper honeycomb by means of a resin is considered a composite.

- e) Plasma. A collection of charged particles that is electrically neutral exhibiting some
properties of a gas, but differing from a gas in being a good conductor of electricity and
in being affected by a magnetic field. Example: Plasma cutting focuses an intense beam
of ionized air, known as plasma, produced by an electric arc, which melts the material to
be cut.
- f) Mixture. A substance containing two or more components which are not in fixed
proportions do not lose their individual characteristics and can be separated by physical means. Example: Expected precipitation for this evening is a mixture of rain,
sleet, and snow. i) Liquid-liquid. A readily flowing combination of two or more fluids, specifically having its molecules moving freely with respect to each other, but because of cohesive forces, not expanding indefinitely. Example: Machine oil and gasoline is a common liquid-liquid mixture used in yard maintenance machines. ii) Gas-gas. A collection of molecules containing two or more components, which are characterized by random motion and the absence of bonds between the molecules. Example: The mixture of argon and carbon dioxide, a gas-gas flow, is commonly used in welding. iii) Solid-solid. A combination of two or more objects with mass having definite, firm shape. Example: Pebbles, sand, gravel, and slag can be used to form concrete, mortar, or plaster. After it cures, concrete is a solid-solid. iv) Solid-Liquid. A combination of two or more components containing at least one solid and one liquid. Example: Iced Tea is a solid-liquid mixture of ice (solid), water (liquid), and tea grounds (solid). v) Solid-Gas. A combination of two or more components containing at least one solid and one gas. Example: Fog is a solid-gas mixture of frozen ice particles (solid) in air (gas). vi) Liquid-Gas. A combination of two or more components containing at least one liquid and one gas. Example: Carbonated drinks are liquid-gas mixtures of flavoured syrup (liquid), purified water (liquid), and carbon dioxide (gas). vii) Solid-Liquid-Gas. A combination or three or more components containing at least one each of a solid, liquid, and gas. Example: In a cup of soda and ice cubes, the cup contains the solid-liquid-gas flow. viii) Colloidal. A solid, liquid, or gaseous substance made up of very small, insoluble non-diffusible particles that remain in suspension in a surrounding solid, liquid, or gaseous medium of a different matter. Example: Aerosols, smoke, and mist can all be considered colloids. Mist is a combination of very fine water droplets suspended in air.

- Energy
  - Generic Complements.
    - Effort. Any component of energy used to accomplish an intended purpose.
    - Flow. Any component of energy causing the intended object to move or run freely.

- Human. Work performed by a person on a device. Example: An automobile requires the flow of human energy to steer and accelerate the vehicle.
  - i) Force. Human effort that is input to the system without regard for the required motion. Example: Human force is needed to actuate the trigger of a toy gun.
  - ii) Velocity. Activity requiring movement of all or part of the body through a prescribed path. Example: The track pad on a laptop computer receives the flow of
    human velocity to control the cursor.
- Acoustic. Work performed in the production and transmission of sound. Example: The
  motor of a power drill generates the flow of acoustic energy in addition to the torque.
  - Pressure. The pressure field of the sound waves. Example: A condenser microphone has a diaphragm, which vibrates in response to acoustic pressure. This vibration changes the capacitance of the diaphragm, thus superimposing an alternating voltage on the direct voltage applied to the circuit.
  - Particle velocity. The speed at which sound waves travel through a conducting medium. Example: Sonar devices rely on the flow of acoustic particle velocity to determine the range of an object.
- Biological. Work produced by or connected with plants or animals. Example: In poultry houses, grain is fed to chickens, which is then converted into biological energy.
  - Pressure. The pressure field exerted by a compressed biological fluid. Example: The high concentration of sugars and salts inside a cell causes the entry, via osmosis,
    of water into the vacuole, which in turn expands the vacuole and generates a hydrostatic biological pressure, called turgor, that presses the cell membrane against
    the cell wall. Turgor is the cause of rigidity in living plant tissue.
  - Volumetric flow. The kinetic energy of molecules in a biological fluid flow. Example: Increased metabolic activity of tissues such as muscles or the intestine automatically induces increased volumetric flow of blood through the dilated vessels.
- Chemical. Work resulting from the reactions by which substances are produced from or
  converted into other substances. Example: A battery converts the flow of chemical energy into electrical energy.
  - Affinity. The force with which atoms are held together in chemical bonds. Affinity
    is proportional to the chemical potential of a compound's constituent species. Example: An internal combustion engine transforms the chemical affinity of the gas
    into a mechanical force.
  - Reaction rate. The speed or velocity at which chemical reactants produce products.
    Reaction rate is proportional to the mole rate of the constituent species. Example: Special coatings on automobile panels stop the chemical reaction rate of the metal with
    the environment.

- Electrical. Work resulting from the flow of electrons from a negative to a positive source. Example: A power belt sander imports a flow of electrical energy (electricity, for convenience) from a wall outlet and transforms it into a rotation.
  - Electromotive force. Potential difference across the positive and negative sources. Example: Household electrical receptacles provide a flow of electromotive force of approximately 110 V.
  - Current. The flow or rate of flow of electric charge in a conductor or medium between two points having a difference in potential. Example: Circuit breakers trip when the current exceeds a specified limit.
- Electromagnetic. Energy that is propagated through free space or through a material medium in the form of electromagnetic waves (Britannica Online, 1997). It has both wave and particle-like properties. Example: Solar panels convert the flow electromagnetic energy into electricity.
  - Generic Complements.
    (1) Effort. Any component of electromagnetic energy used to accomplish an intended purpose.
    (2) Flow. Any component of electromagnetic energy causing the intended object to move or run freely.
  - Optical. Work associated with the nature and properties of light and vision. Also, a special case of solar energy (see solar). Example: A car visor refines the flow of optical energy that its passengers receive.
    (1) Intensity. The amount of optical energy per unit area. Example: Tinted windows reduce the optical intensity of the entering light.
    (2) Velocity. The speed of light in its conducting medium. Example: NASA developed and tested a trajectory control sensor (TCS) for the space shuttle to calculate the distance between the payload bay and a satellite. It relied on the constancy of the optical velocity flow to calculate distance from time of flight measurements of a reflected laser.
  - Solar. Work produced by or coming from the sun. Example: Solar panels collect the flow of solar energy and transform it into electricity.
    (1) Intensity. The amount of solar energy per unit area. Example: A cloudy day reduces the solar intensity available to solar panels for conversion to electricity.
    (2) Velocity. The speed of light in free space. Example: Unlike most energy flows, solar velocity is a well-known constant.
- Hydraulic. Work that results from the movement and force of a liquid, including hydrostatic forces. Example: Hydroelectric dams generate electricity by harnessing the hydraulic energy in the water that passes through the turbines.
  - Pressure. The pressure field exerted by a compressed liquid. Example: A hydraulic jack uses the flow hydraulic pressure to lift heavy objects.
  - Volumetric flow. The movement of fluid molecules. Example: A water meter measures the volumetric flow of water without a significant pressure drop in the line.

- Magnetic. Work resulting from materials that have the property of attracting other like materials, whether that quality is naturally occurring or electrically induced. Example: The magnetic energy of a magnetic lock is the flow that keeps it secured to the iron based structure.
  - Magnetomotive force. The driving force which sets up the magnetic flux inside of a core. Magnetomotive force is directly proportional to the current in the coil surrounding the core. Example: In a magnetic door lock, a change in magnetomotive force (brought about by a change in electrical current) allows the lock to disengage and the door to open.
  - Magnetic flux rate. Flux is the magnetic displacement variable in a core induced by the flow of current through a coil. The magnetic flow variable is the time rate of change of the flux. The voltage across a magnetic coil is directly proportional to the time rate of change of magnetic flux. Example: A magnetic relay is a transducer that senses the time rate of change of magnetic flux when the relay arm moves.
- Mechanical. Energy associated with the moving parts of a machine or the strain energy associated with a loading state of an object. Example: An elevator converts electrical or hydraulic energy into mechanical energy.
  - Generic Complements.
    (1) Effort. Any component of mechanical energy used to accomplish an intended purpose.
    (2) Flow. Any component of mechanical energy causing the intended object to move or run freely.
  - Rotational energy. Energy that results from a rotation or a virtual rotation. Example: Customers are primarily concerned with the flow of rotational energy from a power screwdriver.
    (1) Torque. Pertaining to the moment that produces or tends to produce rotation. Example: In a power screwdriver, electricity is converted into rotational energy. The more specific flow is torque, based on the primary customer need to insert screws easily, not quickly.
    (2) Angular velocity. Pertaining to the orientation or the magnitude of the time rate of change of angular position about a specified axis. Example: A centrifuge is used to separate out liquids of different densities from a mixture. The primary flow it produces is that of angular velocity, since the rate of rotation about an axis is the main concern.
  - Translational energy. Energy flow generated or required by a translation or a virtual translation. Example: A child’s toy, such as a projectile launcher, transmits translational energy to the projectile to propel it away.
    (1) Force. The action that produces or attempts to produce a translation. Example: In a tensile testing machine, the primary flow of interest is that of a force which produces a stress in the test specimen.

(2) Linear velocity. Motion that can be described by three component directions. Example: An elevator car uses the flow of linear velocity to move between floors.

- Pneumatic. Work resulting from a compressed gas flow or pressure source. Example: A BB gun relies on the flow of pneumatic energy (from compressed air) to propel the projectile (BB).
  - Pressure. The pressure field exerted by a compressed gas. Example: Certain cylinders rely on the flow of pneumatic pressure to move a piston or support a force.
  - Mass flow. The kinetic energy of molecules in a gas flow. Example: The mass flow
    of air is the flow that transmits the thermal energy of a hair dryer to damp hair.
- Radioactive (Nuclear). Work resulting from or produced by particles or rays, such as alpha, beta and gamma rays, by the spontaneous disintegration of atomic nuclei. Example: Nuclear reactors produce a flow of radioactive energy which heats water into steam and then drives electricity generating turbines.
  - Intensity. The amount of radioactive particles per unit area. Example: Concrete is an effective radioactive shielding material, reducing the radioactive intensity in proportion to its thickness.
  - Decay rate. The rate of emission of radioactive particles from a substance. Example: The decay rate of carbon provides a method to date pre-historic objects.
- Thermal. A form of energy that is transferred between bodies as a result of their temperature difference. Example: A coffee maker converts the flow of electricity into the flow of thermal energy, which it transmits to the water. Note: A pseudo bond graph approach is used here. The true effort and flow variables are temperature and the time rate of change of entropy. However, a more practical pseudo-flow of heat rate is chosen here.
  - Temperature. The degree of heat of a body. Example: A coffee maker brings the temperature of the water to boiling in order to siphon the water from the holding tank to the filter basket.
  - Heat rate. (Note: this is a pseudo-flow) The time rate of change of heat energy of a
    body. Example: Fins on a motor casing increase the flow heat rate from the motor by
    conduction (through the fin), convection (to the air) and radiation (to the environment)

- Signal
  - Status. A condition of some system, as in information about the state of the system. Example: Automobiles often measure the engine water temperature and send a status signal to the driver via a temperature gage.
    - Auditory. A condition of some system as displayed by a sound. Example: Pilots receive an auditory signal, often the words "pull up," when their aircraft reaches a dangerously low altitude.
    - Olfactory. A condition of some system as related by the sense of smell or particulate count. Example: Carbon monoxide detectors receive an olfactory signal from the environment and monitor it for high levels of CO.
    - Tactile. A condition of some system as perceived by touch or direct contact. Example: A pager delivers a tactile signal to its user through vibration.

- Taste. A condition of some dissolved substance as perceived by the sense of taste. Example: In an electric wok, the taste signal from the human chef is used to determine when to turn off the wok.
- Visual. A condition of some system as displayed by some image. Example: A power screwdriver provides a visual signal of its direction through the display of arrows on the switch.

- Control. A command sent to an instrument or apparatus to regulate a mechanism. Example: An airplane pilot sends a control signal to the elevators through movement of
  the yoke. The yoke movement is transformed into an electrical signal, sent through wiring to the elevator, and then transformed back into a physical elevator deflection.
  - Analog. A control signal sent by direct, continuous, measurable, variable physical quantities. Example: Turning the volume knob on a radio sends an analog signal to
    increase or decrease the sound level.
  - Discrete. A control signal sent by separate, distinct, unrelated or discontinuous quantities. Example: A computer sends discrete signals to the hard disk controller during read/write operations.

Appendix 2: Function Definitions

- Branch. To cause a flow (material, energy, signal) to no longer be joined or mixed.
  - Separate. To isolate a flow (material, energy, signal) into distinct components. The separated components are distinct from the flow before separation, as well as each other. Example: A glass prism separates light into different wavelength components to produce a rainbow.
    - Divide. To separate a flow. Example: A vending machine divides the solid form of coins into appropriate denominations.
    - Extract. To draw, or forcibly pull out, a flow. Example: A vacuum cleaner extracts debris from the imported mixture and exports clean air to the environment.
    - Remove. To take away a part of a flow from its prefixed place. Example: A sander removes small pieces of the wood surface to smooth the wood.
    - Distribute. To cause a flow (material, energy, signal) to break up. The individual bits are similar to each other and the undistributed flow. Example: An atomizer distributes (or sprays) hair-styling liquids over the head to hold the hair in the desired style.
  - Channel. To cause a flow (material, energy, signal) to move from one location to another
    location.
    - Import. To bring in a flow (material, energy, signal) from outside the system boundary.
      Example: A physical opening at the top of a blender pitcher imports a solid (food) into the system. Also, a handle on the blender pitcher imports a human hand.
    - Export. To send a flow (material, energy, signal) outside the system boundary. Example: Pouring blended food out of a standard blender pitcher exports liquid from the system. The opening at the top of the blender is a solution to the export subfunction.

- Transfer. To shift, or convey, a flow (material, energy, signal) from one place to another.
  i) Transport. To move a material from one place to another. Example: A coffee maker transports liquid (water) from its reservoir through its heating chamber and then to the filter basket.
  ii) Transmit. To move an energy from one place to another. Example: In a hand held power sander, the housing of the sander transmits human force to the object being sanded.
- Guide. To direct the course of a flow (material, energy, signal) along a specific path. Example: A domestic HVAC system guides gas (air) around the house to the correct locations via a set of ducts.
  i) Translate. To fix the movement of a flow by a device into one linear direction. Example: In an assembly line, a conveyor belt translates partially completed products from one assembly station to another.
  ii) Rotate. To fix the movement of a flow by a device around one axis. Example: A computer disk drive rotates the magnetic disks around an axis so that the head can read data.
  iii) Allow degree of freedom (DOF). To control the movement of a flow by a force external to the device into one or more directions. Example: To provide easy trunk access and close appropriately, trunk lids need to move along a specific degree of freedom. A four bar linkage allows a rotational DOF for the trunk lid.

➢ Connect. To bring two or more flows (material, energy, signal) together.
- Couple. To join or bring together flows (material, energy, signal) such that the members
  are still distinguishable from each other. Example: A standard pencil couples an eraser
  and a writing shaft. The coupling is performed using a metal sleeve that is crimped to
  the eraser and the shaft.
  i) Join. To couple flows together in a predetermined manner. Example: A ratchet joins a socket on its square shaft interface.
  ii) Link. To couple flows together by means of an intermediary flow. Example: A turnbuckle links two ends of a steering cable together.
- Mix. To combine two flows (material, energy, and signal) into a single, uniform homogeneous mass. Example: A shaker mixes a paint base and its dyes to form a homogeneous liquid.

➢ Control Magnitude. To alter or govern the size or amplitude of a flow (material, energy,
signal).
- Actuate. To commence the flow of energy, signal, or material in response to an imported control signal. Example: A circuit switch actuates the flow of electrical energy and turns on a light bulb.
- Regulate. To adjust the flow of energy, signal, or material in response to a control signal, such as a characteristic of a flow. Example: Turning the valves regulates the flow rate of the liquid flowing from a faucet.
  i) Increase. To enlarge a flow in response to a control signal. Example: Opening the valve of a faucet further increases the flow of water.

ii) Decrease. To reduce a flow in response to a control signal. Example: Closing the value further decreases the flow of propane to the gas grill.

  - Change. To adjust the flow of energy, signal, or material in a predetermined and fixed manner. Example: In a hand held drill, a variable resistor changes the electrical energy flow to the motor thus changing the speed the drill turns.
    i) Increment. To enlarge a flow in a predetermined and fixed manner. Example: A magnifying glass increments he visual signal (i.e. the print) from a paper document.
    ii) Decrement. To reduce a flow in a predetermined and fixed manner. Example: The gear trains of power screwdriver decrements the flow of rotational energy.
    iii) Shape. To mold or form a flow. Example: In the auto industry, large presses shape sheet metal into contoured surfaces that become fenders, hoods and trunks.
    iv) Condition. To render a flow appropriate for the desired use. Example: To prevent damage to electrical equipment, a surge protector conditions electrical energy by excluding spikes and noise (usually through capacitors) from the energy path.
  - Stop. To cease, or prevent, the transfer of a flow (material, energy, signal). Example: A
    reflective coating on a window stops the transmission of UV radiation through a window.
    i) Prevent. To keep a flow from happening. Example: A submerged gate on a dam wall prevents water from flowing to the other side.
    ii) Inhibit. To significantly restrain a flow, though a portion of the flow continues to be
    transferred. Example: The structures of space vehicles inhibit the flow of radiation to protect crew and cargo.
  - Convert. To change from one form of a flow (material, energy, signal) to another. For completeness, any type of flow conversion is valid. In practice, conversions such as convert electricity to torque will be more common than convert solid to optical energy. Example: An electrical motor converts electricity to rotational energy.
- Provision. To accumulate or provide a material or energy flow.
  - Store. To accumulate a flow. Example: A DC electrical battery stores the energy in a
    flashlight.
    i) Contain. To keep a flow within limits. Example: A vacuum bag contains debris vacuumed from a house.
    ii) Collect. To bring a flow together into one place. Example: Solar panels collect ultraviolet sun rays to power small mechanisms.
  - Supply. To provide a flow from storage. Example: In a flashlight, the battery supplies energy to the bulb.
- Signal. To provide information on a material, energy or signal flow as an output signal flow. The information providing flow passes through the function unchanged.
  - Sense. To perceive, or become aware, of a flow. Example: An audiocassette machine senses if the end of the tape has been reached.
    i) Detect. To discover information about a flow. Example: A gauge on the top of a gas cylinder detects proper pressure ranges.

ii) Measure. To determine the magnitude of a flow. Example: An analog thermostat measures temperature through a bimetallic strip.

- Indicate. To make something known to the user about a flow. Example: A small window in the water container of a coffee maker indicates the level of water in the machine.
  i) Track. To observe and record data from a flow. Example: By tracking the performance of batteries, the low efficiency point can be determined.
  ii) Display. To reveal something about a flow to the mind or eye. Example: The xyz coordinate display on a vertical milling machine displays the precise location of the cutting tool.
- Process. To submit information to a particular treatment or method having a set number
  of operations or steps. Example: A computer processes a login request signal before allowing a user access to its facilities.

➢ Support. To firmly fix a material into a defined location, or secure an energy or signal into a
specific course.
  - Stabilize. To prevent a flow from changing course or location. Example: On a typical canister vacuum, the center of gravity is placed at a low elevation to stabilize the vacuum when it is pulled by the hose.
  - Secure. To firmly fix a flow path. Example: On a bicycling glove, a Velcro strap secures the human hand in the correct place.
  - Position. To place a flow (material, energy, signal) into a specific location or orientation. Example: The coin slot on a soda machine positions the coin to begin the coin evaluation and transportation procedure.

Appendix 3: Screening Matrix

❖ Advantage

They represent the most important consideration, because if an idea doesn't present any advantage, then it isn't worth the trouble to closely examine it. De Bono distinguishes between value and advantage, defining the first one as an intrinsic attribute of the idea, and the second one as a benefit deriving from that idea. Then you always should ask you questions like these: "What are the advantages?" "What's their origin?", "What do they depend on?". As an example, the financial advantages of a new concept might finish when competitors copy it. Another fundamental question is: "Who will enjoy the advantages?". He might be the producer thanks to less cost and more benefit, or the customer who will have less expensive or highly improved products. Sometimes both the customer and the producer have advantages. As an example, a better design can be more attractive for the purchasers, while the producer benefits of the greater consequent sales. Certainly there are many other questions, but what is important to emphasize is the necessity to list all the possible advantages in detail, showing the logical reasons and the information that may justify their forecast.

❖ Feasibility

You might think that feasibility should be the first aspect to consider, as it is absurd to estimate the advantages of an idea which is not practicable; however it is also true that if they turn out consisting, certainly you will try to make that operating. Anyway you should abandon ideas that violate some fundamental principle. Sometimes ideas are not feasible because they break some regulations or because they are clearly illegal. In these cases you should save the concept and modify the idea so as to make it legal and corresponding to the regulations. Other times ideas are not usable because it does not exist a standard way in order to realize them or necessary technology is not available and therefore they are discarded.

❖ Resources

It is clear that a realistic appraisal of the necessary resources for the realization of an idea is very important. The key questions, in this case, are: "Do those resources exist?", "How much does it cost the realization in money and in time resources?", "How many hours of labour and which specializations are necessary?", "Who will be responsible for the realization of the idea?".

❖ Adequacy

The question is to establish if an idea is right for the organization. Then you should ask you: "Is the idea coherent with business politics, strategy and objectives?", "And with the public imagine of the organization and the expectations of the consumers?". As to the inner business environment, difficulties derive from the fact that just traditional ideas seem to be in accordance with the usual behaviour of the organization and in this sense every new idea is not suitable. At the same time, it is very difficult to realize with success an idea if this is not right for the style and the motivations of the firm, and it might be that also a good idea fails just for this lack of adequacy to the business context. Then it is necessary to examine the situation in order to estimate which is the best positioning for an idea.

❖ Vital factors

These factors are necessary for the survival of the idea in the sense that if they lack the idea can not work. They are: profit, respect of law, existence of a well-defined market and of channels of distribution, resources… An adequate capitalization is a vital factor for the success of every new company, just like resources are a vital factor for the realization of a new idea.

❖ Fatal factors

They can cause the death of the idea. Thus, if the idea includes them, it can't work. Nowadays environmental pollution is a fatal factor in many Countries, just like a too high price, or legal costs, the violation of the rights of intellectual property, the association with firms in bankrupt conditions. If the idea has a potential big value you should try to eliminate these factors or to add some vital ones.

❖ Flexibility

Rigid ideas are not a good choice because of the uncertainty of the future conditions and of the continuous change of the values; then it is very important for ideas to be endowed with flexibility.

❖ Risk

In every judgment, decision, or appraisal it is implicit the risk factor. There is the risk that the idea may not be successful, or that it reveals itself to be very expensive or damaging or to the image of the firm, or to the relationships with the dealers and so on. Then there is the risk that an idea might provoke some extremely effective reactions of the competitors which will make the idea lose its validity. A list of the possible risks could be unlimited as what is concerned with the future is uncertain. Any way you can take precautions against risks in various ways:

- Being aware of the possible risks.
- Predisposing some systems for the control of the damages.
- Reducing the risk with opportune verifications and
- Experimentations.
- Redesigning the idea.
- Predisposing systems of pre-alarm.
- Trying to collect as much information as possible.
- Assuring a rapid reaction.
- Sharing the risk with partners.
- Estimating the relationship risk/advantages.

Appendix 4: Partial coding of MMET Software

❖ MMET Component Function Oriented Search

```
private void reloadComponentsListAccordingToFunction(int idOfFunction)
{
    List<ListItem> items = new List<ListItem>();
    foreach (Component c in FunctionRetrieval.GetComponentsByFunctionId(accdbConnectionString, idOfFunction))
    {
        items.Add(new ListItem(c.ComponentName, c.ComponentID));
    }

    lb_components.Items.Clear();
    lb_components.Items.AddRange(items.ToArray());
}
```

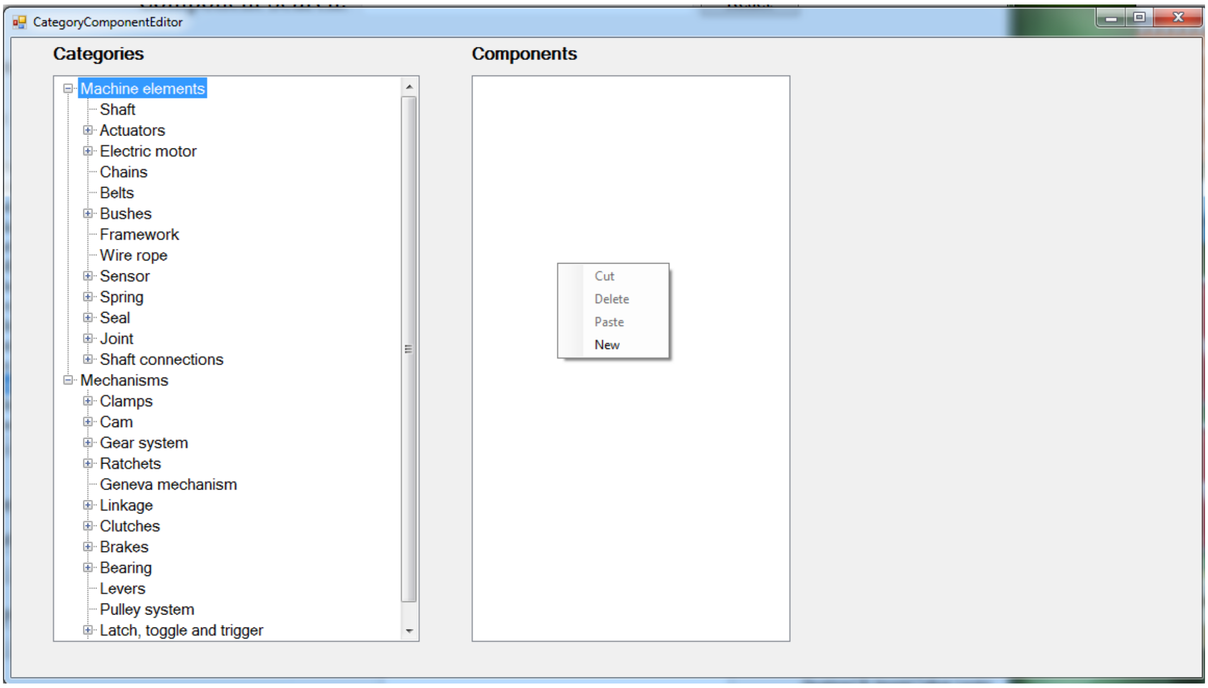
```
private void tb_searchFunctions_TextChanged(object sender, EventArgs e)
{
    lb_functionalRequirements.Items.Clear();

    foreach (Function f in FunctionRetrieval.GetFunctionsBySearchString(accdbConnectionString, tb_searchForFunctions.Text))
    {
        lb_functionalRequirements.Items.Add(new ListItem(f.FunctionName, f.FunctionID));
    }


}
private void lb_functionalRequirements_SelectedIndexChanged(object sender, EventArgs e)
{
    if (lb_functionalRequirements.SelectedItem != null)
    {
        clearAllComboBoxExcept((Control)sender);

        int id = ((ListItem)lb_functionalRequirements.SelectedItem).Id;
        reloadComponentsListAccordingToFunction(id);
    }
}
```

❖ Component Information Display

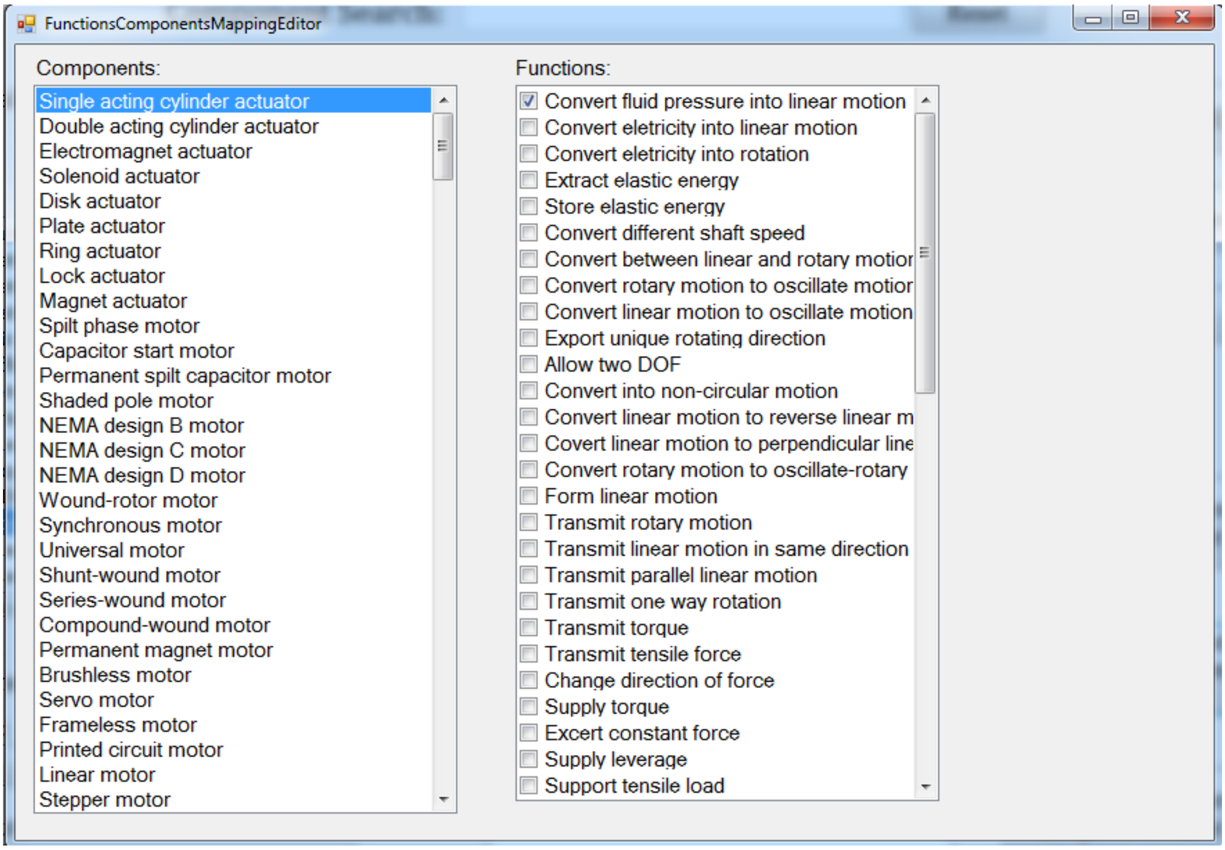
```
private void reloadData(string accdbConnectionString)
{
    this.Text = titlePrefix + "Component ID: " + component.ComponentID + ", Component Name: " + component.ComponentName;
    this.lb_componentID.Text = lb_componentIDPrefix + component.ComponentID.ToString();
    this.lb_ComponentName.Text = lbTextComponentNamePrefix + component.ComponentName;

    // Fill in functions of this component
    lb_functionsOfThisComponent.Items.Clear();
    foreach (Function f in FunctionRetrieval.GetFunctionsBelongToComponent(accdbConnectionString, component.ComponentID))
    {
        lb_functionsOfThisComponent.Items.Add(new ListItem(f.FunctionName, f.FunctionID));
    }

    // Fill in movements of this component
    lb_movementInputOfThisComponent.Items.Clear();
    lb_movementOutputOfThisComponent.Items.Clear();
    foreach (MovementIO m in Movement_Component.GetMovementIOsByComponent(accdbConnectionString, component.ComponentID))
    {
        lb_movementInputOfThisComponent.Items.Add(new ListItem(m.NameOfInputMovement, m.IdOfInputMovement));
        lb_movementOutputOfThisComponent.Items.Add(new ListItem(m.NameOfOutputMovement, m.IdOfOutputMovement));
    }

    // Fill in similar components
    lb_similarComponents.Items.Clear();
    foreach (Component c in SimilarComponents.GetSimilarComponents(accdbConnectionString, component.ComponentID))
    {
        lb_similarComponents.Items.Add(new ListItem(c.ComponentName, c.ComponentID));
    }

    // Fill in connecting components
    lb_connectingComponents.Items.Clear();
    foreach (Component c in Database.ConnectingComponents.GetConnectingComponents(accdbConnectionString, component.ComponentID))
    {
        lb_connectingComponents.Items.Add(new ListItem(c.ComponentName, c.ComponentID));
    }
```

Appendix 5: MMET Software Editor Interface

❖ Component editor



❖ Functional attributes editor



- Movement attributes editor