DEVELOPMENT OF INTEGRATED SYSTEMATIC APPROACH CONCEPTUAL DESIGN AND TRIZ USING SAFETY PRINCIPLES IN EMBODIMENT DESIGN FOR COMPLEX PRODUCTS

By

KHAIRUL MANAMI KAMARUDIN

Thesis submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

February 2017

DEDICATION

I dedicate this work to my father, mother and brother, my beloved husband, Nazjimee and my lovely son Aariz.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy.

DEVELOPMENT OF INTEGRATED SYSTEMATIC APPROACH CONCEPTUAL DESIGN AND TRIZ USING SAFETY PRINCIPLES IN EMBODIMENT DESIGN FOR COMPLEX PRODUCTS

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February 2017

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There are many conceptual design methods available for the engineering design world. Of all the methods, two significant methods are chosen to be integrated for the effective conceptual design process. These are the Systematic Approach (SA) and the Theory of Inventive Problem Solving (TRIZ). SA consists of the Systematic Approach Conceptual Design (SACD) and Systematic Approach Embodiment Design (SAED), which were established by Pahl and Beitz, and widely used in industry and by academics. In addition, TRIZ is actively practiced in companies that wish to innovate creative and inventive designs. Although both methods have contrasting features there are some similarities that enable them to be united and harmonized. Many scholars have attempted to develop a new methodology by combining SA and TRIZ but none have integrated the safety principles of SAED with the inventive principles of TRIZ. In designing complex artefacts, constraints and safety are the main issues in the design change process. Implementing safety at a later stage might compromise the concept ideas and end up being a conventional and common concept design. This study developed a conceptual design method, TRIZ-SA, with a specialized safety approach combining the Function Constraint Model (FCM) and the Safety Principle Guide (SPG) as the method's tools. The method aims to encourage the intervention of safety in the conceptual design process to stimulate ideas for solutions that are efficient in safety and creativity. The development of TRIZ-SA is through qualitative content analysis of the work of many scholars and patents. The pairwise comparative analysis is also conducted in the development of the 8-Step. The validation of the combined method for the safety approach is done through a conceptual design case study on the geometric and shape design of an aircraft's Main Landing Gear (MLG). The combination of SA and TRIZ resulted in an easier solution finding process for an artefact that requires high concern in terms of safety, thereby opening up a new perspective in the designing concept of a complex artefact and shaping the design path towards a safe and creative concept design. The implications of this study will help designers optimize and develop a safe and inventive concept design in an effective and creative way.

Keywords: Conceptual design, SA, TRIZ, principles, main landing gear

Abstrak yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah.

PEMBANGUNAN INTEGRASI PENDEKATAN REKABENTUK KONSEPTUAL BERSISTEMATIK DAN TEORI PENYELESAIAN MASALAH INVENTIF (TRIZ) MENGGUNAKAN PRINSIP KESELAMATAN DARI REKA BENTUK REALISASI UNTUK PRODUK KOMPLEKS

Oleh

KHAIRUL MANAMI KAMARUDIN

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Terdapat pelbagai kaedah rekabentuk wujud khusus untuk dunia rekabentuk kejuruteraan. Melalui kebanyakan kaedah-kaedah reka bentuk itu, dua kaedah yang ketara dipilih untuk disepadukan untuk proses reka bentuk konsep yang lebih berkesan. Dua kaedah itu adalah Pendekatan Sistematik (SA) dan Teori Penyelesaian Masalah Inventif (TRIZ). SA merangkumi Pendekatan Konseptual Bersistematik (SACD) dan Pendekatan Sistematik Reka Bentuk Realisasi (SAED), dibina oleh Pahl dan Beitz digunakan secara meluas dalam industri dan dunia akademik, dan TRIZ pula diamalkan secara aktif di syarikat-syarikat yang ingin membuat pembaharuan produk dari segi reka bentuk kreatif juga berdaya cipta. Kedua-dua kaedah mempunyai ciri-ciri yang berbeza namun terdapat beberapa persamaan yang membolehkan mereka untuk bersatu dan diharmonikan. Ramai para ilmiah telah mencuba untuk membangunkan metodologi baharu dengan menggabungkan SA dan TRIZ, namun masih tiada lagi yang menggunakan prinsip keselamatan dari SAED untuk diintegrasikan dengan prinsip inventif TRIZ. Dalam mereka bentuk artifak yang kompleks, kekangan dan keselamatan adalah isu utama dalam proses perubahan reka bentuk. Melaksanakan isu keselamatan pada peringkat yang lewat mungkin akan mengganggu dan mengubah idea konsep dan akhirnya menjadi reka bentuk konsep yang konvensional dan biasa. Kajian ini bertujuan untuk membantu pereka melakukan reka bentuk konsep menggunakan pendekatan keselamatan dari peringkat awal dengan membangunkan Panduan Prinsip Keselamatan (SPG) berstruktur bersama Model Kekangan Fungsi (FCM). Kaedah yang dibina dalam kajian ini bertujuan untuk menggalakkan penggunaan keselamatan dalam proses reka bentuk konsep untuk merangsang idea penyelesaian yang berkesan dalam keselamatan mahupun kreativiti. TRIZ-SA dibangunkan melalui analisis kandungan kualitatif pada kebanyakan hasil kajian penyelidik dan juga paten. Analisis perbandingan pasangan juga dijalankan dalam membangunkan 8-Step. Metodologi yang terhasil dari kajian ini disahkan melalui ujian pembinaan reka bentuk konsep geometri dan rupa bentuk pada Gear Pendaratan Utama (MLG) pesawat. Gabungan SA dan TRIZ ini dapat menghasilkan proses penemuan penyelesaian dengan lebih mudah untuk artifak yang

memerlukan tahap keselamatan yang tinggi, membentuk acuan reka bentuk ke arah konsep yang selamat dan kreatif. Implikasi dari kajian ini akan membantu pereka mengoptimumkan dan membangunkan reka bentuk yang selamat dan berdaya cipta dengan menggunakan kaedah yang berkesan dan kreatif.

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Khairul Manami Binti Kamarudin

I certify that a Thesis Examination Committee has met on 6 February 2017 to conduct the final examination of Khairul Manami binti Kamarudin on her thesis entitled "Development of Integrated Systematic Approach Conceptual Design and TRIZ using Safety Principles in Embodiment Design for Complex Products" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

39-P	39 Parameters
40-IP	40 Inventive Principles
AbsGen	Abstraction and Generalization
AFD	Anticipatory Failure Determination
ARIZ	Algorithm of Inventive Problem Solving
Artefact	Current or as-is object/component/problem
CEC	Cause and Effect Chain
CPC	Cooperative Patent Classification
EC	Engineering Contradiction
F3	Form, Fit and Function
FAM	Functional Analysis Model
FEA	Finite Element Software
FoS	Factor of Safety
FS	Function Structure
HOQ	House of Quality
IFR	Ideal Final Result
IPC	International Patent Classification
MF	Main Function
MLG	Main landing gear
MoS	Margin of Safety
PC	Physical Contradiction
Prototype	Future design/ conceptual design of object/component/new design/ new concept design
QFD	Quality Function Deployment
SA	Systematic Approach

SACD	Systematic Approach Conceptual Design
SAED	Systematic Approach Embodiment Design
SFR	Substance and Field Resources
SPG	Safety Principle Guide
Su-Field	Substance-Field
TESE	Trend of Engineering System Evolution
TRIZ	Theory of Inventive Problem Solving

CHAPTER ONE

INTRODUCTION

The conceptual design activity approach to creative and systematic design requires work collaboration with many design tools, experts from the design and engineering fields, plus information on recent and available technologies. By combining these factors, designers can produce a creative design in a controlled and systematic manner, so that the design activity produces an effective design and a definitive work. A conceptual design of a high-risk artefact, however, requires much greater work effort, especially in terms of the design constraints irrespective of other engineering requirements. The relationship of the components with each other must function properly to avoid any mishap that could spark a more serious occurrence or disadvantage in respect of performance. This research focuses on the systematic conceptual design activity, which emphasizes inventive problem-solving with respect to the design constraints and safety. The new conceptual design method was validated on a complex subject matter, i.e. an aircraft's main landing gear (MLG) component.

1.1 Background

The normal practice of conducting conceptual design for a complex component requires greater skills, experience, and a relatively longer period of time to design a single concept. This is due to the higher number of characteristics, process varieties among the characteristics, and constraints in terms of design parameters, material behaviour, working principles, and, especially, safety. To achieve the best concept design, designers have to equip themselves with in-depth knowledge of the component of study or artefact. A systematic conceptual design process is also a crucial necessity to further enhance complex artefacts, their function, and new applications of technology.

Despite the extensive research on the conceptual design methodology, most manufacturers prefer to apply empirical methods in their conceptual design process because of the higher confidence and rate of success than those applied in the theoretical method concept of design. This may be caused by several factors: firstly, the term 'concept' produces scepticism among most designers and manufacturers thereby reducing their confidence to invest in such an activity. They tend to be very conservative in response to change and mostly utilise existing parts and components wherever possible. Secondly, limited resources cause companies and manufacturers to be more comfortable with existing designs and to only make minor modifications to avoid the increased cost. Typical design methods, such as empirical methods, however, are less advantageous for capturing new technology (March, 2012).

Apart from improving the performance of an artefact, the involvement of creativity and inventiveness in the conceptual design is also important. Creativity promotes the use of new approaches to the artefact's main function, new technology and may turn the prototype into a revolutionary product if it is designed creatively and systematically. The creativity also involves, using better, less and lighter material, hybrid movements instead of mechanical movements, less pollutant energy, other added value, and beneficial input by using available natural resources rather than creating an additional or artificial mechanism. A systematic conceptual design process further increases the understanding of the characteristics of the component and its functions towards the whole system of the artefact by the designer, and, later, they are able to manipulate them according to the design aims.

Design method helps ease and guide designers to achieve a design solution efficiently. In conducting the conceptual design process of an artefact, designers have to be analytic, avoid only implementing conventional problem-solving processes and fixating on a conventional solution without careful examination of the problem. Designers should also be concerned with the constraints and safety of the artefact when conducting the problem-solving process, especially for complex artefacts.

1.2 Research Problem Statement

There are many design methodologies and problem-solving techniques available to help designers construct conceptual designs efficiently and stimulate creative thinking. From the category of systematic design methodologies, these include Pahl and Beitzs' Systematic Approach (SA) (Pahl et al., 2007), Total Design (Pugh, 1991; Pugh & Clausing, 1996), Quality Function Deployment (QFD) (Akao, 2004), Six-Sigma (Smith, 1993) and many more. Meanwhile, from the design methodology for the creative design category are the Theory of Inventive Problem Solving (TRIZ) (Altshuller & Shulyak, 1996; Altshuller, 1999; Altshuller et al., 2002), Brainstorming (Osborn, 1962), Six Thinking Hats (Bono, 1989; Bono, 2010), and 6-3-5 Brainwriting (Rohrbach, 1969) to name a few. Several design methods are tabulated in Table 1.0, to differentiate each method's approach to systematicity, creativity and safety implementation in its problem-solving procedures.

Table 1.1: Comparison of the respective approaches between the systematic design process and creative design process, and safety integration

Design Method (with Conceptual Design)	Developer	Systematic Design Process	Creative Design Process	Safety Integratio n
Systematic Approach	Pahl & Beitz (1984)	✓		✓
Total Design	Pugh (1991)	✓		
Six Thinking Hats	Edward De Bono (1985)	✓	✓	
Quality Function Deployment (QFD)	Yoji Akao (1966)	✓		✓
Failure Mode & Effect Analysis (FEA)	Reliability Engineers (1950s)	✓		✓
Axiomatic Design	Suh Nam Pyo (2001)	✓		
Six-Sigma	Bill Smith (1986)	✓		✓
Theory of Inventive Problem Solving	Genrikh Altshuller (1946)	✓	✓	

Among all the design methods shown in the table, none implement all three processes – systematicity, creativity and safety inside conceptual design process. The research selected SA and TRIZ as the main focus for the integration of safety in conceptual design. SA is treated as the underlying design process model because of its wider design scope, from problem identification to detail design and has a systematic flow in its conceptual design process. TRIZ is chosen for its unique problem-solving techniques. Most of its tools and problem-solving procedures helps in triggering innovative solutions and focused based rather than spontaneuos and by chance. Tomiyama et al. (2009) categorized both Pahl and Beitzs' work and TRIZ as concrete design theories and methodologies.

Pahl and Beitz's SA (Pahl et al., 2007) is widely accepted in education as well as in industry for its effectiveness in delivering engineering design artefacts. From the electronic industry to aircraft design, the SA application has helped, especially in the study of functions through its Function Structure (FS) tool. The SA is a strategy method to increase the probability of success in design by prioritizing the clarification of tasks, the use of abstraction and constraints in problem formulation, plus a firm validating process. In general, SA implements a detailed and systematic process in its methodology. However, the drawbacks of SA are that when the creative stage begins, SA adopts a number of creative methods outside SA, such as the Classification Scheme, Morphological Matrix (Zwicky, 1969), Consistency Matrix (Lindemann, 2006), House of Quality (HOQ) from Quality Function Deployment (QFD) (Akao, 2004) and other domain-specific design tools. Such activities adds extra work for the designer as different design tools require different work methods. SA also practices a wider solution scope, meaning non-focused solution finding using a solution-neutral approach.

TRIZ, on the other hand, is a unique method for producing inventive and creative artefacts. TRIZ has helped small companies flourish in the product market by introducing radical change and encouraging the integration of new technology in the development of artefacts. Companies, such as Intel, Samsung, Proctor & Gamble, and Boeing for example, implement TRIZ in their development of conceptual products. TRIZ emphasizes the principles, standards and effects in the problem-solving process, and highlights the causes of the problems for the determination of contradiction. Different to SA, TRIZ uses focused solution space, only considering the problem's characteristics and other elements inside the problem's boundary. The focused approach reduces the designer's work and fixates solely on resolving the problem. The drawbacks of TRIZ, however, concern its scope, which is not for simple problems. TRIZ also has too generic way of formulating contradiction and only uses a checklist to support evaluation process. In addition, the TRIZ process only ranges from problem identification up to the conceptual design and provides little support at the system-level, but, instead, focuses on the component level. TRIZ adopted the Functional Analysis Model (FAM) to understand the system of an artefact for the improvement of the component level focus. However, there is no provision for the safety approach within either the TRIZ Engineering Contradiction (EC) or the Physical Contradiction (PC) processes at this time.

Both SA and TRIZ methodology does not acknowledges the implementation of safety principles during the conceptual design process. The SA has a firm application of safety principles in its Systematic Approach Embodiment Design (SAED) process. This research addresses the issues of safety principle implementation in the Systematic Approach Conceptual Design (SACD) process by integrating safety in the idea generation process for the establishment of safe and creative concept design. Apart from SA and TRIZ, four methods that combines TRIZ with SA of other scholars: Malqvist et al. (1996), Dietz and Mistree (2009), Nix et al. (2011), and Mayda and Börklu (2014) are reviewed and also found no integration of safety.

1.3 Research Objectives

This research integrates all three elements – systematic, creative and safe design methodology – and develops a new conceptual design method. The objectives of this research are:

1. To develop a conceptual design framework using the TRIZ and SA methodology.
2. To construct a safety principle guide and function constraint model.
3. To validate the conceptual design framework, the safety principle guide and function constraint model with an aircraft's main landing gear as the design artefact.

Objective 1 of this research concerns developing a new conceptual design method in the form of a conceptual design framework. The framework consists of a combination of tools from both SA and TRIZ, with two additional new tools developed for the safety approach. Although generally for complex products, the new framework is applicable for any artefact, and not just the case study artefact demonstrated in this research.

Objective 2 pertains to the safety intervention inside the outcome of objective 1. Design constraints are necessary because significant innovations happen despite the inadequacy of resources and various design limitations. Indeed, constraints can be the catalyst for the creation of greater innovation and a better conceptual design. Safety requirements should be placed alongside functional requirements to help designers define the system and limitations of the artefact's system better. It is hoped that the outcome will help designers to understand problem-solving better, experience an efficient conceptual design process, and gain the ability of an understandable and accessible design methodology.

Objective 3 is a validation process that demonstrates the new conceptual design method. The process is to show the efficiency of the method, and how systematic it is to conduct a conceptual design on a complex artefact. Another reason for performing validation is to show the effectiveness of the method in the development of new concept ideas with elements of safety and creativity.

1.4 Research Aims

By combining the advantages of SA and TRIZ methodologies, it will increase the effectiveness and empower the conceptual design process where the deficiencies of SA are compensated for by the advantages of TRIZ and vice-versa. This research mainly integrates the advantages of both methods with the intervention of safety principles within the conceptual design framework, putting the safety pursuit before further embodiment and detailed design.

In general, this research aims to empower the TRIZ methodology by solidifying the TRIZ inventive tools with the SA systematic structure, and to ensure it is applicable for an artefact that involves a high safety concern. At the same time, the research also aims to apply TRIZ within the creativity process of SACD, in combining working principles and the selection of a suitable combination of procedures. The potential outcome from this research could be used as an alternative method in prevention through design or 'Safety by Design', or 'Safety by Design' and in addition to TRIZ's Anticipatory Failure Determination (AFD) (Kaplan, 1999; Thurnes et al., 2015). Figure 1.1 shows the proposed approach of this research as opposed to the current conceptual design practice. The proposed practice of conceptual design flow suggest intervention of constraint and safety in between function analysis and idea analysis, resulted to defining safety earlier than current practice.

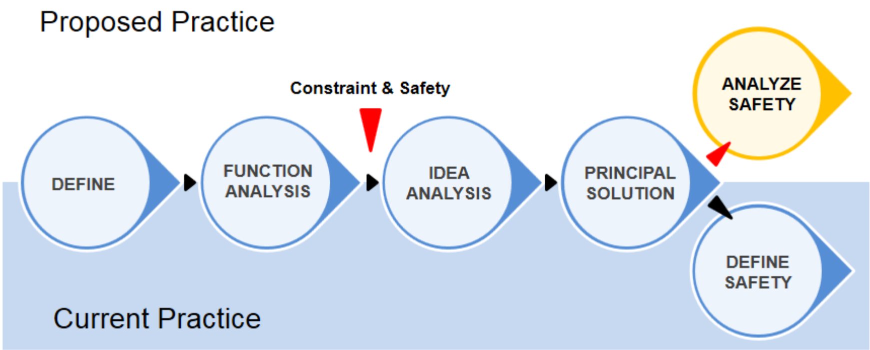


Figure 1.1: The process flow of proposed and current practice of conceptual design process

1.5 Research Scope

Referring to Figure 1.2, the general view of the research objectives can be described as an integration of TRIZ tools inside SACD and combining safety principles from SAED. The constraints and safety must work hand-in-hand; therefore, a constraint model should be introduced.

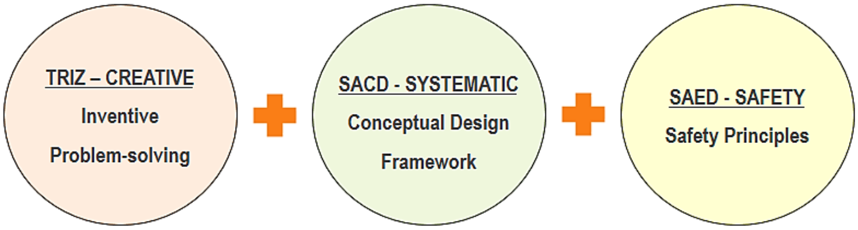


Figure 1.2: The research generic conceptual framework, where the TRIZ and SACD procedures, and SAED safety principles are merged

The scope of this research focuses on the conceptual design process of an artefact and does not involve the embodiment and detailed design. The research focuses on the development of a new conceptual design method consisting of TRIZ, SACD, and the SAED safety principles. The validation of this research's outcome is through a conceptual design of an aircraft's main landing gear (MLG).

1.6 Structure of Thesis

The structure of this thesis is presented in five chapters. The first chapter is the introduction. This chapter briefly explains the problem statement, research objectives and provides an overview of the research scope. Chapter 2 is the literature review, which provides a comprehensive review of related information within the research scope. Chapter 3 presents the research methodology. It describes the overall research methodology and techniques used, outlines the research aims and research framework, and briefly explains each approach according to the research objectives. The results from the research method outlined in Chapter 3 and the discussion are presented in Chapter 4. In this chapter, the problems and issues in the conceptual design framework, validation of TRIZ-SA, and discussion concerning the theoretical and methodological contributions are carried out. The last chapter, Chapter 5, is the conclusion, and features future work and the recommendations of this research. The research is intended to be part of an important contribution for design research, generally, and for TRIZ practitioners, specifically.

1.7 Summary

The subsequent motivation for conducting the research on the integration of TRIZ and SA methodology was to enhance the systematic and safety aspect inside the TRIZ methodology, and to strengthen the TRIZ methodology in a substantial way. The next motivation was to challenge the efficiency of TRIZ-SA in designing complex artefacts in terms of a new possible-to-produce concept design. The research hopes to find the opportunity to implement creative design inside complex components to make it possible to integrate new technology, and enhance or replace old ones.

CHAPTER TWO

LITERATURE REVIEW

This chapter encompasses the foundation of TRIZ-SA and the discussion here surrounds the conceptual design perspective. The research does not involve manufacturing ability in the conceptual design process. A review of the literature regarding conceptual design, safety principles, TRIZ, the work of Pahl and Beitz (Pahl et al., 2007), and artefacts are discussed. Through observations, insights concerning the importance of this research are presented. The review justifies why several approaches are applied for validating the efficiency of the proposed conceptual design methodology.

2.1 The Literature Review Structure

The literature review structure is systematized accordingly from the higher level of design knowledge towards the specific design focus of the research to identify the current scenario of the conceptual design process in relation to the design methodology. Towards the end of this chapter, the justification of how this thesis addresses the issues, gaps and opportunities found in the review is presented. There are five main structures (Figure 2.1) supported by the research method and case study artefact reviews.

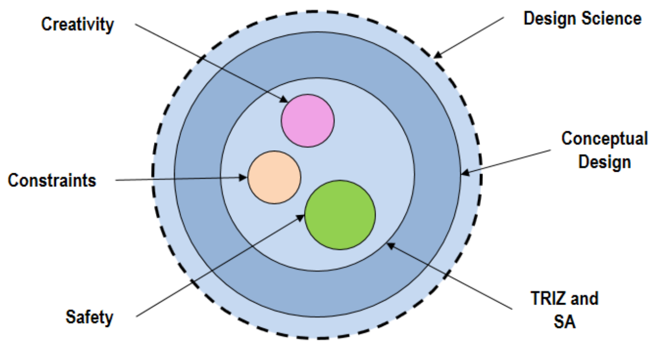


Figure 2.1: The literature review structure of this research

The higher-level knowledge related to this research is the design science, which is briefly discussed. Next, the research focuses on the conceptual design knowledge, where the research core is based. Here, several design methods are reviewed and compared with the objective of this thesis. Then, an explicit review of the literature concerning immediate discipline, the TRIZ and SA methodology are presented. In the specific structure, reviews on the design constraints, safety approach and creative problem-solving are comprehensively presented.

2.2 Design Science

The ‘Design Science Research’ or ‘Design Science’ falls into the epistemology branch of philosophy, a body of knowledge that studies the design process and continuously improves the design process for a broader range of design problems rather than being domain specific. The knowledge pertaining to design science is mostly contributions from designers and scientists’ empirical findings, and design explorations on specific design processes. Most of their practices and findings are centred on developing domain specific systematic design procedures. Then, the design science community gathers the contributions and provides a more generic design practice that is applicable to a wider domain. Design science is consistent in spreading and disseminating knowledge for systematizing the design process until today.

The history of design science can be traced back to the ‘Conference of Design Methods’, which was first held at the Department of Aeronautics, Imperial College London, 19th to 21st September 1962 (Christopherson, 1963; Cross, 1993). Initially, the terms ‘Design Research’ was commonly used. According to Cross (1993), the event marks design methodology as a field of modern design methodology, which previously originated from a scientific method.

Many scholars from 1965 onwards developed a systematic form of design process, especially for engineering, medicine, computer science, architecture and management studies. One example of a successful researcher in design research is the Nobel Prize Laureate Herbert Simon, who authored the book ‘A Science of Design’ (Simon, 1996). His significant work in design science concern the complex architecture of computer systems and cognitive psychology, and highly cited publications in Artificial Intelligence (AI) (Simon, 1988) and decision-making sciences (Simon, 2013). Later, Buckminster Fuller (Fuller et al., 1999) introduced the term ‘Design Science’, which is defined as the systematic form of designing, where the research on design methodology falls in the field of science. From this time until today, design science has spread its application to complex engineering, such as AI, information systems, architecture, complex engineering design and much more.

There are four significant categories of knowledge under design science – theory of technical systems, design knowledge about objects (system), theory of design processes, and design process knowledge (design methodology) (Hubka & Eder, 1988). Design methodology is a process for generating an object’s specification based on its existence in the environment, desired structural and behavioural properties, goals set for the object, object history, and limitations or the constraints in the object solution. Conducting design methodology guides designers in understanding a current problem, the artefact’s function and knowledge advancements, design planning and problem-solving. Design methodology helps the designer to identify areas of the artefact for improvement or manipulation (functions or embodiment), and helps in decision-making during the process of conceptual design. The progress of design science and the current trend of advocacy on systematic methods and problem-solving in design science is actively borrowing techniques and management theories from the Information Technology (IT) and computer science domain (Archer, 1964). The approach of such techniques is supported by Cross (2001), where new design research, such as for IT, research method and user-experience (UX) are now developed. Cross coined the word 'Designerly Ways' for the recent design advancements.

A research by Venable (2006) identified the significant role in developing design science research, where theory and theorizing constitute the key role. Extensive knowledge on the theory of the artefact enables the researcher to build new theory and further prove it by implementing it into a problem, a technology or an evaluation strategy. The framework of design research activity developed by Venable (Figure 2.2) shows that theory building is the central activity of design science and ties together areas of technology design, problem diagnosis and technology evaluation.

The technology design is the major contributor for design science where advancements and creations of design method, product, system, practice or technique become one of the drivers for theory building. Another two driving elements for theory building are the problem diagnosis and technology evaluation process. In short, Venable concluded that the accomplishment of a design science research is to have technology invention and evaluation.

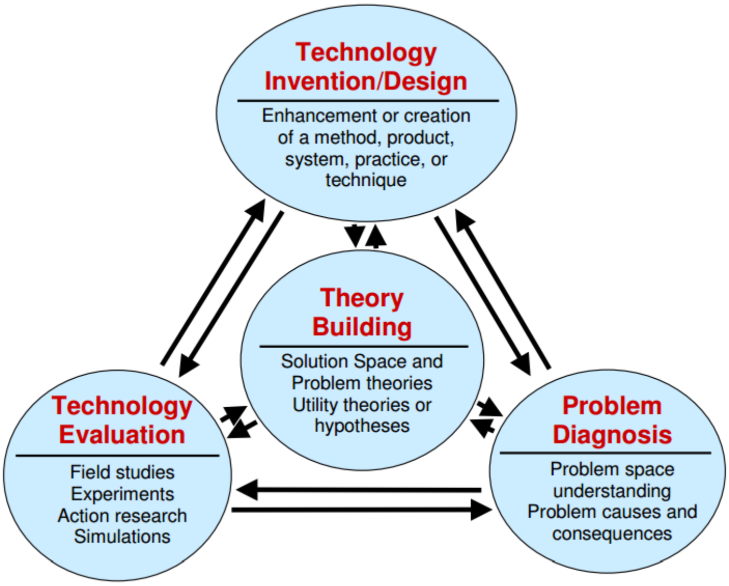


Figure 2.2: An activity framework for design science research (Venable, 2006)

Apart from increasing the holistic understanding of the design process, greater attention is needed for the application of new technology for the enhancement of human and environmental quality, energy efficiencies, safety, and cost effectiveness. Tomiyama et al. (2009) compiled many design methods and divided the methods into two categories:

a) Abstract: this has two subcategories. The first is *‘Abstract and individual’*, where the method is applicable to a specific class of artefact design. The method often uses mathematics and algorithms, usually with the integration of computation. The method does not include geometric modelling and is more of an abstract approach, such as the Taguchi method (Taguchi, 1986; Taguchi et al., 2005). The Taguchi method emphasizes the statistic model and aims to increase the quality of goods. The second sub-category is the *‘Abstract and general’,* where the general approach means that the method emphasizes the design theory, design processes and knowledge. The method can be applied to a wider class of artefact but requires additional processes when it comes to a non-obvious and complex artefact. An example of the abstract and general design method is the General Design Theory (GDT), by Yoshikawa (Yoshikawa, 1981; Tomiyama & Yoshikawa, 1986), which consists of assumptions (axioms) and predictions (theorems).

b) Concrete: this category also has two sub-categories. The first is *‘Concrete and individual’*. The methods that fall in this category mostly apply to individual design cases, specific artefacts with specific problems, and are often solved using the procedural design method, such as aircraft component design. The second sub-category is the *‘Concrete and general’*. The design methods that fall in this category have a concrete process and method but can be applied to a wider variety of artefacts. The method focuses on the characteristics of artefacts but that are common or identical in different artefact domains. The method often adopts a prescriptive method, such as TRIZ, Pahl and Beitz’s work, concurrent engineering and Design for X (DfX).

2.3 Conceptual Design in Product Development

The conceptual design is one of the important phases in the development of an artefact, and is usually conducted at the earliest phase of research and development in manufacturing companies or technology development institutions. In the engineering design context, conceptual design is the process for developing a new product or an improvement to an existing product so that the product continues to give benefit to the user, and, at the same time, continues to sustain in the market.

The process of conceptual design requires considerable data processing, where designers obtain the resources of the artefact, examine and analyse the resources, and evaluate which resources to use to turn the artefact into a successful prototype. The process requires immense skills and experience of micro-decision-making, creative thinking skills and evaluating skills in finding the best alternative solutions to the current problem.

Apart from the skills of analysing, decision-making, evaluating and creative thinking, designers should also acquire the ability to make criticism, predict the outcome of the design and the future of the artefact, and whether it will sustain in the market dominantly or secondary. This is due to the changes made to the artefact. Although the conceptual design stage requires analytical skills and creative brain activities, the stage is actually an iterative process, and requires flexible time and cost for the process of obtaining ideas, information and knowledge depending on the nature of the artefact. Within the conceptual design stage, a mixture of generic and specific approaches take place.

There are several popular conceptual design methodologies for successfully producing dominant products in the market, as shown in Table 1.0 in the previous chapter. The next sections elaborate on some of the design methods taken from the table.

2.3.1 Pahl and Beitz's Systematic Approach

The 'Systematic Approach' (SA) is the work of Pahl and Beitz (Pahl et al., 2007). It is commonly used in engineering design activities today and is used as a text book for mechanical design subjects in many universities. Their first book on SA was published in German, in 1977 titled *"Konstruktionlehre: Handbuch für Stadium und Praxis"* (Engineering Design: Handbook for Learning and Practice) (Beitz, 1986). It was later translated into English in 1988 by Arnold Pomerans and Ken Wallace.

Gerhard Pahl, is an alumnus of Technishe Universität of Darmstadt and was a professor for Product Design and Machine Elements - *Produktentwicklung und Maschinenelemente* (PMD) at the same university (Marjanović, 2015), vice-president of the German Research Foundation (*Deutsche Forschungsgemeinshaft*), and an extraordinary member of the Berlin-Brandenburg Academy of Sciences (*Berlin-Brandenburgische Akademie Der Wissenshaften*) (Pahl et al., 2007). The second author, Wolfgang Beitz is an alumnus of the Technische Universität of Berlin, and works as a professor in the Department of Mechanical Engineering at the same university. He led both the VDI Directive "*Approach to the development and design of technology system and product*" and VDI guideline of "*Construction of recyclable technical products*".

2.3.2 Theory of Inventive Problem Solving

TRIZ is the Russian acronym for *Teoriya Rescheniya Izobretatelskich Zadach*, which means the Theory of Inventive Problem Solving. In 1946, the creator of TRIZ, Genrikh Altshuller, a Soviet engineer, established a unique problem-solving methodology while he was working in the patent office in Baku, Azerbaijan, USSR. He found that contradiction is the key to inventive problems and he developed the solution principles, standards and algorithm to solve the inventive problems. The TRIZ methodology provides its methods with instruments and tools to support creativity processes in the context of technology know-how innovation (Schuh et al., 2011). TRIZ approaches are to understand and provide mutual appreciation of problem-solving, rigour analysis, ideal solution selection, and forecasting approach.

2.3.3 Quality Function Deployment

The Quality Function Deployment, or, in short, 'QFD', was developed in Japan by Yoji Akao in early 1966. The method was developed to include customers' requirements in the design process and its primary function is for product development, quality management and customer need's analysis. The function of one if its tools, called the Voice of Customer (VoC), is to turn the customer's voice features into engineering characteristics for prototype development.

The procedures of conducting QFD consists of four phases and tabulated in its famous House of Quality (HOQ) model (Figure 2.3), the central element of the QFD (Xie, et.al, 2003). The first phase is the customer attributes, the "Whats" placed at the HOQ rows, with the engineering characteristics, the "Hows" at the HOQ columns. Second phase is between engineering characteristics, now placed at the rows, and part characteristics, at the column. Continuing to the next phase, the parts characteristics placed at the rows to be assessed with key process operations at the column. Lastly, the key process operations at the rows to be assessed with production requirements. All the four phases have its own equations.

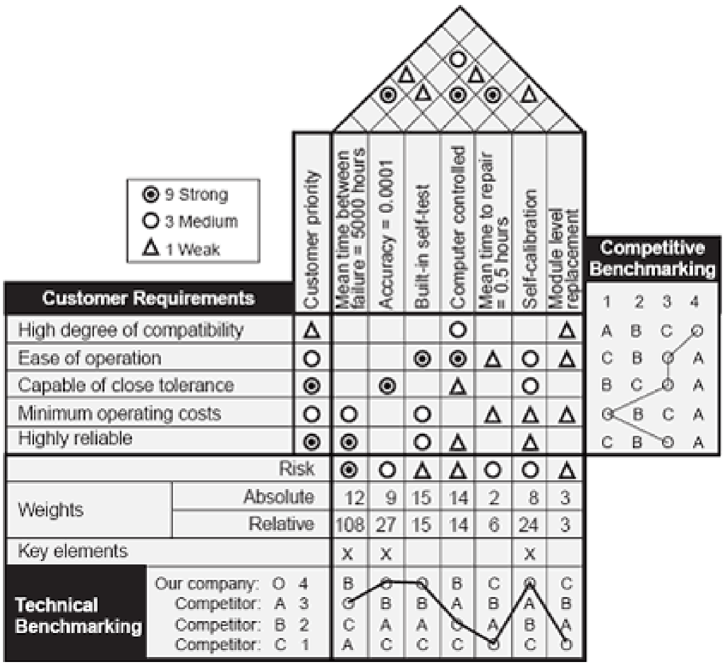


Figure 2.3: An example of HOQ from QFD (Picture Source: ReVelle, 2004)

The strength of QFD are that the method helps in reaching compromises both customer requirements and company's ability (Chien & Su, 2003). The QFD also facilitates involvements from many departments of the company. The members of each department involved in fulfilling the customer's requirements need to be in function, high effort and have strong team work. In the conventional process, attaining market analysis is through customer and competitor surveys and the product planning department will select the one that suits company's ability (Maritan, 2015). Different from the conventional way, the implementation of QFD is actually enhances market analysis itself. This can be done through matrix calculation flow, from design to production.

The weaknesses of QFD, however, are that the method experiencing difficulties interpreting VoC in terms of innovative product for future (Xie, et.al, 2003). Many of its applications are successful for current solutions. Another weaknesses of QFD is that the management of larger matrices, especially for complex projects, is complicated (Lowe & Ridgway, 2000).

2.3.4 Axiomatic Design

Axiomatic Design (AD) was developed by an MIT professor, Suh Nam Pyo in the year 1990. It is a method to identify the fundamental laws for solution finding and decision-making in engineering design. It aims to guide in establishing design objectives that satisfies customers, generate ideas for plausible solutions, analyze alternative solutions and implement the selected design (Yang & Zhang, 2000). The 'axiomatic' was adopted from the word *axiom*, defined as a fundamental truth and cannot derive from other laws of nature or principles.

The AD emphasizes on four main concepts in its methodology: the domains, hierarchies, zigzagging and design axioms. AD consists of two axioms: Axiom 1 is the independence axioms and Axiom 2 is the information axioms. The AD have separated design activity into four domains: the customer, functional, physical and process (Suh, 1990), as shown in Figure 2.4. The customer domain (CAs) is the benefits customer seek and needs reside (Babic, 1999).

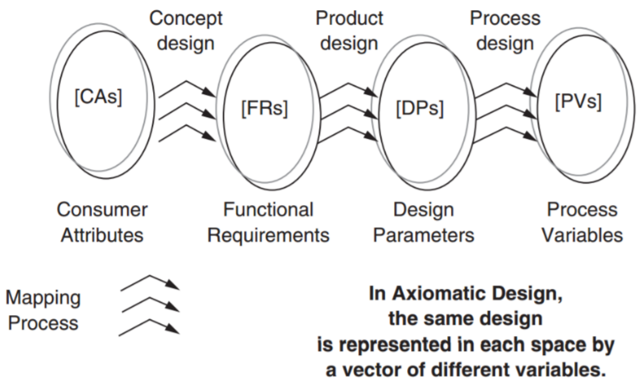


Figure 2.4: Axiomatic design's four domains of the Design World
(Dieter & Schmidt, 2012)

Within the domains of AD, terms like Functional Requirements (FRs), Constraints (Cs), Design Parameters (DPs) and Process Variables (PVs) mingled around. According to Suh (2005) each of the four terms are defined as follows:

a) the FRs is about functional requirements of the design solution, the functional needs of the artefact and each FR is independant of every other FR.
b) The Cs consist of input constraints and system constraints, where the input constraints are design specifications meanwhile the system contraints are constraints imposed by the system.
c) The DPs is related to design parameters of the design solution, the key physical variables in the physical domain, and
d) The PVs is the key variables in process domain that generates the specified DPs.

According to Dieter and Schmidt (2015), the strength of AD lies on its mathematical base, where its model of axioms, theories and corollaries are made with mathematical approach. This enable design theory and methodology community to incorporate it in practice. The AD is a vehicle to relate FRs and DPs using its design matrix that opens up linear algebra mathematical interpretation. The design matrix is a powerful conceptual tool when working with linear relationships between FRs and DPs. Although many refers the AD as a basis for comparisons with other design method, there are few weaknesses. The major weakness of AD is that there are diffculties in decoupling existing design for improvements. Another disadvantages is that Axiom 2 of AD is ill-defined and hard to understand by most designers. Some interpret it as a complexity and other assume it is reliability.

2.3.5 Morphological Analysis

The Morphological Analysis (MA) is a tool developed by Fritz Zwicky in the early year of 1967, and applied on astronomical studies, development of jet and rocket propulsion systems (Zwicky, 1969). He discover that some problems cannot be solved quantifiably. The MA aimed to explore possibilities of generating solutions to multi-dimentional, and qualitative complex problem (Ritchey, 2011; Zwicky, 1967), where quantitative and causal modelling could not be applied. The tools of MA is a simple table that places a minimum of two variables which interacts in the same type or crossing. Two variables presented in a four-fold table is considered as typology, but when variables are more than two, the typology table is not sufficient.

Zwicky develop a morphological box or 'Zwicky Box' (Hai-Jew, 2015) (Figure 2.5, left) that represents a more complex representative of variables in a single structure. At the right side of Figure 2.5, the table represents the blue ball shown in the Zwicky box in blue coloured indications. The procedures of establishing the MA should be in group oriented, must be in generic and non-quantified modelling and easy to update.

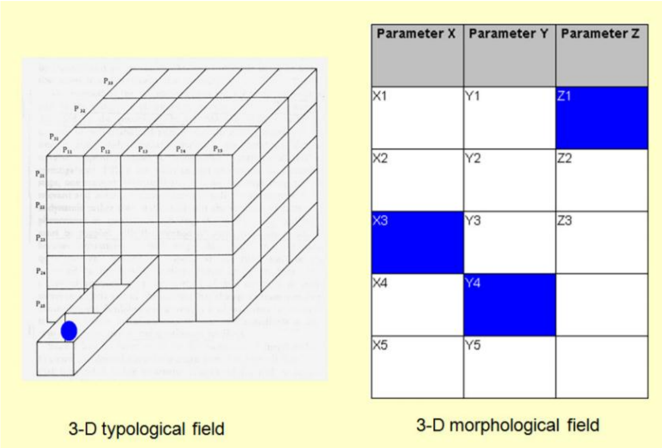


Figure 2.5: An example of morphological analysis of 3-D configuration space
(Ritchey, 2002)

The strengths of MA is that it is compatible with other modelling procedures because of its simple structure. The MA too is an unbiased method to derive solutions from any given problem, and helps in discoveries of new relationships and ideas that might be overlooked. The scientific communities found MA a positive advantage for group work and clearly defined parameters, underlying issues and conditions of problem. The weaknesses of MA is that it is time consuming. The more complex and ambitious a problem need to be resolved is, the more time and effort from group members need to be applied. In order to effectively construct MA, group members should not exceed 8 participants. Another weaknesses of MA is that the method requires strong and experienced facilitations, where linking variables and parameterizing problem is difficult and requires time (Ritchey, 2005).

2.3.6 Six Sigma

Six sigma or in symbol '6σ' is a technique for improving manufacturing process through design process, introduced by Smith (1993) while working in Motorola in 1986. It is developed to improve the quality of output through identification and removing of defects causes. It is also built to minimize variability in processes and manufacturing activity. The method's objectives are to increase the quality of product, revenues and customer satisfaction by reducing process cycle time, costs, waste, and rework.

Six sigma significant tools are the DMAIC (Define-Measure-Analyze-Improve-Control): a problem-solving process that helps in organizing design improvements and optimizations, and DMADV (Define-Measure-Analyze-Design-Verify) a tool to reduce variables (Pyzdek & Keller, 2014). The method's DMAIC have become industry standards for quality improvement. Both tools usually uses empirical and statistical method for quality managements. Figure 2.6 is an example of normal distribution of capability studies with six standard deviations .

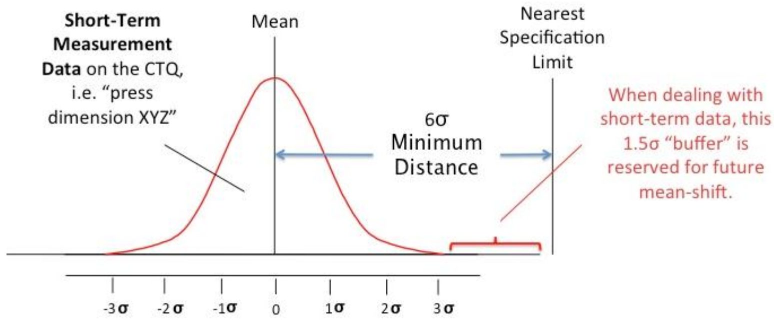


Figure 2.6: A Six Sigma graph that shows a normal distribution in six standard deviations between mean and nearest specification limit

Kwak et al. (2006) have outlined several benefits and weaknesses of Six Sigma. The strength of the method lies on its proven successful implementation in many manufacturing companies. Six Sigma is specialized in tackling and raising customer satisfaction, as well as reducing cost. It is an incremental innovation and problem-solving tool that gives oganizations ability to articulate benefits in financial returns. The weakness of Six Sigma however, it is an excellent method in improving existing process but inefficient in introducing break-through innovation and creative problem-solving. Six Sigma implements over reliance on statistical tools which requires bigger reliable and amount of data.

2.4 Inventive Problem-Solving

Problems have two types, those that can be solved with known solutions, and those that use new knowledge for the solution since the known solutions are inadequate. The latter is an inventive problem. To date, the design method that works with inventive problems is the TRIZ methodology.

2.4.1 TRIZ

TRIZ can be further explained as an empirical, constructive and qualitative methodology to generate ideas and to solve problems. It is defined as a *"methodology that develops solution(s) based on models of contradictions in technical systems"* (Altshuller et al., 2002) and a method for finding solutions derived from known inventions. To enable designers to accept, process and produce an effective conceptual design, first they have to separate the design process into four main processes. Figure 2.7 illustrates the four main processes for implementing the TRIZ methodology.

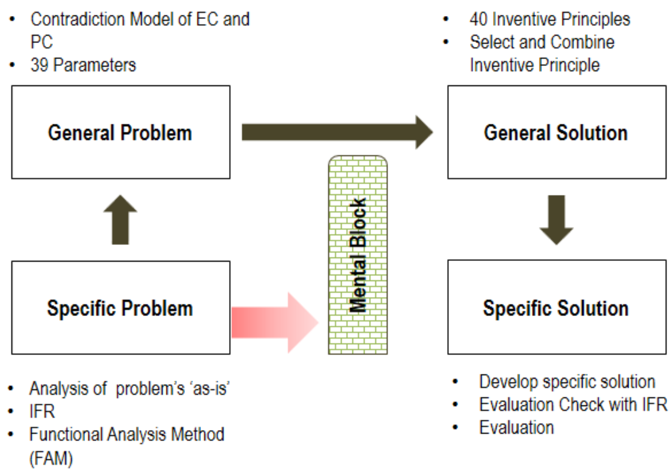


Figure 2.7: TRIZ basic steps of problem solution (Mann, 2002)

2.4.2 TRIZ Tools

Most of the TRIZ tools consist of parameters and principles. In this thesis, the list of tools discussed are only the tools used in the development of TRIZ-SA.

2.4.2.1 Ideal Final Result

The Ideal Final Result (IFR) is defined as a far-fetched goal, formulated to encourage ideas and concept to be as advance as it can be. The IFR formulation often made for an artefact or a system that will not be materially existed but achieved the functions it should provide. TRIZ scholars such as Domb (1997) stated that IFR is an implementation-free situation after the problem is solved, Belski defined it as *"the ideal system performs a required function without actually existing"* stated by (Belski, 1998 para. 9), and Mann (2001b) defined IFR as an evolutionary limit of a system. The IFR is essential for design goal-setting, guiding the designer to achieve all positive elements, eliminate negative elements and achieve all result, after identifying the core and abstraction of the problem. The most important feature of an IFR assessment is the forecasting approach by empowering future potential of the artefact. The IFR equation (1) shows that ideality is increasing the benefits and decreasing cost and harm.

$$Ideality = \frac{\sum \boldsymbol{Benefits}}{\sum \boldsymbol{Cost} - \sum \boldsymbol{Harm}} \quad (1)$$

Basically, the IFR has the following four characteristics, as mentioned by Domb, (1997):

i. Elimination of deficiencies of the original system
ii. Preserving advantages of the original system

iii. Uncomplicated system
iv. No new disadvantages introduced

Hipple (2012) stated that the first 'envisioning' is a critical step to the rest of the problem-solving process, not necessarily guarantee that the artefact fulfill the intended result but at least achieving 80% to 90% of its goal. An obvious example of IFR product is the calculator. The IFR set for the calculator in to remain its function whithout existing tangibly. In previous time, the calculator runs with mechanical functions, sizing around 20cm by 40cm, gradually have been replaced to an application inside smart phone, which, the function is still there but the body is non existant (Figure 2.8).

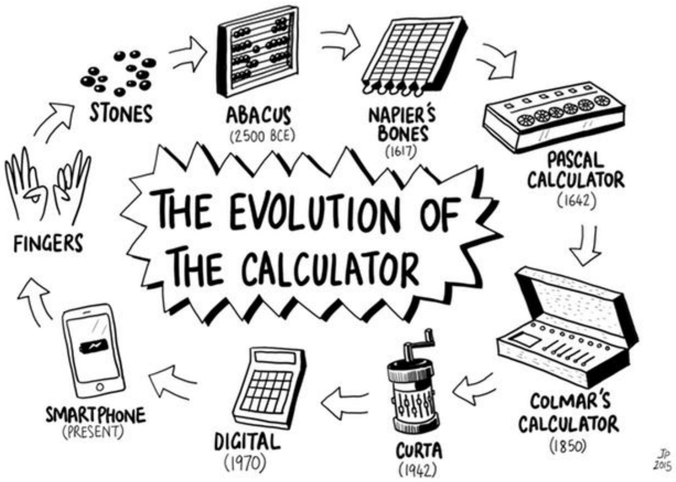


Figure 2.8: The evolution of a calculator, an example of IFR
(Source: England, 2016; Illustrated by Phillips, J.)

2.4.2.2 Function Analysis Model: A Three Flow System

The Function Analysis Model (FAM) is a model for the function analysis of an artefact. Indications of the functions and relationships between components are indicated by simple keywords and line types. The system principles pertaining to the FAM are divided into three types of system:

a) System: this is a set or a combination of procedures, components or things that function to form a unitary assemblage, and, as mentioned by Hubka and Eder (1996), such an assemblage accomplishes a specific task in a given working environment. As defined by the Collins English Dictionary (2015), a system is *"a group of interacting, interrelated or interdependent elements, that are organized, then formed in a collective unity, to achieve a common objective."*

b) Sub-system: this is a group of interconnected and interactive parts that performs an important job or task as a component of a larger system. (Kosiakoff et al., 2011; Wasson, 2015).

c) Super-system: this is a system that includes the system under consideration as a sub-system. In the event of simplifying a system, the use of a super-system is necessary to begin with (Ball et al., 2015).

2.4.2.3 TRIZ Engineering Contradiction

The Engineering Contradiction (EC) is about eliminating contradictions that have advantage characteristics as well as disadvantages from other characteristics. In identifying the contradiction, firstly a problem statement of the artefact in the arrangement of *'If-then-but'* should be established. The if-then-but is the generic approach of formulating contradiction. The *'if'* is the manipulative variable, where the variable's character can be exchanged, or modified. The *'then'* represents the advantage of the artefact and the *'but'* pertains to the disadvantages. Contradictions are then represented using an appropriate 39 Parameters (39-P) (Table 2.1) before using it in the Contradiction Matrix (Appendix C). In the matrix, recommendations of up to four 40 inventive principle (40-IP) is generated with a single EC formulation. It is a binary system for finding a solution provided that the improving and worsening parameters are identified and represented in 39-P.

The 40-IP is a collection of generic inventive solution established by Altshuller after examining more than two hundred thousands of patents. It is used in resolving contradictions of different features or elements (EC) and of the same (PC). Using 40-IP can enhance innovation abilities by brainstorming ideas within the selected inventive principles understanding. The principles can be found in the contradiction matrix. The inventive principles requires reinterpretations depending on the problem or artefact's characteristics, enabling the applicability of the inventive principles not only in technical domain but in biology, agriculture, business, management, and social relations as well (Zlotin et al. (2000). Details of each 40-IP can be seen in Appendix B.

Table 2.1: The list of TRIZ 39 Parameters (39-P)

TRIZ 39-P	
1: Weight of Moving Object	21: Power
2: Weight of Stationary Object	22: Loss of Energy
3: Length (or Angle) of Moving Object	23: Loss of Substance
4: Length (or Angle) of Stationary Object	24: Loss of Information
5: Area of Moving Object	25: Loss of Time
6: Area of Stationary Object	26: Quantity of Substance
7: Volume of Moving Object	27: Reliability (Robustness)
8: Volume of Stationary Object	28: Measurement Accuracy
9: Speed	29: Manufacturing Precision (Consistency)
10: Force (aka Torque)	30: Object Affected Harmful Factors
11: Sress/Pressure	31: Object Generated Harmful Factors
12: Shape	32: Ease of Manufacture (Manufacturability)
13: Stability of the Object's Composition	33: Ease of Operation (Manufacturability)
14: Strength	34: Ease of Repair (Reparability)
15: Duration of Action of Moving Object	35: Adaptability or Versatility
16: Duration of Action of Stationary Object	36: Device Complexity

17: Temperature	37: Difficulty of Detecting and Measuring
18: Illumination Intensity	38: Extent of Automation
19: Use of Energy of Moving Object	39: Productivity
20: Use of Energy of Stationary Object	

If the contradictions do not have any 40-IP suggestions, the solution finding should use the Physical Contradiction (PC) formulation.

2.4.2.4 TRIZ Physical Contradiction

The Physical Contradiction (PC) is the process of identifying the advantage and disadvantages of the same characteristics. This type of contradiction cannot apply the use of contradiction matrix, instead the solution to the physical contradiction problem uses Separation Principles. There are four significant Separation Principles: separation of space, time, condition and transition (Altshuller, 2002), with two other Separation Principles – structure and material (energy) – being added by Orloff (2013). Mann (2002) developed a list of 40-IP compatibility in accordance with the four Separation Principles, as shown in Table 2.2. The compatibility of 40-IP and Separation Principles can be used in the solution of PC solution ideas.

Table 2.2: 40-IP applicable for the TRIZ Separation Principles, developed by Mann (2002)

Separation Principles	40-IP	Separation Principles	40-IP
Separation of Space	1, 2, 3, 4, 7, 13, 14, 17, 24, 26, 30, 37	Separation on Condition	12, 28, 31, 32, 35, 36, 38, 39, 40
Separation of Time	1, 9, 10, 11, 15, 16, 18, 19, 20, 21, 29, 34	Separation by Transition	1, 5, 6, 7, 8, 13, 22, 23, 25, 27, 35

2.4.2.5 The Trend of Engineering System Evolution

The Trend of Engineering System Evolution (TESE) is a study of the ability to predict the future of the system and provide insights (San, 2014) for designers who want to develop future products. The TESE derives from studies of many product's S-curves. TESE is a natural transition of engineering systems, the laws of evolution of an object's state. The arrangements of the trends are based on a hierarchical structure. There are nine types of TESE, as shown in Figure 2.9. All nine concern increasing the value of a specified path, so that when designers apply the trend's transition path, the prototype may be highly accepted by the user.

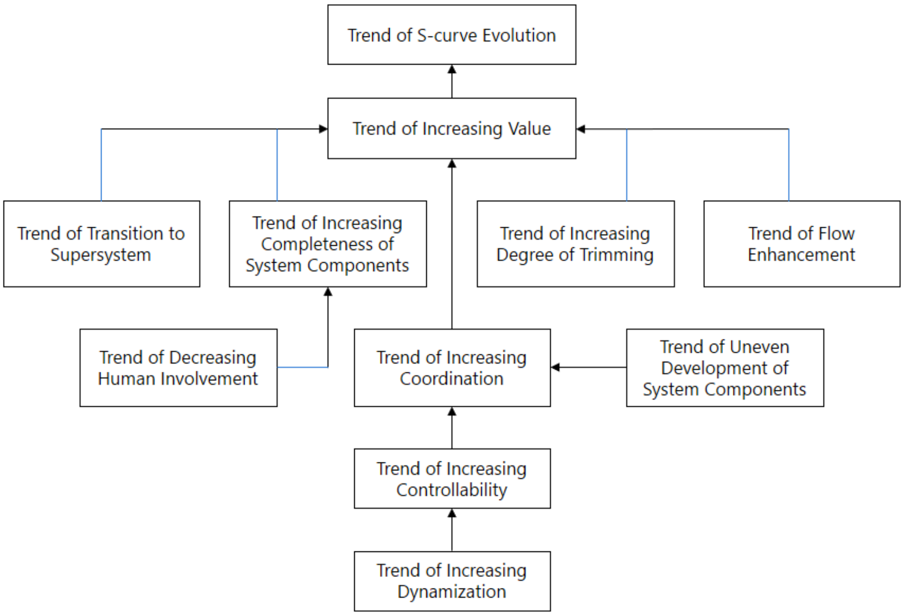


Figure 2.9: Trend of Engineering System Evolution (TESE) (San, 2014)

Since this research addresses problem-solving on the geometric design, only the trend of increasing coordination from TESE is further elaborated. The increasing trend of coordination has four sub-trends:

a) Coordination of action: the coordination of action is about analysing the interaction with the object, and very much relates to the geometry of the object, where the dimension of the object should be in four phases: 0 Dimension (0D), 1D, 2D and 3D, depending on the level of interaction. If the interaction is low, a 3D object should be turned towards 0D evolution. If the interaction is high, a 0D object should be turned to a more physical, 3D form. This type of coordination forecasting is important, especially when the design changes are intended to reduce energy transmission, which may include, heat, vibration and sound.

b) Coordination of shapes: the coordination of shapes has three ways: identical shapes, self-compatible shapes and compatible shapes. The identical shapes mean where the interaction of two shapes is connected with an identical shape, e.g. a bolt and nut are connected by the shape of the thread. Self-compatible shapes mean two or more objects connected with a similar or different shape but with the compatibility to connect, for example a Lego block and jigsaw puzzle. Finally, compatible shapes are those that are compatible with the user, for example, an ergonomic handle, aerodynamic flaps, etc.

c) Coordination of rhythms: there are two rhythm types – identical and complementary. The former is about coordinating the same element and being coordinated in sync. An example of identical rhythm is 3D glasses, where the right and left contra coloured glasses synchronize to generate a 3D visual. The latter is about complementary rhythm, meaning that two different elements are harmonized to generate a functional object or performance. An example of a complementary rhythm is when a high-definition picture and high resolution audio are coordinated to generate an outstanding and theatrical effects video.

d) Coordination of materials: the coordination of materials also has three ways: Inert material: which is a sort of artificial material that replaces the body but still retains its function; similar materials: nearly the same material or exactly the same material but from different origins, e.g. the vitamin C from apples and oranges, and identical materials: e.g. cloned materials.

2.4.2.6 Substance and Field Resources

Substance and Field Resources (SFR) is a tool from the ARIZ method of TRIZ, which requires detailed listings of tangible, intangible and even hidden elements inside the system of the artefact for eliminating conflict. ARIZ outlines three main approaches for analysing a high constraints artefact: Operational Zone (OZ), which indicates conflict space; Operational Time (OT), which indicates the resource of time of before T1, time of operation T2 and time after T3; and the third is Substance and Field Resources (SFR) where indications of the substances and field exist in the problem. The SFR consists of three types:

a) SFR of the tool: system or internal resources, which consist of the analysis of the tool and artefact substance and field.

b) SFR of the environment: available or external resources, which consist of the problem's environment and common environment.

c) SFR of the super-system: super-system resources consist of a system that is not part of the artefact's system but may influence the system to work.

An example of an SFR table is presented in Table 2.3. The most common uses in SFR are the space, time, substance and field. The information and functional analysis are often found in the FAM process. SFR is not about analysing the system but rather an inventory of all the components including the super-system (Cameron, 2010). Derivatives include hidden components, potential threats (for safety), experimental and analytical data, frequency of occurrence, and changes related to time. The fields indicated in the SFR table correspond to the specified fields shown in Table 2.4; a list of fields developed by Cascini (2012).

Table 2.3: The SFR table in accordance with resources on the system (internal), available (external) and super-system with examples (Kucharavy, 2006)

	System resources (internal)	Available resources (external)	Super-system resources
Space Void, empty space, areas	Distance, location, position		
Time T1, T2, T3	Before start, in performance, after performance		
Substances Solid, liquid, gas	Gas/wind		
Field Fmech, FCh (refer Table 2.4)	Kinetic		Energy harvest
Information Measurement, signal		Feedback indicator	
Functional Additional function of subsystem		Colours for different situation	

Table 2.4: Field types and related symbols (Cascini, 2012)

Field type	Description	Symbol
Gravitational	The natural force of attraction between any two massive bodies, which is directly proportional to the product of their masses and inversely proportional to the square of the distance between them	FGr
Mechanical	Interaction relating to, or governed by, mechanics, i.e. forces on matter or material systems (friction, inertia, elasticity, lifting, buoyancy, pressure of fluids)	FMec
Acoustic	Interaction arising from, actuated by, containing, producing or related to sound waves, even outside the audible frequency range	FAc
Thermal	Interaction related to heat transfer of any type (conduction, convection, radiation)	FTh
Chemical	Interaction related to the composition, structure, properties and reactions of a substance	FCh
Electrical	Physical phenomena arising from the behaviour of electrons and protons that are caused by the attraction of particles with opposite charges and the repulsion of particles with the same charge	FEl
Magnetic	Force exerted between magnetic poles, producing magnetization	FM
Electromagnetic	Interactions related to the generation, propagation, and detection of electromagnetic radiation having wavelengths greater than X-rays, e.g. light and vision	FEM
Biological	Interactions related to, caused by or affecting, life or living organisms, e.g. fermentation, decay	FB
Nuclear	Interactions related to forces, reactions and internal structures of atomic nuclei, e.g. fusion, fission, rays	FN

Another list of fields compiled by TRIZ opensource scholars, Ball et al. (2015) can be found in Figure 2.10. The table is used in the separation principles, transformation, interaction and merging solutions in resolving contradictions.

Elastic Stress	Gravity	Friction	Adhesion			
Buoyant Force	Hydrostatic Pressure	Jet Pressure	Surface Tension			
Centrifugal Force	Inertial Force	Coriolis Force				
Oder & Taste	Diffusion	Osmosis	Chemical Fields			
Sound	Vibrations & Oscillations	Ultrasound	Waves			
Thermal Heating or Cooling	Thermal Shocks	Information				
Corona Discharge	Current	Eddie Currents	Particle Beams	Nuclear Forces		
Electrostatic Fields	Magnetic Fields	Electromagnetic Fields				
Radio Waves	Micro Waves	Infrared	Visible Light	Ultraviolet	X-Ray	Cosmic

Figure 2.10: Table of fields used in resolving contradictions (Ball et al., 2015)

2.4.2.7 TRIZ Su-Field

The Su-Field is a short form for 'Substance-Field'. The analytical tool models existing technological system and identify whether the system is complete, incomplete, insufficient or harmful (Altshuller, 1984: Gadd, 2011). Every system is built to perform a function that requires object or substance, S1 that interact with another substance, S2. The interaction between the two substance is helped by a mean, an energy, *F*. A simple complete Su-Field consist of three element, but with a system that has a harmful complete system, the substances may be added to eliminate harmful effect, as shown in Figure 2.11.

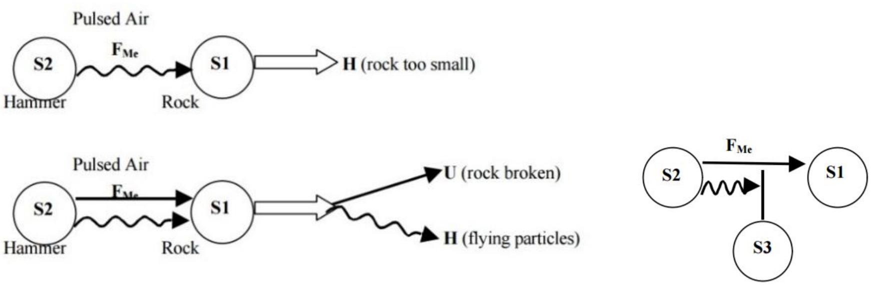


Figure 2.11: The harmful complete Su-Field (left) and resolved Su-Field (right)
(Source: Terninko, 2000)

The Su-Field often used with zone of conflict, or OZ tools of TRIZ and a specific process of problem-solving, identifying causes of harmful effect to a micro analysis. This tool can inspire the process of identifying constraints.

2.5 Systematic Problem-Solving

Systematic problem-solving is a problem-solving process that is constructed in a systematic way, within a set of rules that helps designers organize problems and solution strategies. One of the systematic methods of problem-solving notably referred to by designers whether in academia or industry is the work of Pahl and Beitz's, SA.

2.5.1 Pahl and Beitz's Systematic Approach

Pahl and Beitz (Pahl et al., 2007) both specialize in the systematic approach to engineering design, conceptual design, manufacturing knowledge, embodiment design process and have constructed an important understanding on safety by constructing safety fundamentals. SA promotes 'Function-Based' design (Kitamura et al., 2004; Erden et al., 2008), using function as the main focus for problem-solving, which is very important in identifying technical problems.

The SA design process is carefully structured and focuses on the process of product embodiment design in stepwise descriptions. The SA pioneered function-based methodology in the design process, and many other design methods are derived from SA. Through their experience from teaching and conducting engineering design, Pahl and Beitz discovered three basic rules of engineering design:

a) Clarity: clarification of design with no ambiguity, reliable prediction of the performance of the product.
b) Simplicity: smaller or simpler shape results in economical and easier manufacturing and maintenance.
c) Safety: preventing unsafe performance, preventing accidents and other risk of unsafe actions and reliable in strength.

2.5.2 Systematic Approach Workflow

The SA forms a model that represents the whole engineering design process. This is named the "planning and design process framework" or Pahl and Beitz' model, as shown in Figure 2.12. The earliest process of engineering design is the clarification of task, which product planners, engineers and designers should discuss and prepare. In this stage, market analysis and company's capabilities, product proposal and requirement list are formulated and the design process starts. The second workflow is the conceptual design process, where the development of ideas and solutions is based on the requirement list previously established. During the conceptual design process, the creativity and ideas that fulfil the goal of design are the aims. The third process is the embodiment, where the design process goes to a more specific approach. In this stage, the development of the construction structure, preliminary form design, material selections and calculations are conducted. The preliminary layout should eliminate weak spots and errors, determine disturbing influences and minimize the cost of the prototypes production. Lastly, the detailed design process commences. During this stage, the preparation for production and operating documents should be at hand. Detailed drawings, part lists, manufacturing layout and transportation are arranged accordingly. The process ends with the production of the finished product. Throughout all four processes, SA implements an evaluation of the technical and economic criteria to ensure that the production of the prototype fulfils the technical requirements as well as minimizes the overall cost.

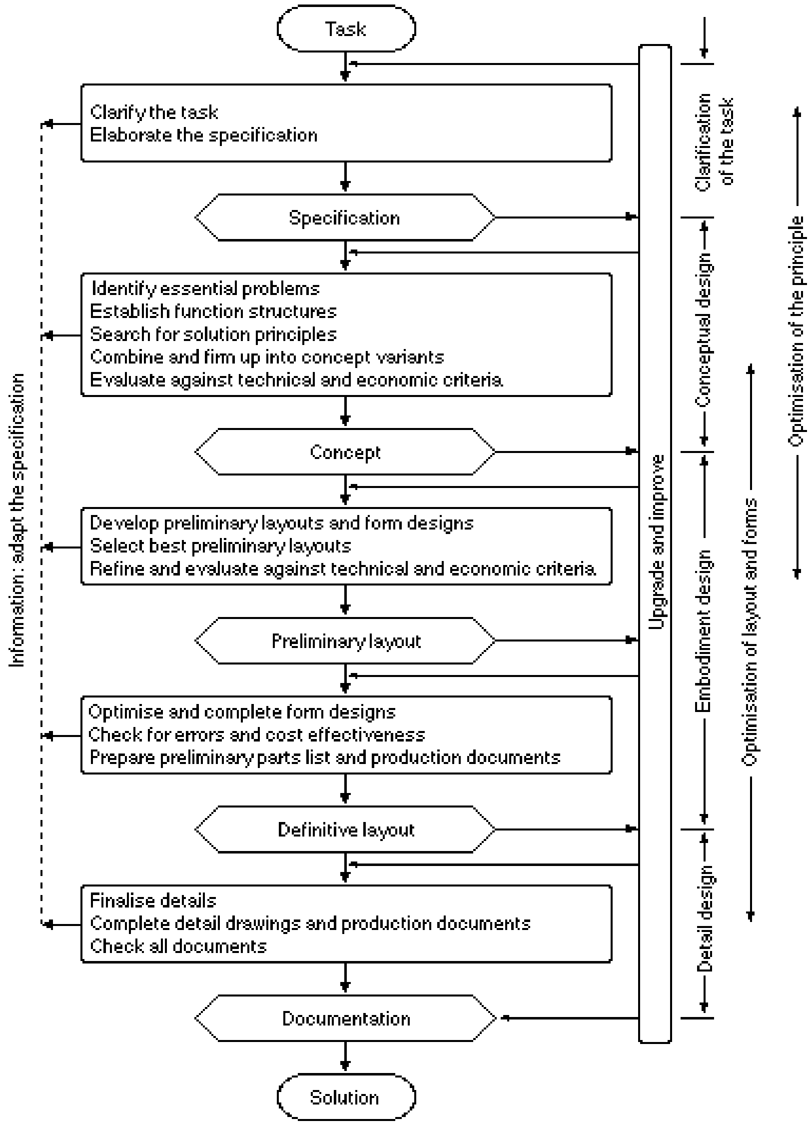


Figure 2.12: The model of engineering design, which many scholars named the 'Pahl and Beitz' model (Source: Pahl et al., 2007)

Within the SA, SACD and SAED is further reviewed.

2.5.3 Systematic Approach Conceptual Design

Conceptual design, the initial stage of design, is the process of problem identification, essentially through abstraction, function structures, working principles and developing the working structure (Pahl et al., 2007; Ralph & Wand, 2009). In the conceptual design stage, a systematic approach, such as the acknowledgement of the origins of the product, needs to be redesigned in the specification documentation that includes details about the design requirements planning, and modelling of the problem before initiating a design process (Pugh, 1991).

The Systematic Approach Conceptual Design (SACD) of Pahl and Beitz's is one part of SA, that consist of procedures specially for conceptual design. In SACD, the analysis of the problem should begin with identifying the crux of the task by asking questions about improving the technical functions or the performance of the product or the production method, or significantly reducing the space, time, cost and material. In general, the questions lead to the goals of the problem-solving. Figure 2.13 is the framework for the conceptual design process proposed by Pahl and Beitz. SA implements the method of abstraction and broadens the mental view into a more generic level; for example, not simply 'adjusting time changes among functions a, b or c into harmony' but rather that of 'time synchronization'. The abstraction technique is also applied to find the essential components inside a problem and relates with the goals set for its solution. One way to construct abstraction is firstly establish a requirement list. The establishment of the requirement list is quite a specific process but really helps in the abstraction process and processes afterwards.

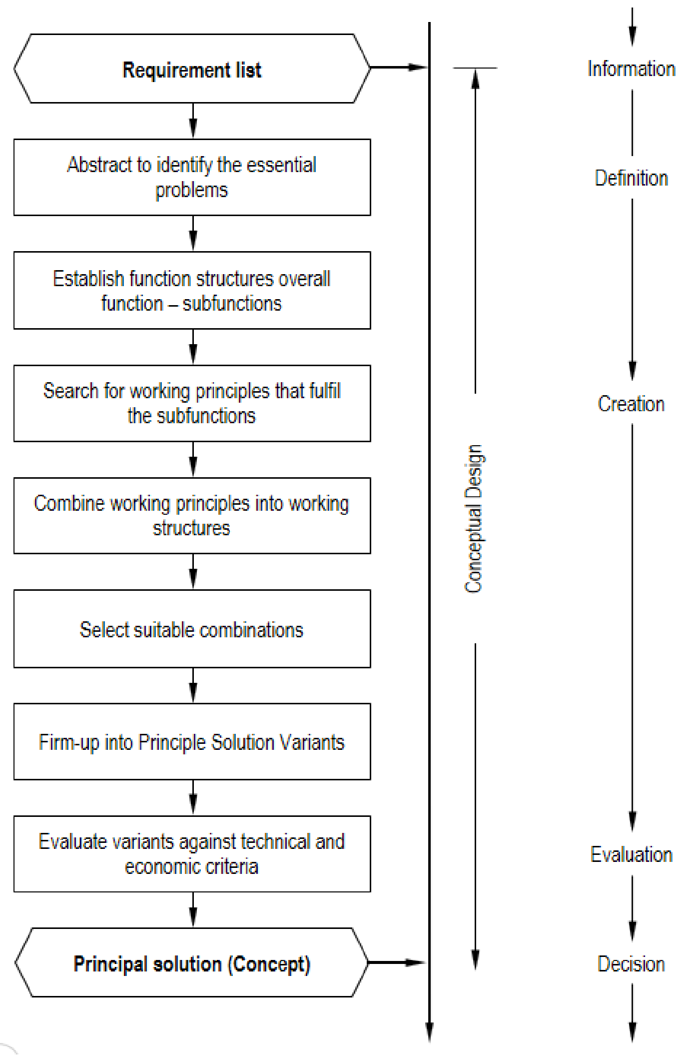


Figure 2.13: The SACD framework (Pahl et al., 2007)

The SACD has a structured conceptual design with individual steps to satisfy the problem-solving systematically with higher clarification. By implementing a proper sequence in the design process, iterations and changes during the conceptual design can be easily traced back.

2.5.3.1 Abstraction and Generalization

Abstraction and generalization constitute one part of the SACD process. When processing the abstraction, the problem's contradiction should be included in the earliest step. During abstraction, several disadvantages directly and closely related to the problem must be included, as the goal of the problem-solving is to contradict the disadvantages.

There are significant differences between abstraction and generalization. The abstraction is the reducing activity, the reduction of complexity by selecting several important elements and hiding irrelevant details. Abstraction focuses on the main structure of the artefact and its goal setting. The example of a flower (Figure 2.14) as an object (artefact) is presented in a sketch of several petals and the centre (consisting of the stigma, ovary, ovule, receptacle and pollen tube) in just the simple shape of a circle. Only the focus of change or improvement of the prototype is highlighted. Meanwhile, the generalization, is the construction of the problem statement containing multiple entities, and having similar functions within a single construct. As shown again in the same figure, many types of flower exist but they are all assembled as a single construction, a flower.

The abstraction requires the designers to simplify the problem statement, only adapting and formulating a few key factors to bring forward for generalization. In the event of formulating complex and higher-risk problems, the use of safety elements, parameters and constraints should be included in the abstraction process.

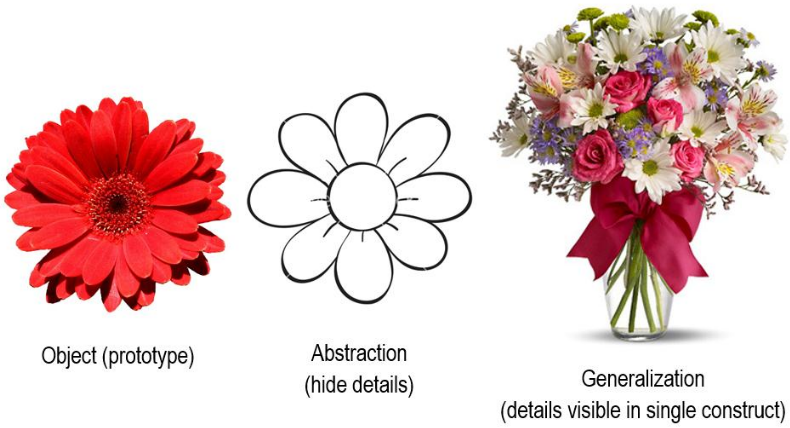


Figure 2.14: The differences between the understanding of the actual object, abstraction and generalization (Inspired by: dtldarek, 2015)

2.5.3.2 Working Principles

SA further analysis of functions requires designer to understand the working principles behind every artefact's performance. The physics of main function should be clarified and later, the constraints within the working principles can be identified.

A working principle consist of *"the physical effects reflected, needed for the fulfilment of a given function as well as geometric and material characteristics"* (Pahl et al., 2007 pg. 181). To begin the search for working principles, the main function of the artefact should be considered first before proceeding to the subfunctions. If the working principle is unknown, the physical effect is the next best consideration. The physical effect SA requires is the physical laws, the behaviour and the effects needed to perform the intended function of an artefact's components. Other than physical effect, the geometric and material characteristics helps in determining the intended functions, according to the ability of the geometric structure and the material capabilities.

An example is shown in Figure 2.15 that illustrates Bernoulli's working principles, which are required as demands (D) of an aircraft wing design, thus reflecting its geometric or form design and aerofoil physical effect. The form design consists of the material and parameters characteristics that help in achieving the physical effect of the aerodynamic lift.

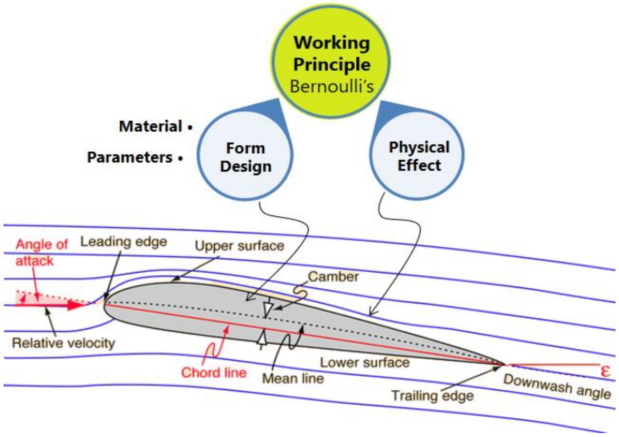


Figure 2.15: An example of an aircraft's wing design sketch. The physical effect and form design depends on the working principle of Bernoulli
(Source: Airfoil Terminology, 2016)

2.5.4 Systematic Approach in Embodiment Design

The systematic approach embodiment design (SAED) extends the results from SACD into a more specific analysis. The SAED requires preliminary layout in order to realize the concept design with.The best opportunity to reduce the risk and failures of a product is in the design stage, where, during the design process, the implementation of safety will secure the awareness of risks, and, at the same time, exhibit a more comprehensive understanding of an artefact's limitations and dangers. By implementing the safety approach in the design process, designers will develop a prototype that will affect the user's trust in the product's security, lower the level of risk and avoid environmental harm, while improving the quality of product, especially in terms of safety. Pahl and Beitz outlined two major safety principles – the direct safety and indirect safety. Under indirect safety principles, there are several sub-principles and this research adopted the 'warning' principles as the third safety principles.

1) Direct safety
2) Indirect safety
3) Warnings

2.5.4.1 Direct Safety Principles

The direct safety means safety measures that are embedded in the system that performs the task given. To ensure the application of direct safety in a system is successful, several criterias must be taken into considerations such as operating conditions, environmental factors and influences, proven principles and calculations, determination of operation limits, durability when overloaded and possible breakdown. The application of direct safety acquires accurate qualitative and quantitative knowledge on the artefact and limitations of operation. This principle calls for careful preliminary investigations and continuous monitoring, on which complex and risky artefact usually requires. The direct safety has three principles:

1) Safe-life principle: this principle applies to an object constructed in such a way that it operates without malfunction or breakdown throughout its lifecycle. For example, in aircraft design, components made of metal, especially the fuselage structures, must be designed to sustain fatigue and varying loads (Figure 2.16, left). The application of safe-life principles requires inspection of the operating conditions and environmental factors. The analysis on a system or component's durability, and limits of safe operation are also important. Safe-life is usually applicable for components with high risk, or the consequence of failure causes serious threat.

2) Fail-safe principle: this is the operation that allows failure to occur for a certain period until the failure or partial failure is detected for repair. The failure must not propagate beyond the immediate boundary of the failing system or entity environment (MIL-STD-188, (DoD, 1969)). To ensure fail-safe in the design, a function or capacity must be preserved, however small, to prevent hazard. The design also needs to restrict the function of components to a given period so that the failed component can be separated from the working boundary and be replaced. The fail-safe component must be identifiable when a breakdown occurs, such as the use of warning sign (warning principles), and the component should be designed in such a way that it is accessible for repair. An example of control rod for reactor shutdown requires electric drive, but in the event of power failure, the rod falls into the reactor core by gravity, shown in Figure 2.16 (right).

3) Redundancy principle: this increases both the safety and reliability of the systems by applying multiple safety arrangements. Redundancy is often used deliberately to allow losses; hence, safeguarding the system by applying multiple barriers, or alternative functions in the background. Example of redundancy principles applied in circuits for modular boiler safety shutdown system is shown Figure 2.17. Redundancy has five types, as mentioned by Pahl and Beitz:

    i. Active redundancy: all parts are active. Should a particular element breakdown, the function is not completely impaired.

ii. Passive redundancy: a backup or additional same function part is located in the system, where, if one breaks down, the backup runs.

iii. Principle redundancy: a multiple arrangement equal in function but with different working principles.

iv. Selective redundancy: one element is not operating when another two components signal critical conditions.

v. Comparative redundancy: the output of multiple active components is compared.

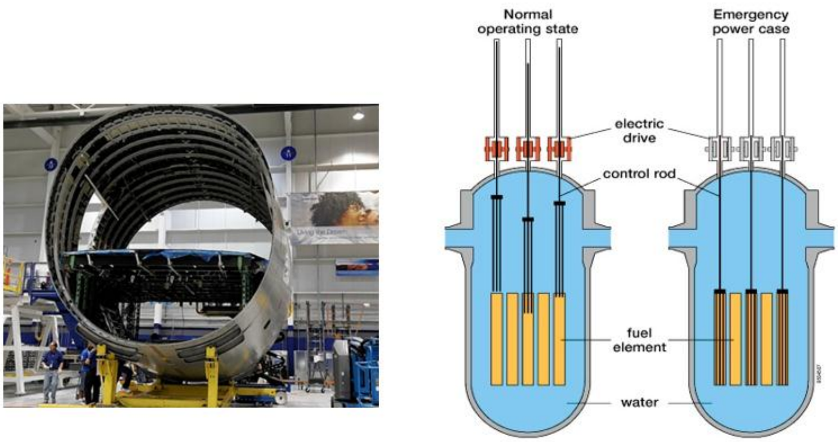


Figure 2.16: Left: Safe-life example of B787-10 body construction (Source: Ostrower, 2014)**. Right: A fail-safe example of reactor control rods** (Source: Thuma, 2010)

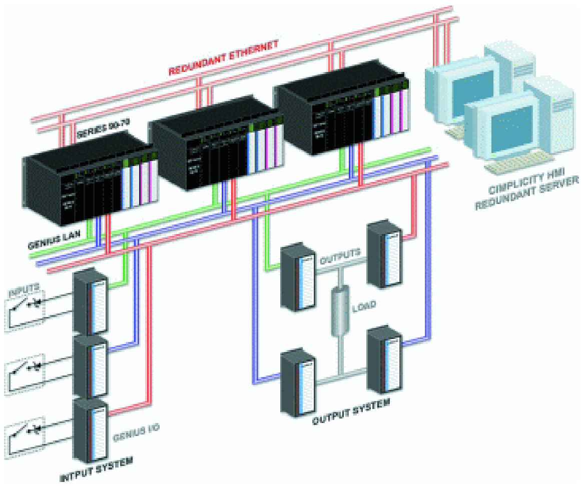


Figure 2.17: An example of modular redundancy arrangements of boiler safety shutdown system (Source: Instrumentation & Control, 2005)

2.5.4.2 Indirect Safety Principle

Indirect safety keyword is best represented as ‘protective’, is about the use of protective systems, protective devices and protective barriers when direct safety is insufficient. The protective system response when a dangers takes place by the common function ‘capture-process-act’. Examples of protective systems are devices that helps in the fulfilment of task in inaccessible or hazardous environment, such multiple layers of temperature monitoring and protection in reactors. Menwhile, the protective device provide protections usually in a limiting form and without transforming signals, for example seat belt with temporary locking to protect passenger from going towards car’s windscreen, a dark ultraviolet sunglasses to filter very bright light and ultraviolet. The protective barriers, on the other hand, is regarding the protection with a stopping action and a passive object, positioned to stop accident or breakdown to further damage, such as child stairgate (Figure 2.18) to stop a small child from falling down the stairs.

Figure 2.18: An example of indirect safety protective barriers, the child stair gate
(Source: Lascal KiddyGuard, 2017)

2.5.4.3 Warnings Principle

Warning is part of indirect safety, but in this research case, warning principle is treated as an independant principle to differentiate the elements of ‘protection’ and ‘signal’. Warning principles provides indication of changes and signals danger causes. Usually warning indications are in the form of optical and acoustic signals such as lighting, sound, colours, short wordings such as ‘alert’, ‘attention’, ‘low energy level’, ‘warning’. The same as indirect safety of ‘capture-process-act’, the warning principles is more of an information provider rather than a safe ‘action’ or a protective elements. Unless, if the devices optical and acoustic signal is the main function, such as high frequency alarm that can scare intuders, then it falls in ‘protective’ category and it applies indirect safety principles. An example of car reverse sensor consist of distance readings as the ‘capture’, the permissable distance is the ‘process’ and the noise that alerts the driver from short beeps to continuous beeps is the ‘act’ (Figure 2.19).

Figure 2.19: An example of warning principle product, the car reverse sensor
(Source: Steelmate Automotive, 2017)

2.6 TRIZ Integration with other Design Methods

There have been many attempts to formulate a method for the conceptual design process through a combination of design methodologies with TRIZ. Obtaining resources for the said combinations and focusing on safety are very limited. Several integrations of TRIZ with other design or problem-solving tools are made with the intention to increase the effectiveness of the design method in terms of inventiveness. TRIZ requires additional procedures for a more efficient design process. The integrations are often made because of a need for a powerful solution, or to increase the understanding in the conceptual design; in addition, most items in TRIZ toolkits (Su-Field, TRIZ software, analogies from other industries) require greatly assisted analogic thinking and a higher understanding of one area of science and technology to be applied to one another (Hipple, 2005).

2.6.1 Integration of TRIZ with Axiomatic Design

The Axiomatic Design (AD) developed by Suh (2001) from MIT, which has the advantages of a systematic problem analysis methodology, made a number of scholars propose a combination of both AD and TRIZ into an effective product development tool. It is a system design methodology with relations between functional requirements (FR) and design parameters (DP). The strength of AD lies in the problem identification, and increases the understanding of the problem, especially in the initial stage. Since TRIZ does not have an exact problem formulation tool, AD is the most suited for the job. A combination of AD with the Functional Basis by Zhang et al. (2007) reduces the diversity of functions and includes TRIZ for problem-solving, which AD lacks. The aim of such a combination is to enable the AD method. They have rearranged the TRIZ matrix by using a partitioning algorithm for the intended design to satisfy the independence axiom of AD. The integration of AD inside the TRIZ framework developed by Ogot (2011) recommended the use of AD in the evaluation process of each decision made in the process of TRIZ; after application of the design principles, reducing condensed TRIZ standards and concept evaluation. Duflou and Dewulf (2011) combined the AD method for the purpose of analysing the FR and DP in a case study of a laser cutting machine, with the TRIZ function being a decoupling instrument.

2.6.2 Integration of TRIZ with Quality Function Deployment

The Quality Function Deployment (QFD), which was developed by Akao (2004), is a method that is structured and used in many organizations for the improvement of product design based on customer demand and product acceptance in the market. Su and Lin (2008) conducted a case study of an online database company, using a combination of fuzzy QFD and TRIZ to increase the service quality. The fuzzy QFD converts the qualitative information into quantitative parameters and indicates critical determinants that are relevant to the customers' requirements. Shaobo et al. (2009) integrated QFD and TRIZ to provide the initial process of product development with users' demand with its focus mainly on the HOQ. A hybrid method of QFD and TRIZ was introduced by Kim and Yoon (2012) on the Product-Service System (PSS). They found that QFD identifies critical features of products and services and analyses functions and elements in the PSS field. Their research used the QFD process to determine the positive and negative correlations elements, and used the TRIZ contradiction matrix to find inventive solutions. The research applied the PSS model on 96 Fortune Global 500 companies.

Another integration of QFD and TRIZ research made by Yeh et al. (2011) considered the four-phase QFD suitable for integration with TRIZ in the research and development of a notebook product. Unlike previous research that integrated TRIZ after the QFD process, they applied TRIZ in the first step of the whole design phase. Their research was conducted using questionnaires to collect the customer requirements and develop product quality characteristics, which led to producing a prototype for a LCD monitor for a notebook.

2.6.3 Integration of TRIZ into Hoshin Kanri

Hoshin Kanri is a methodology that treats the foresight goal as the core target of an organization; it is a strategic or directive management concept popularized by Akao (1991). Mann and Domb (2009) found that Hoshin Kanri has two significant differences from the usual Management by Objective (MBO) planning practice. Thus, proving that Hoshin Kanri is an extensive process for translating strategic objectives into a set of plans and a three-level review system, for a decision of valid or not valid to proceed for goal realization. TRIZ in this research is applied on the term *'Sense-Interpret-Design'*, sensing conflict and contradictions in the discovery of a discontinuity stage, interpreting interrelationships between different parts of internal and external systems, and leading to the '*Decide-Align-Respond'* stage.

2.6.4 TRIZ Integration with Six Sigma

Fullbright and Hansen (2014) have done incorporation of Inventive Problem Solving (IPS) and Directed Evolution (DE) from I-TRIZ into Six Sigma procedures. The IPS is embedded in the analysis and improve stages of DMAIC, meanwhile the DE is applied during analyze and design stages in DMADV. The methods combination resulted to a model consisting 'Problem Formulator' (PF). A research done by Wang et al. (2016) found that the combination of TRIZ with Design for Six Sigma (DFSS) is an effective method applied in new product development. They had implemented the combined method onto very-high-bit-rate digital subscriber line 2 found in network device. They perform IFR, and TRIZ engineering contradiction in the DFSS' DMADV, together with partial QFD and Pugh method. To ensure that the product meets specifications, the DFSS fulfills the criteria, meanwhile TRIZ is an effective mechanism for the development of new products. They have projected profits of nearly USD 6.6 million from the successful application of the combined method and produced 7 patents during the 4-year case study.

In summary, almost all integrations of other design method with TRIZ is about enhancing thec reativity process within problem-solving. Most of the design method have lower concern on creativity, more on the optimization and improvement of artefacts. These findings proves that the TRIZ is an effective method for inventive and creative approach in systematic design, specifically conceptual design.

2.7 TRIZ Integration with Systematic Approach

2.7.1 Systematic Approach Pahl and Beitz integrated with Theory of Inventive Problem Solving

The earliest study on the integration of the Theory of Inventive Problem Solving (TIPS), another name for TRIZ, with the Systematic Approach of Pahl and Beitz, or, in short, SAPB, was done by Malmqvist et al. (1996). This anticipated important findings between both methodologies through comparative analyses. They identified similarities in both methodologies yet significant differences that can be used to complement each other. In conducting the comparative analysis, both methodologies must propose similar actions and process steps, the same goal and level of resolution as well as describe the same phenomena; however, both methodologies should exist and be developed independently.

The basis of their comparison is by a description of the methodologies in which they found 14 aspects of comparison, such as task clarification, problem formulation, function vocabulary, product models and evaluation, to name a few. By function vocabulary analysis, a mapping of thirty TIPS functions with five SAPB function vocabulary of change, vary, connect, channel and store are tabulated. Another comparison they made is between twenty nine TIPS principles with fifteen SAPB principles, shown in Figure 2.20. The comparison made is on the similarity between the two methods on design principles. They found TIPS have more principles based on ideas that can exploit physical phenomena while SAPB uses design principles that are based from fundamental mechanical engineering knowledge. During the period when this research was done, unlike SAPB, TIPS did not have specific tools or a method to build function analysis. They also pointed out that TIPS did not state where to apply the scientific effects in the EC, PC or ARIZ process, but recommended the use of a library or archive means, adopted from Sushkov (1994), to organize functions, effect and design cases.

TIPS	SAPB: Principle of balanced forces	Self-reinforcing solutions	Self-balancing solutions	Self-protection	Assignment of sub-functions	Division of distinct functions	Division of identical functions	Safe-life principle	Fail-safe principle	Redundancy principle	Change system boundary	Change sequence of sub-functions	Integrate functions	Change energy domain	Synectics
1. Principle of segmentation					●	●	●								
2. Principle of removal						●									
3. Principle of local quality						●									
4. Principle of asymmetry						●									
5. Principle of joining													●		
7. Principle of “nesting”													●		
8. Principle of antiweight	●														
9. Principle of preliminary counteraction				●											
10. Principle of preliminary action											●	●			
11. Principle of “previously placed cushion”									●	●					
13. Principle of “the reverse”															●
25. Self-service principle		●	●	●											
27. Cheap short life instead of expensive longevity								●	●	●					
28. Replacement of a mechanical pattern											●			●	
29. Use of pneumatic or hydraulic structures											●			●	

Figure 2.20: The comparison of design principles between TIPS and SAPB
(Malmqvist et al., 1996)

The significant result of this research integrated some of the TIPS process into SAPB theoretically but did not include the value of the integration, as their article did not have any case study application. Finally, they proposed a unification of several TIPS elements into the SAPB framework, as shown in Figure 2.21. Nevertheless, the deficiencies of TIPS found in this research sparked TRIZ experts to enhance the function tools within the method.

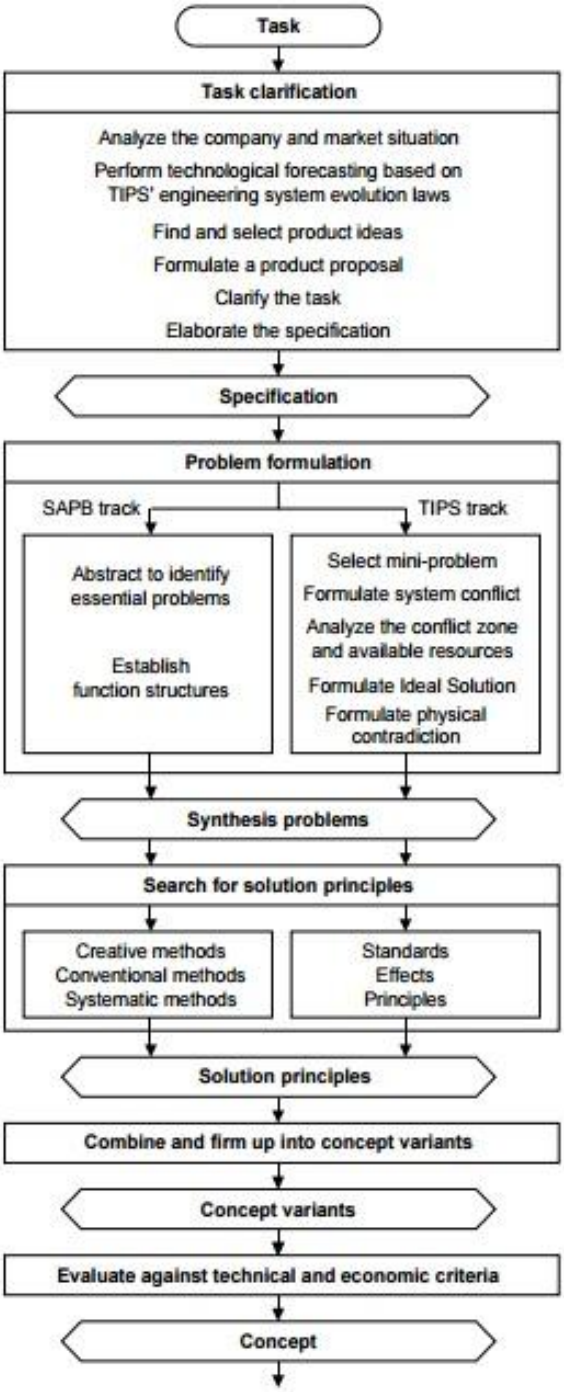


Figure 2.21: SAPB task clarification and conceptual design phases integrated with TIPS (Malmqvist et al., 1996)

2.7.2 Integration of Pahl and Beitz Work with TRIZ's Algorithm of Inventive Problem Solving

Dietz and Mistree (2009) explained the whole process of their integration of TRIZ, specifically the Algorithm of Inventive Problem Solving (ARIZ) with the work of Pahl and Beitz in the context of a multi-domain system (Figure 2.22). This is the process of amending the original domain to a more effective domain so that the application of new technology can be implemented. This study also emphasized the aid of empirical knowledge with problem solving and solution triggering tools to process a more rapid and accurate design.

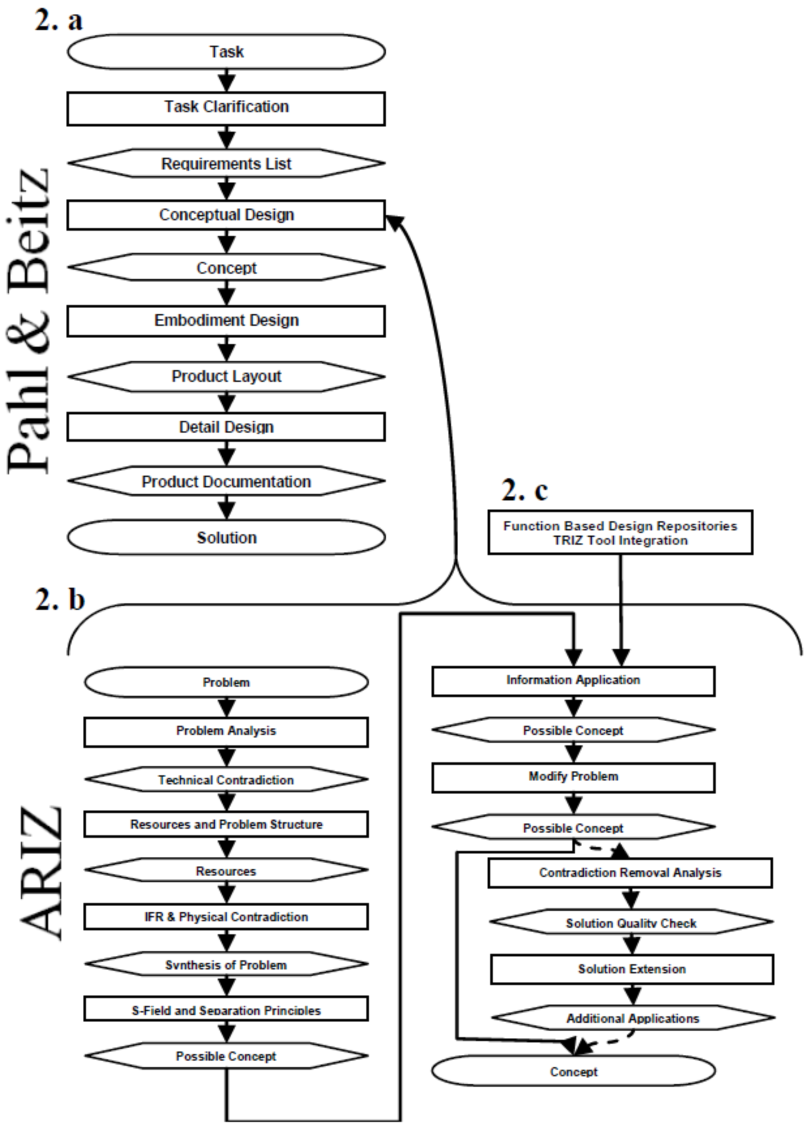


Figure 2.22: The multi-domain system, augmenting ARIZ with the Pahl and Beitz process (Dietz & Mistree, 2009)

Their research is particularized by using the work of Pahl and Beitz in the conceptual design stage and using the TRIZ abstract way of transferring information. Their problem formulation at the beginning of the concept design is using the ARIZ abstraction, by these several steps:

a) Stating the original problem
b) Stating overall function of the system
c) Define subfunctions
d) Define system boundaries along with its subsystems
e) Identifying any super-system and environment
f) Identifying the beneficial functions of the system
g) Identifying the undesired functions of the system

The research focused on the supplementation of material selections into conceptual design, synthesizing materials with performance and phenomena, and to built domain-independent method for engineers and designers. The characteristics of materials are the key objective of this study to ensure the design fits with the material to be used. In the process of problem identification, they proposed designing products and materials concurrently, systematically and innovatively by using the design process of TRIZ and integrating it with the work of Pahl and Beitz. They too encourage the use of design repository, work from Messer (2008) or design catalogue for easier solution finding. In terms of the TRIZ approach, this study used the ARIZ technique, a tool of TRIZ methodology, to solve problems concurrently with the material design using the structure-property relations.

2.7.3 Function Basis with TRIZ

Nix et al. (2011) constructed a table of Function Basis with TRIZ, in short FB-TRIZ, its correlation matrix (Table 2.5) where each functional basis from Pahl and Beitz subject-verb nature had similarities to the word tendencies of TRIZ solution principles. They found that the stage of conceptual design is the most appropriate location to integrate TRIZ in the overall framework of function based design. They then studied each 40-IP of TRIZ to be suited with FB terms, where the technical characteristics of TRIZ were correlated to a flow class of Functional Basis. They identified that function design tends to be highly ‘functional’ but less aesthetic, and suggested that the TRIZ method produced a more creative and aesthetically appealing design.

Table 2.5: FB-TRIZ correlation matrix (Nix et al., 2011)

Functional Basis Functions	Classical TRIZ Principles
Separate Material	1, 2, 15, 27, 30
Export Material	2, 27, 34
Transfer Material	10, 24, 34
Convert Energy	14, 19, 22, 28, 37
Guide Material	12, 15, 17
Change Material	4, 14, 31, 32, 33, 34, 35, 36, 38, 39
Export Visual Signal	2

A case study of an ice breaker ship was conducted using this integrated methodology to produce four concept designs. The objective of this research was to integrate the understanding of the FB method and TRIZ method so that when either one of the methods have deficiencies in problem solving, the other one helps. One thing interesting about the FB-TRIZ is that the method uses the freehand sketching for idea generation process and potrays the TRIZ principles used for solving the case study problem.

2.7.4 Innovative Conceptual Design Process

Mayda and Börklu (2014) integrated the TRIZ method in the conceptual design process based on the SA of Pahl and Beitz, specifically for the solution finding step. The objective of the integration was to overcome certain deficiencies in the conceptual design using the systematic approach alone. The relation matrix of QFD was implemented at the beginning of the problem-solving process and the TRIZ process of abstraction was applied. In detail, its task clarification begins with TRIZ trends of evolution law for determining the design development that follows the technological trend. The research used a case study of a paper puncher, and identified both standard and radical contradictions during its problem-solving. They applied multiple TRIZ tools such as contradiction analysis, 40-IP, Separation Principles, Su-Field analysis (Figure 2.23) and 76 Standard Solutions of TRIZ to resolve radical contradictions. They also implemented some ISO standard documents in the conceptual design process.

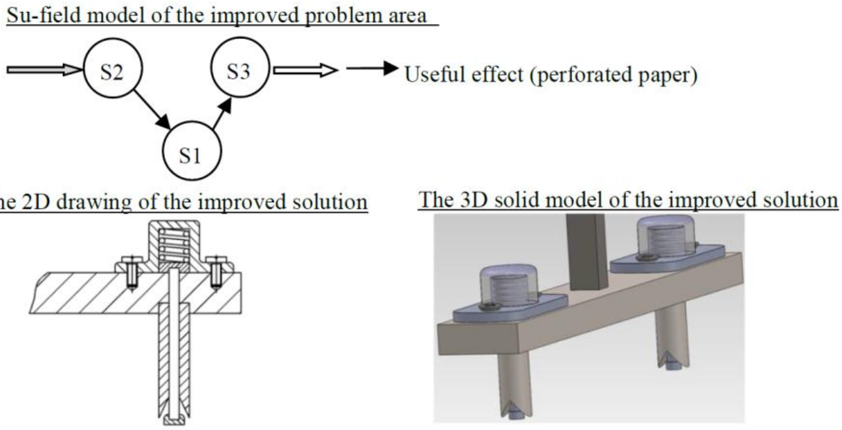


Figure 2.23: The work of Mayda and Börklu on paper pucher case study, using Su-Field (Mayda & Börklu, 2014)

In the results and discussion section of their research, they found a design time reduction by accelerating the process of solution finding, and that focusing on conflicts and radical improvements encourages designers towards innovation. The research made a table of comparisons between five integrated methods with TRIZ and used Altshuller criteria (Rantanen, 1997), in which the level of ranking was from 1 being a simple improvement and not so innovative, to level 5, creating a new technology and phenomenon. The overall process of their research is shown in Figure 2.24.

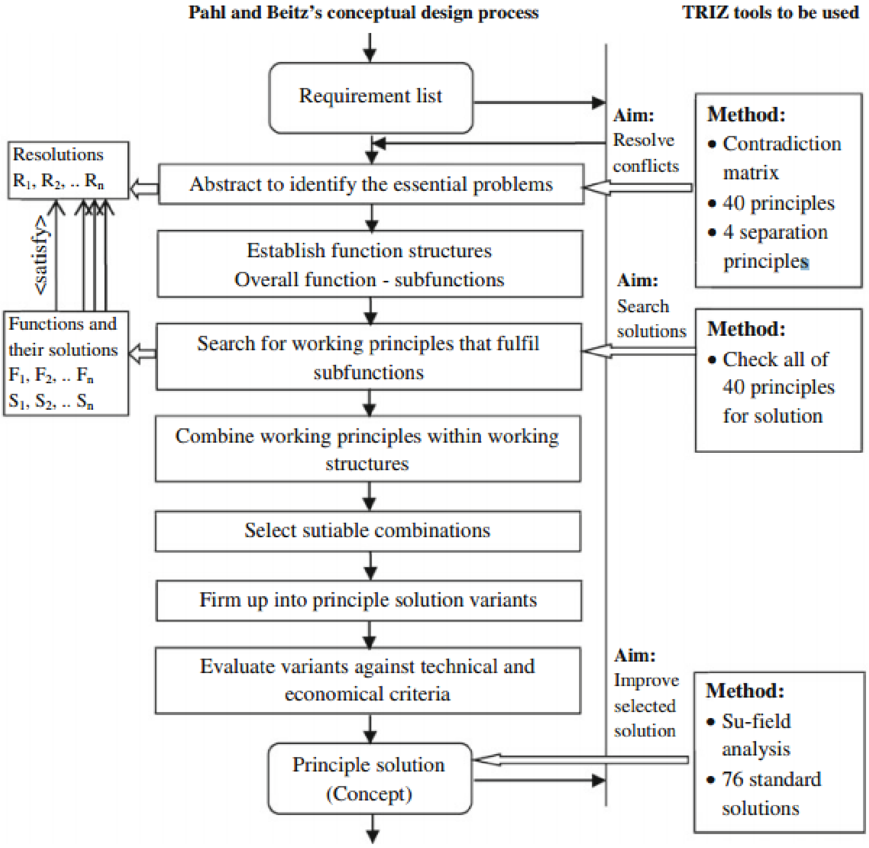


Figure 2.24: The innovative conceptual design process framework
(Mayda & Börklu, 2013)

To summarize, research on the integration of TRIZ and SA by these scholars gave tremendous help in terms of guidance and motivation to enhance TRIZ and SA, respectively. The summary of all four TRIZ and SA integration methods is tabulated in Table 2.6.

Table 2.6: The comparison summary of TRIZ and SA integration methods developed by four groups of scholars

Criteria	TIPS-SAPB	PB-ARIZ	FB-TRIZ	TRIZ, SA & QFD
Developer	Malmqvist et al.	Dietz & Mistree	Nix et al.	Mayda & Börklü
Objective	Empower SAPB by unification	Addition to ARIZ and integrate it with PB embodiment design process	To clarify TRIZ principles with FB function terms	Empower conceptual design process
Tools/Method developed	The function vocabularies matrix	Concept variants table	FB-TRIZ Matrix	Integrate TRIZ tools in between SA process
Application	Not applied	Spring design	Ice breaker ship	Paper puncher

2.8 Constraints

In designing complex artefacts, designers often face several design requirements and limitations, and must strive to provide a solution that is closest to satisfying all the requirements. Constraints constitute the key to understanding such complexity. Inappropriate constraint management in the conceptual design can develop a concept that invites harm and risks, but removing constraints will result in a chaotic system. When developing a concept design, designers must consider a multitude of artefact's constraints. The best way to handle constraints is to determine which constraint is the top priority and then sequence them until the lowest priority is reached. Constraints and safety have a mutual relationship, because safety is one of the elements of constraints, in addition to the limitations on the manufacturing process, material capabilities, costing limitations, and the artefact's life cycle.

According to a dictionary source Dictionary.com (2015), the definition of constraint means a *'limitation'* or *'restriction'*. In addition, the BusinessDictionary.com (2015) defines constraint as *"a factor that restricts an entity or system from achieving its higher level of output with reference to its goals."* Another definition of constraint by the Merriam-Webster Dictionary (2015) is *"the state of being checked, restricted, or compelled to avoid or perform some action."* The keywords *'boundary', 'control', 'force',* and *'restraint'* are the most relevant for the understanding of constraints in the context of the conceptual design activity.

In the study conducted by Kaur et al. (2010), they compiled constraints adoption in the conceptual design from a collection of significant research findings; as shown in Figure 2.25. Many scholars have integrated the constraint analysis process in the search for principal solution and later stage. Several studies that integrate constraints in the abstraction process were made by Paz-Soldan and Rinderle (1988), Pape (1998) and Davies (2006).

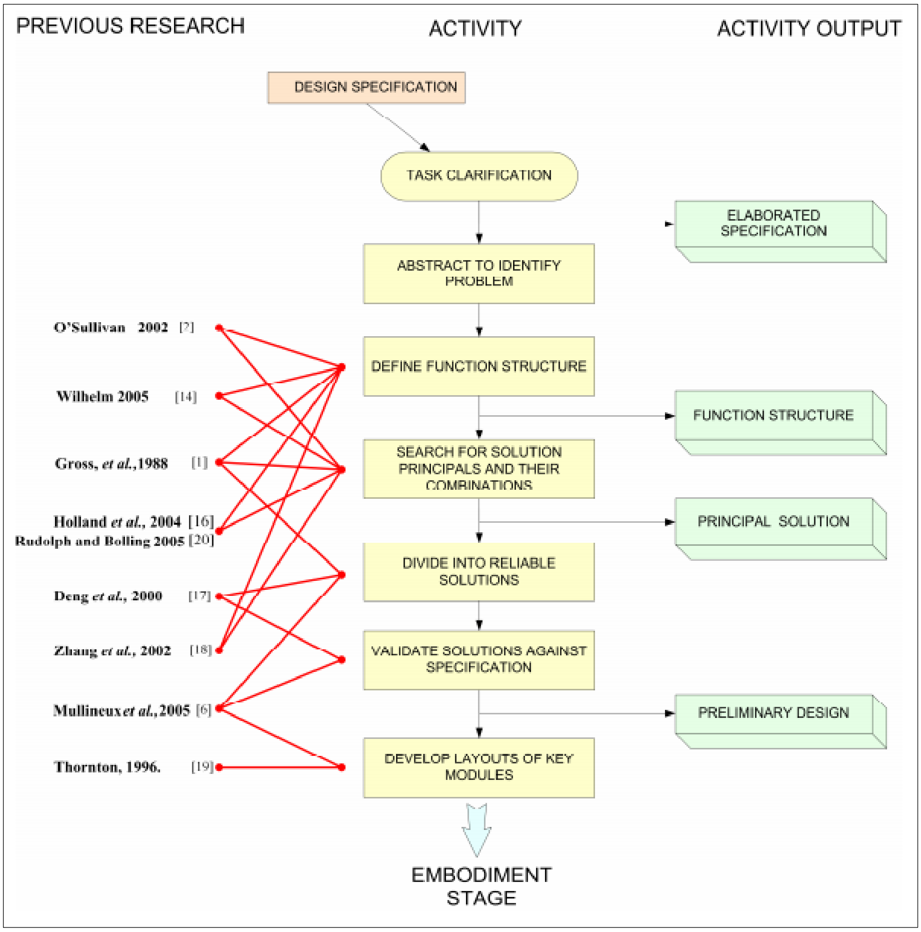


Figure 2.25: Studies on constraints intervention in conceptual design by Kaur et al. (2010)

However, there is still room for improvement for constraint modelling, particularly in conceptual design. Much of the literature suggests that constraint-based techniques improve problem-solving for the preliminary design of artefacts (Smith & Browne, 1993; Zha, et al., 2001; Matar et al., 2012; Meurant, 2012).

2.8.1 Design Constraints

There are four commonly used types of constraint – functional, topological, geometric and quantitative constraints (Killian, 2006; Gross, 1986) – within design exploration. According to both scholars, the functional constraints relate to the function requirements that the artefact must accomplish; the topological constraints pertain to the relationships between entities that make the topology form; geometric constraints relate to dimensioning, shapes and appearances; and quantitative constraints concern the quantifiable elements and parameters, such as volume, density and material related measures.

It is important to monitor constraints constantly during the concept design process and diagnose them when changes occur to ensure that the performance of the artefact satisfies the main function, and does not violate the constraints given (Lin & Chen, 2002; O'Grady et al., 1991). Several scholars have built constraint models to ease the identification and analysis process of the design constraints, especially in the conceptual design stage (Meurant, 2012). Interestingly, Leffingwell and Widrig (2000) compiled a list of the characteristics of constraints according to the three sources of design constraints, as elaborated in Table 2.7. Although the domain of their constraint analysis is for software management, the understanding concerning the constraints findings from their research is actually applicable to any domain.

Table 2.7: Three sources of constraints (Leffingwell & Widrig, 2000)

Constraint Sources	Details	Types of Constraint
Restriction of design options	• A degree of flexibility and development freedom has been lost due to design constraint, • Mostly internal constraints.	Functional, technology, time, material, motion, aesthetic, health and safety.
Conditions imposed on the development process	Requirements imposed on the process of design, for example: • Compatibility with existing/current systems, • Application standards, • Corporate best practices and standards, • Mostly external constraints.	Manufacturing, inspectability, quality sustainability, life-cycle.
Standards and regulations	The body of regulations and standards related to the artefact prototype to be designed, • Examples of design standards and regulations: German Industrial Standard (DIN) for mechanical parts, EASA & FAA (for Aviation), etc., • External constraints.	Economic, environmental, social, legality, ethical.

2.8.2 Constraints Characteristics

Constraints actually stimulate creative and inventive solutions by reframing problems and formulating the problem-solving process creatively. The reframing of problems is through modelling to clarify the design process involving multiple constraints. Constraints in conceptual design are usually defined according to the design parameters and choice of parameter values. The constraints of a prototype artefact can be categorized as *inherent* or *imposed* (Scudieri, 2013). The inherent constraint is usually about the laws of nature of the design problem, the capability of the material, the sturdiness of the shape and its lifecycle. The inherent constraints are unavoidable. Imposed constraints factor in when the component receives energy, loads or external functions, and interactions when in motion. Design regulations, customer requirements, and design standards also fall into the imposed constraints category. An artefact will not give an ideal design solution if the constraints are too controlled and will become inefficient if too loose. Designing a prototype artefact creatively with constraints requires the skill of critical thinking and content expertise. In terms of the characteristics of constraints, a single object has several constraint characteristics:

a) Constraint that it is not allowed to perform exceeding its limitations, and restrained from performing more than permissible range. The question arises of *"What risk will arise if the performance reaches more than the permissible limit?"* Usually, factors regarding danger, hazard or emergency situations to others would be the concern.
b) Constraint that it cannot perform after reaching its limit, that is, when the limitation is reached, the object cannot perform anymore. The question arises of *"What is the risk after the performance limit?"*
c) Constraints that forbid the object to touch or come in contact with another object to avoid risk in performance.
d) Constraints pertaining to the supply of a certain energy, load, force, or tension.
e) The object's reaction to a certain application, contact, performance action or the environment.
f) The constraint frequency: where the input frequency is 1, the sub-component frequency might be more than 1, with a limitation of a certain frequency quantity.
g) A combination of two or more objects will experience more quantity and multiple types of constraint.

In TRIZ, the term *contradiction* complements constraints, but contradiction in TRIZ understanding is something that is able to be eliminated, while, in general, constraints can be the existing characteristics of the component, such as inherited constraints. It can only be reduced or optimized. The imposed constraints are those that can be eliminated. Identifying the artefact's types of constraint, especially the imposed constraints, can encourage designers to find alternative ways or to manipulate the limitations simultaneously to develop a creative outcome, provided the change does not create new disadvantages. For example, a wooden chair has inherent limitations concerning the wooden material itself, and the means of joining the parts. The advantages are the comfortability of the wooden material (positive inherent constraint), in that it is softer than metal. The disadvantages lie in the durability (negative inherent constraint) of the wood material opposed to load, which is less durable. Through the contradiction identified in the wooden chair, imposed characteristics can be introduced to reduce the negative inherent constraint, such as inserting metal rod inside the wooden leg.

2.8.3 Reasons for Modelling Constraints

By modelling constraints, it is possible to describe how individual components behave and to inform us about a system's behaviour. Visualizing parameter constraints is easier through the model representation; whether on the relationships of the parameters (weight, size, material type, and the quantity of components, joints), how they interact, and work with each other, or the possibility of adding or reducing components.

Modelling constraints can increase the understanding of the overall design process. According to Medland et al. (2003), initially, the constraints are not all known and are usually viewed in set-theoretic terms. Constraint modelling helps designers adjust the values of the design parameters, by adding or removing constraints. One strategy for improving designing with constraints is to begin with a model of an artefact system. To start, San (2014) has recommends obtaining the list of components and the respective position and pivot points inside the overall system. The data may be incomplete or incorrect, but, with proper mapping, the visibility of the actual size of the artefact prototype network becomes clearer.

At the highest level, usual practice of TRIZ utilizes the if-then-but rule tool for determining the contradiction (constraints) at the outset of the problem-solving process. The tool is dedicated to find one improving parameter (the current problem's advantage) and one worsening parameter (the problem's constraint or disadvantage). San further constructed a structure that is simple and easy to understand; as presented in Table 2.8. This tool is beneficial for identifying the parameters used for the selection of 39-P. The contradicting responding parameters is the first constraint identified in the problem-solving process of TRIZ. Later, EC comes in.

Table 2.8: The If-Then-But Rule structure (San, 2014)

If-Then-But Rule	Substance	Parameters
If	Manipulative	Potential for change of parameter/subject
Then	Responding	Improving parameter
But	Responding	Worsening parameter

2.8.4 Form-Fit-Function

The utilization of the *Form-Fit-Function,* or F3, for segmenting the constraint model into separate system categorizations, which is quite abstract in visualization, helps streamline a complex constraint model through just three segments:

a) Form: is a single or group of parts (with a single construct) that is developed by specifications, such as geometric shape, dimensions, weight, and material compositions. It is often an embodiment of the part or component. In the context of this thesis, the form consists of an artefact's components and subcomponents.
b) Fit: is the association between two or more forms, the interface and interconnectivity to fulfil a certain task. The fit in general understanding is the interaction of the physical and function between components, including tolerances. An assembly that contains greater complexity also falls into this category due to multiple constraints.

c) Function: is the action or actions, which a form or fit is intended to do and is designed to perform. In the context of this thesis, the function is not limited to the work done but also the field used, and the constraints that the component must face.

2.9 Creativity

NASA's Goldin et al. (1999) said that the desire to increase performance, increase environmental friendliness, increase quality of end product makes designers and engineers work many ways to improve the way of designing things. This is true when designing things or artefacts is becoming much more challenging every day. Complex artefacts are definitely a challenging object to do a conceptual design with. But the most challenging process of designing a complex artefact is the part when the designer needs to come out with a creative outcome.

Creativity, according to the standard definition, means the requirements of both originality and effectiveness (Runco & Jaeger, 2012). The definition can be supported by the findings of Pahl and Beitz, who categorized the types of engineering design into three approaches:

1) Original design: original solution principles, where the output of the design is new,
2) Adaptive design: adapting known system to a changed task, and
3) Variant design: the design incorporates various small tasks, additional functions and parameters into the same solution.

A creative design often falls in the original design and is accepted in the market as a new technology, or new approach to solving an old problem. However, a creative design is not just merely original but has values of effectiveness, usefulness, appropriateness and benefits. A creative design should encourage designers to explore more knowledge, expand it for a better understanding and share the advantages with other areas of knowledge. There is a high need for creativity in the design of complex artefacts to fulfil customer's desires as well as to promote new technology.

2.9.1 Creativity in Engineering Design

The common pursuits or path in engineering design are the process that generates creative ideas, the object that contains creative ideas or the persons who produce creative ideas. To be able to grasp the way of these three creativity paths lies in the creative idea itself. How does one know if the idea is creative? Altshuller developed levels of invention to help designers achieve or to measure their design creativity or inventiveness. Often designers who develop new prototypes aim to be in the Levels 2 to 4. Listed below are the levels of invention taken from Zlotin and Zussman (2003), and Mishra (2014):

1) Level 1: apparent, simple improvement; company knowledge,
2) Level 2: improvement, new object; industrial knowledge,
3) Level 3: invention with paradigm, major changes; new industry,

4) Level 4: invention outside paradigm, new application; technology, and
5) Level 5: discovery, breakthrough; science.

Usually a prototype that contains creative ideas is the goal of any designer, where the success of developing creative products manifests the designer's ability and creativity. To be able to produce a creative product, designers should avoid common solutions, repetition of the same solution on different complex problems or favour certain problem-solving ways without critical thinking, or having the mentality of cognitive inertia. The cognitive inertia or psychological inertia is defined as the *"predilection toward conventional ways to analyze and solve problems"* (Fey & Rivin, 2005 pg. 235). It is a human tendency to solve problems with an inclination to familiar ways or assumptions and exhibit reluctance to try new ways or revise the familiar way, even if it is no longer effective.

2.9.2 Sketching as a Creative Process

In the development of solution ideas, it is advisable to roughly draw the solution ideas and the fastest way is to sketch by hand to capture the inspiration and idea stimulus. SA encourages the emphasis of sketches and 3D models for better visualization of the conceptual prototype ideas. Other design science experts, such as Ulrich and Eppinger (2015), also promote the use of sketches, stating that it helps ease the process of idea brainstorming. Freehand sketches speed up the recording of theoretical ideas, especially when designers try to jot down anything that comes to mind. Freehand sketches are a medium for communication between the designer and other stakeholders. Sketches of an understandable idea can help many parties discuss the idea together and give comments to further improve the conceptual ideas.

Sketches are an effective way to convey ideas, in fact, they amplify the mind to imagine and create a limitless generation of ideas. Sketches are a process of plotting anything that the mind can think of, commonly in a generic description or illustration rather than specific. Sketches help the designer to interpret the information at hand and easily link the interpretations with future perceptions of the artefact. Visualizing solutions to the problem and future appearance of the artefact is best using sketches (Macomber & Yang, 2011; Shah et.al, 2001). Sketches are an abstract representation of the conceptual ideas, preferrably shown with indications on function relationships of components and subcomponent, discarding unimportant components. Figure 2.26 shows some freehand sketches of aircraft concept design by industrial design designers.

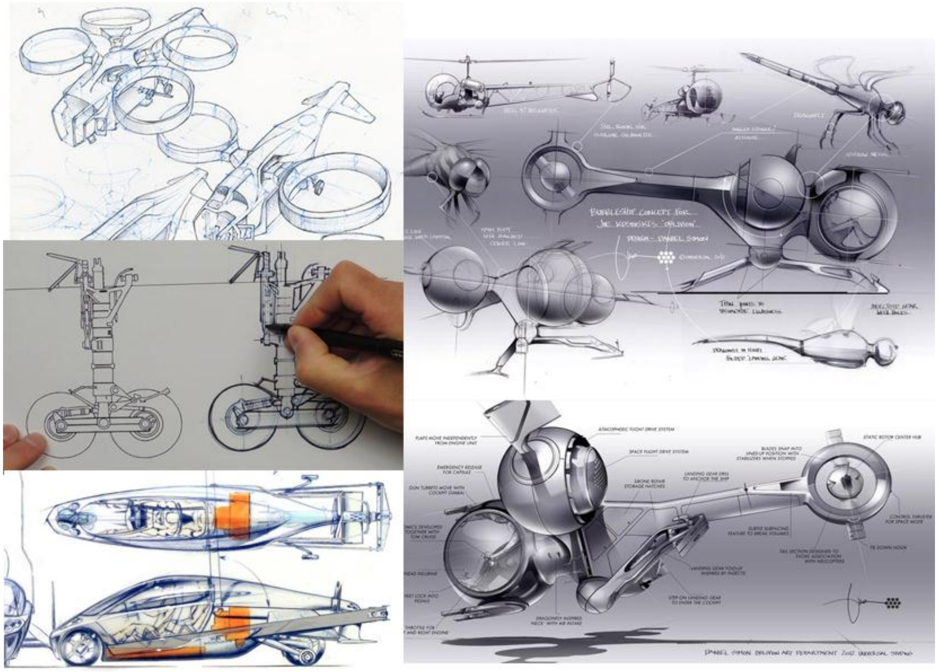


Figure 2.26: Hand-sketch of concept ideas is like an 'idea discussion'
(Source: Ouchterlony, 2014; Design Sketching, 2017; Blain, 2016 and Simon, 2013)

2.10 Reviews on Qualitative Content Analysis

According to Hsieh and Shannon (2006), qualitative content analysis consists of three distinctive approaches: conventional, directed, or summative. The directed qualitative content analysis is where the analysis intends to complete an incomplete phenomenon, which this research chose to implement. The summative approach has two types of analysis, manifest content analysis, a word count method and latent content analysis, beyond word counts. This research adapts the latent content analysis that requires interpretation and identification of the underlying meanings of the content and word usage.

2.10.1 Patent and Documents Qualitative Content Analysis Procedures

The qualitative content analysis method is chosen as the core research method, and is applied according to the tasks previously explained in Chapter 1. The qualitative content analysis acquires three procedures to analyse the documents, specifically patents:

a) Content inventory: this identifies patterns in patent structures, in detailed meticulous accounting of items ranging from identifying published and granted patent date, patent classifications, and finding prior art disadvantages, safety issues, design solutions, substance of the design, technology used and if there are trimmings involved. The inventory is managed and recorded in a spreadsheet (Appendix A) and is the initial tool for the content mapping.

b) Content audit: a process for evaluating the content inventory spreadsheets and assessing the supporting and non-supporting elements of this research focus. The content audit aims to find quality information and relationship accuracy.
c) Content map: after the content audit, a modelling or mapping of the relationships between key codes helps in identifying the higher and lower frequencies of the type of safety approach and solutions.

Manual text analysis or curation was chosen because of its accuracy. Inferring conclusions and the idea solutions from disconnected facts is quite impossible with automatic curation. Manual curation has the ability to identify and translate complex concepts into an understandable form, and summarize a large amount of information into a distilled version. Relating figures and tables with collected information is also easily handled with manual curation. The disadvantage of manual curation is that it is a time-consuming process since it needs pattern matching and ontology skills.

2.11 Main Landing Gear

The most important part of designing and locating MLG on an aircraft is the centre of gravity (*cg*) (Chai & Mason, 1996; Gudmundsson, 2014). The *cg* of MLG very much relates to the ground stability, manoeuvrability and clearance requirements. Second, the distribution of weight, which depends on the distribution of the aircraft *cg*, nose gear and gear assembly, is critical in MLG design. The third consideration in designing MLG is the ground clearance. Extreme MLG weight minimizing can cause interference in the fail-safe safety requirements associated with a 'single load path' structure. The essential features of MLG's moving components, such as tyres and wheels, brakes and shock absorption mechanism should be determined before the concept design phase commences (Sadraey, 2012; Torenbeek, 2013).

Focused on the noise problem the aircraft industries faces, one of the dominant noise source is the MLG. Interactions between non-aerodynamic components with wind flows generates turbulence and noise, and continues to be an ongoing problem. There are two branches of airframe noise research:

i. Noise experimental research on landing gear: door panel, side and drag struts, pin hole, streamlined fairings, and other supporting components. The experimental research usually applied on existing MLG and for quantifying airframe noise using dedicated test equipment, such as a wind tunnel. Example of fairing test on a landing gear can be seen in Figure 2.27 and noise simulation on significant aircraft component that produces noise shown in Figure 2.28.
ii. Noise prediction research on landing gear: research on noise prediction consists of the finite element method in certain atmosphere, altitude or latitude. Mostly a mathematical prediction.

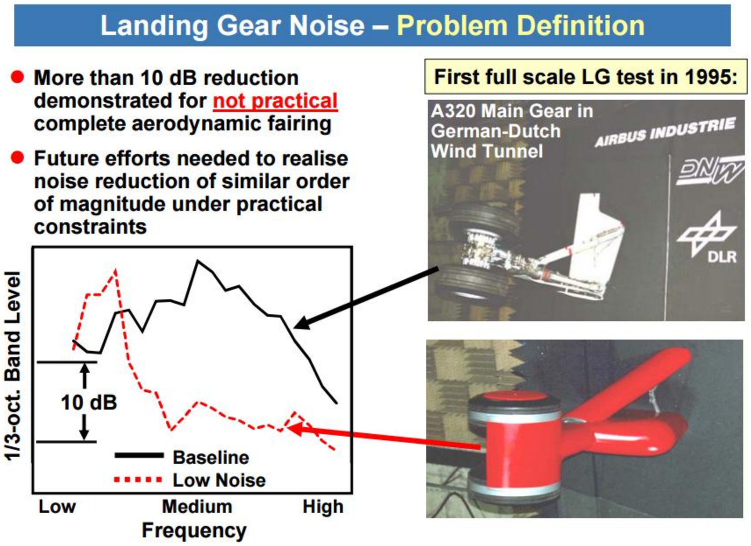


Figure 2.27: Current scenario of MLG noise done by researchers and how to reduce such noise (Dobrzynski, 2010)

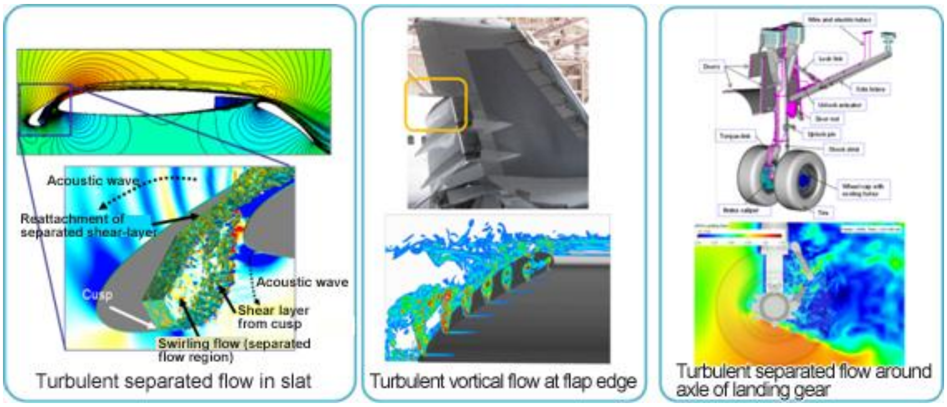


Figure 2.28: The study on turbulence and research on airframe noise. Far right is the landing gear turbulence analysis (Source: Dobrzynski, 2010)

CHAPTER THREE

RESEARCH METHODOLOGY

A new conceptual design method can be developed as an alternative method to design an inventive and safe new concept design. In addition to the safety approach, the proposed method helps designers to determine constraints in the artefact's system, provides a potentially radical improvement and stimulates the search for non-conventional technology for the solution. This chapter discusses the research methodology used in this research for the development of the TRIZ-SA conceptual design framework, and two new tools to support the framework. In the initial stage, essential fundamentals, guidelines and resources are obtained, and validation concerning the conceptual design framework is demonstrated.

The SA, has solid conceptual design procedures but requires many creativity tools. In contrast, the TRIZ methodology is a unique problem-solving technique, with a proven, inventive and creative approach to develop new inventions or innovations. These findings lead towards combining the SA and TRIZ in terms of:

i. Systematic conceptual design framework: the conceptual design framework from SACD process as the basis of TRIZ-SA,
ii. Creativity and inventiveness: the use of TRIZ inventive tools for the generation of a prototype.

The research integrates another two important particulars:

i. Use of safety principles: integration of SAED safety principles and system safety,
ii. Constraint studies: the similarity and differences of constraint studies between SACD and TRIZ methodology, with the integration of Form-Fit-Function (F3).

The combination of both methodologies is known as the 'feature transfer' in TRIZ terms, reflecting TRIZ-SA's objective to deliver a system with enhanced functions (Zhang et al., 2011) by integrating the advantages of alternative systems into the base system. The feature transfer further comprehends that the same base or elements are used with distinct different characteristics, and combined to make the resulting combination better and effective. The results of this research are presented in a prescriptive method.

3.1 Research Methodology Flow

The flow of the research methodology is shown in Figure 3.1 starting with the literature review on several design methodologies on artefacts that require safety as the top priority. From the number of design methodologies, the SA is selected as the most structured and systematic design process that implements safety principles. The TRIZ methodology is then selected for its simpler problem-solving and solution finding method. By combining the advantages of both methods, a systematic-creative-safe design method can be developed.

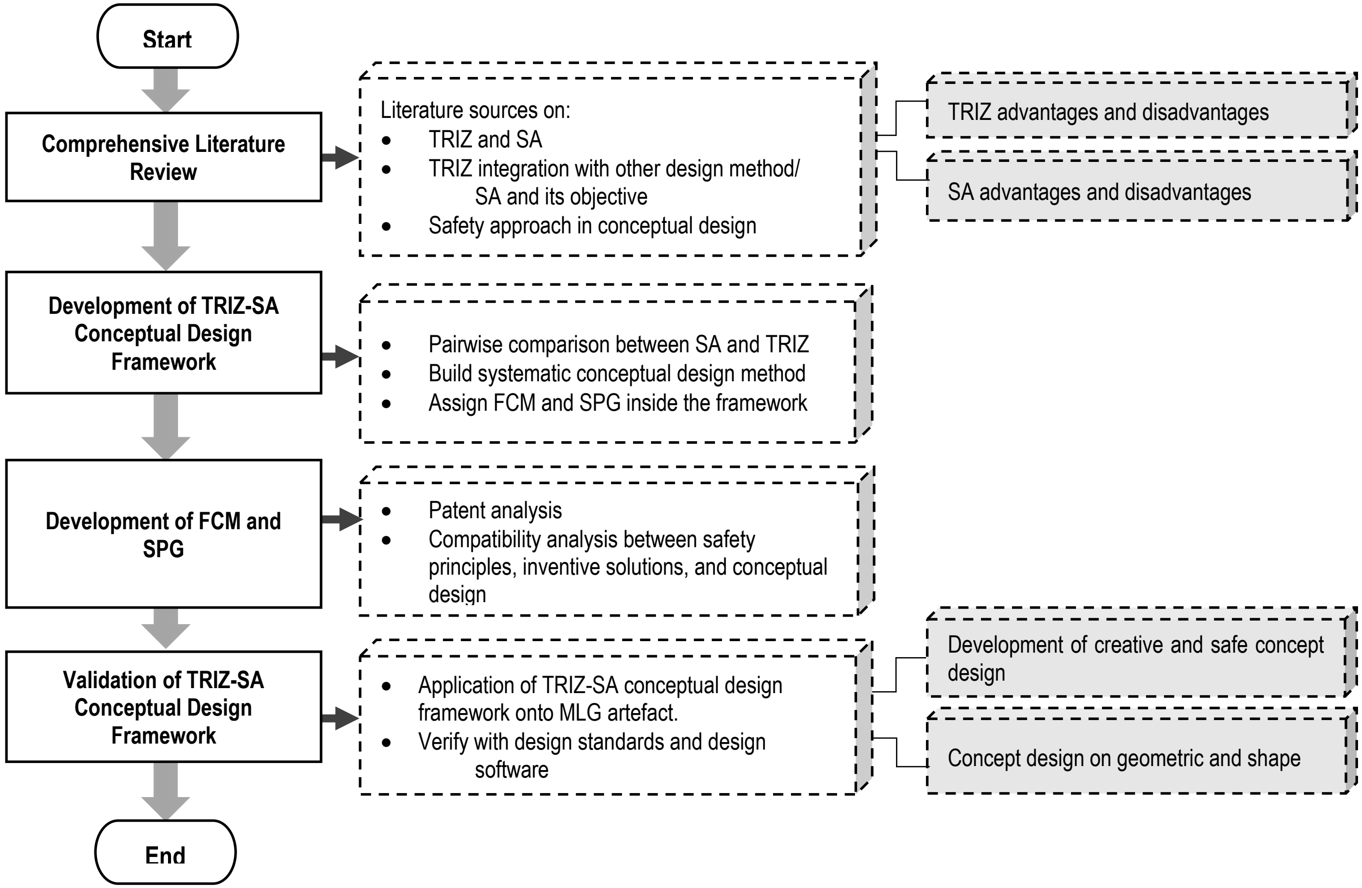


Figure 3.1: The overall research methodology flow diagram

The main approach of this research is to implement safety assessment during the analysis of artefacts and within concept solution finding. In order to do so, analysis of the constraints is necessary to identify any function limitations, risks, threats or failures; thus, a constraint model, named the Function Constraint Model (FCM), is developed. Only after determining the safety issues through constraints studies can the safety principles be utilized for the process of designing safety concepts. In completing the tasks, a safety principle guide, the SPG, is developed, which is compatible with TRIZ 40-IP to guide designers to develop concept ideas using TRIZ inventive principles.

3.2 Development of TRIZ-SA 8-Step

The important features from both methodologies are placed on each method's process flow, the systematic steps and tools.

3.2.1 SA and TRIZ Process Flow

The research starts by comparing the overall problem-solving process of both SA, particularly SACD, and TRIZ. Figure 3.2 illustrates the differences in the way that SACD and TRIZ find solutions. The SACD procedures are common in many modern design methodologies where the process undergoes multiple analysis. TRIZ, on the other hand, uses principles in its overall problem-solving process. Looking at the design process flow of both methods, obtaining a solution by SA and TRIZ is very contrasting. The contrasting way of finding a solution from both methodologies ignites the idea to combine and integrate some simpler tools from TRIZ into SACD.

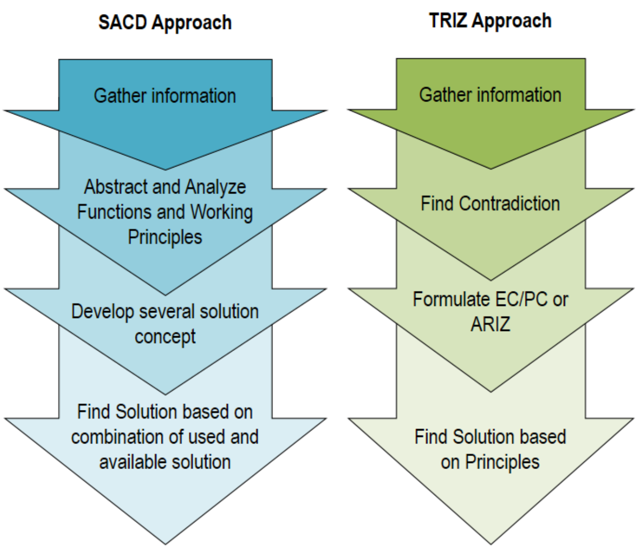


Figure 3.2: General process flow of SACD and TRIZ

3.2.2 Pairwise Assessment on TRIZ and SA

The development of the TRIZ-SA framework begins with pairwise assessment on both TRIZ and SA, to find and select proven efficient constructs or procedures. The comparative analysis between both design methodologies identifies the similarities and differences in the decision-making steps in each process. Several TRIZ and SA integrations from other scholars are reviewed, especially concerning their objectives, method of integration, and the developed outcome. The reviews help in the development of a better design process and avoid redundancy with the work of other scholars. The selection of suitable design steps or tools from either method, or a combination of both is conducted.

3.2.3 The TRIZ-SA Framework Structure

The TRIZ-SA basis structure is adopted from the SACD framework (Figure 2.13, at section 2.5.3.), and includes the requirement list, which is originally situated before SACD, inside the product planning and customer requirements stage. Following this, the conceptual design process starts, which consists of seven steps from abstraction to the evaluation of the principal solution. Since the requirement list is needed to initiate a conceptual design, TRIZ-SA places the requirement list procedures to be included in the conceptual design framework, situated in Step 1.

Figure 3.3 shows the conceptual framework of the development of TRIZ-SA. Several TRIZ tools are integrated into the SACD procedures. The IFR and FAM are used several times in different steps to ensure that the concept design fulfils the solution and performance goals. The safety principles from SAED are included in the SACD fifth step, where a working structure is built from a combination of working principles. This means that the application of safety principles is introduced in the early part of the product design process. To integrate the safety principles efficiently, the safety principles must be compatible with TRIZ 40-IP for the EC and PC solution findings.

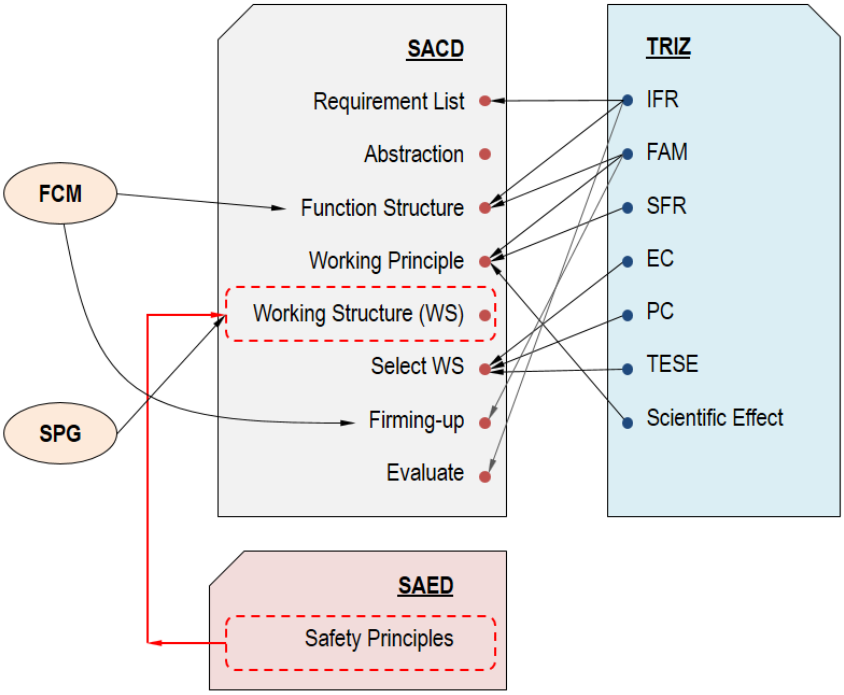


Figure 3.3: The conceptual framework of TRIZ-SA framework development

Some of the SACD steps are optionally integrated with TRIZ tools, such as TESE, SFR and scientific effects for the idea finding activity, while the evaluation process is only for the technical criteria, where an economic analysis is done in the later stage of engineering design, outside of the conceptual design context. Selection of the best conceptual design procedures, between TRIZ and SACD, are justified by their simplicity of use, the effectiveness of the tools, and the consistency of each step for furthering the design process.

3.3 Development of Function Constraint Model

3.3.1 Constraint Types

The FCM should indicate the maximum and minimum limitations of the constraint, or the min-max proposition when in performance and the ideal state of the functions; furthermore, the parameters of the artefact are placed in the system level order to show a visible picture of the constraint network. The FCM should not be too specific, instead, it should show in simple keywords, a higher-level presentation to analyse the most important inherent and imposed constraints so that designers can think of a way to manipulate them. Eliminating unnecessary imposed constraints, or trimming in TRIZ terms, further elevates ideas for a simpler artefact concept design, and replacing it with new technology means adding-up new imposed constraints.

3.3.2 Constructing Function Constraint Model

To implement safety in the conceptual design process, analysis of an artefact's constraints is the best way to determine its limitations, especially limitations in respect of safety. This can be achieved by using a model to map the safety constraints. The FCM adopted FAM structure but with a more focused component analysis, smaller analysis boundary, and indication of min-max propositions, all in F3 structure. This model aims to identify the constraint types, priorities, limitations, opportunities of changes, and determine which constraints can be eliminated or reduced. The designer must consider a multitude of constraints, especially for complex artefacts.

When designing artefacts with a safety approach, the design and safety constraints of the artefact must be known, so that the design changes can consider its limitations, boundaries, acceptable risks, and ensure that they are within the design and safety requirements. Designers should identify and analyse inherent constraints for their optimization, and imposed constraints for their reduction or elimination. Further details on the types of constraint that should be included in the conceptual design process are presented in Chapter 4.

Therefore, referring to FAM is much more helpful in determining safety constraints. The TRIZ tool involved in the development of the FCM model is the FAM, and heavily refers to the SFR and field types table; as shown in Table 2.4 and Figure 2.10. The FCM model is based by the FAM structure, with additional indications of further functions' constraints, and relationships between two substances. To enable designers to easily find and pinpoint constraints within the system, the model is divided into three levels of relationship – form-fit-function or F3 – which is employed in dividing the levels of relationships.

Segmenting the FCM into F3 can help designers plan and organize resources. In addition to that mentioned in section 3.4, other constraints, such as technology concept, incorporation of new materials and time taken to develop the system pertaining to the constraints, are also included. Below is a description of F3 in the context of FCM:

a) Form: is a single or group of parts (with a single construct) that is developed by specifications, such as geometric shape, dimensions, weight, and material composition. It is often an embodiment of the part or component. In the context of this research, the form consists of the component and subcomponent of the prototype.
b) Fit: is the association between two or more forms, the interface and interconnectivity to fulfil a certain task. The fit is the interaction of the physical and function between components, including tolerances. An assembly that contains greater complexity also falls into this category due to multiple constraints.
c) Constraint or Function: is the action(s), which a form or fit is intended to do and designed to perform. In the context of this research, the function is not limited to the work done but also the field used, and the constraints that the component must face. This research suggests that the viewpoint of the design constraint is to model with the F3 structure.

A more generic constraint model with the Form-Fit-Function (F3) divisions ease the process of differentiating the constraint types and characteristics. The structure of FCM is also inspired by the TRIZ Su-Field model, where the connection between two substances is not only focused on the 'field' but also the 'main function', performance outcome, and constraint's values.

3.4 Development of Safety Principle Guide

The main objective of this research is to develop a conceptual design framework with a safety approach, with the framework goal is to produce a creative, or inventive and safe concept design. The process of developing SPG is the most dominant analysis of this thesis. Solving problems with safety applications can be addressed by adopting the SAED safety principles. The problem is how to apply the most appropriate safety principle and for which inventive principle. This is where the compatibility between the safety principles and 40-IP is developed. Qualitative content analysis is the research method used for the development of SPG, where patents are the resources.

3.4.1 Deductive Qualitative Content Analysis

As shown in Figure 3.4, the process begins with assigning codes to the safety principles and 40-IP. These two key principles are vital in linking variables inside the patent's content. The variables for prior art disadvantages, the safety risk, the solutions to the disadvantages, and the proposed design substances are identified through a patents latent search on text and images. The key principles codes and the variables are then recorded in a content inventory using the Microsoft Excel application. The completed content inventory is then further delivered to the content audit process. The content audit ensures that the information gathered on the content inventory is adequate.

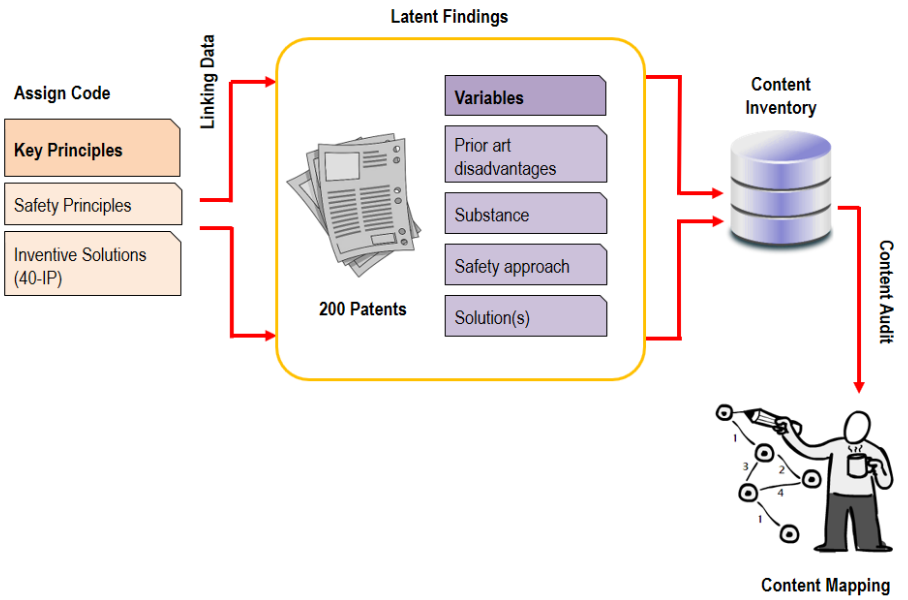


Figure 3.4: The overall process flow for the patent qualitative content analysis of this research

After completing the content audit, the content mapping proceeds for the evaluation of the compatibility between the safety principles and 40-IP. The final process is to integrate the compatibility result into the TRIZ-SA 8-Step.

In addition to extracting important information concerning the safety principles from SAED, and system safety from books, journals, articles and proceedings, patent documentation helps in determining the application of safety for the conceptual design product. Patents are the perfect source of empirical evidence because they consist of conceptual solutions concerning the other important elements. The concept designs recorded in patents have high potential to be developed in real form. Patent analysis is the same method used by Altshuller and Shulyak (1996) for the development of TRIZ's 40-IP, Separation Principles, and 76 Standard Solutions.

All the key principles and variables extracted from the patent analysis are recorded in a content inventory table; as shown in Table 3.1. Other important information, such as published and granted date, the International Patent Classification (IPC), and Cooperative Patent Classification (CPC), are also included for direct reference to the analysed patent.

Table 3.1: The content inventory table of MLG patents

No	Patent Num.	Grant/ Publish Date	Title	Assignee	IPC/ CPC	Problem and Solution	QCA Codes	SP	40-IP
1									
2									

The qualitative content analysis methodology is the main driver of this research, specifically the *interpretative* method of document analysis, which was conducted on the research materials obtained. The qualitative content analysis approach is precisely relevant for investigation of the compatibility issue between TRIZ 40-IP and safety principles; thus, achieving the goal to build the SPG. The evaluation of the contents resulted in categorization of the safety approach in accordance with TRIZ 40-IP. The categorization process is not exactly a linear process, as, sometimes, the extraction of information requires re-reading and relating to the safety principles several times to ensure extraction of the right information and that insights are placed at the right 40-IP.

The directed qualitative content analysis approach uses inductive reasoning, which is a more structured process for validating and extending a theory or a theoretical framework, while deductive reasoning is used throughout the completing the SPG and the FCM. The patents analysis also helps in identification of the frequent problems that arise in aircraft's MLG design and potential areas for design change. The results from the patent analysis are also the best way to identify the trend of the safety approach in MLG design. Details on all the analyses for the development of the safety principle guide are discussed in chapter 4, section 4.4.1

The selection of patents used in this research are particularly related to the MLG design or its method of operation, and issued within five years between January 2011 and December 2015. The collected research materials from the listed patents search engine was set using Boolean operation with the specification of: 'Main Landing Gear'; specific search particulars were required for the different patent search engines. Below is the list of patent search engines:

a) Google Patents at https://patents.google.com/
b) ESPACENET Patent Search (European Patent Office) at https://worldwide.espacenet.com/
c) World International Property Organization (WIPO) at https://patentscope.wipo.int

A total of 200 patents relating to the MLG are obtained through all three online patent search engines, and 73 are extensively used for the investigation to develop the Safety Principle Guide. The list of the extensively analysed patents can be found in the patent analysis table, Appendix A. At this point, refining the framework is crucial to enable both FCM and SPG to be placed at the appropriate step. After analysing the whole framework, the FCM should be placed earlier, before utilizing the SPG.

3.5 Validation of TRIZ-SA Conceptual Design Framework

Validating the TRIZ-SA conceptual design framework refers to the 'Validation Square' (Seepersad et al., 2006) where the usefulness of TRIZ-SA 8-Step is achieved through *'effectiveness'* qualitative evaluation. The further process of the qualitative evaluation is demonstrated to show two areas:

1) The *appropriateness* of example problems conducted to verify usefulness
2) The *correctness* of method-construct, in:
   a) separate application, and
   b) integrated application

In conducting the 'appropriateness' of the application, the validity should refer to 'Theoretical structural validity', meaning accepting the method step or procedure validity through the appropriateness of the author and publisher of the literature, the number of references in association with the step, and the number of benchmarks by other methods. Another way of ascertaining the appropriateness of the example problem is through accepting method consistency through:

a. information flow
b. adequate input for each step
c. anticipated output based on input
d. the anticipated output become input to next step
e. facilitate evaluation against real problem

Inadequate, invalid or unrelative methods to each other means that the method is inconsistent. Meanwhile, conducting the *'correctness'* of the example problem, which, in this case, is the aircraft MLG, the validity obtained pertains to the 'Empirical structural validity', meaning accepting the example problem with confidence through viewpoint, compatibility of example with the method, method intended to apply to actual problem, and data associated with the example to support the conclusion.

A conceptual design framework is merely just an idea framework if it is not practically utilized. In order to ensure the proposed TRIZ-SA framework is useful, applicable and able to guide designers to develop a safe and creative output, a validation process should be enforced to increase confidence in its usefulness and effectiveness. Validation determines whether the 8-Step procedure offers improvements in two areas; its methodology and the prototype. Figure 3.5 illustrates the validation process flow of the TRIZ-SA with reference to the artefact case study. The procedures, analyses, limitations, reasoning and ideas developed are all documented and qualitatively evaluated.

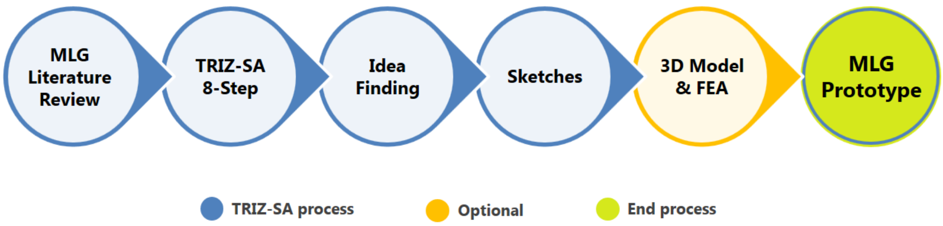


Figure 3.5: The validation process flow for TRIZ-SA

In validating the TRIZ-SA framework, questions on how to process the quality and the effectiveness level arose. While the common procedures of validating engineering research require formal and quantitative endorsement, the effectiveness of a design method relies on subjective qualitative affirmation. Seepersad et al. has developed a holistic model concerning how to validate the design method called the 'Validation Square' (Figure 3.6); this model is adopted in validating the TRIZ-SA conceptual design framework. Apart from proving the validity of the TRIZ-SA framework and theoretical performance, the effectiveness of its practicality also requires several criteria such as efficiency, systematicity and usability of TRIZ-SA. On the output of case study MLG, the level of inventiveness and creativity are also discussed.

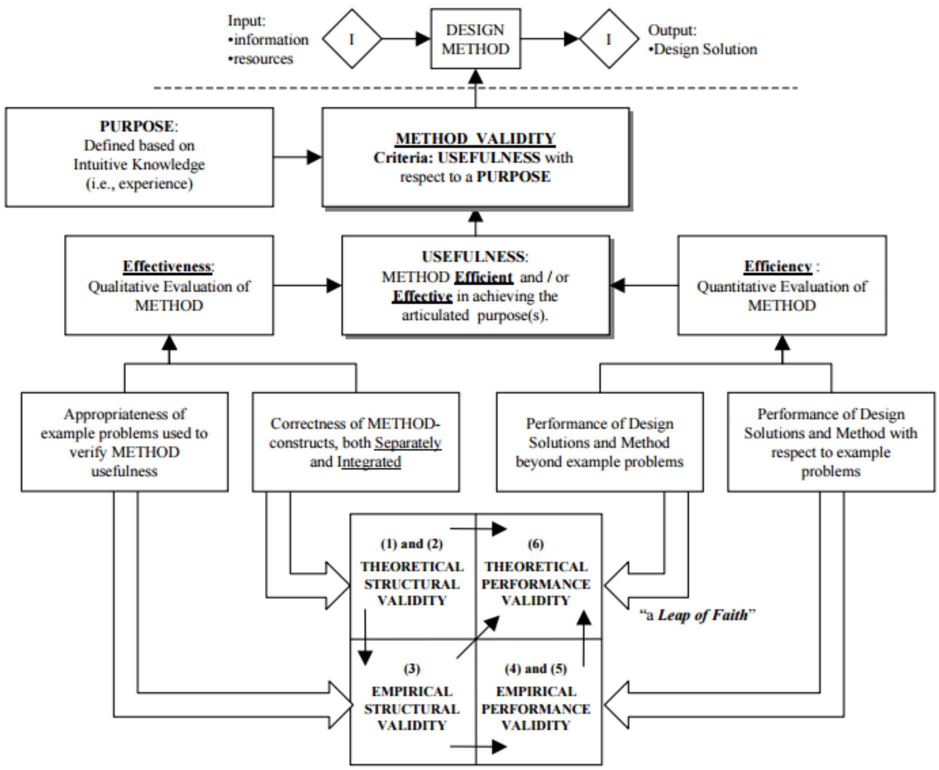


Figure 3.6: The framework for validating design methods (Seepersad et al., 2006)

Experimenting with the framework for the MLG concept design requires background knowledge on the component, its disadvantages, scenarios of current use, trends, and its safety requirements. A number of sources are obtained and analysed; namely, 60% patents, 20% books and journals, 10% FAA design and safety documents, and 10% on related websites.

3.6 Case Study Artefact

The aircraft main landing gear (MLG) is chosen to be the artefact for this research case study. The reasons behind selecting the MLG as the case study are because; firstly, this research tries to develop a concept design example that focuses on the geometrics and shape of a complex artefact. This aim is very applicable to MLG because the MLG experiences major noise problems most of which come from the inefficiency of its shape. Second, the MLG is a complex artefact, yet design changes can be conducted, depending on the design of the fuselage and runway type. Lastly, the patent search surrounds the MLG design, albeit the results for the development of SPG are not specifically applied to MLG. It can be applied to any object of conceptual design.

CHAPTER FOUR

TRIZ-SA CONCEPTUAL DESIGN FRAMEWORK WITH SAFETY PRINCIPLES

4.1 The Framework

The development of the TRIZ-SA conceptual design framework is through the selection of the best and most effective tools from both methodologies, in accordance with the eight conceptual design steps. The decision to construct such a framework is to conduct the conceptual design process onto artefact that is complex and has higher safety requirements within its system, besides its performance towards other system, humans and the environment. This chapter discloses how the TRIZ-SA framework is developed and functioned, how each of the procedures is used for obtaining an inventive concept design.

During the application of the TRIZ-SA framework on the artefact, the process of abstraction and generalization is repeated several times. Firstly at the initial step, detail resources are obtained and abstracted for the the establishment of FAM. Secondly, abstraction and generalization occurs in the process of determining the 39-P. In finalising the TRIZ-SA process, the firming-up principal solution requires abstraction and generalization again finally, in selecting the best theoretical idea solutions among the several sketches; with several 3D models of the concept design. This process is similar to the deductive reasoning procedures.

The TRIZ-SA concerns safety and constraints analysis, abstracting, generalizing, linking as-is problems with future solutions, referring to scientific effects database and TESE forecasting tool, which results in a systematic yet simple problem-solving process that, simultaneously, changes the perspective of creative and safe problem solving as a whole. Along the framework, three major design works are proposed: the defining or ‘identifying and understanding’, idea developing or ‘formulating and finding solution’, and ‘evaluating and confirming’; as shown in Table 4.1.

Table 4.1: Comparison of the conceptual design process flow structure for SACD, TRIZ and TRIZ-SA

Step	SACD	TRIZ	TRIZ-SA	
1	Requirement List	IFR	SACD + TRIZ	**Defining**
2	Abstraction	-	SACD	
3	Function Structure (FS)	Functional Analysis Model (FAM)	TRIZ	
4	Working Principle	Scientific Effect	SACD/TRIZ + *FCM	
5	Working Structure	-	SACD	**Develop Idea and Solution**
6	Select Suitable Combination	EC, PC, 39-P, Contradiction Matrix, 40-IP & Separation Principles	TRIZ + *SPG	
7	Firm-up to a Solution	-	SACD + Sketches/3D Model	
8	Evaluate Against Technical and Economic Criteria	Evaluate Against Technical Criteria	TRIZ	**Evaluation**

*New tool developed in this research

The steps from Table 4.1 are presented in the framework model shown in Figure 4.1. The IFR is seen used and reused in several steps, Steps 1, 3 and 8. The FAM is another tool reused in several steps, Steps 3, 4 and 7. The reason for the reuse activities is to reduce the number of tools. A newly proposed tool developed from this research, the FCM, is introduced in Step 4 and again in Step 7. Another newly proposed tool developed by this research is the SPG, which is applied in Step 5. The intervention of SPG in Step 5 should begin after the use of the FCM model in Step 4. The FCM and SPG are the tools specifically developed for the safety aspect of the prototype's conceptual design. The motivation for the development of TRIZ-SA is to develop a conceptual design process that is systematic and able to produce a creative and safe solution. Details of each step are explained further in later sections of this chapter. The new conceptual design framework is represented with the name '8-Step'.

4.2 TRIZ-SA 8-Step

The new framework is an improved conceptual design steps, with several of the steps being a combination of both the TRIZ and SA methodology, or a replacement with TRIZ tools. The new framework (Figure 4.1) aims to not just analyse problems and formulate inventive solutions but add value to the safety in design with the help of the constraint modelling and safety principles guide. The TRIZ-SA framework emphasizes three major stages during the conceptual design process:

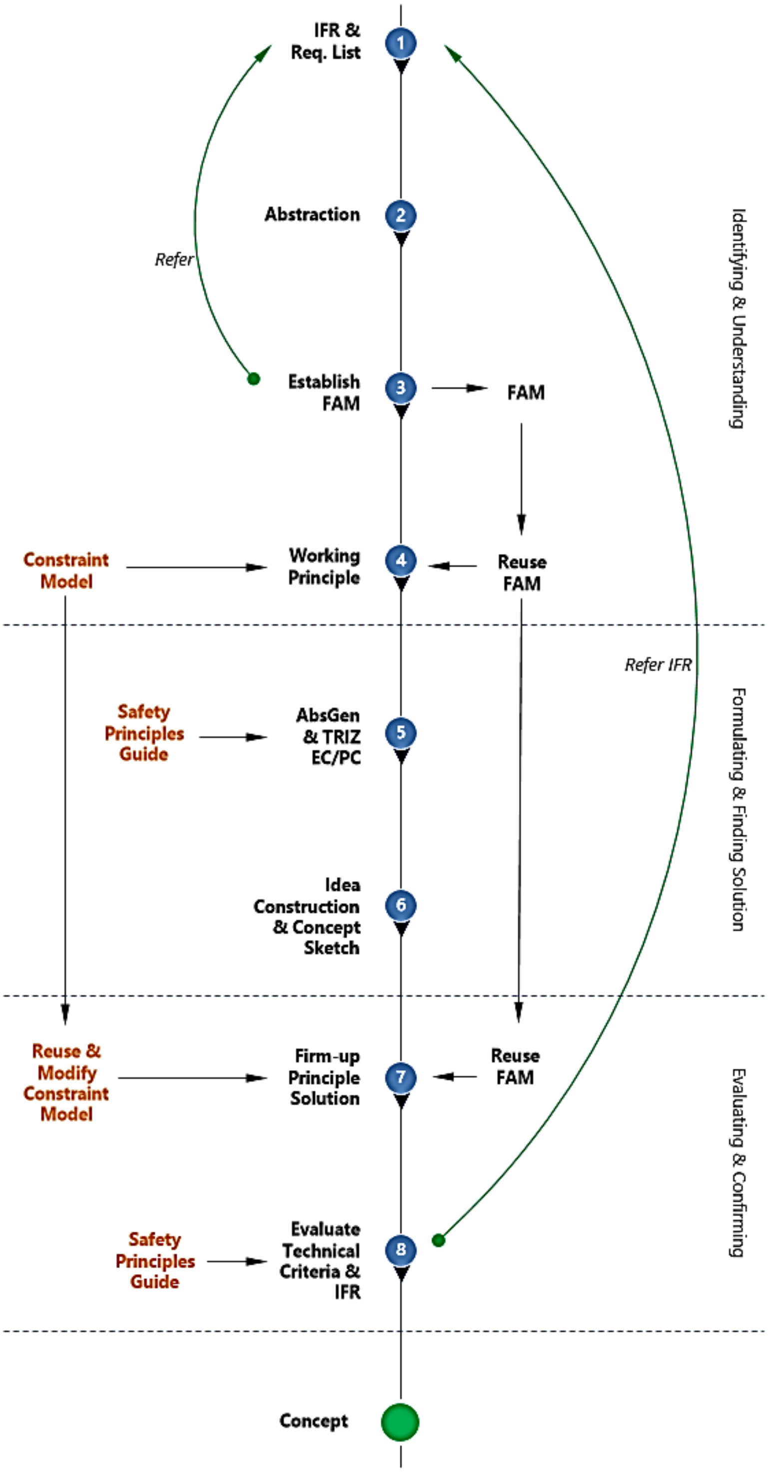


Figure 4.1: The TRIZ-SA conceptual design framework steps named '8-Step'

a) Identifying and understanding: this stage is the initial conceptual design stage where in-depth understanding of the artefact's advantages and disadvantages are identified. In this stage, the characteristics of the artefact, its functions and its design parameters are listed and modelled with several tools such as the requirement list, IFR, FAM and FCM. The steps involved in this stage are Steps 1, 2, 3 and 4.

b) Formulating ideas and finding solutions: the next stage is to formulate ideas using AbsGen, TRIZ EC and PC to excite and expand the understanding of the artefact's functions and constraints before proceeding further to idea development. The SPG is used in the process of solution finding and to embed safety characteristics into the proposed conceptual design. Sketching is also part of this stage. The steps involved are Steps 5 and 6.

c) Evaluating and confirming: the last stage of the TRIZ-SA process - before confirming the principal solution, the selected ideas and problem solutions undergo internal and external evaluation procedures. The internal evaluation pertains to the product's performance abilities and constraints involved; TRIZ-SA recommends the use of design feasibility analysis to evaluate the performance effectiveness and safety solution efficiencies. The external evaluation is through application of design standards and regulations, to ensure the developed concept design fulfils IFR established earlier, and improves the appointed design constraints. At this stage, the FAM is reused again for the evaluation purpose, together with FCM and SPG. The steps involved in this stage are Steps 7 and 8.

4.2.1 Step 1: Requirement List and IFR

At the start of the conceptual design process, a good grasp of the problems is necessary. Step 1 is the initial stage of starting the conceptual design activity where the problems need to be defined and all available resources are enlisted. When the artefact chosen requires greater safety concerns, details on the artefact's components, sub-components and design requirements must be listed to avoid any missing resources, which will lead to misleading problem-solving formulations. The SA requirement list can do the job, specifying important information especially the information of D (demand) items. The decision to use requirement list from SA and IFR from TRIZ is based on pairwise comparison.

4.2.1.1 The Pairwise Comparison on Step 1

The initial step in both the SACD and TRIZ methodology is to acquire the resources of the artefact and analyse its values. The SACD requires the establishment of the artefact's requirement list in D and W value notations. In other hand, TRIZ requires analysis of the causal factor of the artefact's problem using the Cause and Effect Chain (CEC) analysis, inspired by the Ishikawa diagram (Ishikawa, 2012). Then, the identified cause will be used in formulating contradictions. The differences between the initial steps of TRIZ and SACD are presented in Table 4.2.

Table 4.2: The differences between the initial steps of SACD and TRIZ

SACD	TRIZ
Proper preparation: listing items related to the problem using the Requirement List	The use of Cause and Effect Chain (CEC) diagram to identify the core problem
Identify all related elements that can influence the change of design. Label with D (demands) and W (wish)	Identifying the contradiction of the core problem
Design objective(s)	IFR
Rationale: The process is quite time-consuming, but the list can avoid any missing information and can give clues to potential solutions. The process is *specific.*	Rationale: The process goes straight to the problem's core and saves a lot of time. But, in the case of safety, it may miss some important items. The process is between *specific* and *generic.*

TRIZ-SA uses the requirement list from SA, and the IFR from TRIZ for the Step 1. The requirement list not only clarify on the components, system and parameters of the artefact but helps in the process of building the FAM in Step 3. The method by Dietz and Mistree (section 2.7.2) implement the same procedures as TRIZ-SA, where the requirement list is indicated with D and W, and refers to the IFR. A slight difference is that they use both requirement list and IFR in the assessment of concept selection and final design performance, while TRIZ-SA use both of tools at the initial conceptual design process. Another method by Mayda and Börklu (section 2.7.4) uses the requirement list at the initial stage of designing, inside a HOQ model consisting mainly customer needs.

Step 1 of TRIZ-SA concludes that the SA requirement list and TRIZ IFR are the initial tools for starting the conceptual design process.

4.2.2 Step 2: Abstraction

When processing the abstraction, the problem's contradiction should be included at the earliest step. In the abstraction in the Step 2 stage, several disadvantages directly and closely related to the problem must be included, as the goal of the problem-solving is to contradict the disadvantages. Throughout the abstraction process, it is best to choose particulars that are connected to the IFR. The IFR leads to the selection of elements that are contradictory to the IFR statement, which means it determines the artefact's disadvantages and simultaneously identify the worsening parameter. From the disadvantages found, the abstraction process relates elements according to IFR and the disadvantages. After careful abstraction of the as-is problem, the more specific analysis of the function and relationship on the abstracted elements commences.

Abstraction process used in work of scholars on TRIZ and SA combinations are varies. Dietz and Mistree uses ARIZ abstraction procedures in their initial design method, meanwhile the method FB-TRIZ (Nix et al, 2011) construct three level of abstraction: *class, basic* and *flow restricted*. The *class* abstraction is a higher level abstraction process, meanwhile the *flow restricted* abstraction being the specific one. TRIZ-SA implements common abstraction method, by selecting component and system related to the core problem and D labelled, as well as referring to design IFR.

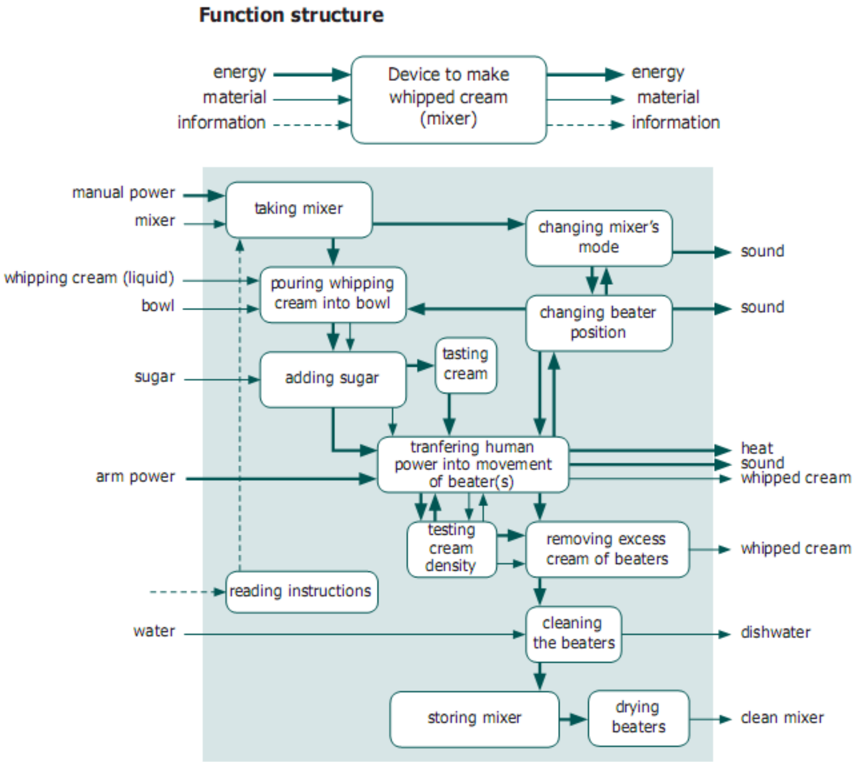
4.2.3 Step 3: Establish Function Analysis Model (FAM)

4.2.3.1 Pairwise Comparison on Function Analysis

In SA, a tool or a method named Function Structure (FS) is the most sought after by many design practitioners for analysing the functions of an artefact and their relationships, including the work of Malqvist et al. (1996), Dietz and Mistree (2009), Nix et al. (2011) and Mayda and Börklu (2014). FS has been the key instrument in the process of artefact's function analysis for the conceptual design because of its systematic procedures. The FS indicates mutual relationships between the components and subcomponent of the artefact, their performance to each other and the whole process, and is always modelled with an abstraction representation to help find solution in different views and perspectives especially concerning the physical characters. This process opens up many design possibilities and prevents designers from quickly jumping to solutions. Apart from FS, there are many other tools suggested by SA, such as HOQ, Morphological Matrix, Compatibility Matrix and other methods of generating solution ideas.

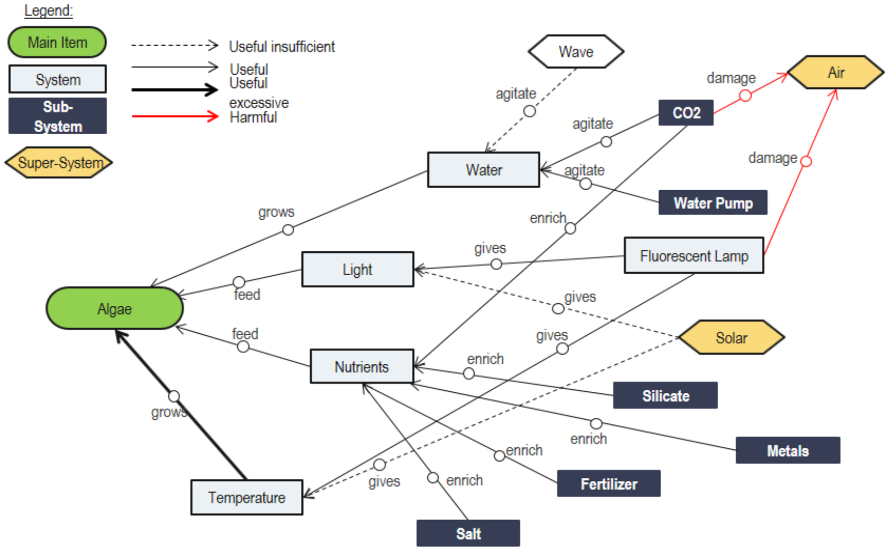
TRIZ also has a tool for analysing the functions of the artefact, named the Functional Analysis Model (FAM). Table 4.3 illustrates and explains the differences between the function structure of SA and the TRIZ FAM.

Table 4.3: The differences between FS and FAM

SA Function Structure (FS)	
 The SA Function Structure. (Source: Function Structure, 2016)	
Definitions	A graphical model representation of an overall function and sub-functions that shows the connections and flows of the operation (Stone & Wood, 2000).
Structure	i. Three flows passing: energy, material and signal/information. Represented in different line types. ii. The flow of component functions inside a system boundary or called the Black Box (Aurisicchio et al., 2013). ii. Have input and output indications.
How-to	Start by determining the main flow in a technical system (system). In the case of new design, the individual subfunctions or their relationships are known at the higher level (generic), mostly in the concept design system. The auxiliary flows should only be considered later (not necessarily in the model).
Characters	According to Pahl and Beitz (Pahl et al., 2007): i. Conversion of energy: changing, channelling, storing, varying energy components, connecting energy with a signal. ii. Conversion of material: changing matter, varying dimensions, connecting matter with energy, signal, types of materials, channelling and storing material. iii. Conversion of signals: changing, channelling, storing, varying signal magnitudes, connecting signals with energy, matter and signals.
Important Procedures	The flows of energy, material and signals are known and specified. All the functions are treated as important because they are needed. Any unrelated and unnecessary elements are discarded.

Auxiliary Functions	Additional functions are usually indicated by the word ‘auxiliary’ or ‘alternative’.

TRIZ Function Analysis Model (FAM)



An example of TRIZ FAM. The system, sub-system and super-system are presented by different shaped boxes.

Definitions	To assimilate systems in which a problem is broken down into its component functions.
Structure	Three flows: system, sub-system, super-system Indicate relationships between element with function keywords. Four line types to indicate useful, useful insufficient, useful excessive or harmful functions.
How-To	Modelling current situation, not the future prototype. The arrow shows the functions towards, with different lines for process efficiency identification.
Characters	Uses three levels of system component. Super-system is included although not directly involved in the system network but potentially useful for problem solution.
Important Procedures	The indications of function need to be in one word (keyword) The relationships among the system, sub-system and super-system must be accurate because the FAM will be reused several times
Auxiliary Functions	The super-system in its current situation.

Different to the FS, which emphasizes energy, material and signal as the three flows passing a component system boundary, the FAM uses a single keyword to represent each component’s function with indications of normal, useful or harmful through linetypes. The FAM works with a mixture of generic and specific processes, whereas the FS is quite specific. In the event of developing a prototype, it is best to build a simple model of functions to avoid a mental block or ‘psychological inertia’.

4.2.3.2 The Function Analysis Model for TRIZ-SA

Through the comparison in Table 4.3, it shows that the FAM is favourable for its simplicity in indicating the artefact's current process and simplicity in visualising the system relationships. The FAM introduces the 'super-system', where indirect elements are included in the model that may influence the system's function and potentially trigger new solution ideas.

In the process of determining an artefact's system and function relationships, FAM is selected for the TRIZ-SA framework. The FAM enables designers to understand the system and its function relationships better, as well as determining which elements or sub-system that can be manipulated, changed or subtracted to optimize the current system. The FAM is reused in Step 4 to identify the working principles and possible trimming, and reused again in Step 7 for the new version of FAM with indications on any modifications, together with any additional or subtraction of components and sub-components.

4.2.4 Step 4: Search for Working Principles or Scientific Effects, Reuse Functional Analysis Model and Establish Function Constraint Model

The SA further analysis of functions requires the designer to understand the working principles behind every artefact's performance. The physics of the main function should be clarified, and, later, the constraints within the working principles can be identified. Here the pairwise comparison between the SA working principle and the TRIZ scientific effects are discussed.++

4.2.4.1 SA Working Principle or TRIZ Scientific Effects

The working principles of SA has been discussed in section 2.5.3.2 in Chapter 2. It requires searching through literature sources, or as-is artefact test to find the existing principal mechanism and potential addition or elimination of working principles. Another way is to search by discursive methods, using classification schemes, intuitive method like brainstorming as well as catalogue of varying forces.

TRIZ on the other hand, has developed a database for a similar activity to working principles called the 'scientific effects'. TRIZ has developed three branches of effects – physical, chemical and geometric. The three effects are the physics relationship, and a phenomenon between the 'actor' and 'receptor' of a certain work. The actor is usually in the form of the function, parameters and sometimes a transformation process, and the receptor means the effects resulting from the actor's action. The effects are divided into three types – function, parameter and transform. Figures 4.2 and 4.3 present the database of scientific effect provided by the Oxford Creativity (2016) website. The results from the database are a non-exhaustive list of the interactions between the three effects; an open-source database of 'effects' and 'phenomena' collections. The utilization of the working principles from the TRIZ scientific effects helps tremendously in fulfilling the

IFR previously formulated; at least close-to ideal, other than using written and observation resources.

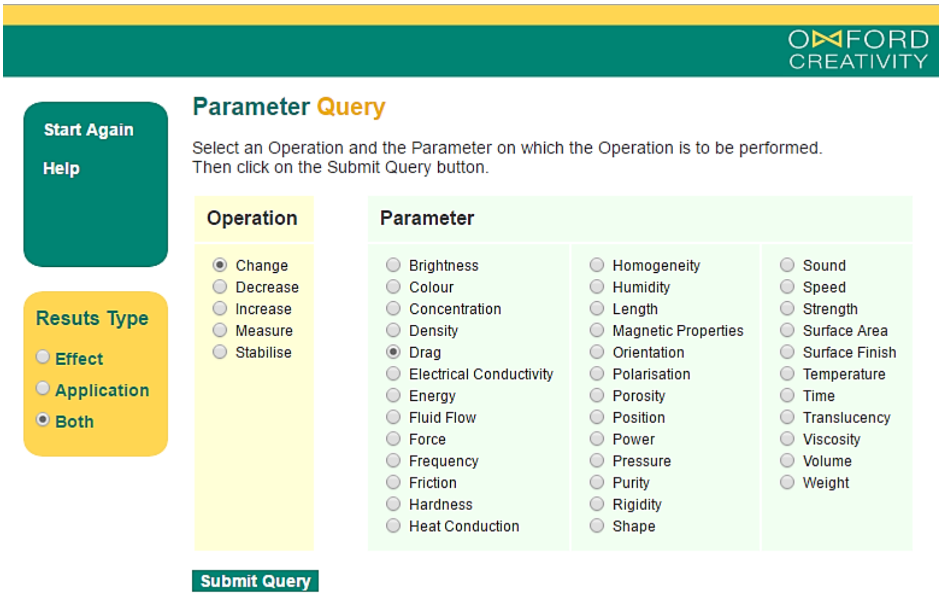


Figure 4.2: Query on changing the drag parameter through the use of the scientific effect database provided by Oxford Creativity
(TRIZ Effects Database, 2016)

Figure 4.3: The suggestions of the scientific effects, from Figure 4.2 configuration.
(Source: TRIZ Effects Database, 2016)

SA applies the process of finding the working principle after the function structure, which is placed in the first phase of conceptual design, while TRIZ applies the scientific effect either before or after the formulation of contradictions, in the middle or near the end phase of the conceptual design process. Meanwhile, TRIZ-SA applies both working principles and scientific effects tools and used either one, separately or combined, depending on the artefact's working principles availability. Mayda & Börklu uses working principles derived from 40-IP, while Dietz and Mistree applies scientific effects after the process of EC and PC.

4.2.4.2 Reusing Functional Analysis Model

According to Pahl and Beitz (Pahl et al., 2007), a working principle must reflect the physical effect required for fulfilling the functions, principal solution, input and output value, auxiliary flows, geometric, and material characteristics. The working principle is more towards understanding the physics of how a product moves, functions and reacts with others to ensure the success of the assigned task. When implementing working principles into the design process, firstly, designers must know the artefact's parameters and the component's relationships with other sub-components as well as the characteristics of the materials. Designers must know how to differentiate the distinctions between form design features and the physical effect. Step 4 retains its SDA approach for the analysis of the artefact’s working principles.

The previously built FAM is used again, but, this time, the information on the working principles, geometric concept and physical effects are indicated in the model. The FAM now displays the system’s relationships and working principles, together with the indications of new functions in the place where working principles are positioned. Looking at the improved FAM, designers can now optionally apply the TRIZ ‘trimming’ process which is another way to find the solution by reducing the components, system or sub-system but still maintaining the artefact’s main function.

Since the SA working principles or TRIZ scientific effect is more towards a specific approach, the inherited and imposed constraints from the identified artefact can be modelled. Here is where the FCM commences. The FCM needs to be addressed so that the designers understand how things work and understand the boundaries of the artefact and its constraints. The FCM should not be too complex as it is only used to guide designers to understand the current functions and limitations of the artefact; hence, guiding them towards solution finding. Nevertheless, the FCM will help immensely in the planning of constructing a safer conceptual design.

TRIZ-SA targets the ideal prototype to accommodate a more flexible but robust safety characteristic. Flexibility here means that the constraints and safety requirements have a bigger tolerance and limitation frame, but are robust in protecting from harm, or efficient in avoiding harm. It is important that the constraints and safety analyses in this step use the as-is situation of the artefact.

In general, the search for working principles or scientific effect should be based on the component's associated parameters and its relationships with the systems and items listed in the requirement list. If the working principle is unknown, the designers should work at finding the working principles from the type of energy (refer to Table 2.5). After determining the physical effect, designers can work on the form or geometric design. Certain cases of redesigning or developing a new prototype do not concern changing to a new physical effect but to a different geometric design. In building many solutions, most design researchers recommend the use of known working principles that are related to the artefact or intuition-based methods, such as subjective perception, expert judgement, or individual or team design imagination.

The working principles or scientific effects are very important and must be used to understand and manage the working relationships between many sub-systems so that any changes, adding to or reducing the sub-system, do not create hazard prone functions or performance or any malfunction.

4.2.4.3 Function Constraint Model in the 8-Step

Before constructing the FCM, using the inventory tool from ARIZ, Substance and Field Resources (SFR) (San, 2009) is suggested to exhibit and determine the constraints characteristics; as shown in Table 2.3. The use of the SFR table aids in identifying the characters of the constraints inherited in the artefact. When an adequate SFR list is obtained, the designer organizes the constraints from the SFR's resources, substances, and parameter list, identifying the constraints from the highest priority to the lowest, the ones that have little possibility of change down to those that can be totally changed. If SFR is not utilized the relationships between the identified elements will not be visually clarified. The constraints should be monitored and continuously diagnosed to ensure that the prototype development does not violate the required design limitations.

The FAM indicates several group components inside boundary lines. The inventory tool SFR from ARIZ, can help exhibit and determine the constraints characteristics. The use of the SFR table aids in identifying the characteristics of the constraints inherited in the artefact. Using SFR, an adequate list of the resources, substances, and parameter fields is obtained and designers can organize things through prioritization for design change.

The external constraints are actually the ones that drive the innovation of the prototype. They influence the decision for change and innovation into a new conceptual design, and for the replacement of components with more sophisticated technology and material; hence, improving the design constraints until they achieve more manageable design limitations.

4.2.5 Step 5: Abstraction and Generalization, TRIZ Engineering Contradiction, Physical Contradiction and Safety Principle Guide

4.2.5.1 Abstraction and Generalization

In Step 5, the abstraction and generalization (later referred to in short form as 'AbsGen') is conducted to find the contradictions and will be used for the Engineering Contradiction (EC) and Physical Contradiction (PC) formulations. The AbsGen is adopted from SACD procedures and conducted using all the information obtained from the previous process steps; from Step 1 to Step 4.

AbsGen is easier to visualise in a sketch or model representation. The example of the AbsGen model (Figure 4.4) shows a simple structure with adequate information to demonstrate the understanding of both processes. On the far left, the abstraction space consists of several selected key points or elements of the artefact's as-is current situation; the advantage, disadvantage, goals, working principle and constraints. The selected abstraction, 'B' for example, is brought into the generalization process next where the understanding of 'many components' is generically translated into 'complexity'. There are three possible TRIZ 39-P related to complexity; parameters 26, 33 and 36. Referring back to the way the component complexities operate, it might help in selecting one right 39-P between the three.

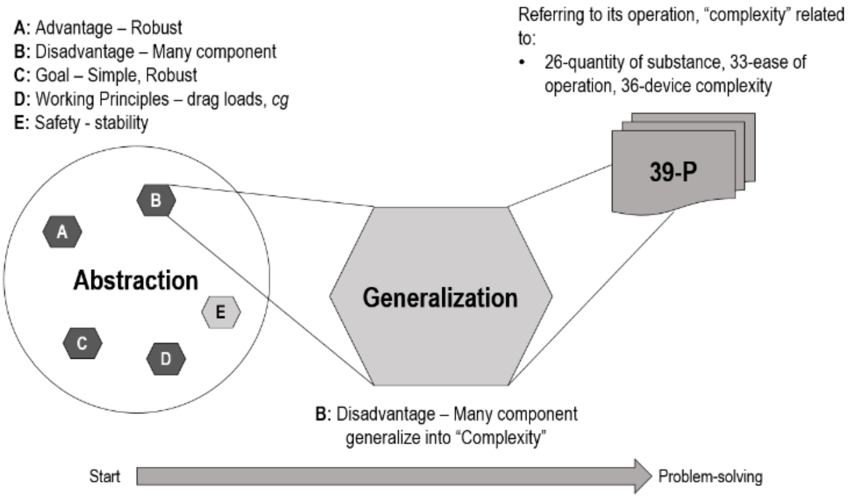


Figure 4.4: The AbsGen model demonstrates the differentiation between abstraction and generalization in the TRIZ EC process
(Source: Kamarudin et al., 2016a)

The contradiction previously found is then divided into two variables, the improving and worsening parameters, which will be represented with 39-P. Later, 39-P are used in the formulation of EC or PC, either with the TRIZ contradiction matrix (Appendix C) or the TRIZ Separation Principles. In the process of using the contradiction matrix, TRIZ suggests up to four of its inventive principles, while, in the use of separation principles, normally up to two separation principles can be used for generating a solution.

4.2.5.2 TRIZ Engineering and Physical Contradiction

All the other four TRIZ and SA combination methods uses TRIZ EC and PC. TRIZ-SA also implements TRIZ EC and PC in Step 5. The EC formulation generates recommendations of up to four 40-IP and the safety principles are acknowledged through assessing the SPG. ARIZ is only applicable when the artefact has a small opportunity for change, which is not the case for a conceptual design change. ARIZ has its own algorithm for problem-solving; the author found it hard to incorporate FCM and SPG within the process. Therefore, ARIZ is not included in the TRIZ-SA framework. Only the SFR tool of ARIZ is used for the FCM.

4.2.5.3 Safety Principle Guide

In accordance with the systematic steps for selecting the right 40-IP for EC and separation principles for PC, a process of cross checking with safety principles and scientific effect is important to ensure the formulation towards problem solutions is on the right track. The intervention of SPG can be referred to as the Step 5 process flow; as shown in Figure 4.5.

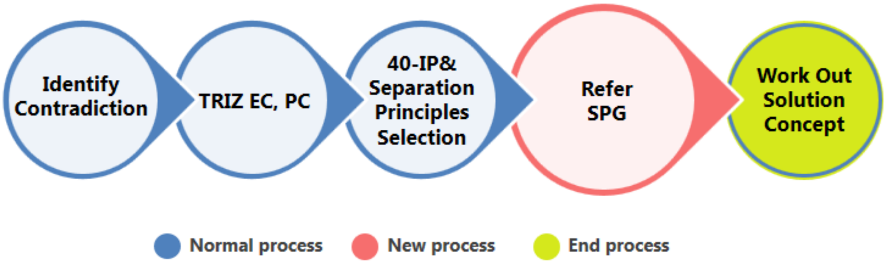


Figure 4.5: The integration of SPG in TRIZ-SA 8-Step

4.2.6 Step 6: Idea Construct and Concept Sketch

4.2.6.1 The Pairwise Comparison on Idea Construct

Both methodologies apply different methods for finding solutions after the artefact's problem has been diagnosed, clarified and abstracted. SA implements a more technical approach, while TRIZ prefers using principles, and a more generic and simplified approach in solving problems. The list of the differences is presented in Table 4.4.

Table 4.4: SA and TRIZ method for finding the solution and developing the concept

<table>
<tr><th>SA</th><th>TRIZ</th></tr>
<tr><td rowspan="3">Mathematical modelling
*Rough sketches, technical drawing
Preliminary experiment/model test
Model construction, e.g. kinematic model
Analogue modelling/system simulations
Further patent and literature search
Market research on proposed technology, materials, etc.
HOQ</td><td>Higher Level
Engineering Contradiction
39-P
40-IP</td></tr>
<tr><td>Intermediate Level
Physical Contradiction
39-P
4 Separation principles
76 Solution Standards</td></tr>
<tr><td>Specific Level
ARIZ
Zone of Conflict
SFR Table
Su-Field
Scientific Effects</td></tr>
</table>

In SA, attaining a higher level of conformity before proceeding further for the next design step is a necessity. SA adopts many micro strategies and decision making when formulating solution ideas. The utilization of mathematical modelling, preliminary test, computational modelling, patent and literature search increases the certainty of the solution path. Utilizing rough sketches, 3D models, technical drawing, analogue modelling and system simulations are among the many tools recommended in the SACD solution finding process and firming up stage. SA repeatedly conducts classification of criteria, associated parameters, working principles, working structures and possible solutions. Although classification is a systematic method it requires analytical skills to evaluate between classified solutions, and bigger resources are needed, adding more work and time.

Again in SA, further concretization of the selected working structure is compulsory. Pahl and Beitz acknowledge that working structures, the term used for a combination of working principles, is the most important process in the creation of original design because it serves as a basis for designers to invite more creative ideas. Within this working structure, the designer should give attention to recognizing the root of the problem and make sure that the problem is solved using a potentially new working structure. If the original design comes without precedents, the main function plays a very important role as a solution enabler. However, recognizing the root of the problem in this step is quite delayed.

Meanwhile, TRIZ utilizes principles while searching for solutions. TRIZ uses EC with supporting tools 39-P, contradiction matrix, 40-IP, and PC with four distinctive separation principles, and 76 Solution Standards for idea and solution search. In TRIZ-SA the working structure, the cause of the problem, or, specifically the contradiction of the artefact, is then synthesized into responding and manipulative variables. The new working structure should improve the benefits with less risk and cost. With every EC formulation, there must also be a PC formulation. To avoid misinterpretation and confusion while using the EC tools, designers need to examine the FAM previously built and the operation of the artefact.

4.2.6.2 Finding Solution and Constructing Ideas

In observing and comparing both the SA and TRIZ methods, the SA emphasizes listings, writing-down the overall working structure and sketching to understand the artefact's performance and find possible ideas. Meanwhile, TRIZ emphasizes the determination of what happened inside the working principle and whether the working principle is useful or otherwise. Under EC and PC formulations, the 40-IPs obtained will trigger radical ideas and give an alternative or new perspective for solving the problems. The TRIZ-SA weight emphasizes the solution finding process of both methods through listing the potential solutions in tables and using the sketching process to visualize the ideas.

4.2.6.3 Concept Sketches

A typical representation of the working structure is in the form of graphical representation or a framework. One type of graphical representation is through hand or digital sketching. In TRIZ-SA, sketches are one part of the process that should be applied when conducting the conceptual design. Expressing creativity and understanding the working principle is best acknowledged in the form of diagrams or freehand sketches.

To compare with scholars work that combined TRIZ and SA, only work of Nix et al.(2011) implement freehand sketching in its FB-TRIZ methodology.

4.2.7 Step 7: Firm Up Into Solution Principal

The firming up process is all about a confident decision-making process. The SA way of firming up into the potential or principal solution is through concrete qualitative and rough quantitative definitions. The concrete qualitative can be the evaluation or comparison analysis with the existing artefact's, finding pros and cons of the prototype, preliminary experiments and analysis of the efficiencies of the concept design. The quantitative justification is conducted to support the decision-making process and is because the quantified information is mostly unknown and incomplete, as it is acquired roughly.

The firming up is a process of defining ideas for each solution for its efficiency, and, mostly, mathematical and rough calculations satisfy the need for the design confirmation. To start, defining any new working principles (through new changes or addition of characters) and new terms used for principal solution are important. Designers should have equipped the FAM by now with new characteristics and functions of the prototype, such as performance, faults prone and risks, the design parameters, and task-specific constraints. The principal solution can be firmed again with the use of analysis tools, such as FMEA, finite element analysis and many more design efficiency analysis tools for the new working principles and risk assessment.

To do the reassuring of principal solution, necessary data should be at hand through simple assumptions using mathematical calculations or qualitative evaluation, rough sketches, technical drawings, preliminary experiments, 3D digital or tangible models, analogue modelling or a patent search of possible conceptual design output. The preliminary test or experiment is useful for the approximate quantitative studies. A CAD approach, such as 3D digital model and digital simulations, are currently the best tools for preliminary tests and experiments because of their near accuracy and low cost operation, and the conceptual design does not require detailed design feasibility analyses. The use of patent search is important for designers in this stage for identifying similarity to the conceptual design to avoid design infringements and widen the idea generation for better solutions.

TRIZ does not have a specific process for selecting the principal solution or validation tools but recommends the approach of forecasting, where the future trend of the artefact is in the right position in the S-curve analysis, and encourages utilization of TESE for the increasing trend in the respective field. Each potential solution is to be revised with the amity of space, time, condition and transition. The revisions are for the purpose of finding once again the necessities that are not present in the prototype. For example, implementing the separation principles will pinpoint the gaps, inefficiencies and give insights into appropriate optimization parameters, the concept geometry and new material properties.

Both methods have positive advantages on the firming-up process although does not suggest the way and specific tools or procedures to do it. Combining both approaches of design assessment and forecasting in this stage will excite designers to develop a more radical innovation and invention.

4.2.8 Step 8: Evaluate Against Ideal Final Result and Technical Criteria

4.2.8.1 Pairwise Comparison on Evaluation Process

SA evaluates the principal solution with many evaluation characteristics to ensure the solution can be brought closer to the detailed design and embodiment design phases. Depending on the artefact's main function, cross checking is done with the new elements of the prototype with theoretical analyses, such as design specifications, design requirements, and safety standards, while practical analysis is conducted through design experiments by either computer simulation or tangible model. Table 4.5 lists the SA and TRIZ method for the conceptual design evaluation process.

Table 4.5: The differences between the SA and TRIZ method of solution evaluation

SA	TRIZ
Identify evaluation criteria Technical characteristics Economical characteristics Safety characteristics Assembly Production Operation Maintenance Weighing the evaluation criteria Compiling parameters Assessing values Use-value Analysis, VDI 2225	Referring IFR S-Curve TESE Checklist

4.2.8.2 TRIZ-SA Evaluation Procedures

The final step before proceeding to the detailed design is Step 8, which is to ensure that the technical criteria are evaluated, and possess the higher possibilities for further design process, such as in-depth computer simulation or experimental prototype. In SA, the technical and economic criteria are adopted for all engineering design procedures, while TRIZ only focuses on the technical criteria, assuming an ideal prototype is a result from the trimming process or technology changes, optimized energy resources or material changes, as well as utilization of natural resources rather than artificially added components. Through these changes, the economic evaluation is done concurrently with the conceptual design process.

The evaluation on the prototype's concept design can be assessed with design requirements, design standards, customer requirements, company's policy and other requirement and regulation materials. The work of Dietz and Mistree (2009) have made its combined methodology able to evaluate the design in terms of material exploration as well as selecting design with minimal usage of energy and material for the firming up. The work of Mayda and Borklu (2014) suggest the use of Pahl and Beitz' evaluation chart for the selection of technical parameters and economic values. TRIZ-SA on the other hand prefers to evaluate and select principal design that fulfills the IFR, safety principles, constraints, design requirements and regulations qualitatively. Quantitative evaluations should commenced in the later phases.

Revisions of the artefact's parameters are very important because the process of design change relies on the measurable units of the parameters. One way to establish the revisions is by reusing the FAM and FCM, and to add new input. The purpose of these revisions further estimate variables with values and whether it is fully functional if the parameter measures do not comply with the constraints. Other than revisions, estimations of the product's reliability and ability to be manufactured and market acceptance is also important. In summary, comparisons between TRIZ-SA and other work of scholars that combined both TRIZ and SA on the tools used can be seen in Table 4.6.

Table 4.6: Comparison on the tools used in respective design method that combines TRIZ with Pahl and Beitz methodology

Tool \ Method	Malmqvist et al.'	Dietz & Mistree'	FB-TRIZ	Mayda & Börklu'	TRIZ-SA
Requirement List		+		+	+
IFR	+	+	+	+	+
Abstraction		+	+		+
FS	+	+	+	+	
FAM					+
Working Principles				+	+
Scientific Effects		+			+
TRIZ EC	+	+	+	+	+
TRIZ PC	+	+	+	+	+
TRIZ ARIZ		+			
40-IP	+	+	+	+	+
Separation Principles					+
Safety Principles					+
Sketches			+		+
Firming Up Principal Solution	+	+	+	+	+
Technical Evaluation		+		+	+
Economical Evaluation				+	
Proposed Tools					
FCM					+
SPG					+

4.3 The Function Constraint Model

A basic framework of the FCM with F3 divisions is shown in Figure 4.6. The term 'form' can be a single part or a group of components or an assembly. The 'fit' is the relationship between the sub-components, their locations and the function associations between the components. Then, the 'function' division indicates the performance between each other when in work, what the functions do and accomplish, and what constraints are involved. The model indicates the min-max propositions; the IFR constraint is the risk probability of a performance less than the IFR constraint. It represents the maximum constraint, while the risk probability is when it exceeds the maximum permitted constraints. Often, designers will create a worst case scenario of a part's performance and failure, and find the ideal state. All this information will assist designers in structuring theoretical solutions together with the safety principles. In addition to assisting designers with the theoretical solutions, the model can also be used for TRIZ 'trimming' purposes.

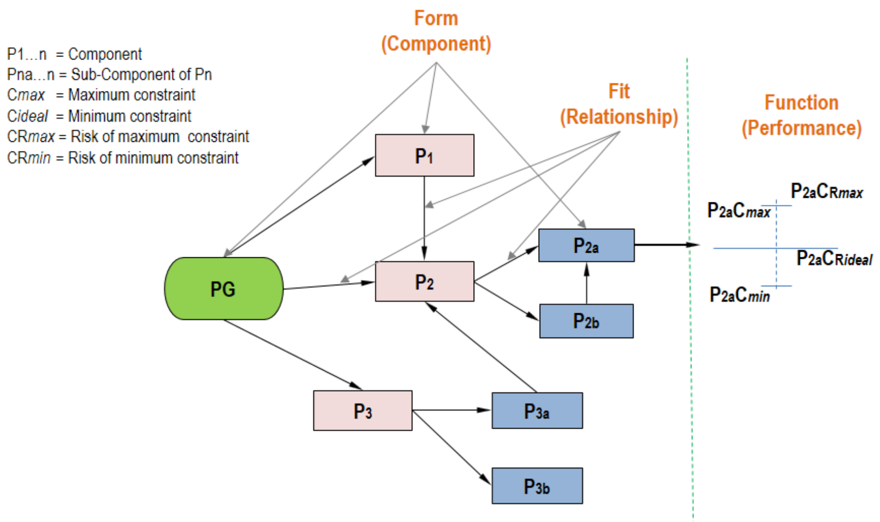


Figure 4.6: The semantics of the FCM with F3 divisions, made to assist designers to identify artefact's constraints

During analysis of the artefact systems and functions, it is important to identify the constraints (both inherited and imposed) of the artefact and its boundary around the whole system. The focus of the constraint study is on the components inside the chosen boundary (Bertrand, 1999). The model is simpler and helps in better understanding the 'fit' characteristics and constraints when there is a need to change the prototype.

4.4 The Development of Safety Principle Guide

The development of SPG starts with assigning codes to both 40-IP and the safety principles from SAED. After linking related sources with the coded principles, the latent findings from qualitative content analysis commenced. The linking process resulted to using patents to link with safety principles and 40-IP because of several factors: safety issues raised, the problem statement, the conceptual ideas and designs, and the inventive solutions found.

4.4.1 Assigning Codes

Firstly, in order to build a safety principle guide, codes are assigned to ease the marking and identification process when conducting text interpretation. Table 4.7 and Table 4.8 are the assigned codes for safety principles and 40-IP, respectively.

Table 4.7: Codes for the SA Safety Principles

Safety Principles Codes	
Direct Safety; Safe-Life Principle	SP-DS-SL
Direct Safety; Fail-Safe Principle	SP-DS-FS
Direct Safety; Redundancy	SP-DS-R
Indirect Safety	SP-IS
Warning	SP-W

Table 4.8: Codes for TRIZ 40-IP

40-IP Codes			
Segmentation	1a, 1b, 1c, 1d	Skipping/Rushing Through	21
Taking Out	2	Blessing In Disguise	22a, 22b, 22c
Local Quality	3a, 3b, 3c, 3d	Feedback	23a, 23b
Asymmetry	4a, 4b, 4c	Intermediary	24a, 24b
Merging	5a, 5b	Self-service	25a, 25b
Universality	6	Copying	26a, 26b, 26c
Nested Doll	7a, 7b, 7c	Cheap Short-living Objects	27
Anti-weight	8a, 8b	Mechanic Substitution	28a, 28b, 28c, 28d
Preliminary Anti-action	9a, 9b	Pneumatics & Hydraulics	29
Preliminary Action	10a, 10b	Flexible Shells & Thin Films	30a, 30b
Beforehand Cushioning	11	Porous Materials	31a, 31b
Equipotentiality	12	Colour Changes	32a, 32b, 32c, 32d
The Other Way Around	13a, 13b, 13c	Homogeneity	33
Curvature	14a, 14b, 14c, 14d	Discarding & Recovering	34a, 34b
Dynamization	15a, 15b, 15c, 15d	Parameter Changes	35a, 35b, 35c, 35d, 35e, 35f
Partial or Excessive Action	16	Phase Transitions	36
Another Dimension	17a, 17b, 17c, 17d, 17e	Thermal Expansion	37a, 37b
Mechanical Vibration	18a, 18b, 18c, 18d, 18e	Strong Oxidants	38a, 38b, 38c, 38d, 38e
Periodic Action	19a, 19b, 19c	Inert Atmosphere	39a, 39b, 39c

Continuity of Useful Action	20a, 20b	Composite Materials	40

4.4.2 Latent Findings

The latent findings are conducted through text interpretation using a deductive approach. The process starts with the research question and theoretical background, which, in this research, applies to obtaining the theoretical background of the safety principles and finding the compatibility with the TRIZ inventive principles.

Other than extracting important information concerning the safety principles from SAED, and system safety from the common literature resources, patent resources help in determining the application of safety on the conceptual design of the artefact. Patents are the perfect source of empirical evidence because they consist of conceptual solutions with multiple important elements. The concept designs recorded in patents have higher potential to be developed in real form, especially granted patents. Patent analysis is the same as the method used by Altshuller and Shulyak (1996) for the development of TRIZ's 40-IP, Separation Principles, and 76 Standard Solutions.

4.4.3 Content Mapping

The content mapping of the compatibility issues is presented in the matrix shown in Table 4.9. The compatibility method maps the artefact's as-is functions, the solution of the design and the safety limitations of the artefact.

Table 4.9: The compatibility mapping of safety principles with 40-IP

40-IP	40-IP Sub	SP-DS-SL	SP-DS-FS	SP-DS-R	SP-IS	SP-W
1	1a	+				
	1b					
	1c	+	+			
	1d					
2		+			+	
3	3a	+				
	3b					
	3c		+			
	3d					
4	4a		Δ	Δ	Δ	
	4b					
	4c					
5	5a	+	+			
	5b		+			
6		+	+	+	+	
7	7a	+		+	+	
	7b		+			
	7c					
8	8a	+				
	8b	+				
9	9a	Δ			Δ	Δ
	9b					
10	10a		+	+		
	10b	+	+		+	
11		+	+	+		
12				+	+	
13	13a					
	13b					
	13c		+			
14	14a				+	
	14b		+			
	14c		+			
	14d					
15	15a				+	
	15b	+				
	15c	+			+	
	15d		+			
16		+	+	+	+	
17	17a					
	17b					
	17c					

40-IP	40-IP Sub	SP-DS-SL	SP-DS-FS	SP-DS-R	SP-IS	SP-W
20	20a	+			+	
	20b					
21					+	
22	22a	+	+			
	22b					
	22c					
23	23a	+	+	+	+	
	23b		+		+	+
24	24a		+	+	+	
	24b	+	+	+	+	
25	25a				+	+
	25b	+				
26	26a				+	
	26b		+			
	26c					
27						Δ
28	28a					+
	28b					
	28c	+			+	
	28d					
29		+			+	
30	30a				+	
	30b				+	
31	31a	+			+	
	31b					
32	32a		Δ		Δ	Δ
	32b					
	32c					
	32d					
33				Δ		Δ
34	34a			Δ		
	34b					
35	35a					
	35b					
	35c	+	+			
	35d					
	35e	+				
	35f		+			
36		Δ				
37	37a	Δ				
	37b					

	17d							38a					
	17e	+	+					38b					
	18a						**38**	38c			Δ		
	18b							38d					
18	18c							38e					
	18d							39a					
	18e		+				**39**	39b				Δ	
	19a		+		+			39c					
19	19b		+				**40**					Δ	
	19c			+									

Note that several 40-IP subs does not have the mark '+'. This is because most of the unmarked 40-IP subs seldom happened in the patents studied, but suggested to use the safety principle from the same 40-IP family. The Δ symbol indicates the author's compatibility proposal due to the unavailable patent that indicates the relationship between the safety principles and 40-IP number 4, 9, 27, 32, 33, 34, 36, 37, 38, 39 and 40. A simpler representation of the compatibility between safety principles and 40-IP is tabulated in Table 4.9.

4.4.4 The Safety Principle Guide

The SPG table shown in Table 4.10 is actually a simplified matrix of the relationships between the inventive solutions and the safety found in the analysis of the MLG patents. During conducting the text interpretation, the feedback is repeatedly found in most of system safety backup solution, in which 40-IP have the inventive principle 23-Feedback to represent it but not exactly found in SAED safety principles. These findings lead to another safety principle 'feedback principle', independant from warning principle because it does not warn but more to feeding information to user and system to alert on changes.

Table 4.10: The Safety Principles Guide (SPG), an arrangement of SA safety principles and 40-IP compatibility and similarity

Safety Principles	40-IP	Information
Direct Safety; *Safe-Life*	1, 2, 3, 5, 6, 7, 8, 9, 10, 15, 16, 17, 20, 22, 23, 24, 25, 28, 29, 31, 35, *36*, *37*	Operate without breakdown or malfunction throughout lifecycle
Direct Safety; *Fail-Safe*	1, 3, *4*, 5, 6, 7, 10, 11, 13, 14, 15, 16, 17, 18, 19, 22, 23, 24, 26, *32*, 35	Signal of any impairment from main function
Direct Safety; *Redundancy*	*4*, 6, 7, 10, 11, 12, 16, 19, 23, 24, *33*, *34*, *38*	Superfluity or excess. Allow transmission losses, hence safeguard the system
Indirect Safety	2, *4*, 6, 7, 9, 10, 12, 14, 15, 16, 19, 20, 21, 23, 24, 25, 26, 28, 29, 30, 31, *32*, *39*, *40*	Use of special protective systems and protective devices (when direct safety inadequate)
Warnings	9, 23, 25, *27*, 28, *32*, *33*	Pointing out dangers and indication of the danger area
Feedback	28, 17, 23	Disseminating information for corrective action

The SPG will be used in the 5th step of the TRIZ-SA 8-Step. At the point when the TRIZ EC with contradiction matrix generates several 40-IP; designers then attribute the 40-IP with the safety principles obtained from the SPG table.

4.5 Validation of TRIZ-SA Conceptual Design Framework

4.5.1 Aircraft's Main Landing Gear Concept Design

This research adopted the aircraft MLG (Figure 4.7) for the TRIZ-SA demonstration, specifically on the shape design of the MLG. The intention of such demonstration is to validate the TRIZ-SA conceptual design framework and assessing the outcome from the validation process, by constructing a concept design proposal or 'prototype', focusing on the geometrics or shape concept of the MLG. A number of theoretical solution ideas are generated through the TRIZ-SA 8-Step. Several freehand sketches of the concept prototype are shown to demonstrate the process of idea generation on shape design with noise reduction approach.

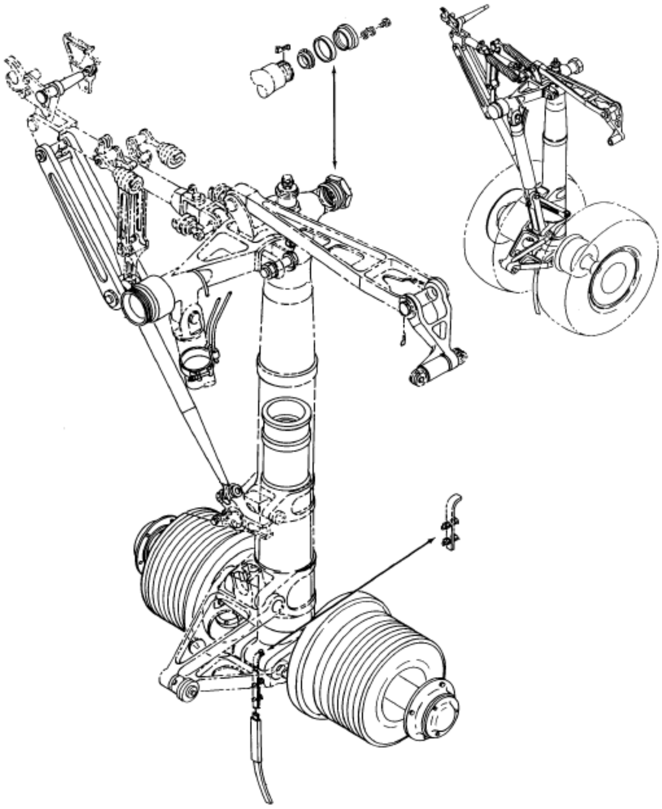


Figure 4.7: MLG components of Boeing 737 aircraft
(Source: Boeing 737 Parts Catalogue, FAA)

According to Kocer (2007), the objectives of the landing gear design can be grouped into three categories, first, being the determination of the damping profile, second, the concept design and optimization of the torsion links, and, third, the component shape optimization. This research only demonstrates the concept design of MLG for the third determination, the selected component's shape optimization and modification. The decision is based on the author's experience of the shape and geometric design, especially the functional shape scope.

4.5.2 Step 1: Main Landing Gear Initial Conceptual Design Process

To demonstrate the effectiveness of the TRIZ-SA 8-Step, the appropriateness of the example problem is very important. The demonstration on MLG issues concerning the noise produced during take-off and landing have been identified. Apart from the noise regulations that commercial aircraft should adhere to, the current MLG noise problem produces parasitic drag, resulting in increased fuel consumption, and considered as a threat to the community within close proximity to the airport therefore, it must be reduced. To start the TRIZ-SA 8-Step, Step 1 comprises the IFR and Requirement List are prepared.

4.5.2.1 Main Landing Gear Ideal Final Result

When adequate information, requirements and resources are at hand, a proper IFR can be formulated. In the construction of the MLG IFR, identifying current scenarios of the MLG regarding parasitic airframe noise safety are obtained for defining the problem and current MLG disadvantages. Before formulating the IFR, determining the MLG's problem should be addressed first, which has been briefly elaborated in Chapter 2, section 2.12. The IFR formulated here will be utilized in several steps within the TRIZ-SA 8-Step. The constant reference to IFR is essential to make sure that the aim of developing the ideal concept design is achieved.

A simple MLG IFR route map is shown in Figure 4.8 indicating the design possibilities per the evolution trends of the MLG. The IFR developed uses TRIZs' TESE of '*Trend of Transition to Super-system'* category; TESE references are actually optional in TRIZ-SA. The MLG's current design is a complex mechanism with many pivoting joints and bracings mostly to support the shock strut when experiencing the high speed turbulent inflow and landing loads, and for retracting the MLG when in flight. The IFR formulated envisions the future of its mechanism as a cleaner and less components with most of the sub-components replaced with super-system elements.

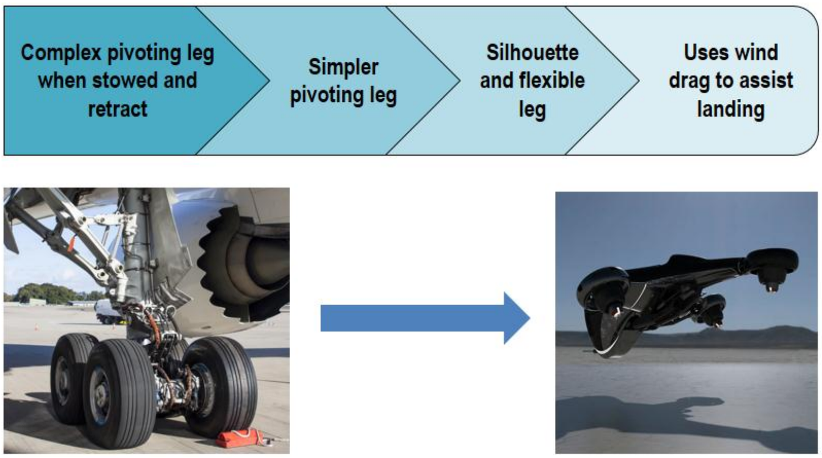


Figure 4.8: The MLG concept IFR route map
(Source: McCarthy, 2017; Harris, 2017)

Evaluating the design possibilities in the IFR, the final IFR route-map *'uses wind drag to assist landing'* seems too advanced to accomplish with the current available limited technology and engineering capabilities. Aiming to achieve at least 80% of the ideal concept design, the IFR beforehand, *'silhouette and flexible leg'* seem much more applicable and practical to establish.

Referring to the TESE transition to the super-system, its sub-trend of *'Increasing Differentiation of Parameters'* inspired the conceptual design process to apply the shifted parameters approach. The transformation involving the conventional straight-shaped struts connected into a more curved silhouette shape that may reduce the drag, resulting in noise reduction. Fulfilling the shape changes, the movement of the MLG when storing and extracting needs attention as well. The ideas concerning the shape design are in accordance with the aerodynamics for MLG.

Another possible TESE for the IFR formulation is the *'Trend of Increasing Coordination'*. In this TESE category, the movements and shape coordination are analysed. In the movement coordination, the interactions between all the MLG system and its subcomponents are examined and it is decided that changing its component shape and form is suitable for the noise reduction solution. Another potential TESE trend that might be applicable is the *'Trend of Increasing Dynamization'*. The TESE suggests that the sub-components of MLG are made to increase its movements, whether by the number of divided sub-components or the number of movements, to potray the 'silhouetteness' of the MLG stowing and extracting movements, and the noise causes. When the MLG experiences drag loads, shape plays an important part in diverting the loads and decreases the noise through a better surface shape design.

There are several conceptual proposals from MLG researchers, such as Roloff (2002), suggesting smart shock struts, integrated control mechanisms, brakes and strut material improvements, maintenance-free components and electrical actuation. Roloff's recommendations are actually highly possible to produce and the technology he proposes is currently available.

4.5.2.2 Main Landing Gear Conceptual Design Requirement List

In the event of preparing resources related to the geometric concept design on MLG, the requirement list is the best tool to compile all the specifications and requirements. Designers can also include any related information to widen the scope of the MLG design solution. The list should also includes safety requirements; Table 4.11 represents the requirements of the common commercial aircraft's MLG for conceptual design purposes.

Table 4.11: The requirement for the MLG

UPM & AMRC with Boeing		Requirement List for an MLG Concept Design	Issued on 16/07/2016 Page 1
Changes	**D/W**	**Conceptual Design Requirements**	**Functions**
		1. **Components** (MIL-L-8552C, 1965)	
	D	Shock strut	Absorb shock
	D	Upper torque beam	Hold shock strut piston
	D	Upper torque link	Align shock strut piston
	D	Pivot point	Connect upper & lower torque link
			Hold shock strut piston
	D	Lower torque beam	Align shock strut piston
	D	Lower torque link	Extend/retract gear
	D	Hydraulic actuator	Extend LG manually
	D	Manual gear extension	Allow gear enter/leave LG housing
✓	D	Door	
			Gear position safety
	D	Safety device	Communicate with pilot
	D	Proximity sensor	Prevent LG retraction
	D	Gear indicator	Extra precaution of LG extension
✓	D	Squat switch	Support shock strut
✓	W	Ground lock	Shock absorbing
			Hold and move entire LG
	D	Side Strut/Drag brace	
✓	D	Telescopic strut	
	D	Trunnion	
			Super-system
	D	**Geometry: Rough dimensioning**	
		Height (HLG): Extended = 2978.7mm Compressed = 2506mm	
		Cg location = 6.5m to 7.1m from NLG	
		L distance between 2 tires = 1005mm	Constraint (not included as the aim is to change shape)
		W distance between 2 tires = 780mm	
		Retraction angle = 80º30	
	D	Distance between left & right MLG = 7.59m	
			Main constraint
		Weight	
✓		MLG Max. Load: Fm = 65983.1N (3.5 x MTOW)	
	D	Take-off weight (FAR regulation)	
		Load = 30,000kg/wheel	
		Safety	Main constraint
		Lifetime = 60,000 hrs/20 years	
		In-service cycle = 20,000hrs (overhaul)	
		Noise reduction = fairings	

An example of a two-tyre B737 aircraft's MLG side strut can be seen in Figure 4.9. Other designs with four or six-tyre equipped with a sturdy side strut are the B767 (Figure 4.10) and Gulfstream 50. Basically, an MLG must have a shock strut, side strut (or brace or stay), upper and lower links with actuators for retraction, axle and lugs.

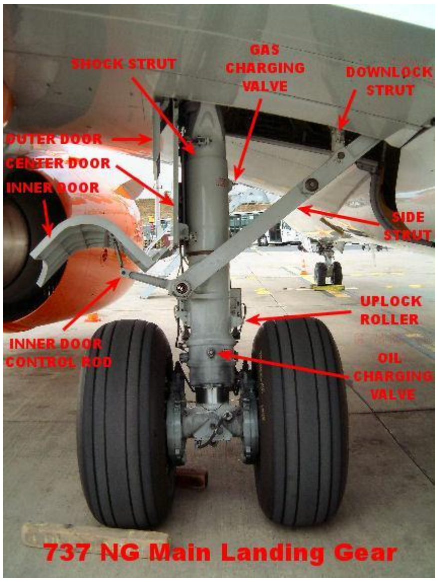


Figure 4.9: The B737 MLG arrangements (Source: Brady, 2017)

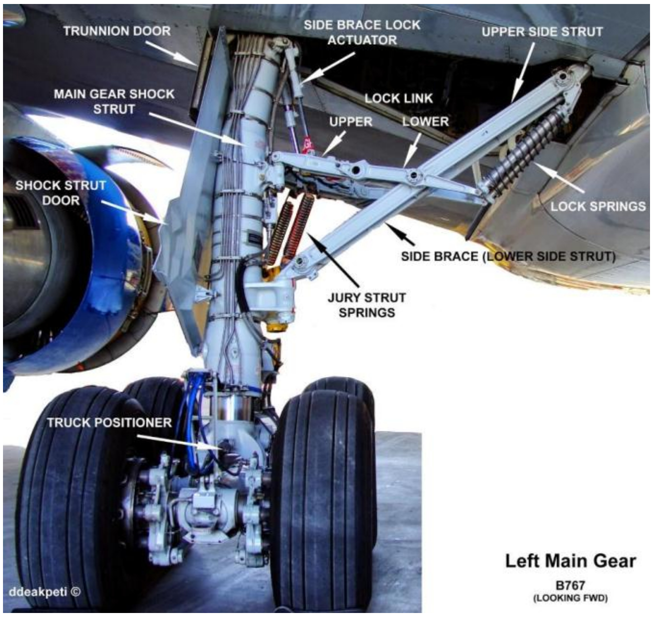


Figure 4.10: The B767 MLG arrangements (Source: Ddeakpeti, 2016)

4.5.3 Step 2: Abstractions from the Requirement List

After the requirement list is established with adequate information on the demand (D) and wish (W) particulars (minus attaching parts, such as screws, clamps, harness, washer, etc.), observing the list gives direction on which to focus and areas of the MLG suitable for shape improvement. Referring back to the previous IFR, changing the MLG's flexibility and geometry, the potentiality of changes can be examined through parameter and functions analysis with FAM. The problem's major constraints should be included in the abstraction procedures as well. This is because the presence of constraints in the prototype is known and understood when other details are still unknown.

4.5.4 Step 3: Main Landing Gear Functional Analysis Model

The FAM of MLG is established by referring to the requirement list and only representing the abstracted list that will fulfil the MLG's IFR. Through FAM, the system, subsystem and super-system relationships are clearly visualized. This aids in analysing the constraints and safety and identifying the right component for further change.

As shown in Figure 4.11, the MLG shock strut is the main component, which functions as the aircraft's major support to carry the aircraft's fuselage. The shock strut usually consists of an oleo-pneumatic absorber, which carries the weight of the fuselage efficiently, and moves and absorbs the landing load. To control the shock strut, components, such as drag brace and side strut, flexible bogie beam and shimmy dampers, are required.

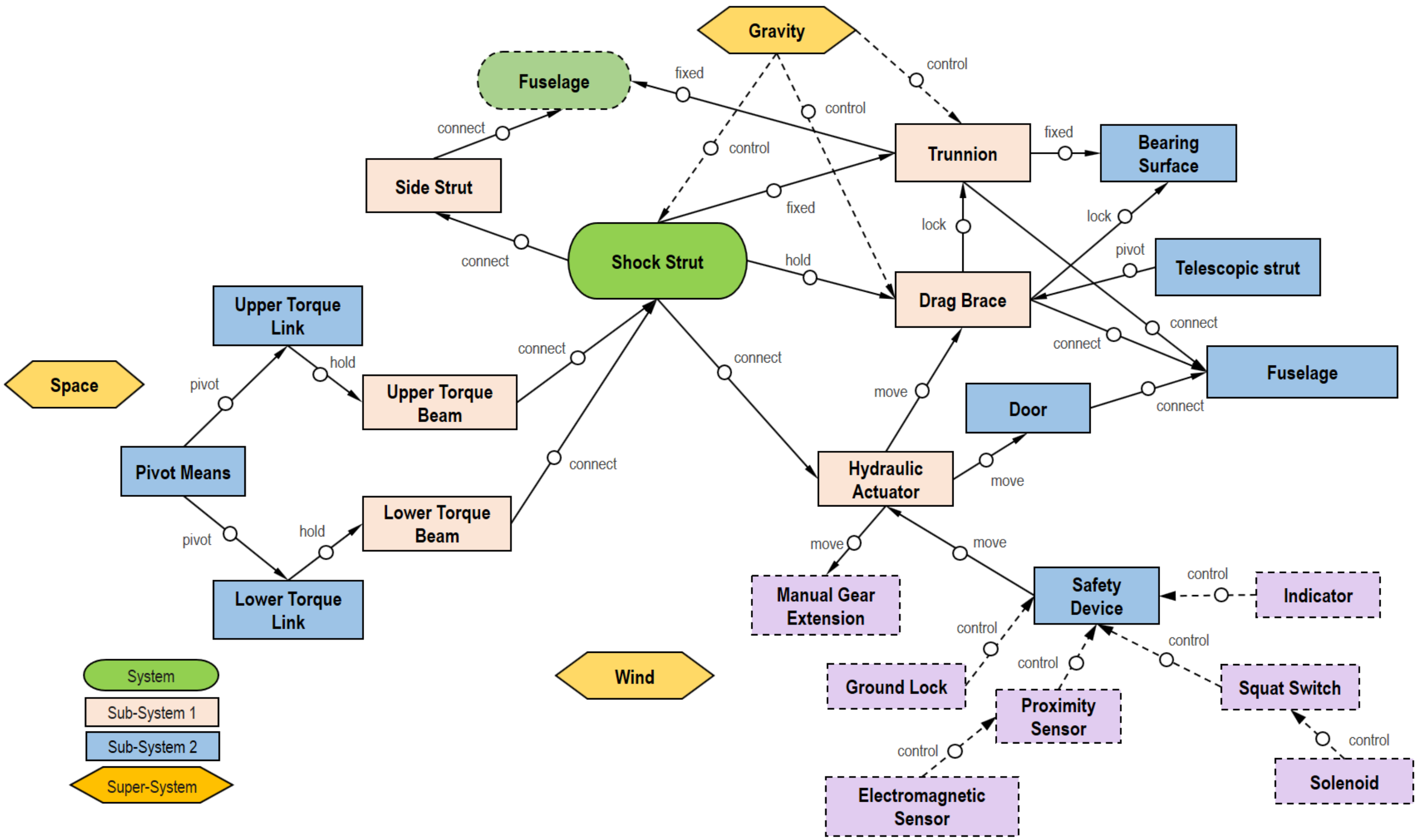


Figure 4.11: A typical MLG function structure

Supporting components that supports the shock strut are the upper and lower torque beam for horizontal alignment, drag brace, trunnion to connect to the fuselage, and hydraulic actuator for the purpose of stowing the MLG. The stowing mechanism should be attached together for usage according to the flight conditions, and for the space purposes. Further subsystems are presented in blue boxes. In the event of an emergency, where the MLG cannot stow automatically, several safety subsystems (purple boxes) that support the 'Safety device', which is connected to the hydraulic actuator, will do the job. Meanwhile, extending the MLG in emergency cases requires manual extension and gravity pull.

Other components, such as the monitoring device, additional safety support, and communication with pilot devices are also necessary for avoiding any risk while in use. Gravity or *cg* is indicated as a super-system as it is not directly a part of the MLG but is a compulsory 'field' and requirement for the MLG design. The weight of the landing gear, in general, is around 3% to 5% of the aircraft's take-off weight, e.g. a Boeing 747 weighs about 16,000lb (Sadraey, 2012). Figure 4.12 shows a focused FAM of the side strut (upper and lower link), as the object or component of study, positioned as the main system and the surrounding components. Other sub-systems presented in the focused FAM are further analysed in terms of their working principles.

The super-system elements *gravity*, *wind*, and *spaces* may trigger some ideas for the trimming of components, where the function remains intact to perform in a similar fashion but the body is replaced with other means. The super-system may guide designers in finding ideas to fulfil the IFR *"Silhouette and flexible leg*".

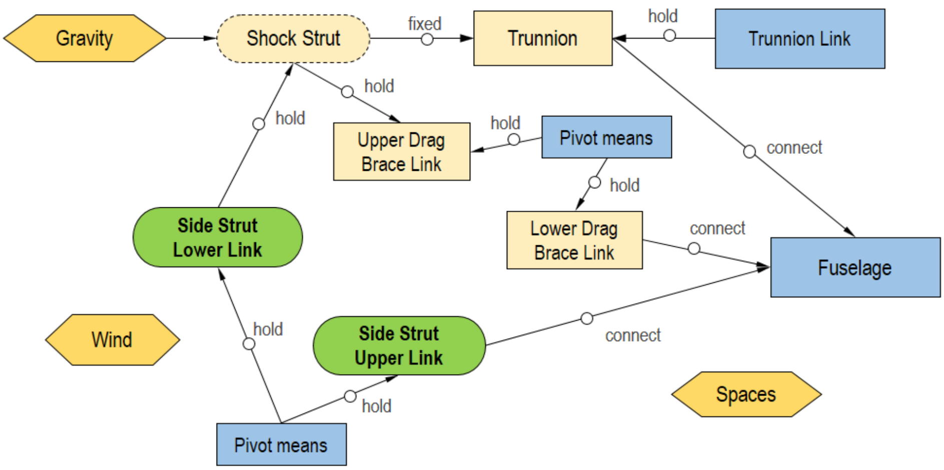


Figure 4.12: The FAM of MLG Side Strut

4.5.5 Step 4: Reuse Functional Analysis Model, Searching Main Landing Gear Working Principles and Function Constraint Model

Step 4 requires the process of constructing working principles and FCM. The best way to start both processes is to look back at the FAM previously established. Reusing the FAM, the working principles of the artefact can be placed on the same FAM sheet. In the FAM, the function between components can be further analysed for its working principles. A boundary of contradiction analysis is reduced and only includes the selected subsystem of the side strut to analyse its working principle. The search for working principles should be in accordance with the IFR; to reduce noise and increase the flexibility of the leg, as in silhouette and flexible characteristics.

According to Dobrzynski et al. (2009), Howcroft et al. (2013) and Bouvy et al. (2016) , the component best for noise reduction is the side stay or side strut. A "clean" design, such as the SILENCER circular telescopic strut, or TIMPAN gear design shield the complex geometry of the side strut resulting significant noise reduction. This research demonstration will adopt the same component of study, the side strut. The working principle of the current side strut design in correlation with the drag or high speed inflow should not be presented too specific. The understanding of the component's physics and law regarding wind drag onto surface design should be minimized into fundamentals and simple working principles. Elements, such as the energy used, the load distributions, and types of safety approach the MLG must apply are the few design characteristics that are included in the formulation of contradictions. Identification of the '*actor*' (the principles that create effects) and '*receptor*' (principles that receive effects) are the important elements for determining the working principle and constraint model.

4.5.5.1 Main Landing Gear Design Constraints

When working principles are understood, the constraints within the working principles should be determined next. The easiest way to understand the constraints characteristics of the side strut is by identifying the side struts' substance and field, then to establish the Substance and Field Resources (SFR) table (Table 4.12). The 'fields' stated in the side strut SFR table consists of the mechanical (FMec), chemical (FCh), and gravitational (FGr) fields. Even though the side strut inherited the mechanical field, deriving idea solutions should not be limited to only the mechanical field but to explore different fields as well.

Table 4.12: The SFR table of selected MLG components and affiliates (Kamarudin et al., 2016b)

Resources	Substance	Parameters	Fields
Tool: Side strut	Metal	Angle, length, size, radius, thickness, fitting, material hardness, weight.	FMec
Product: LG Assy.	Metal, rubber, air/oil	Distance between forward *cg* and most aft *cg*, height, wheelbase, wheel track, strut diameter, ground loads, weight.	FMec
Operating Space: Aircraft runway	Asphalt, concrete	Width, thickness,	FCh, FGr

The parameters listed inside the SFR table included the imposed constraints, such as force direction, magnitude, drag, loads, and clearance at the retractable door movement. These information can be used for the constraint optimization or elimination purposes. There are two types of constraints in the MLG's side strut design in relation to the noise problem:

1) Internal constraints:
   i. Where the side strut is positioned, moved around the hydraulic mechanism, multiple strut and arm, mechanism associated with the shock strut and other small joints.
   ii. Other than position issues, the side strut must be dynamized, for retraction and storing the MLG but needs to be as slim as possible to avoid larger high-speed inflow exposures.
   iii. Operational: gear location determined by lateral stability and rotation before take-off. On the condition of brake cooling, fairings would delay cooling and will increase the turn-around time at the airport.

2) External constraints:
   i. The 'moving-passage', wind resistance, runway surface and weather factors that give boost to take-off and landing performance, as well as stabilizing the aircraft in general.
   ii. Surroundings: door clearance, movements, tyre sizing, weight assessment, kinematic attachments, materials, coatings, crash-worthiness structure and topology constraints, and the goal to reduce or eliminate of constraints, or turning constraints into benefits.
   iii. Operational: limitations of runway load that define the number of wheels and spacing.

In terms of safety constraints, the MLG should adhere to the free fall requirement where the MLG leg door cannot be used as a spoiler (Dobrzynski, 2008) When experiencing tyre burst, the location and redundancy of the dressings should be considered as well. Figure 4.13 shows an FCM of the side strut and analysis of the constraints as well as function constraints and the field and energy used, from which the designer can find what the appropriate technology or the suitable design changes for the new concept design.

The constraints and risk probabilities shown in the figure are for both side strut's upper and lower link, where both components have different inherited constraints but functions together to complete the work.

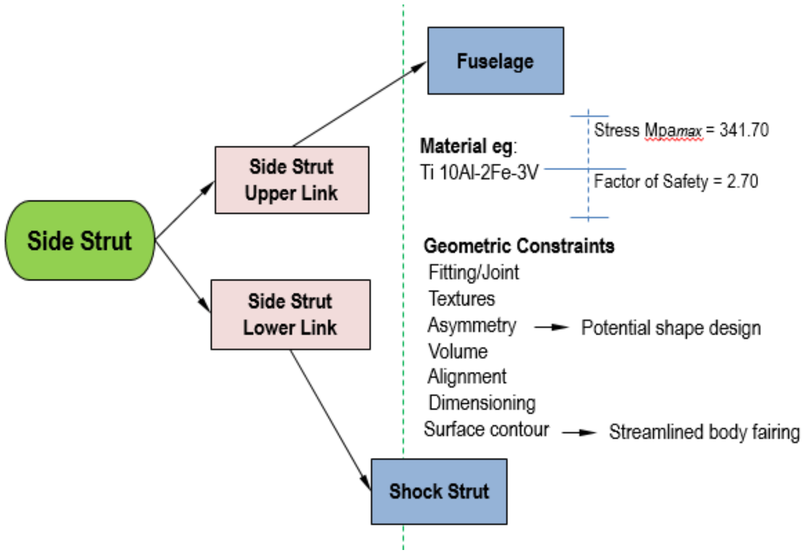


Figure 4.13: An example of simple FCM on several parameters useful for design problem-solving

4.5.5.2 Multiple Constraints Modelling

Multiple constraints of the side strut are also much easier to visualize with a constraint network model, with determinations of inherent and imposed constraints. The IFR of any artefact is to increase the existing component's values so that the solution leads to fewer constraint limitations. This can be achieved by reducing the inherent constraints by simplifying the working principle of the existing side strut. Another way is to reduce the quantity of the imposed constraints so that the possibility of design change is higher. This can be achieved by analysing the relationship of the components and finding the imposed constraints that can be optimized or eliminated. The geometry constraint of the side strut is found to be the main design constraint, and under the shape constraint, multiple constraints related to shape are identified – space, volume, surface contact, fitting, positioning, material and kinematics (Chai & Mason, 1996).

Designers should focus on the problem-solving and prototype development of the side struts' shape to sustain the multiple constraints stated earlier with a simpler shape solution. The proposed ideas for new shape efficiency might include the use of external flexible materials such as silicon as a fairing, or integrated within the side strut. This way it can optimize the area of drag manipulation, and, at the same time, reduce the risk of noise due to higher wind drag exposures. An additional benefit for the integration of the fairing is that it may remain efficiently in contact when hard landing, but more critical research is needed to design such integration into the existing component. The constraint analysis should also relate to the number of cycles (frequency constraints), in accordance with the maintenance procedures of the life limit cycles, where for as many as 75,000 cycles (Avtrac, 2014), both parts must be re-evaluated for a replacement.

4.5.6 Step 5 : Main Landing Gear Solution Finding Process

Before proceeding with the process of TRIZ EC and PC, the contradiction of the problem is identified through the AbsGen process.

4.5.6.1 Main Landing Gear Abstraction and Generalization

The AbsGen requires abstracted information and the IFR for the formulation of artefact's contradictions. The contradictions should be in the form of two responding variables; the improving and worsening parameters, to be used in the TRIZ EC process. At the beginning of AbsGen, a condensed list of the side strut's main function (MF) is built. The list is then generalized into a single keyword which represents the abstracted list. Figure 4.14 demonstrates the abstraction and generalization process for idea generation involving the side strut's constraints. The AbsGen process determines that the MLG side strut have responding variables of *'stability of object'* as the improving parameter and the *'produce noise'* as the worsening parameter. These two generalized terms will be use with both EC and PC process.

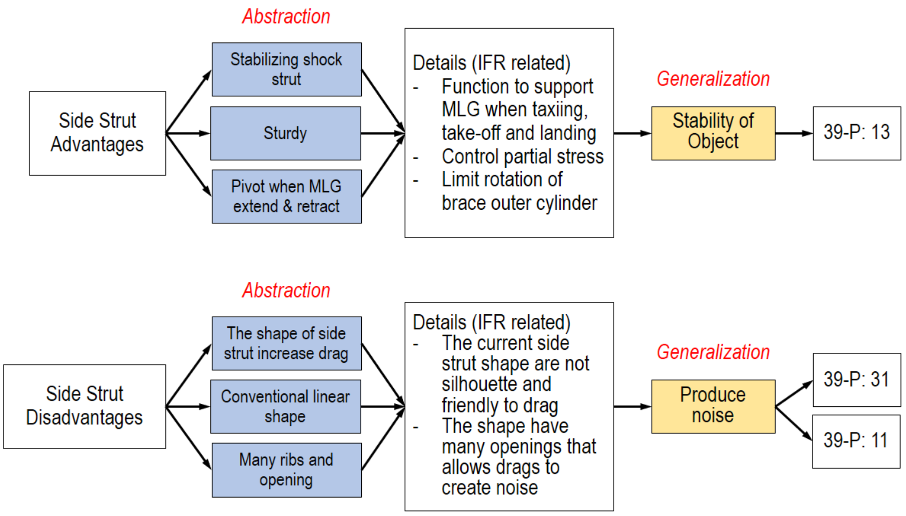


Figure 4.14: The AbsGen activity of MLG's side strut advantages and disadvantages

4.5.6.2 Main Landing Gear Engineering Contradiction

TRIZ EC begins when the AbsGen process collected the contradicting parameters of the MLG problems concerning the noise generated by the MLG structure during take-off and landing. The contradicting parameters are then used for the TRIZ EC formulations. Figure 4.15 shows the model of TRIZ EC, inspired by Orloff's (2012) binary model. EC1 formulation consists of 39-P improving parameter *13-Stability of the object*, where the side strut component design is giving good support to the MLG stability, sturdiness in sustaining side loads and function as a retraction support. The worsening parameter is the *31-Object generated harmful factor*, where the harmful factor is the noise generated because of the side strut's shape. From the EC1 formulations, a few suitable 40-IP for the prototype are selected, *35-Parameter changes, 40-Composite material, 27-Cheap short-living object* and *39-Inert atmosphere.*

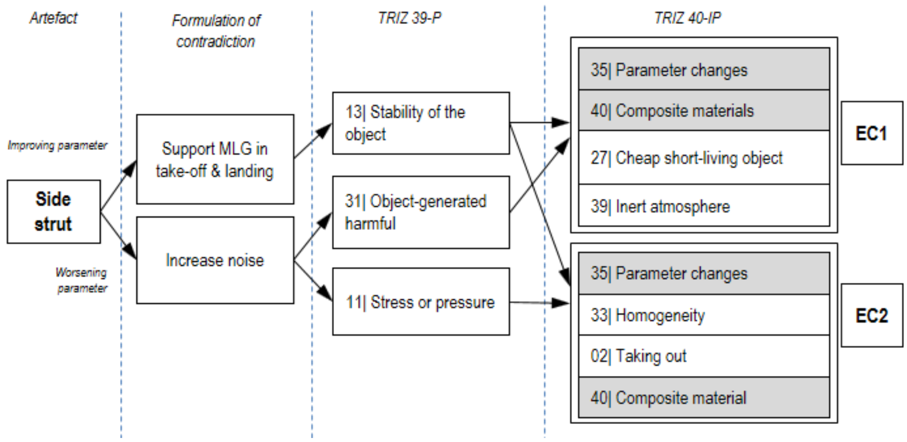


Figure 4.15: TRIZ EC model of the side strut. Shown here are two EC formulations between TRIZ 39-P number 13 with 31 and 11

Meanwhile, the EC2 formulation consists of improving parameter *13-Stability of the object* and worsening parameter *11-Stress or pressure*, where the generated noise comes from high speed turbulent inflow onto the non-uniform side strut's surfaces (Lopes, 2010). The EC2 contradiction suggests the same 40-IP *35-Parameter change* and *40-Composite materials* as the EC1. Other 40-IP from EC2 are *33-Homogeneity* and *02-Taking out.*

4.5.6.3 Main Landing Gear Physical Contradiction

The PC formulation does not refer to the contradiction matrix as both improving and worsening parameters are of the same parameter. Figure 4.16 demonstrates the PC formulation of the side strut physical contradictions.

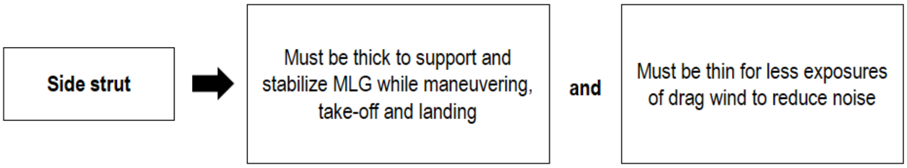


Figure 4.16: TRIZ PC model of the side strut with contradictions for the thickness features

The side strut component has PC on the side strut's shape thickness issues, expressing the silhouette characteristic. The side strut needs to be thick and firm to enable to support and balance the aircraft's whole MLG and fuselage. However, the side strut needs to be thin as well to avoid wide exposures on turbulence that causes the noise. The side strut also need to be flexible and lightweight to enable it to be stored easily while in flight. From the given PC formulations, the analysis goes further to the selection of separation principle by referring to Table 2.2, and then identifying the appropriate 40-IP.

After obtaining the 40-IP lists from both TRIZ EC and PC, the nearest 40-IP to the IFR and in relevance to the side strut geometric issues is chosen. Then, appropriate safety principles should be found from the SPG table (Table 4.10), and each safety principle will be examined further to ensure that the future geometrics and shape design of side strut is in accordance with the safety requirements and standards. The side strut's concept design requires a safety approach or failure detection abilities, and compensating or correcting using appropriate measures, providing backup for random failures to ensure the safety of landing, and obtaining different types of safety support to make sure the performance of the whole MLG is safe, e.g. additional safety components, emergency system or easy manual MLG extension. The following are the list of safety principles associated with the selected 40-IP:

a) 35-Parameter changes: Safe-life, Fail-safe
b) 40-Composite Materials: Indirect-safety (proposal)
c) 27-Cheap short-living object: Warning (proposal)
d) 02-Taking out: Safe-life, Indirect safety

The selected 40-IP, separation principles and the safety principles are further analysed for the solution finding process and to develop an effective shape design. Another tool from TRIZ, the *Scientific Effect*, is applied for formulating the best shape design that fulfils the IFR and safe design.

4.5.7 Step 6: Main Landing Gear Theoretical Solution Ideas

Several processes in Step 6 justifies the selected 40-IP and safety principles, emphasizes sketching, 3D model or 3D computer model for better visualization of the conceptual ideas during solution finding process. The next sections discusses the process steps in Step 6.

4.5.7.1 Analysis on Selected 40-IP and Safety Principles

The previously selected principles from Step 5 are tabulated in a solution idea table, Table 4.13, where several theoretical ideas are generated in accordance with 40-IP, safety principles and TRIZ scientific effects, particularly geometric effects. However, the 40-IP '*40-Composite materials'* and *'27-Cheap short living object'* are not included as their associated safety principles are still in proposals. Distinctive two 40-IPs are selected; principle *35-Parameter changes* and *02-Taking out*, for the solution finding process. The design changes for the MLG problem focuses on the retracted position during take-off, landing and emergency landing. The goal is to reduce noise, reduce or manipulate wind drag and to support other MLG components while in normal operation, and to have a structured and safe emergency landing operation.

Table 4.13: Solution ideas with safety principles

No	40-IP	Safety Principles	Analysis and Solution Ideas
1	35-Parameter Changes	Safe-life	**40-IP: 35c - Change the degree of flexibility** - E.g. changing dry plaster to moist plaster (Rantanen & Domb, 2010) – meaning changing the physical material so that the flexibility of the material increased. Solution: **Safe-life – Flexibility change** - Shape flexibility – noise reduction – safe-life = divisions of thin but sturdy components - A shape that is sturdy in each independent component but flexible when functioning in assembled pivoting physical, similar to the F-16 Fighting Falcon. This is to achieve 'flexibility' to withstand side wind drag by having the leg in 'tripod-like' movement (triangle shape) rather than vertical movement (like in common commercial aircrafts). - The benefit of reducing wind drag exposures is that it can reduce community noise and is more fuel efficient. At the front of the tripod-like MLG, the volume of exposed surface should be minimized to avoid mass drag from the front. - *What flexibility change?* Structure

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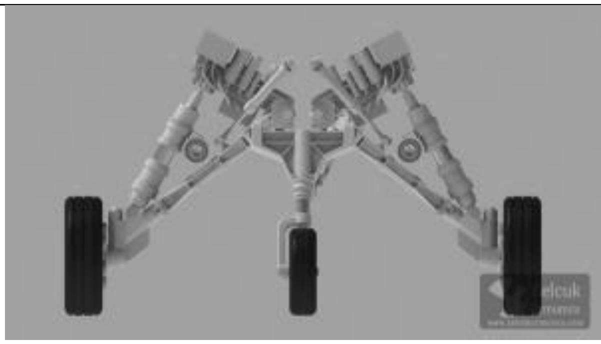

The front view of F-16 Fighting Falcon landing gear (Source: Ozmumcu, 2016)

- Shape flexibility – noise reduction – safe-life = fairing
  - The side strut is shaped to enable it to receive and direct wind flexibly. The existing solution to this is by attaching an additional fairing component to the struts.
  - What flexibility change? shape, super-system wind.

Quiet Technology Demonstrator Two (QTD2) Tobbogan fairings attached to MLG of B777 aircraft (source: www.boeingimages.com)
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<td>Fail-safe</td>
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40-IP: 35f - Change to other parameters

- E.g. 1: Shape memory alloys/polymers, having both sturdy and flexibility at the same material/surface (Mann & Cathain, 2001),
- E.g. 2: Use high conductivity materials, e.g. carbon fibre, sponges (Mann & Cathain, 2001)

Solution:

Fail-safe – Parameter change

- Shape design – noise reduction fail-safe = fairings
  - With regards to shape design and the aim to reduce community noise, the use of a fairing is suggested. The fairing may be an additional component, or the MLG and its struts and braces are shaped to have fairing features.
  - What parameter has changed? From rigid and complex features to silhouette and clean shape.
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			- System design – noise reduction – fail-safe = back-up system - With regards to the fail-safe system and noise reduction, a system that **turns the position** of struts and braces to reduce surface contact with high speed turbulent inflow may be applied. - *What parameter has changed?* From static to automated component positioning.
2	02- Taking out	Safe-life, Indirect safety	Separating incompatible property of the object, or turned completely around, separate the only necessary property (Orloff, 2006). Solution: **Safe-life - Taking out** - Lessen the sub-component by merging with other neighbouring components. The torque links connected to the shock strut can be removed and replaced with an asymmetric shock strut. The positioning of the shock strut may be turned upside down to increase the landing load endurance. - *What component is out?* The upper and lower torque link. **Indirect safety - Taking out** - not applicable.

A safe-life approach is usually applied to a product that is to be designed to sustain higher risk, that must not malfunction or broken and able to withstand harsh treatment for a longer period of time. The drawback of safe-life safety, however, is that it is uneconomic. However, with careful planning and careful analysis, in the embodiment and detail design phases, on the characteristics and behaviour of the artefact, an economic safe-life prototype can be achieved. In the case of safe-life MLG design, it should have its sub-components designed to sustain a higher performance risk, such as hard landing, and in the context of the shape concept, the side strut's shape "thin but sturdy" sturdiness and efficiency must comply with the susceptibility upon higher loads. The component of focus here is the side strut since most of its component are exposed to wind drag when the MLG is in the retracted position, resulting noise generation. Another idea is to attach sturdy fairings to the MLG to avoid drag exposures, but considerations on weight is important, as the fairing weight add-in the factor of design disadvantage.

In terms of fail-safe conceptual design, there are three approaches that can satisfy the constraints of safety with the fail-safe principle approach, as shown in Table 4.14. The first approach is by component-based: in the event of side strut malfunctioning or breaking down, neighbouring sub-components, such as the drag brace, link braces, trunnions and actuators can support the side strut temporarily. These neighbouring components should be placed close to the side strut and act as temporary back-ups. Secondly, by system-based: if it is impossible to back-up the main side strut with a tangible supportive component that can work similar to the side strut, a 'system backup' that functions similar to the side strut is applicable. Lastly, with information-based: to have an indicator and other supporting system that warns and guides the pilot to do a temporary MLG support operation for an emergency landing.

Table 4.14: MLG side strut concept solution according to fail-safe principle

Fail-safe Solutions for MLG Side Strut		
Component-based	**System-based**	**Information-based**
a) Additional component (multi-lock, b) neighbouring component (drag brace, door, beam), increase sturdiness	Slows speed, increase readiness on the other MLG pair, to assist side strut	Warning sign, indications, feedback to pilot

In general, the safe-life principles of the side strut requires the shape of the struts to sustain for a longer period and withstand harsh treatment, while the fail-safe suggests a supporting system close to the side strut as back-up when the side-strut is not functioning. The aim to change the geometric shape is not relevant for the fail-safe principle, but may give some ideas for creating additional 'help'.

The inventive solution for the PC formulation mostly suggests the *'Separation in Condition'*, as shown in Table 4.15. The condition of the side strut can satisfy both stability (improving) and noise (worsening) parameters by making the side strut shape sturdy in the centre along the strut rod with a sharp-flat surface on the side along the strut rod (Figure 4.18 (right)) to deflect the drag loads away from the surface.

Table 4.15: The PC's Separation Principles in accordance with selected 40-IP

Principle	Separation in Space	Separation in Time	Separation in Condition	Separation in Transition
35			✓	✓
40			✓	
27			✓	
02	✓			

From here, the safety solution can be applied to suit both side strut working positions. In Step 6, the conceptual design process must ensure that, in the event of failure, the new MLG concept causes no harm to the fuselage and performs efficient taxiing, take-off, and, especially landing activity.

4.5.7.2 Generate Concept Design Ideas and Sketches

In the case of the artefact problem related to IFR previously stated, the use of the 'geometrical effect' (Appendix D) from TRIZ scientific effect is useful. Through sketching, the application of geometrical effects inspire the idea development process to produce even more exciting solution ideas. Figure 4.17 shows several freehand sketches that demonstrate the ideas and discussion concerning shape and movement of the MLG especially on the side strut shape. For example, the geometric effect *'Ellipse and Ellipsoid'* from the geometric effect database helps in the solution idea generation of:

i. force and pressure transfer through the ellipsoidal shape of the strut (physical), or
ii. adjusting the contact or area that receives stress by ellipse-like movements (non-physical).

Added advantages of the ellipse and ellipsoid shape relates to the acoustic energy, where, quite interestingly, the noise produced through the ellipse and ellipsoidal movements have potentials in contributing to the advancement of harvesting energy (Carrara et al., 2012; Carrara et al., 2013).

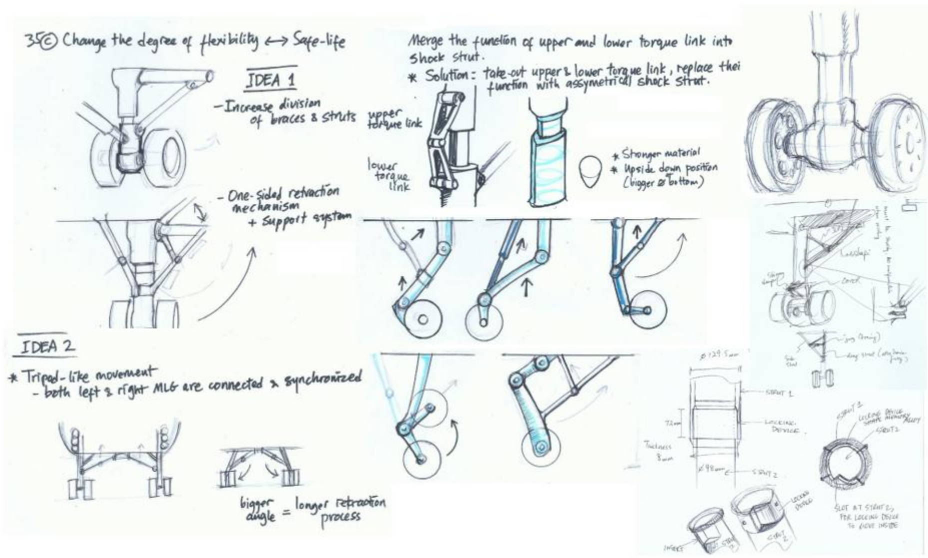

Figure 4.17: Freehand sketch of side strut shape design proposals for noise reduction new concept

4.5.7.3 Options of Generating Concept Design with CAD Model

For better visualization and concept design efficiency and safety analysis, computer aided 3D model construction is encouraged. Besides better visualization, the model is useful for design efficiency analysis, simulation purposes and prediction of risks. The computer model is also the best way to do multiple experimentation economically. The model and its analyses aid in the evaluation process to ensure the possibility of the concept design progressing to the detailed and embodiment design phases. The 3D model shown in Figure 4.18 represents examples of new shape concept design.

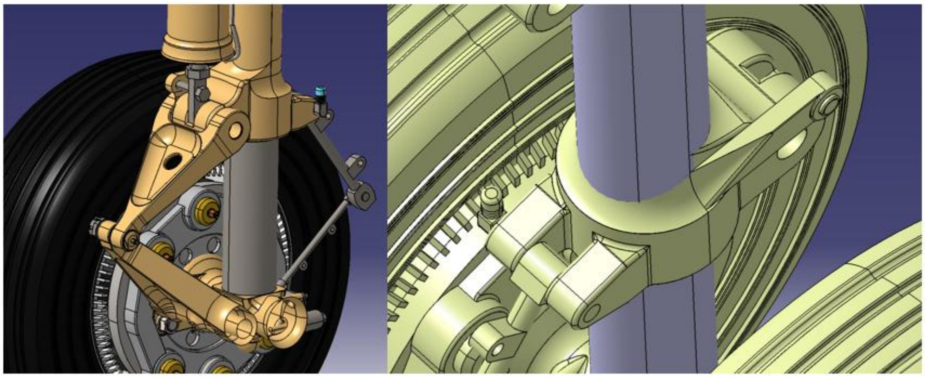

Figure 4.18: The example of MLG current struts shape (left) and modified strut (right)

4.5.8 Step 7: Firming Up the New Main Landing Gear Conceptual Design

In Step 7, the firming up process consist of evaluation of the design safety and performance effectiveness, that will help in determining which idea offers the most ideal, safe and creative solution. In addition, referring to the IFR is also important. TRIZ-SA proposes using VDI 2225 (1998) to clarify the safety features of the prototype in accordance with DIN 31000 (2017) or ISO 31000 (2009). Other than the stated standards, other supporting documents related to the artefact is useful for the firming up process.

4.5.9 Step 8: Evaluate the New Main Landing Gear Conceptual Design

In furthering the concept design to the embodiment and detailed design phases, there will be new functions and components introduced in which the design changes take place. Again, the FCM model can be established to identify new inherited and imposed constraints, while simultaneously assisting in identifying the ideal safety features of the prototype. The evaluation of the prototype's safety should be conducted with recommendations for at least two approaches: 1) the use of design analysis theory or software, and 2) the use of design and safety standards, before progressing to further phases of the design.

Since the optimization and design changes in the validation focuses on the shape of the side strut, specifically, and the MLG, as a whole, a design validation should be conducted of the shape and noise evaluation procedures, where the relationships between the take-off and landing aerodynamics are analysed. Such an evaluation can be obtained through computational aerodynamic analysis, such as Computational Fluid Dynamics (CFD) of the efficiency of the prototype's shape. Another analysis, the computational noise evaluation, can accurately identify any deficiencies in the shape design in terms of the shape's angles and surfaces manipulation, and even simulate worst case scenarios. In the theoretical approach, the effectiveness of the safety features can be evaluated with the FCM.

A computational assessment on the cad data using finite element analysis is recommended to identify the level of design and safety efficiencies of the new side strut design. The design efficiencies are related to the new shape, and how it optimizes the efficiencies of receiving drag loads and manipulating the loads to help in landing and take-off. Safety efficiencies present the performance of the new side strut when reaching certain limitations and whether or not they achieve the ideal state.

The evaluation of the prototype is then examined in respect of the aircraft's safety standards provided by the FAA, EASA and other aircraft airworthiness authorities. The proposed safety standards and requirements for the MLG concept design are listed mainly from military resources, as follows:

1) MIL-STD-1530C (DoD, 2005): Standard Practice – Aircraft Structural Integrity Program (ASIP)
2) MIL-STD-882E (DoD, 2012): Standard Practice – System Safety
3) MIL-STD-1472F (DoD, 1999): Design Criteria Standard – Human Engineering
4) MIL-STD-1629RevA (DoD, 1980): Procedures for Performing A Failure Mode, Effects, and Criticality Analysis

Changes to the inherent constraint level, imposed constraints and safety limits within the new system are also to be referred to the safety standards and design requirements. The aircraft safety documentation provides evaluation guidance for auditing purposes on the efficiency of the prototype. Another form of safety evaluation is the feedback records of aircraft malfunctions, incidents and any data pertaining to occurrences of MLG safety and risk. Studies on aircraft feedback has been conducted by many researchers for advancement of the safety and conceptual design of aircraft, such as those by Wan Husain (2012); Stevens et al. (2015), and Wise et al. (2015).

CHAPTER FIVE

CONCLUSION AND FUTURE RESEARCH

5.1 Conclusion

In every conceptual design, each development must have safety characteristics, be it a simple baby's bottle up to complex machinery like an aircraft turbine. Although a simple prototype requires less effort in terms of safety intervention in its design process, we should not ignore the importance of safety until the prototype is introduced to the public and used to not only eases everyday life but to protect from harm as well. In fact, the assurance of a prototype's ability lies in the effectiveness of its performance and the safety it provides.

A complex component with higher safety requirements also needs exposure to changing its design into a better form, changes that will make it last longer in use, last longer in the market and provide better performance with additional benefits, such as less energy usage, environmentally friendly, simpler component structure and many more. Complex components require flexibility in their working condition, and, despite the safety constraints, must be be able to adapt to a wider working scope, be flexible in performing in many weather conditions, and be able to be used in a wide range of geographical places. By integrating the safety approach in the conceptual design process, somewhere between problem definition and the generation of ideas, the inventive and creative design change on complex components is highly possible.

5.1.1 Constraint-Safety-Based Support for Conceptual Design

This study aims to guide designers to administer conceptual design with systematic execution. This research process has gone through safety and constraints studies on the artefact's functions and working conditions, determining the violation of constraints and consequences to the violations, which thereafter resulted in an unsafe design. When safety and constraints are implemented in the earlier part of the design process, designers have a better understanding concerning the artefact's structure and will develop ideas or design solutions based on the constraints and safety studies that have been established. Therefore, the goal to implement the safety and constraint handling method as the basis for supporting the conceptual design process has been achieved.

5.1.2 Motivation for New TRIZ Features

The TRIZ-SA conceptual design framework can be the basis for supporting TRIZ, specifically, the conceptual design as a whole. The experiments and design analyses on the MLG design outlines the significance of the integration of safety principles being embedded in the conceptual design, as being as imperative as the artefact's working principles and other concurrent principles in the process. Despite the fact that safety and constraints are technical necessities, the TRIZ methodology implies creativity and inventiveness that overcomes safety and constraint enforcement. This is true, as without TRIZ intervention in the process of constraint and safety modelling, determining possible designs is less artistic and psychologically inertia like. Finally, this research helps determine whether constraints and safety motivate TRIZ to have a branch of problem-solving solely for safety studies.

5.2 Future Research

Based on the conducted research and its findings, several recommendations to further this study are identified. These are:

1) Empower the safety principle guide: which is the novel tool developed in this research. It cannot be completed for all 40-IP because of the limited number and scope of patents utilized. Further analysis and a wider scope of patents with safety standard documents, and a collection of safety-based designs can be added to enhance the Safety Principle Guide (SPG).

2) Micro-decision-making: a suggestion for building a framework for micro-decision-making in the conceptual design process, e.g. modelling how to select the best idea for the safety-based problem, and to equip the constraint model with a more stable and structured parameter relationships. Integration with other design knowledge such as case-based reasoning, user experience and TRIZ data or knowledge pool are also recommended.

3) TRIZ effects and trends: encourage the use of TRIZ physical, chemical and geometric effect in the conceptual design, especially the geometric effects for industrial design processes. The Trend of Engineering System Evolution (TESE) also helps designers to initiate radical ideas and concepts.

4) Integration in CAD/CAID: it is hoped that this research outcome can be implemented in Computer Aided Design or Computer Aided Industrial Design tools, meaning that the characteristics of each safety principle in relation to the geometric effects are recommended in the design analysis of 3D model software.

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APPENDICES

APPENDIX A

MLG Patent Analysis

No	Patent Number	Grant/ Publish Date	Title	Assignee	IPC/CPC	Problem and Solution	QCA Codes	SP	40-IP
1	US8955798B2	17-Feb-15	Aircraft landing gear	Messier-Dowty Ltd	B64C25/02	• Non-streamlined geometries resulted to aircraft noise. • The solution is to house the lock springs, hydraulic piping and electronic cabling inside the hollow side stay – removed from the air stream therefore no contribution to noise and to eliminate the risk of impact damage during takeoff and landing	Insert or merging elements	SP-DS-FS	5a, 7b
2	US9221556B2	29-Dec-15	Airplane off ground advisory system	Boeing Co	B64D45/0005 B64C25/28 B64C25/34	• Induce bounce causing aircraft to become airborne. Pre-mature rapid de-rotation of NLG and off ground advisory system for the compressed condition of MLG. • Solution - Airplane Off Ground Advisory System (AOGAS) consist of attachment of sensor, for safe landing.	Visual assist	SP-IS	24a, 23a
3	US8967535B2	3-Mar-15	Aircraft landing gear	Airbus Operations Ltd	B64C25/12 B64C25/16	• Door opening and closing interferences, staggered door movement sequences. • Solution by desinging starboard door, opening by very close sequence, by outward rotation away. • The aim is to save space.	Close sequence operation	SP-DS-SL	10a, 19b,

No	Patent Number	Grant/ Publish Date	Title	Assignee	IPC/CPC	Problem and Solution	QCA Codes	SP	40-IP
4	US8944382B2	3-Feb-15	Method for mounting an aircraft component and aircraft assembly	Airbus Operations GmbH	B64C25/10 Y10T29/4978	• Mounting LG assembly in a position that the fuselage is not lifted. This method aims to mount LG in a simple, in motion to work concurrently with other component assembly. • Avoiding uncomfortable work position	Ergonomic position	SP-DS-SL	15c, 35c, 20a
5	US8973866B2	10-Mar-15	Transverse flux machine utilized as part of a combined landing gear system	Hamilton Sundstrand Corp	B64C25/405	The use of transverse flux technology on LG, to provide efficient braking.	Adding brake force	SP-DS-FS	18e, 24a
6	US9027878B2	12-May-15	Aircraft landing gear including a fairing	Messier-Dowty Ltd	B64C25/001, B64C2025/003	• Reducing noise by the use of pivoting fairings. • Fairing is designed to allow some airflow pass through. • LG protection from damage caused by impact from foreign bodies.	Fairing, Protection	SP-IS	10b, 15c,
7	US9010690B1	21-Apr-15	Airborne recovery system for aircraft with disabled landing gear	Abdulrahman S. J. M. Al-Heraibi	B64D5/00	• Cradle aircraft for emergency rescue of an aircraft with LG malfunction. • Airborne recovery system	Rescue in motion	SP-DS-SL	5b, 17e
8	US9102403B2	11-Aug-15	Emergency gravity free-fall deployment systems for retractable aircraft	Embraer SA	B64C25/30	• Control or locking systems for door opening when emergency free-fall aircraft LG. • Uplock mechanism equipped with control system for door opening.	Rushing procedure	SP-IS	21, 23b

No	Patent Number	Grant/ Publish Date	Title	Assignee	IPC/CPC	Problem and Solution	QCA Codes	SP	40-IP
			landing gear assemblies						
9	US9169025B2	27-Oct-15	Method for inflight de-icing of landing gear and wheel bays in aircraft with onboard drive means	Borealis Technical Ltd	B64D15/16	• Method for preventing icing on exterior surfaces of aircraft by mechanical means. • FAA prohibits flight when frost, ice, or snow adhere on aircraft surface. • Having heat production mechanism in MLG structures from taxi to point of take-off.	Heat drive	SP-DS-FS	14c, 24a
10	US8955799B2	17-Feb-15	Aircraft landing gear stop pad	Messier-Dowty Ltd	B64C25/02 B64D2045/008	• Increase braking and protection against impact between first and second LG elements • Avoiding damage to the bogie beam • Visual indication included for examination of bogie beam	Stop pad, Visual assist	SP-DS-SL	23a, 31a
11	US9073629B2	7-Jul-15	Main landing gear of an aircraft, comprising two walking beams joined to the structure of the aircraft in an articulated manner	Messier Bugatti Dowty	B64C25/10 B64C25/34	Pivoting rocker beam. To restore in fuselage/wing body for compact folding.	Pivoting means	SP-IS	15c, 28c

No	Patent Number	Grant/ Publish Date	Title	Assignee	IPC/CPC	Problem and Solution	QCA Codes	SP	40-IP
12	US8965657B2	24-Feb-15	System and method for detecting an on ground condition of an aircraft	Goodrich Corp	Arrangements or adaptations of brakes	• Applying brakes before wheels accelerated to a sufficient velocity after touchdown may causes wheels to lock and damage the wheels and aircraft. • Determining moving & braking of MLG on ground, device is attached to MLG axles, measures by weight-on-wheel system	Brake assist	SP-DS-SL	23a
13	US9096315B2	4-Aug-15	Apparatus for recovering kinetic energy released during landing of an aircraft after contact with the ground, and method	Airbus Operations GmbH	B64C25/32	• Energy converter for conversion of the kinetic energy into another energy form. • Previously, braking the aircraft assisted by reverse thrust engines, but uses more energy. • The collected energy from kinetic) during landing will be used for taxiing	Convert to energy	SP-DS-FS	22a
14	US9207136B2	8-Dec-15	Brake manufacturer identification system and method	Goodrich Corp	G01L5/28 B60T17/22	• Improper identification by a brake control system may degrade brake system performance and compromise safety. • Apparatus for, or methods of, identifying types of brakes, leading to type of the brake manufacturer.	Identify element	SP-IS	23a, 6
15	US9038950B2	26-May-15	Arrangement of aerodynamic auxiliary surfaces for an aircraft	Airbus Operations GmbH	B64C23/06	• Influencing air-flow underside aircraft surfaces, by aerodynamic auxiliary surface means. • Improve stability of the aircraft and may reduce aerodynamic drag. • Fuselage surface design, includes fairing	Aerodynamic manipulation	SP-DS-SL	3a, 25b

No	Patent Number	Grant/ Publish Date	Title	Assignee	IPC/CPC	Problem and Solution	QCA Codes	SP	40-IP
16	US9045236B2	2-Jun-15	Device for exciting a landing gear of an aircraft while on the ground	Airbus Operations Sas	B64F5/0045	Test or inspection of aircraft components or systems. Lifting MLG with excitation device.	Provide lift	SP-IS	25a
17	US9205918B2	8-Dec-15	System and method for maximum braking	Goodrich Corp	B64C25/44	Electronic brake control system, with actuator may deliver an emergency maximum clamping force on the first braked wheel via a brake stack, through signal received.	Brake component	SP-DS-SL	5a, 11, 16
18	US9026280B2	5-May-15	Method for detecting the landing quality of an aircraft	Air China Ltd	B64D2045/008 G07C5/085	• A method to detect vertical speed rate when aircraft lands and collect landing data. • The hard/heavy landing can impose strong impact and vibration on the structure of the aircraft, may cause structure failure	Monitoring system	SP-IS	20a, 6
19	US9051048B2	9-Jun-15	Main landing gear bias axle steering	Goodrich Corp	B64C25/50 B64C25/34	• Steerable MLG system, for taxiing and manouvering large MLG with 6 or more wheeled bogie beam. • Ability to bias MLG when turning	Pivoting means	SP-DS-FS	15c, 28c
20	US9169004B2	27-Oct-15	System for motorizing a wheel connected to a suspension	Michelin Recherche et Technique SA Switzerland Compagnie Generale des Establissements Michelin et	B64C25/405 Y02T50/823	Powered wheels for taxiing. Previous device has sensitivity to shocks, uses gearings, damaging when the MLG equipped with such motor travel in high speed on uneven ground. The device is less sensitive to shocks, with an electric motor unit in association with suspension and the wheel. Uses engage & disengaged procedures.	Powered Wheel	SP-DS-R	19c, 12

No	Patent Number	Grant/ Publish Date	Title	Assignee	IPC/CPC	Problem and Solution	QCA Codes	SP	40-IP
				Cie, Airbus Operations Ltd					
21	US9067675B2	30-Jun-15	Airplane emergency supplemental braking system and method	Boeing Co	B64C25/42 B60T1/14	• Decelerating aircraft when landing by means of braking. Supplemental brake system- using frictions on runway. • Avoiding overrunning on normal brake, on insufficient runway distance, which is very catastrophic.	Brake component	SP-DS-R	24a, 24b
22	US9156451B2	13-Oct-15	Brake control system comprising tire/runway friction property estimation mapping	Goodrich Corp	B60T8/171 G01L5/28	• Detecting tire/runway friction estimation (coefficient)– measuring wheel speed, acceleration, force. • Related to brake system, with brake control algorithm – to process best braking application	Brake component	SP-IS	23a
23	US9193449B2	24-Nov-15	Method for optimizing operation of aircraft ground travel drive system	Borealis Technical Ltd	B64C25/405 Y02T50/823	Optimizing operation of aircraft taxiing. Use of electric drive motor to power movement to avoid engine use.	Powered wheel	SP-IS	16, 7a

No	Patent Number	Grant/ Publish Date	Title	Assignee	IPC/CPC	Problem and Solution	QCA Codes	SP	40-IP
24	US9045011B2	2-Jun- 15	Controlled landing gear tire traction system	Boeing Co.	B60C11/1612 B64C25/36	Tire traction system design, depressurizing tire of an aircraft wheel in response to a non-optimal aircraft landing condition. The inner rotor placed inside the tires will move the depresurizing tires in condition that all related materials can withstand the movement of the tires on non-optimal runway.	Tire assist	SP-DS-R	7a, 11
25	US9022316B2	5-May-15	System and method for failsafe operation of aircraft ground movement system	Borealis Technical Ltd	B64C25/405 Y02T50/823	• A failsafe system and method for ensuring the safe operation of an aircraft – independant ground movement system. Indications of safe or unsafe aircraft. • Communications with the pilot.	Taxiing assist	SP-IS	24a
26	US9193447B2	24-Nov-15	Landing gear with noise reduction apparatus	Airbus Operations Ltd	B64C25/10	Mounting cover plates on MLG assembly with high drag void exposures, leading to noise. Removable cover plate, with sealing elements, functions as fairings	Fairing	SP-IS	30
27	US9205758B2	8-Dec-15	Electric vehicle traction control system and method	Borealis Technical Ltd	B60L15/20	A system for controlling and maintaining optimum traction, help to prevent or limit wheels from slipping during acceleration on different surfaces. Electric drive means designed to translate torque	Control system	SP-IS	19a
28	US8979019B2	17-Mar-15	Aircraft taxi system including drive chain	Honeywell International Inc	B64C25/405 Y02T50/823	Consist of piston, gears and axle with motor to move MLG tires for taxiing, without relying on main engine. Attached and de-attached between taxxing and take-off as well as landing.	Powered wheel	SP-IS	16, 15a

No	Patent Number	Grant/ Publish Date	Title	Assignee	IPC/CPC	Problem and Solution	QCA Codes	SP	40-IP
29	US9045237B2	2-Jun-15	Automated inspection of aircraft landing gear internal fluid levels	C. Kirk Nance	B64F5/0045 G01M17/04	• Monitoring, measuring, computing and displaying the internal liquid and gas volumes inside telescopic strut, • Measuring the compression, can be monitored while the aircraft is in operation, transporting passengers and/or cargo	Monitoring system	SP-IS	20a, 23a
30	US9174727B2	3-Nov-15	Landing gear steering using eccentric bearings	Messier-Dowty Limited	B64C25/50 B64C2025/345	• An elongate bogie beam with bearing attachment for movement of MLG with six or more tires. • Steerable axle and avoiding tire wears. The arrangements of the bearings are unique that when cornering the bearing moves with the beam accordingly, avoiding tilting and torsion.	Steering	SP-DS-FS	5b, 14b
31	US8939400B2	27-Jan-15	Air-ground detection system for semi-levered landing gear	Boeing Co	B64D45/06	• Toes touching landing, semi-levered with sensors. Provided with air-ground detection system - detect a change from the steady state to the locked state. • Pivoting truck beam, for smooth landing. Aims to align all MLG for stable landing.	Landing aids	SP-DS-FS	16, 10b
32	US8950775B2	10-Feb-15	Receiver device for engaging a landing gear adapter with a tug	Redfab Inc	B60D1/01	• A receiver device for engaging a landing gear adapter unit with a tug (towbarless). • Moving in and out of hangars with external taxiing device. • Previous tugs tend to break turning linkages and towbars and scratch wheel fairings when being installed or removed.	Moving device	SP-IS	2, 26a
33	US9014878B2	21-Apr-15	Method for detecting performance of an aircraft based on a	Air China Ltd	B64D45/00	• Method for detecting the performance of the aircraft by collecting data & generating the customized message. • Aims to detect performance of aircraft based on the customized message.	Monitoring method	SP-IS	23a

No	Patent Number	Grant/ Publish Date	Title	Assignee	IPC/CPC	Problem and Solution	QCA Codes	SP	40-IP
			customized message						
34	US9114791B2	25-Aug-15	Electric brake for an aircraft wheel, the brake including an electromechanical actuator fitted with a temperature sensor	Messier-Bugatti Dowty	B60T17/22	• Electric brake for LG wheel fitted with electromechanical actuator, equipped with temperature sensor that enables turnaround time (TAT) to be reduced. • To monitor temperature, to know the time brake disks cool down and making it possible to shorten TAT	Braking component, Temperature monitor	SP-DS-R	6, 23a, 16
35	EP2470423B1	22-Jul-15	Main landing gear with rigid rear stay	Messier-Dowty Limited	B64C25/14	• Rigid rear stay restrain the path of the shock strut when in motion, as main pillar of MLG when deployed, storage and when landing. • The stay/strut arrangements are compact when in storage. • Enabling the mounting of the landing gear assembly to the wing to be reduced in strength and weight.	Dominant component	SP-DS-SL	6, 8a, 25
36	EP2366623B1	22-Apr-15	Landing gear steering systems	Goodrich Corporation	B64C25/34	• Turning a six-wheel MLG to reduce side loads & tire scrubbing using push-pull steering movement (aft axle and hydraulic actuators) but the steering torque gets higher than required, plus using LVDT movement gives false steering movement signals. • Solution with a rack with rack teeth moving in linear, connected to an actuator, with sensor to detect amount of travel.	Steering	SP-DS-FS	35f, 15d

No	Patent Number	Grant/ Publish Date	Title	Assignee	IPC/CPC	Problem and Solution	QCA Codes	SP	40-IP
37	EP2686243B1	18-Nov-15	Method and system for determining friction coefficient for an aircraft landing event	Messier-Dowty Limited	G06F17/5009	• Hard landing studies with visual inspection by the maintenance crew is non accurate. Normal procedures is by using FDR and dynamic model assessment by LG manufacturer. • Monitoring methods using computational model to study frictions when hard landing to avoid overload condition, btter maintenance and keep the safety level.	Monitoring	SP-IS	23a,
38	EP0980828B2	21-Jan-15	Airplane ground maneuvering camera system	Boeing Co.	B64D47/08	• The restricted widths of the runways and taxiways, with greater airport congestion, have made difficult for pilots of large commercial airplanes to make tight maneuvers. Previously use guiding fairing, non accurate. • Solution with camera assist to manouvre help pilot & a perfect real-time feedback mechanism.	Taxiing assist	SP-W Feedback	28a
39	EP1993887B1	9-Dec-15	Method for brake proportioning in at least one brake group of an aircraft	Messier-Bugatti-Dowty	B60T8/1703	• Prior art brake method reduce overall wear of friction elements on brakes by segmenting brakes and fraction brakes but heats faster resulting to accelerated friction. • The solution is to build a method to distribute brakes by group, having friction elements, estimations of energy, minimizing wear.	Brake method	SP-DS-FS	1c, 23b
40	EP2327067B1	4-Nov-15	Method and device for aiding the piloting of an aircraft during a landing phase	Airbus Opérations SAS	G08G5/02	• Piloting assistant for landing with known runway characters, automatic braking system with multiple types of braking strengths – automatic selection of braking strength, calculated runway features for automatic braking. • Equipped with alarm.	Brake assist	SP-W	23b, 25a

No	Patent Number	Grant/ Publish Date	Title	Assignee	IPC/CPC	Problem and Solution	QCA Codes	SP	40-IP
41	US20150353190A1	10-Dec-15	Method For Managing The Braking Of An Aircraft Wheel	Messier-Bugatti-Dowty	B64C25/42	• A motor that reduce fuel consumption, reserve, steering remotely. • Braking method with anti-skid function. Together with an magnet electric motor to drive the wheel, fitted with sensor (resolver, Hall-effect) to measure angular position of rotor.	Multipurpose Motor	SP-DS-FS	6
42	US20150323019A1	12-Nov-15	Landing Gear With A Bi-Directional Clutch	Airbus Operations Limited	F16D41/086	• Avoiding the use of low power engines because of the application of wheel brakes, increases tire wears. Reversing aircraft using engines is not permitted, due to safety (use of tow trucks) • A bi-directional clutch for permitting one or more wheels of the main landing gear to be operated in a driven mode for taxiing and an overrunning mode.	Taxiing assist	SP-DS-FS	3c, 6, 13c
	US20150316438A1	5-Nov-15	Method For Determining Aircraft Center Of Gravity Independent Of Measuring The Aircraft Weight	C. Kirk Nance	G01M1/125	• If the aircraft *cg* is outside certified limits, the aircraft nose can rise uncontrollably st take-off, will become unstable and resulting to a stall and possible crash. • Load measuring apparatus, identifying the proper MLG load and *cg* for aircraft balance • Determining safety for take-off, aircraft *cg* - critical factor in flight operations. Efforts to reduce fuel consumption with *cg*.	Flight control	SP-DS-SL	17e, 8b
50	US20150151835A1	4-Jun-15	Load Transfer in a Powered Aircraft Drive Wheel	Isiah W. Cox, Scott Perkins. Borealis Technical Ltd	B64C25/405	• Engines-off taxi technology. Moving aircraft safely without using main engines or external vehicle. • Move autonomously during taxiing without engines or tow vehicle. Engines-off taxi	Taxiing assist	SP-IS	24a

No	Patent Number	Grant/ Publish Date	Title	Assignee	IPC/CPC	Problem and Solution	QCA Codes	SP	40-IP
						technology. Excess drive forces are transferred and distributed.			
51	US2015159968 A1	11-Jun-15	Heat Dissipation System for Aircraft Drive Wheel Drive Assembly	Borealis Tech Ltd	B64C25/40 F28F13/00	• Previous design had motor to move the tires and provided fan to cool the motor, but none had a heat dissipation system. • Heat dissipation of drive means to move tires without use of engine. • Use of heat transfer fluid, clutch to connect the drive means to aircraft wheels, stator and rotor element, sensor, intelligent control means.	Heat control for taxiing	SP-DS-FS	6, 11, 19a
52	US8746615B2	10-Jun-14	Landing gear	Airbus Operations Ltd	B64C25/001	• MLG deploy early for safety purpose but noisy. • Reduce noise, reduce turbulent air flow. To lessen disruption or inconvenience to public. • Fairing for aircraft landing approach, air flow pass MLG. • The mechanism of MLG retracting mechanism is configured that it is positioned inside bay.	Noise reduction	SP-IS	12, 14a
53	US8899518B2	2-Dec-14	Engine debris guard	Airbus Operations Ltd	B64C25/32	• A debris guard, to avoid tire debris striking aircraft engine. Pivotally connected to MLG • Fail-safe safety, the debris guard consist of second actuator backup in the event of the failure of the primary actuator.	Debris guard	SP-DS-FS SP-DS-R	10a, 11,
54	US8684299B2	1-Apr-14	Ancillary device with an air turbine for taxiing an	Airbus Operations Sas	B64C25/405	• Over-consumption of kerosene, additional costs of maintenance and repair of damages. • A turbine machine (pneumatic) for driving at least one wheel for taxiing.	Taxiing assist	SP-IS	24a, 29

No	Patent Number	Grant/ Publish Date	Title	Assignee	IPC/CPC	Problem and Solution	QCA Codes	SP	40-IP
			aircraft on the ground						
55	US8661902B2	4-Mar-14	Method, apparatus and software for detecting yield in a mechanical structure by means of acoustic emission data from said structure	Airbus Operations Ltd	G01L1/255	• Waves and acoustic measurement technology for detecting yield. • Mechanical structure yield control for aircraft safety, permanent deformation risks, detecting the overload on MLG. • Attaching AE (acoustic emission) sensors at MLG struts	Failure detection	SP-F	17e, 23a
56	US8651417B2	18-Feb-14	Bogie stop block	Messier-Dowty Limited	F16B39/36	• Bogie beam stop pads, for limiting MLG pivotal movements. Design to exert varying and constant bending moment of the bogie beam. Previously use aluminium and nylon material. • Prevent bogie damage when over-rotation and hitting neighbouring component.	Stop pads	SP-DS-FS	11
57	US8628285B2	14-Jan-14	Retaining nut	Airbus Operations Ltd	F16B39/36	• Retaining nut and washer combination. For fitting of components at the MLG assembly. • Prevent loose nuts when in operations (for large diameter nuts) usually at the MLG, without using special locking devices. Features of frusto-conical inner surface, deflectable locking fingers & spanner slots.	Fitting device	SP-DS-SL	1c

No	Patent Number	Grant/ Publish Date	Title	Assignee	IPC/CPC	Problem and Solution	QCA Codes	SP	40-IP
58	US8684300B2	1-Apr-14	Aircraft landing gear	Airbus Operations Ltd	B64C25/405	• Pivoting powered wheel for taxiing. • To secure driving engagement without damaging the tyre, prevent excessive ground taxi speeds, prevent excessive wear on drive pinions. • Uses electric or hydraulic motor, with toothed drive belt.	Taxiing assist	SP-IS	15c, 24b
59	US8857544B2	14-Oct-14	System for electric motorization of a wheel	Michelin Recherche et Technique SA Switzerland	B64C25/405 Y02T50/823	• Deformations occur during various manoeuvres, affecting most sub parts of gear wheel. • Powered wheels for taxing. Using electric motor, engage & disengaged position. • The motor have output gear consist of velocity joint, for angular movements & torque.	Taxiing assist	SP-IS	24a
60	US8800920B2	12-Aug-14	Aircraft landing gear of the rocker-arm and deformable-parallelogram type	Messier Bugatti Dowty	B64C25/12	LG with rocker arm and deformable-parallelogram type. Connected with pivot hinge and simpler than prior art. For amphibian aircraft.	Pivoting arm	SP-DS-SL	2, 15b
61	US8668163B2	11-Mar-14	Rack and pinion landing gear steering system	Goodrich Corp	B64C25/34	• Turning a six-wheel MLG to reduce side loads & tire scrubbing using push-pull steering movement (aft axle and hydraulic actuators) but the steering torque gets higher than required, plus using LVDT movement gives false steering movement signals. • Solution with a rack with rack teeth moving in linear, connected to an actuator, with sensor to detect amount of travel.	Steering	SP-DS-FS	35f, 15d

No	Patent Number	Grant/ Publish Date	Title	Assignee	IPC/CPC	Problem and Solution	QCA Codes	SP	40-IP
62	US8806992B2	19-Aug-14	Landing gear axle nut safety socket	United Airlines Inc	B25B23/14	• Arrangement of torque limiters or torque indicators in axle nut. • Prevent premature wear or friction, accidentally leave out spacers/washers during wheel changes, damages, aircraft downtime. • Consist of socket with special features, rotatable gear hub, ball bearings moves in linear direction.	Fitting device	SP-DS-SL	1a, 35e
63	US8897930B2	25-Nov-14	Motor controller	Borealis Technical Ltd	B64C25/405	• Software invented to control an electric motor system, to powered wheels, avoiding steering conflict, tipping uncontrol movements. • Separation mechanism of controlling brakes and manouvers for safety, includes Graceful Stopper as a safety device, speed control.	Taxiing assist	SP-DS-FS	17e, 24b
64	US8666598B2	4-Mar-14	Method of controlling the yawing movement of an aircraft running along the ground	Messier Bugatti Dowty	G05D1/0083 Y10T70/5664	• A method of controlling a yawing movement of an aircraft running along the ground, using closed-loop control. • The close-loop control generates command to steer according to calculated angle, controlled yaw and torque application.	Taxiing assist	SP-DS-FS	17e, 26b
65	US8630750B2	14-Jan-14	Method of controlling steering control equipment for aircraft, and steering control equipment for aircraft and aircraft	Sumitomo Precision Products Co Ltd	B64C25/50	• Possibility of aircraft may swerve from runway, large traveling direction, uncontrolled speed due to head winds. • A method of controlling a steering handle, ruder pedals, coupled to steering mechanism which detect and control ground-speed, changes traveling direction by changing angular position.	Steering assist	SP-DS-FS	23a, 17e

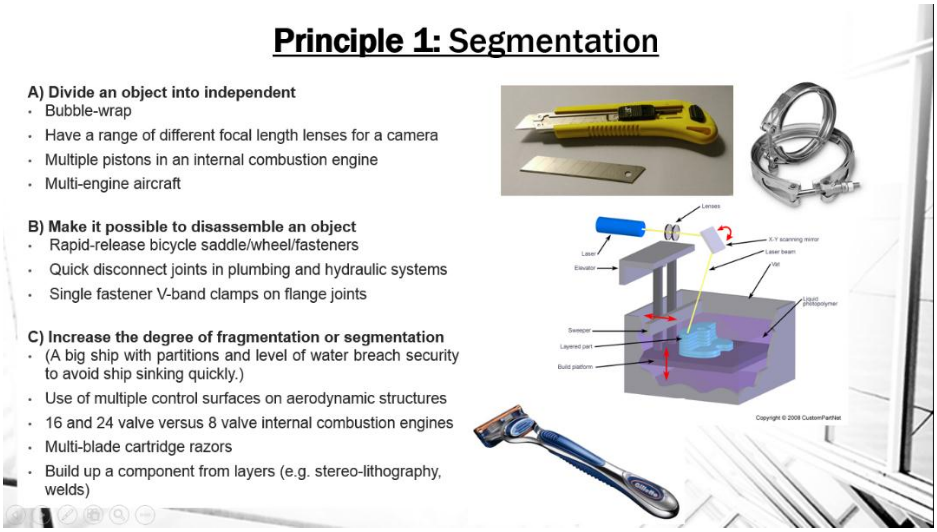
No	Patent Number	Grant/ Publish Date	Title	Assignee	IPC/CPC	Problem and Solution	QCA Codes	SP	40-IP
			provided therewith						
66	US8708272B1	29-Apr-14	Landing gear door liners for airframe noise reduction	The United States of America as represented by the Administrator of the NASA	B64C9/18	• Noise is a significant issue to public health implications, especially for communities near airports • To lessen disruption or inconvenience to public, regarding MLG opening door, the door cover MLG when retracting and surface design uses porous surface with special geometric design.	Noise reduction	SP-IS	31a
67	US8794092B2	5-Aug-14	Disengageable interface mechanism between a motorization system of an aircraft landing gear assembly and a wheel	Airbus Operations Sas	B64C25/405	• Prior art have acoustically disruptive, unefficient fuel consumption, early wear of brake parts, current motorize drive train poorly integrated with landing gear apparatus. • Mechanism comprising motor-reducer unit, in between the unit and wheel is an interface device. Pendulum element,	Taxiing assist	SP-DS-FS	24b, 35c
68	US8833694B2	16-Sep-14	Split circumference aircraft wheel assembly with integrated drive motor assembly	Borealis Technical Ltd	B64C25/405	• Prior art powered motor is attched with bolts to the drive wheels, so when removing for repair/maintenance requires proper tools available. • The split circumference wheel assembly includes separable inboard and outboard support walls so that motor driver assembly is completely contained within.	Powered wheel assembly	SP-DS-SL	7a, 24b

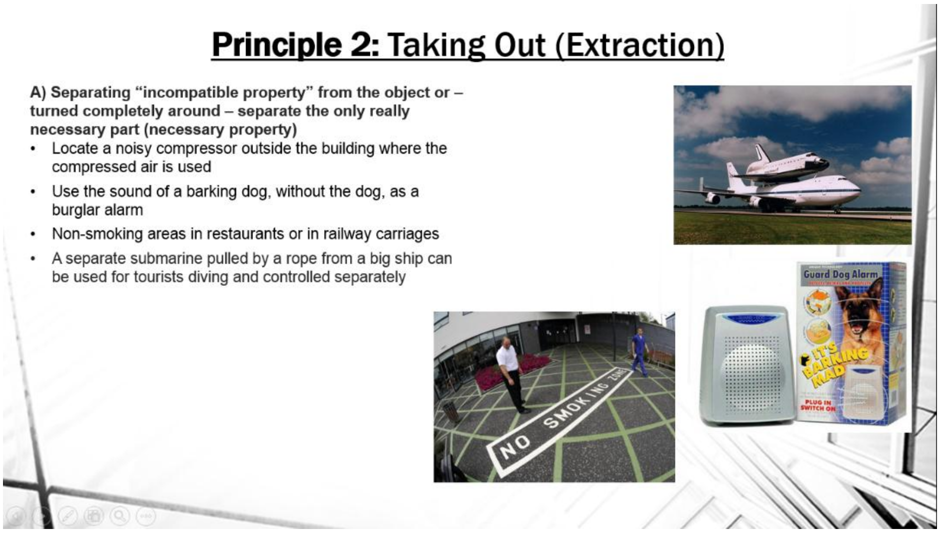
No	Patent Number	Grant/ Publish Date	Title	Assignee	IPC/CPC	Problem and Solution	QCA Codes	SP	40-IP
						• Safe and efficient ground movement, eliminate the need to use the aircraft main engines while taxiing.			
69	US8820675B2	2-Sep-14	Motor for driving aircraft, located adjacent to undercarriage wheel	Borealis Technical Ltd	B64C25/001	• A self-propelled aircraft undercarriage for driving an aircraft on the ground, avoids using aircraft turbines or a separate tug to move the aircraft. • Using electric motor, with clutch system, automatically engage and disengage when a predetermined speed is reached.	Taxiing assist	SP-DS-FS	24b,
70	US8851418B2	7-Oct-14	Landing gear attachment	Airbus Operations Ltd	B64C25/04	• To prevent damage to the fuselage and/or wing in the event of an unexpected impact. • Attachment of MLG to fuselage, using aircraft mount and trunnion block. Applicable to wider range of aircraft type.	Attachment means	SP-DS-SL	1c, 10b
71	EP2803569A1	19-Nov-14	Aircraft selectively engageable electric taxi system	Charles David Lane	B64C25/405	• The need to have Electrical Taxi Systems (ETS) with self-disengaging system so that there is no interference with normal take-off and landing procedures. • Relates to landing gear with integrated electric drive systems to propel an aircraft during taxiing. Using ETS, but does not impact normal take-off and landing procedures - pinion-driven ring gear, compact, clockwise & counter-clockwise movement.	Taxing assist	SP-DS-FS	24a
72	US8548652B2	1-Oct-13	System for reducing carbon brake wear	Hydro-Aire Inc	B60T17/18	• Avoiding frequent carbon brakes replacements, wear and lessen the use of brakes applied on carbon brakes. • A brake monitoring system is described for use on aircraft having carbon brakes. Brake	Monitoring device	SP-IS	16, 23a

No	Patent Number	Grant/ Publish Date	Title	Assignee	IPC/CPC	Problem and Solution	QCA Codes	SP	40-IP
						temperature indications. Brake application count signal using microprocessor.			
73	US8459590B2	11-Jun-13	Landing gear strut extender	Hydro-Aire Inc	B64C25/001	• A mechanism for increasing the ride height of aircraft by increasing the hydraulic fluid content in landing gear struts. temporarily lengthen a landing gear for purposes such as liftoff rotation or engine ground clearance • Adequate engine ground clearancebavoids prone to damage during on-ground operations, reduce costly FOD damage to engines, to reduce considerable weight.	Strut extender	SP-DS-SL	29, 11

APPENDIX B

The Sub Principles of 40-IP and Examples (Sources: Multiple sources, from Orloff EasyTRIZ software (2006), The TRIZ Journal at https://triz-journal.com/ and Oxford Creativity at https://www.triz.co.uk. Compiled by Kamarudin, K.M.)





Principle 3: Local Quality

A) Change an object's structure from uniform to non-uniform
- Reduce drag on aerodynamic surfaces by adding riblets or 'shark-skin' protrusions
- Moulded hand grips on tools
- Drink cans shaped to facilitate stable stacking
- Material surface treatments/coatings - plating, erosion/corrosion protection, non-stick,

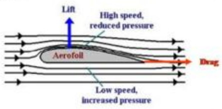
B) Change an external environment (or external influence) from uniform to non-uniform
- Use a temperature, density, or pressure gradient instead of constant temperature, density or pressure
- Introduce turbulent flow around an object to alter heat transfer properties

C) Make each part of an object function in conditions most suitable for its operation
- Freezer compartment in refrigerator
- Different zones in the combustion system of an engine

D) Make each part of an object fulfil a different and/or complementary useful function.
- Swiss-Army knife
- Combined can and bottle opener
- Hammer with nail puller

Principle 4: Asymmetry

A) Change the shape or properties of an object from symmetrical to asymmetrical
- Introduce a geometric feature which prevents incorrect usage/assembly of a component (e.g. earth pin on electric plug)
- Asymmetrical funnel allows higher flow-rate than normal funnel
- Put a flat spot on a cylindrical shaft to attach a locking feature
- Oval and complex shaped O-rings
- Introduction of angled or scarfed geometry features on component edges
- Aerofoil – asymmetry generates lift
- Eccentric drive
- Blohm und Voss observation aircraft



B) Change the shape of an object to suit external asymmetr (e.g. ergonomic features)
- Car steering system compensates for camber in road
- Wing design compensated for asymmetric flow produced by propeller
- Turbo machinery design takes account of boundary layer flows ('end-bend')
- Uneven staircase to make sure people look at the stairs to avoid falls.

C) If an object is asymmetrical, increase its degree of asymmetry.
- Use of variable control surfaces to alter lift properties of an aircraft wing
- Special connectors with complex shape/pin configurations to ensure correct assembly
- Introduction of several different measurement scales on a ruler

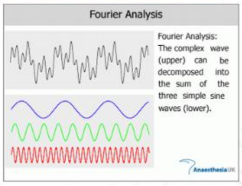
Principle 5: Merging

A) Bring closer together (or merge) identical or similar objects or operations in space

- Automatic rifle/machine gun
- Multi-colour ink cartridges
- Multi-blade razors
- Bi-focal lens spectacles
- Double/triple glazing
- Strips of staples
- Catamaran / Trimaran
- A scissor of 5 parallel blades to shred pepper easily or shred documents to avoid identity theft.

B) Make objects or operations contiguous or parallel; bring them together in time

- Combine harvester
- Manufacture cells
- Grass collector on a lawn-mower
- Mixer taps
- Pipe-lined computer processors perform different stages in a calculation simultaneously
- Vector processors perform the same process on several sets of data in a single pass
- Fourier analysis – integration of many sine curves



Principle 6: Universality (Multi-functionality)

A) Make a part or object perform multiple functions; eliminate the need for other parts

- Child's car safety seat converts to a stroller
- Home entertainment centre
- Swiss Army knife
- Radio-alarm clock
- CD used as a storage medium for multiple data types
- Use of Standards in e.g. data exchange
- Bathroom light-switch starts extractor fan
- Car instrument panel incorporates cup-holders
- Cordless drill also acts as screwdriver, sander, polisher, etc
- Fishing stool/container
- A printer with fax, scanner, photo print and copier.
- A robot with universal learning abilities has been developed at the TU Berlin, Germany to dismantle complex household appliances and industrial facilities that are no longer in use.

Principle 7: Nested Doll (*Matryoshka*)

A) Place one object inside another
- Place a safe inside a wall or under floorboards
- Retractable aircraft under-carriage
- Introduce voids into 3D structures
- Injected cavity-wall insulation
- Paint-brush attached to inside of lid of nail-varnish, etc
- Lining inside a coat
- Egg chocolate with detached toy parts inside, requires building the toys after opening an egg shape casing.

B) Place multiple objects inside others
- Nested tables
- Telescope
- Measuring cups or spoons
- Stacking chairs
- Multi-layer erosion/corrosion coatings
- Telescopic fishing; the retractable arm of the mechanism of lifts for automobiles.

C) Make one part pass (dynamically) through a cavity in the other.
- Telescopic car aerial
- Retractable power-lead in vacuum cleaner
- Seat belt retraction mechanism
- Tape measure
- Stacked charge ammunition

Principle 8: Anti-Weight

A) To compensate for the weight of an object, merge it with other objects that provide lift
- Kayak with foam floats built into hull cannot sink
- Aerostatic aeroplane contains lighter-than-air pockets
- Hot air or helium balloon.
- Swim-bladder inside a fish
- Flymo cutting blade produces lift
- Lighting reflected on a huge inflatable spheres, as powerful projector

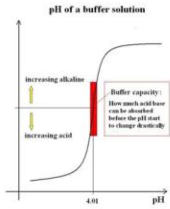
Enlarged area shows Micro VGs installed on the flap of a Piper Malibu Meridian.

B) To compensate for the weight of an object, make it interact with the environment (e.g. use aerodynamic, hydrodynamic, buoyancy and other forces)
- Vortex generators improve lift of aircraft wings
- Wing-in-ground effect aircraft
- Hydrofoils lift ship out of the water to reduce drag
- Make use of centrifugal forces in rotating systems (e.g .Watt governor)
- Maglev train uses magnetic repulsion to reduce friction

Principle 9: Preliminary Anti-Action/Prior Counter-Action

A) If it will be necessary to perform an action with both harmful and useful effects, this action should be replaced with anti-actions to control harmful effects

- Make clay pigeons out of ice or dung in order that they do not have to be collected afterwards.
- Masking objects before harmful exposure: Use a lead apron on parts of the body not being exposed to X-rays, use masking tape when painting difficult edges, etc.
- Predict effects of signal distortion / attenuation and compensate before transmitting
- Buffer a solution to prevent harm from extremes of pH



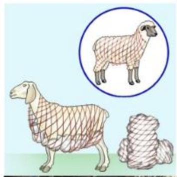
B) Create beforehand stresses in an object that will oppose known undesirable working stresses later on.

- Pre-stress rebar before pouring concrete.
- Pre-stressed bolts
- Pre-shrunk jeans
- Decompression chamber

Principle 10: Preliminary Action (Prior Action – "Do It In Advance"

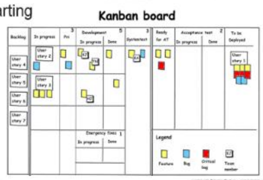
A) Preliminary action is a requirement to change an object fully or partially.

- Nets around sheep in advance to collect wool - special chemical preparation (avoid time consuming shearing)
- Sterilize all surgical instruments before surgical procedure.
- Self-adhesive stamps
- Holes cut before sheet-metal part formed



B) Prepare objects in advance so that they can be put to work from the best position and are available without loss of time.

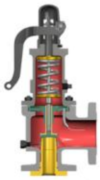
- "Kanban" in a JIT factory
- Pre-deposited blade in a surgery cast facilitates removal.
- Collect all the tools and materials for the job before starting



Principle 11: Beforehand Cushioning

A) Prepare emergency means beforehand to compensate for the relatively low reliability of an object ('belt and braces')

- Magnetic strip on photographic film that directs the developer to compensate for poor exposure
- Back-up parachute
- Dual channel control system
- Air-bag in a car
- Spare wheel
- Safety Relief valve
- Emergency lighting circuit
- Battery back-up
- Automatic save operations performed by computer programs
- Zip-files
- "Masking" borders of objects to be painted, use stencils
- Crash barriers on motorways
- "Touch-down" bearing in magnetic bearing system
- Multiple hydraulic systems
- "Slime" – tube sealant



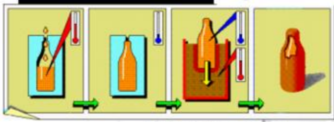
Principle 12: Equipotentiality (Remove Tension)

A) If an object has to be raised or lowered, redesign the object's environment so the need to raise or lower is eliminated or performed by the environment

- Canal locks
- Spring loaded parts delivery system in a factory
- Mechanic's pit in a garage means car does not have to be lifted.
- Place a heavy object on ice, and let ice melt in order to lower it.
- Angle-poise lamp; changes in gravitational potential stored in balancing springs
- Descending cable cars balance the weight of ascending cars

Principle 13: The Other Way Around






A) Invert the action(s) used to solve the problem (e.g. instead of cooling an object, heat it)

- To loosen stuck parts, cool the inner part instead of heating the outer part.
- Vacuum casting
- Test pressure vessel by varying pressure outside rather than inside the vessel
- Instead of ready-moulded chocolate bottle inserted with syrup, the syrup is cold-moulded and then dipped in warm chocolate.
- Place nuts in a vacuum to get them out of their shells
- "Upside-down" motorcycle forks

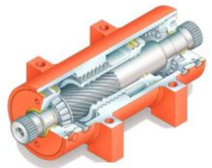
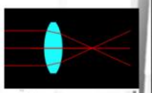
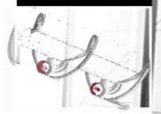
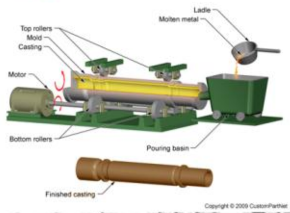
B) Make movable parts (or the external environment) fixed, and fixed parts movable)

- Hamster wheel
- Rotate the part instead of the tool.
- Wind tunnels
- Moving sidewalk with standing people

C) Turn the object (or process) 'upside down'

- Clean bottles by turning upside down, injecting water from below; the water then drains by itself.
- Turn an assembly upside down to insert fasteners

Principle 14: Curvature

A) Instead of using rectilinear parts, surfaces, or forms, use curvilinear ones; move from flat surfaces to spherical ones; from parts shaped as a cube (parallelepiped) to ball-shaped structures

- Use arches and domes for strength in architecture.
- Introduce stress relieving holes at the ends of slots
- Change curvature of lens to alter light deflection properties

B) Use rollers, balls, spirals, domes

- Spiral gear (Nautilus) produces continuous resistance for weight lifting.
- Use spherical casters instead of cylindrical wheels to move furniture
- Archimedes screw

C) Go from linear to rotary motion (or vice versa)

- Rotary actuators in hydraulic system.
- Switch from reciprocating to rotary pump
- Linear motors

D) Use centrifugal forces

- Centrifugal casting for even wall thickness structures
- Spin components after painting to remove excess paint
- Watt governor
- Vortex/cyclone separates different density objects

Principle 15: Dynamization

A) Allow (or design) the characteristics of an object, external environment, or process to change to be optimal or to find an optimal operating condition

- Adjustable steering wheel (or seat, or back support, or mirror position)
- Gel fillings inside seat allow it to adapt to user
- Shape memory alloys/polymers.
- Racing car suspension adjustable for different tracks and driving techniques

B) Divide an object into parts capable of movement relative to each other

- Articulated lorry
- Folding chair/mobile phone/laptop
- Brush seals

C) If an object (or process) is rigid or inflexible, make it movable or adaptive

- Bendy drinking straw
- Flexible joint

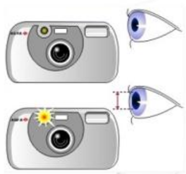
D) Increase the degree of free motion

- Use of different stiffness fibres in toothbrush – easily deflected at the edges to prevent gum damage, hard in the middle
- Loose sand inside truck tyre gives it self-balancing properties at speed

Principle 16: Partial or Excessive Action

A) If 100% of an object is hard to achieve using a given solution method then, by using 'slightly less' or 'slightly more' of the same method, the problem may be considerably easier to solve

- When painting walls, don't use the roller right up to the ceiling; touch up with a brush
- 'Roughing' and 'Finishing' - machining operations.
- Over-fill holes with plaster and then rub back to smooth.
- Use of software analysis when not all can be achieved with the available resources for experiments.
- Harvest fruits in immature state, ripen while transporting.
- A single or several flashes at low intensity are produced before the main flash in order to prevent the "red-eye effect" when taking photos with a flash camera. This causes the pupils of the eye to contract so that less light reaches the retine of the eyes.



Principle 17: Another Dimension

A) If an object contains or moves in a straight line, consider use of dimensions or movement outside the line
- Curved bristles on a brush
- Coiled telephone cable
- "Stacked" elevator Petronas towers

B) If an object contains or moves in a plane, consider use of dimensions or movement outside the current plane
- Spiral staircase uses less floor area
- Introduction of down and up slopes between stations on railway reduces train acceleration and deceleration power requirements

C) Use a multi-storey arrangement of objects instead of a single-storey arrangement
- Cassette with 6 CDs to increase music time and variety
- Multi-storey office blocks or car-parks

D) Tilt or re-orient the object, lay it on its side
- Dump truck

E) Use 'another side' of a given area.
- Mount computer chip components on both sides of a silicon card
- Fix a leaking car radiator or pipe by adding fluid sealant to the inside rather than trying to seal from outside
- Mirrors are installed on every sides and under a vase so that it can be closely examined from all perspectives without moving it

Principle 18: Mechanical Vibration/Oscillation

A) Cause an object to oscillate or vibrate
- Electric carving knife with vibrating blades
- Shake/stir paint to mix before applying
- Hammer drill

B) Increase its frequency (even up to the ultrasonic)
- Ultrasonic cleaning
- Non-destructive crack detection using ultrasound

C) Use an object's resonant frequency, application of quartz vibrators
- Destroy gall stones or kidney stones using ultrasonic resonance.
- Ease bottle cleaning by pulsing washing action at resonant frequency of bottles

D) Use piezoelectric vibrators instead of mechanical ones
- Quartz crystal oscillations drive high accuracy clocks.
- Piezoelectric vibrators improve fluid atomisation from a spray nozzle

E) Use combined ultrasonic and electromagnetic field oscillations.
- Mixing alloys in an induction furnace
- Ultrasonic drying of films – combine ultrasonic with heat source
- Grow plants with mixtures of mineral substances and irradiated with laser/sound

Principle 19: Periodic Action

A) Instead of continuous action, use periodic or pulsating actions

- Hitting something repeatedly with a hammer
- Pile drivers and hammer drills can exert far more force for a given weight
- Replace a continuous siren with a pulsed sound.
- Pulsed bicycle lights make cyclist more noticeable to drivers
- Pulsed vacuum cleaner suction improves collection performance
- Pulsed water jet cutting

B) If an action is already periodic, change the periodic magnitude or frequency

- Replace a pulsed siren with sound that changes amplitude and frequency.
- Washing machine/dish-washer water injection operates uses different cycles for different load types.
- Dots and dashes in Morse Code transmissions
- Use AM, FM, PWM to transmit information

C) Use pauses between actions to perform a different action

- Clean barrier filters by back-flowing them when not in use.
- Inkjet printer cleans heads between passes
- Brush between suction pulses in vacuum cleaner.
- Multiple conversations taking place along the same telephone transmission line.
- Use of energy storage – e.g. batteries, fly-wheels.

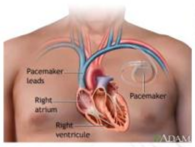
Principle 20: Continuity of Useful Action

A) Carry on work continuously; make all parts of an object work at full load or optimum efficiency, all the time

- Flywheel stores energy when a vehicle stops, so the motor can keep running at optimum power.
- Constant output gas-turbine in hybrid car, or APU in aircraft, runs at highest efficiency all the time it is switched on.
- Constant speed/variable pitch propeller
- Self-tuning engine – constantly tunes itself to ensure maximum efficiency
- Heart pacemaker
- Continuous glass or steel production
- A laser beam methods creates a "drawing" on a photo pattern by moving back and forth (the "moving" mirror).

B) Eliminate all idle or intermittent actions or work

- Self-cleaning/self-emptying filter eliminates down-time
- Print during the return of a printer carriage-dot matrix printer, daisy wheel printers, inkjet printers.
- Digital storage media allow 'instant' information access (as opposed to tapes which require to be rewound)
- Kayaks use double-ended paddle to utilise "recovery" stroke
- Computer operating systems utilise idle periods to perform necessary "housekeeping" tasks.
- Rapid-drying paint



Principle 21: Skipping (Rushing Through/Hurrying)

A) Conduct a process , or certain stages (e.g. destructible, harmful or hazardous operations) at high speed

- Use a high speed dentist's drill to avoid heating tissue.
- Laser eye surgery - LASIK
- Cut plastic faster than heat can propagate in the material, to avoid deforming the shape.
- Break toffee with an impulsive blow from a hammer
- Drop forge
- Flash photography
- Supercritical shaft – run through resonant modes quickly

Principle 22: Blessing in Disguise (*"Turn Lemons into Lemonade"*)

A) Use harmful factors (particularly, harmful effects of the environment or surroundings) to achieve a positive effect

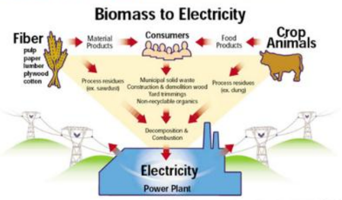
- Use waste heat to generate electric power.
- Use waste heat from engine to heat passenger cabin
- Recycle waste (scrap) material from one process as raw materials for another (e.g. chipboard)
- Use centrifugal energy in rotating shaft to do something useful – e.g. seal, or modulate cooling air
- Use pressure differences to help rather than hinder seal performance

B) Eliminate the primary harmful action by adding it to another harmful action to resolve the problem

- Add a buffering material to a corrosive solution (e.g. an alkali to an acid, or vice versa)
- Use a helium-oxygen mix for diving, to eliminate both nitrogen narcosis and oxygen poisoning from air and other nitrox mixes.

C) Amplify a harmful factor to such a degree that it is no longer harmful

- Use a backfire to eliminate the fuel from a forest fire.
- Old tires broken into granule shape and used in road construction. Street noise reduced and prolong road and transport's tires life.



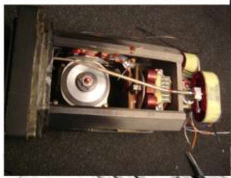
Principle 23: Feedback

A) Introduce feedback (referring back, cross-checking) to improve a process or action

- Automatic volume control in audio circuits
- Signal from gyrocompass is used to control simple aircraft autopilots.
- Engine management system based on exhaust gas levels more efficient than carburettor
- Thermostat controls temperature accurately
- Statistical Process Control - Measurements are used to decide when to modify a process
- Feedback turns inaccurate op-amp into useable accurate amplifier

B) If feedback is already used, change its magnitude or influence in accordance with operating conditions

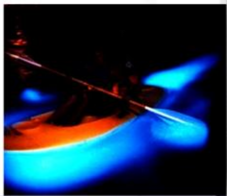
- Change sensitivity of an autopilot when within 5 miles of an airport.
- Change sensitivity of a thermostat when cooling vs. heating, since it uses energy less efficiently when cooling.
- Use proportional, integral and/or differential control algorithm combination
- Device that maintains a given speed continuously measures the true speed and adjusts the flow of fuel to the motor accordingly, just like an experienced driver.



Principle 24: Intermediary

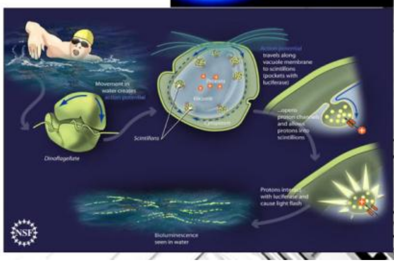
A) Use an intermediary carrier article or intermediary process

- Play a guitar with a plectrum
- Use a chisel to control rock breaking/sculpting process
- Drink coasters
- Dwell period during a manufacture process operation



B) Merge/connect an object temporarily with another (which can be easily removed)

- Gloves to get hot dishes out of an oven
- Joining papers with a paper clip
- Introduction of catalysts into chemical reaction
- Abrasive particles enhance water jet cutting
- Single-cell micro-organisms that starts to glow in agitated water were introduced into salt water pools to investigate the movements of dolphins. The water flowing around the dolphin's bodies can then be recorded with High definition cameras. (Bioluminescent Bay, Puerto Rico)



Principle 25: Self-Service

A) Make an object serve or organise itself by performing auxiliary helpful functions

- A soda fountain pump that runs on the pressure of the carbon dioxide that is used to "fizz" the drinks. This assures that drinks will not be flat, and eliminates the need for sensors.
- Halogen lamps regenerate the filament during use - evaporated material is redeposit.
- Self-aligning/self-adjusting seal
- Self-cleaning oven/glass/material
- Self-repairing structures
- Abradable materials used in engines such that initial running-in 'cuts' optimum seals into lining
- "Self-healing" cutting mat.
- Automatically open trash can

B) Use waste resources, energy, or substances

- Use heat from a process to generate electricity: "Co-generation".
- Use animal waste as fertilizer.
- Use food and lawn waste to create compost.
- Use pressure difference to reinforce seal action

Principle 26: Copying

A) Instead of an unavailable, expensive, fragile object, use simpler and inexpensive copies

- Imitation jewellery.
- Astroturf
- Crash test dummy
- UAV excludes pilot

B) Replace an object, or process with optical copies

- Do surveying from space photographs instead of on the ground.
- Measure an object by scaling measurements from a photograph.
- Laser anemometry
- Virtual reality
- Virtual mock-ups/electronic pre-assembly modelling

C) If visible optical copies are already used, move to infrared or ultraviolet copies

- Make images in infrared to detect heat sources, such as diseases in crops, or intruders in a security system.
- Use UV as a non-destructive crack detection method
- UV light used to attract flying insects into trap
- Nasa "CAMPOUT" - copies the behaviour of humans.

Principle 27: Cheap Short-Living Object (Cheap Disposables)

A) Replace an expensive object with a multiple of inexpensive objects, compromising certain qualities, such as service life

- Disposable nappies/paper-cups/plates/cameras/torches
- Matches versus lighters
- Throw-away cigarette lighters
- Industrial diamonds used in cutting tools
- Sacrificial coatings/components
- Post-Its
- Discarding-sabot armour piercing round.
- Melt and strip fuses to protect electrical devices against overloading.

Principle 28: Mechanics Substitution

A) Replacing mechanical schemes with optical, acoustic, or olfactory schemes

- Replace a physical fence to confine a dog or cat with an acoustic "fence" (signal audible only to the animal).
- Finger-print/retina/scan instead of a key
- Putting bad smells when a leakage of gases.

B) Use of electrical, magnetic, or electromagnetic fields for the interaction of objects,

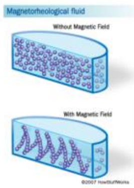
- Magnetic bearings
- Electrostatic precipitators separate particles from airflow
- Improve efficiency of paint-spraying by oppositely charging paint droplets and object to be painted.

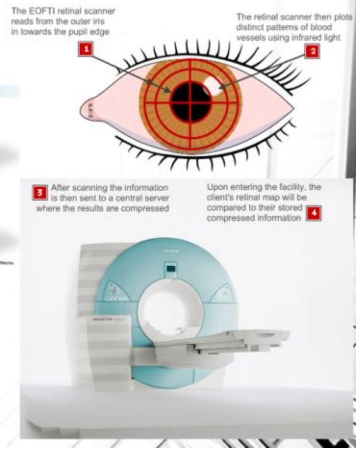
C) Replacement of static fields with dynamic ones, from temporally fixed to flexible fields, from un-structures fields to specific structure

- Analog antenna signal to digital antenna signal.
- Magnetic Resonance Imaging (MRI) scanner

D) Use of fields in connection with ferric-magnetic particles.

- Magnetorheological effect – uses ferromagnetic particles and variable magnetic field to alter the viscosity of a fluid





Principle 29: Pneumatic and Hydraulics

A) Use gas and liquid parts of an object instead of solid parts (e.g. inflatable, filled with liquids, air cushion, hydrostatic, hydro-reactive)

- Transition from mechanical to hydraulic or pneumatic drive
- Inflatable furniture/mattress/ Air tents for exhibition pavilions, temporary "buildings" such as play tents for children
- Gel filled saddle adapts to user
- Hollow section O-rings
- Hovercraft
- Gas bearings
- Hydraulic tappets
- A japanese firm "Mugen-denko" produces an inflatable life vest for motorcyclist.

Principle 30: Flexible Shells and Thin Films

A) Use flexible shells and thin films instead of three dimensional structures

- Use inflatable (thin film) structures.
- Taut-liner trucks
- Tarpaulin car cover instead of garage
- Webbing
- Store energy in flexible/stretchable bags – e.g. accumulators in a hydraulic system
- Membrane keyboards
- ABS – The Avalanche Airbag

B) Isolate the object from the external environment using flexible shells and thin films

- Bubble-wrap
- Bandages/plasters
- Egg-box
- Tea bag
- Canvas canopy/roof

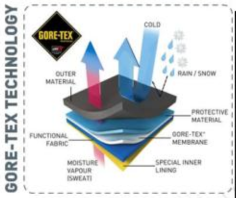
Principle 31: Porous Materials

A) Make an object porous or add porous elements (inserts, coatings, etc.)

- Drill holes in a structure to reduce the weight.
- Cavity wall insulation
- Transpiration film cooled structures
- Foam metals
- Use sponge-like structures as fluid absorption media
- Gore-tex fabric
- Coconut milk sterilization without heating – using microporous filters detaining microbes and their spores

B) If an object is already porous, use the pores to introduce a useful substance or function

- Use a porous metal mesh to wick excess solder away from a joint.
- Store hydrogen in the pores of a palladium sponge. (Fuel "tank" for the hydrogen car--much safer than storing hydrogen gas)
- Desiccant in polystyrene packing materials
- Medicated swabs/dressings



Principle 32: Colour Changes

A) Change the colour of an object or its external environment

- Use safe lights in a photographic darkroom.
- Use colour-changing thermal paint to measure temperature
- Light-sensitive glasses
- Camouflage
- Employ interference fringes on surface structures to change colour (as in butterfly wings, etc)
- Colour changing plastic/temperature sensitive for child feeding spoon

B) Change the transparency of an object or its external environment

- Use photolithography to change transparent material to a solid mask for semiconductor processing.
- Smoke-screen

C) In order to improve observability of things that are difficult to see, use coloured additives or luminescent elements

- Fluorescent additives used during UV spectroscopy
- Use opposing colours to increase visibility – e.g. butchers use green decoration to make the red in meat look redder

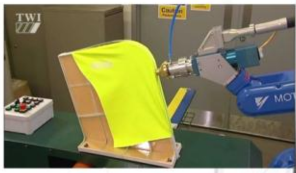
D) Change the emissivity properties of an object subject to radiant heating

- Use of black and white coloured panels to assist thermal management on space vehicles.
- Paint object with high emissivity paint in order to be able to measure it's temperature with a calibrated thermal imager

Principle 33: Homogeneity (Uniformity)

A) Make objects interacting with a given object of the same material (or material with identical properties)

- Make the container out of the same material as the contents, t reduce chemical reactions.
- Friction welding requires no intermediary material between the surfaces to be joined.
- 'Liquid paper' for correcting mistakes when writing
- Temporary plant pots made out of compostable material
- Human blood transfusions/transplants, use of bio-compatible materials
- Make ice-cubes out of the same fluid as the drink they are intended to cool
- Join wooden components using (wood) dowel joints
- Graphite "solid" pencil.
- Gears that interact with each other to transmit power are usually manufactured from the same material to avoid uneven wear.
- In istitute of welding in cambridge, a shirt from rags of a synthetic fabric was welded by laser



Principle 34: Discarding and Recovering

A) Make portions of an object that have fulfilled their functions go away (discard by dissolving, evaporating, etc.) or modify these directly during operation

- Use a dissolving capsule for medication.
- Ice structures: use water ice or carbon dioxide (dry ice) to make a template for a rammed earth structure, such as a temporary dam. Fill with earth, then, let the ice melt or sublime to leave the final structure.
- Bio-degradable containers, bags, etc.
- Casting processes – lost-wax, sand, etc.
- Sacrificial anode

B) Conversely, restore consumable parts of an object directly in operation

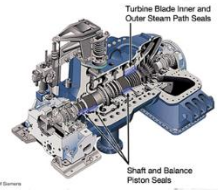
- Self-sharpening blades – knives/lawn-mowers
- Strimmer dispenses more wire automatically after a breakage.
- Self-tuning automobile engines
- Propelling pencil
- Automatic rifle

Principle 35: Parameter Changes

A) Change an object's physical state (e.g. to a gas, liquid, or solid)
- Transition from mechanical to fluid or electrical drives
- Vaporise (or freeze) mercury to ease placing of very small amounts into fluorescent light-bulb

B) Change the concentration or consistency
- Liquid versus bar or powder detergents.
- Abradable linings used for gas-turbine engine seals

C) Change the degree of flexibility
- Use to reduce the noise of parts falling into a container by restricting the motion of the walls of the container.
- Compliant brush seals rather than labyrinth or other fixed geometry seals



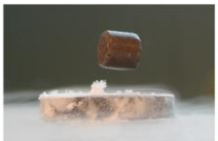
D) Change the temperature
- Raise the temperature above the Curie point to change a
- Lower the temperature of medical specimens to preserve them for later analysis

E) Change the pressure.
- Pressure cooker cooks more quickly and without losing flavours.
- Electron beam welding in a vacuum.

F) Change other parameters
- Shape memory alloys/polymers
- Use high conductivity materials – e.g. carbon fibre

Principle 36: Phase Transitions

A) Use phenomena occurring during phase transitions (e.g. volume changes, loss or absorption of heat, etc.)
- Latent heat effects in melting/boiling
- Soak rocks in water, then freezing causes water to expand – thus opening fissures in rock, making it easier to break
- Heat pumps use the heat of vaporization and heat of condensation of a closed thermodynamic cycle to do useful work.
- Volume expansion during water-to-steam transition
- Superconductivity
- Phase change hand-warmers
- Cryonic medical for pain and inflammatory treatment
- Transport sensitive material in ice-cubes



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Principle 37: Thermal Expansion

A) Use thermal expansion (or contraction) of materials
- Fit a tight joint together by cooling the inner part to contract, heating the outer part to expand, putting the joint together, and returning to equilibrium
- Metal tie-bars used to straighten buckling walls on old buildings
- Thermal switch/cut-out
- Shape memory alloys/polymers
- Shrink-wrapping

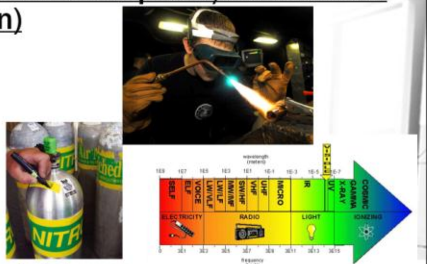
B) If thermal expansion is being used, use multiple materials with different coefficients of thermal expansion
- Bi-metallic strips used for thermostats,
- Two-way shape memory alloys.
- Passive blade tip clearance control in gas-turbine engines.
- Combine materials with positive and negative thermal expansion coefficients to obtain alloys with zero (or specifically tailored) expansion properties – e.g. Cerrotru alloy used in the mounting and location of fragile turbine blade components during manufacture operations
- Instapak®

Principle 38: Strong Oxidants (Enriched Atmosphere/Accelerated Oxidation)

A) Replace common air with oxygen-enriched air
- Scuba diving with Nitrox or other non-air mixtures for extended endurance
- Use of nitrous oxide injection to provide power boost in high performance engines

B) Replace enriched air with pure oxygen
- Cut at a higher temperature using an oxy-acetylene torch.
- Control oxidation reactions more effectively by reacting in pure oxygen
- Treat wounds in a high pressure oxygen environment to kill anaerobic bacteria and aid healing.

C) Expose air or oxygen to ionising radiation
- Irradiation of food to improve preservative qualities.
- Use ionised air to destroy bacteria and sterilise food
- Positive ions formed by ionising air can be deflected by magnetic field in order to (e.g.) reduce air resistance over an aerodynamic surface
- Quick and intensive processing of storage facilities and the fruit or vegetables stored there.



D) Use ionised oxygen
- Speed up chemical reactions by ionising the gas before use.
- Separate oxygen from a mixed gas by ionising the oxygen (using a platinum activator)

E) Replace ozonised (or ionised) oxygen with ozone.
- Oxidisation of metals in bleaching solutions to reduce cost relative to hydrogen peroxide
- Use ozone to destroy micro-organisms and toxins in corn
- Ozone dissolved in water used to remove organic contaminants from ship hulls

Principle 39: Inert Atmosphere (Calmed Atmosphere)

A) Replace a normal environment with an inert one

- Prevent degradation of a hot metal filament by using an argon atmosphere.
- MIG/TIG welding
- Food packaging done in CO2 or nitrogen rich atmosphere to prevent spoilage
- CO2 fire extinguisher

B) Complete a process in a vacuum.

- Electron beam welding conducted in a vacuum
- Vacuum packaging

C) Add neutral parts, or inert additives to an object

- Naval aviation fuel contains additives to alter flash-point.
- Add fire retardant elements to titanium to reduce possibility of titanium fire.
- Add foam to absorb sound vibrations – e.g. hi-fi speakers
- Fluidic dampers
- Use of dry ice for lifting a fog

Principle 40: Composite Materials

A) Change from uniform to composite (multiple) materials where each material is tuned to a particular functional requirement

- Aircraft structures where low weight and high strength are required.
- Composite golf club shaft aligns structures to give low weight, high shaft-wise flexibility and high torsional stiffness.
- Concrete aggregate.
- Glass-reinforced plastic
- Fibre-reinforced ceramics
- Hard/soft/hard multi-layer coatings
- Fiberglass
- Fibre brick, for buidling houses. It is highly durable, absorbs heat and radiation but light in weight

APPENDIX C

The TRIZ Contradiction Matrix (Source: Oxford Creativity, at https://www.triz.co.uk)

Contradiction Matrix for Solving **Technical Contradictions**

Improve this one without making this one **worse**

39 Technical Parameters

		1 Weight of moving object	2 Weight of Stationary Object	3 Length of moving object	4 Length of Stationary object	5 Area of moving object	6 Area of stationary object	7 Volume of moving object	8 Volume of stationary object	9 Speed	10 Force (intensity)	11 Stress or pressure	12 Shape
1	Weight of moving object		-	15 8 29 34	-	29 17 38 34	-	29 2 40 28	-	2 8 15 38	8 10 18 37	10 36 37 40	10 14 35 40
2	Weight of stationary object	-		-	10 1 29 35	-	35 30 13 2	-	5 35 14 2	-	8 10 19 35	13 29 10 18	13 10 29 14
3	Length of moving object	8 15 29 34	-		-	15 17 4	-	7 17 4 35	-	13 4 8	17 10 4	1 8 35	1 8 10 29
4	Length of stationary object		35 28 40 29	-		-	17 7 10 40	-	35 8 2 14	-	28 10	1 14 35	13 14 15 7
5	Area of moving object	2 17 29 4	-	14 15 18 4	-		-	7 14 17 4		29 30 4 34	19 30 35 2	10 15 36 28	5 34 29 4
6	Area of stationary object	-	30 2 14 18	-	26 7 9 39	-		-		-	1 18 35 36	10 15 36 37	
7	Volume of moving object	2 26 29 40	-	1 7 4 35	-	1 7 4 17	-		-	29 4 38 34	15 35 36 37	6 35 36 37	1 15 29 4
8	Volume of stationary object	-	35 10 19 14	19 14	35 8 2 14	-		-		-	2 18 37	24 35	7 2 35
9	Speed	8 28 13 38	-	13 14 8	-	29 30 34	-	7 29 34	-		13 28 15 19	6 18 38 40	35 15 18 34
10	Force (Intensity)	8 1 37 18	18 13 1 28	17 19 9 36	28 10	19 10 15	1 18 36 37	15 9 12 37	2 36 18 37	13 28 15 12		18 21 11	10 35 40 34
11	Stress or pressure	10 36 37 40	13 29 10 18	35 10 36	35 1 14 16	10 15 36 28	10 15 36 37	6 35 10	35 24	6 35 36	36 35 21		35 4 15 10
12	Shape	8 10 29 40	15 10 26 3	29 34 5 4	13 14 10 7	5 34 4 10		14 4 15 22	7 2 35	35 15 34 18	35 10 37 40	34 15 10 14	
13	Stability of the object's composition	21 35 2 39	26 39 1 40	13 15 1 28	37	2 11 13	39	28 10 19 39	34 28 35 40	33 15 28 18	10 35 21 16	2 35 40	22 1 18 4
14	Strength	1 8 40 15	40 26 27 1	1 15 8 35	15 14 28 26	3 34 40 29	9 40 28	10 15 14 7	9 14 17 15	8 13 26 14	10 18 3 14	10 3 18 40	10 30 35 40
15	Duration of action by moving object	19 5 34 31	-	2 19 9	-	3 17 19	-	10 2 19 30	-	3 35 5	19 2 16	19 3 27	14 26 28 25
16	Duration of action by Stationary object	-	6 27 19 16	-	1 40 35	-		-	35 34 38	-			
17	Temperature	36 22 6 38	22 35 32	15 19 9	15 19 9	3 35 39 18	35 38	34 39 40 18	35 6 4	2 28 36 30	35 10 3 21	35 39 19 2	14 22 19 32
18	Illumination Intensity	19 1 32	2 35 32	19 32 16		19 32 26		2 13 10		13 19 10	26 19 6		32 30
19	Use of energy by moving object	12 18 28 31	-	12 28	-	15 19 25	-	35 13 18	-	8 15 35	16 26 21 2	23 14 25	12 2 29
20	Use of energy by stationary object	-	19 9 6 27								36 37		
21	Power	8 36 38 31	19 26 17 27	1 10 35 37		19 38	17 32 13 38	35 6 38	30 6 25	15 35 2	26 2 36 35	22 10 35	29 14 2 40
22	Loss of energy	15 6 19 28	19 6 18 9	7 2 6 13	6 38 7	15 26 17 30	17 7 30 18	7 18 23	7	16 35 38	36 38		
23	Loss of Substance	35 6 23 40	35 6 22 32	14 29 10 39	10 28 24	35 2 10 31	10 18 39 31	1 29 30 36	3 39 18 31	10 13 28 38	14 15 18 40	3 36 37 10	29 35 3 5
24	Loss of Information	10 24 35	10 35 5	1 26	26	30 26	30 16		2 22	26 32			
25	Loss of Time	10 20 37 35	10 20 26 5	15 2 29	30 24 14 5	26 4 5 16	10 35 17 4	2 5 34 10	35 16 32 18		10 37 36 5	37 36 4	4 10 34 17
26	Quantity of Substance	35 6 18 31	27 26 18 35	29 35 14 18		15 14 29	2 18 40 4	15 20 29		35 29 34 28	35 14 3	10 36 14 3	35 14
27	Reliability	3 8 10 40	3 10 8 28	15 9 14 4	15 29 28 11	17 10 14 16	32 35 40 4	3 10 14 24	2 35 24	21 35 11 28	8 28 10 3	10 24 35 19	35 1 16 11
28	Measurement Accuracy	32 35 26 28	28 35 25 26	28 26 5 16	32 28 3 16	26 28 32 3	26 28 32 3	32 13 6		28 13 32 24	32 2	6 28 32	6 28 32
29	Manufacturing Precision	28 32 13 18	28 35 27 9	10 28 29 37	2 32 10	28 33 29 32	2 29 18 36	32 23 2	25 10 35	10 28 32	28 19 34 36	3 35	32 30 40
30	Object affected harmful factors	22 21 27 39	2 22 13 24	17 1 39 4	1 18	22 1 33 28	27 2 39 35	22 23 37 35	34 39 19 27	21 22 35 28	13 35 39 18	22 2 37	22 1 3 35
31	Object-generated harmful factors	19 22 15 39	35 22 1 39	17 15 16 22		17 2 18 39	22 1 40	17 2 40	30 18 35 4	35 28 3 23	35 28 1 40	2 33 27 18	35 1
32	Ease of manufacture	28 29 15 16	1 27 36 13	1 29 13 17	15 17 27	13 1 26 12	16 40	13 29 1 40	35	35 13 8 1	35 12	35 19 1 37	1 28 13 27
33	Convenience of Use	25 2 13 15	6 13 1 25	1 17 13 12		1 17 13 16	18 16 15 39	1 16 35 15	4 18 39 31	18 13 34	28 13 35	2 32 12	15 34 29 28
34	Ease of repair	2 27 35 11	2 27 35 11	1 28 10 25	3 18 31	15 13 32	16 25	25 2 35 11	1	34 9	1 11 10	13	1 13 2 4
35	Adaptability or versatility	1 6 15 8	19 15 29 16	35 1 29 2	1 35 16	35 30 29 7	15 16	15 35 29		35 10 14	15 17 20	35 16	15 37 1 8
36	Device complexity	26 30 34 36	2 26 35 39	1 19 26 24	26	14 1 13 16	6 36	34 26 6	1 16	34 10 28	26 16	19 1 35	29 13 28 15
37	Difficulty of detecting and measuring	27 26 28 13	6 13 28 1	16 17 26 24	26	2 13 18 17	2 39 30 16	29 1 4 16	2 18 26 31	3 4 16 35	36 28 40 19	35 36 37 32	27 13 1 39
38	Extent of automation	28 26 18 35	28 26 35 10	14 13 17 28	23	17 14 13		35 13 16		28 10	2 35	13 35	15 32 1 13
39	Productivity	35 26 24 37	28 27 15 3	18 4 28 38	30 7 14 26	10 26 34 31	10 35 17 7	2 6 34 10	35 37 10 2		28 15 10 36	10 37 14	14 10 34 40

Stability of the object's composition	Strength	Duration of action of a moving object	Duration of action of a stationary object	Temperature	Illumination Intensity	Use of energy by a moving object	Use of energy by a stationary object	Power	Loss of energy	Loss of substance	Loss of information	Loss of time	Quantity of substance	Reliability	Measurement accuracy	Manufacturing precision	Object-affected harmful factors	Object-generated harmful factors	Ease of manufacture
13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1 35 19 39	28 27 18 40	5 34 31 35	-	6 29 4 38	19 1 32	35 12 34 31	-	12 36 18 31	6 2 34 19	5 35 3 31	10 24 35	10 35 20 28	3 26 18 31	3 11 1 27	28 27 35 26	28 35 26 18	22 21 18 27	22 35 31 39	27 28 1 36
26 39 1 40	28 2 10 27	-	2 27 19 6	28 19 32 22	19 32 35	-	18 19 28 1	15 19 18	18 19 28 15	5 8 13 30	10 15 35	10 20 35 26	19 6 18 26	10 28 8 3	18 26 28	10 1 35 27	2 19 22 37	35 22 1 39	28 1 9
1 8 15 34	8 35 29 34	19	-	10 15 19	32	8 35 24	-	1 35	7 2 35 39	4 29 23 10	1 24	15 2 29	29 35	10 14 29 40	28 32 4	10 28 29 37	1 15 17 24	17 15	1 29 17
39 37 35	15 14 28 26	-	1 40 35	3 35 39 18	3 25	-		12 8	6 28	10 28 24 35	24 26	30 29 14		15 29 28	32 28 3	2 32 10	1 18		15 17 27
11 2 13 39	3 15 40 14	6 3	-	2 15 16	15 32 19 13	19 32	-	19 10 32 18	15 17 30 26	10 35 2 39	30 26	26 4	29 30 6 13	29 9	26 28 32 3	2 32	22 33 28 1	17 2 18 39	13 1 26 24
2 38	40	-	2 10 19 30	35 39 38		-		17 32	17 7 30	10 14 18 39	30 16	10 35 4 18	2 18 40 4	32 35 40 4	26 28 32 3	2 29 18 36	27 2 39 35	22 1 40	40 16
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34 28 35 40	9 14 17 15	-	35 34 38	35 6 4		-		30 6		10 39 35 34		35 16 32 18	35 3	2 35 16		35 10 25	34 39 19 27	30 18 35 4	35
28 33 1 18	8 3 26 14	3 19 35 5	-	28 30 36 2	10 13 19	8 15 35 38	-	19 35 38 2	14 20 19 35	10 13 28 38	13 26		10 19 29 38	11 35 27 28	28 32 1 24	10 28 32 25	1 28 35 23	2 24 35 21	35 13 8 1
35 10 21	35 10 14 27	19 2		35 10 21	-	19 17 10	1 16 36 37	19 35 18 37	14 15	8 35 40 5		10 37 36	14 29 18 36	3 35 13 21	35 10 23 24	28 29 37 36	1 35 40 18	13 3 36 24	15 37 18 1
35 33 2 40	9 18 3 40	19 3 27		35 39 19 2	-	14 24 10 37		10 35 14	2 36 25	10 35 3 37		37 36 4	10 14 36	10 13 19 35	6 28 25	3 35	22 2 37	2 33 27 18	1 35 16
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13 3 35	27 3 10		-	19 35 39	2 19 4 35	28 6 35 18		19 10 35 38		28 27 3 18	10	20 10 28 18	3 35 10 40	11 2 13	3	3 27 16 40	22 15 33 28	21 39 16 22	27 1 4
39 35 3 23		-		19 18 36 40		-		16		27 16 18 38	10	28 20 10 16	3 35 31	34 27 6 40	10 26 24		17 1 40 33	22	35 10
1 35 32	10 30 22 40	19 13 39	19 18 36 40		32 30 21 16	19 15 3 17		2 14 17 25	21 17 35 38	21 36 39 31		35 28 21 18	3 17 30 39	19 35 3 10	32 19 24	24	22 33 35 2	22 35 2 24	26 27
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19 13 17 24	5 19 9 35	28 35 6 18	-	19 24 3 14	2 15 19		-	6 19 37 18	12 22 15 24	35 24 18 5		35 38 19 18	34 23 16 18	19 21 11 27	3 1 32		1 35 6 27	2 35 6	28 26 30
27 4 29 18	35				19 2 35 32	-				28 27 18 31			3 35 31	10 36 23			10 2 22 37	19 22 18	1 4
35 32 15 31	26 10 28	19 35 10 38	16	2 14 17 25	16 6 19	16 6 19 37			10 35 38	28 27 18 38	10 19	35 20 10 6	4 34 19	19 24 26 31	32 15 2	32 2	19 22 31 2	18 2 35	26 10 34
14 2 39 6	26			19 38 7	1 13 32 15			3 38		35 27 2 37	19 10	10 18 32 7	7 18 25	11 10 35	32		21 22 35 2	21 35 2 22	
2 14 30 40	35 28 31 40	28 27 3 18	27 16 18 38	21 36 39 31	1 6 13	35 18 24 5	28 27 12 31	28 27 18 38	35 27 2 31			15 18 35 10	6 3 10 24	10 29 39 35	16 34 31 28	35 10 24 31	33 22 30 40	10 1 34 29	15 34 33
		10	10		19			10 19	19 10			24 26 28 32	24 28 35	10 28 23			22 10 1	10 21 22	32
35 3 22 5	29 3 28 18	20 10 28 18	28 20 10 16	35 29 21 18	1 19 26 17	35 38 19 18	1	35 20 10 6	10 5 18 32	35 18 10 39	24 26 28 32		35 38 18 16	10 30 4	24 34 28 32	24 26 28 18	35 18 34	35 22 18 39	35 28 34 4
15 2 17 40	14 35 34 10	3 35 10 40	3 35 31	3 17 39		34 29 16 18	3 35 31	35	7 18 25	6 3 10 24	24 28 35	35 38 18 16		18 3 28 40	3 2 28	33 30	35 33 29 31	3 35 40 39	29 1 35 27
	11 28	2 35 3 25	34 27 6 40	3 35 10	11 32 13	21 11 27 19	36 23	21 11 26 31	10 11 35	10 35 29 39	10 28	10 30 4	21 28 40 3		32 3 11 23	11 32 1	27 35 2 40	35 2 40 26	
32 35 13	28 6 32	28 6 32	10 26 24	6 19 28 24	6 1 32	3 6 32		3 6 32	26 32 27	10 16 31 28		24 34 28 32	2 6 32	5 11 1 23			28 24 22 26	3 33 39 10	6 35 25 18
30 18	3 27	3 27 40		19 26	3 32	32 2		32 2	13 32 2	35 31 10 24		32 26 28 18	32 30	11 32 1			26 28 10 36	4 17 34 26	
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32 35 30	32 40 3 28	29 3 8 25	1 16 25	26 27 13	13 17 1 24	1 13 24		35 34 2 10	2 19 13	28 32 2 24	4 10 27 22	4 28 10 34	12 35	17 27 8 40	25 13 2 34	1 32 35 23	2 25 28 39		2 5 12
2 35	11 1 2 9	11 29 28 27	1	4 10	15 1 13	15 1 28 16		15 10 32 2	15 1 32 19	2 35 34 27		32 1 10 25	2 28 10 25	11 10 1 16	10 2 13	25 10	35 10 2 16		1 35 11 10
35 30 14	35 3 32 6	13 1 35	2 16	27 2 3 35	6 22 26 1	19 35 29 13		19 1 29	18 15 1	15 10 2 13		35 28	3 35 15	35 13 8 24	35 5 1 10		35 11 32 31		1 13 31
2 22 17 19	2 13 28	10 4 28 15		2 17 13	24 17 13	27 2 28 29		20 19 30 34	10 35 13 2	35 10 28 29		6 29	13 3 27 10	13 35 1	2 26 10 34	26 24 32	22 19 29 40	19 1	27 26 1 13
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35 3 22 39	29 28 10 18	35 10 2 18	20 10 16 38	35 21 28 10	26 17 19 1	35 10 38 19	1	35 20 10	28 10 29 35	28 10 35 23	13 15 23		35 38	1 35 10 38	1 10 34 28	18 10 32 1	22 35 13 24	35 22 18 39	35 28 2 24

	Convenience of Use	Ease of repair	Adaptability or versatility	Device complexity	Difficulty of detecting and measuring	Extent of automation	Productivity
	33	34	35	36	37	38	39
1	35 3 2 24	2 27 28 11	29 5 15 8	26 30 36 34	28 29 26 32	26 35 18 19	35 3 24 37
2	6 13 1 32	2 27 28 11	19 15 29	1 10 26 39	25 28 17 15	2 26 35	1 28 15 35
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5	15 17 13 16	15 13 10 1	15 30	14 1 13	2 36 26 18	14 30 28 23	10 26 34 2
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7	15 13 30 12	10	15 29	26 1	29 26 4	35 34 16 24	10 6 2 34
8		1		1 31	2 17 26		35 37 10 2
9	32 28 13 12	34 2 28 27	15 10 26	10 28 4 34	3 34 27 16	10 18	
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23	32 28 2 24	2 35 34 27	15 10 2	35 10 28 24	35 18 10 13	35 10 18	28 35 10 23
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37	2 5	12 26	1 15	15 10 37 28		34 21	35 18
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39	1 28 7 19	1 32 10 25	1 35 28 37	12 17 28 24	35 18 27 2	5 12 35 26	

40 Inventive Principles

Separation Principles for Solving Physical Contradictions

	Principle	Space	Time	Condition	Scale
1	Segmentation	✓	✓		✓
2	Taking Out	✓			
3	Local Quality	✓			✓
4	Asymmetry	✓			
5	Merging				✓
6	Universality				✓
7	Nested Doll	✓	✓		
8	Anti-Weight				✓
9	Prior Counteraction		✓		
10	Prior Action		✓		
11	Cushion in Advance		✓		
12	Equipotentiality				✓
13	The Other Way Round	✓			✓
14	Spheroidality - Curvature	✓			
15	Dynamics		✓		
16	Partial or Excessive Action		✓		
17	Another Dimension	✓			
18	Mechanical Vibration		✓		
19	Periodic Action		✓		
20	Continuity of Useful Action		✓		
21	Rushing Through		✓		
22	Blessing in Disguise				✓
23	Feedback				✓
24	Intermediary	✓	✓		
25	Self-Service				✓
26	Copying	✓	✓		
27	Cheap Short-Living Objects		✓		✓
28	Replace Mechanical System			✓	
29	Pneumatics and Hydraulics		✓	✓	
30	Flexible Membranes / Thin Films	✓			
31	Porous Materials			✓	
32	Colour Change			✓	
33	Homogeneity				✓
34	Discarding and Recovering		✓		
35	Parameter Change			✓	
36	Phase Transition			✓	
37	Thermal Expansion		✓		
38	Accelerate Oxidation			✓	
39	Inert Environment			✓	
40	Composite Materials	✓			✓

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APPENDIX D

The Geometric Effects Database (Source: TRIZ.it! at http://triz.it/eng/)

Effect - Action		
Spherical Surfaces	1. Forming and profiling of objects 2. Support and transfer of forces, pressure, vibration 3. Damping of mechanical shock and shockwaves 4. Decrease of friction and static friction 5. Filtration and separation of substances with the help of balls 6. Orientation and connection of objects, e.g. ball bearing and guideways 7. Focusing of optical (light, radiation) or acoustic (sonic waves) energy in focal point of spherical surfaces 8. Measuring elements and sensors	a. Transition: EFFECT -> BI-EFFECT, e.g. helix -> double helix b. Combination of two distinct effects or forms: EFFECT 1 + EFFECT 2 c. Combination of EFFECT with MOTION FORM d. Combination of geometrical FORM with a FILLING SUBSTANCE e. Combination of geometrical Effects or form (with or w/o filler) with physical or chemical effect
Helix & Spiral	1. Dosers and filters, e.g. through gap adjustment between the turns of a tape helix 2. Telescopic tape helix as a movable safety coating 3. Accumulation of mechanical energy in a helix or spiral spring. 4. Gripper and clamping devices 5. Transformation of rotary motion into linear motion e.g. with cam or helix mechanisms	Application patterns of geometrical effects and forms: a. Transition: EFFECT -> BI-EFFECT, e.g. helix -> double helix b. Combination of two distinct effects or forms: EFFECT 1 + EFFECT 2 c. Combination of EFFECT with MOTION FORM d. Combination of geometrical FORM with a FILLING SUBSTANCE e. Combination of geometrical Effects or form (with or w/o filler) with physical or chemical effect
Mobius Band	1. Double working area or length of the bands; e.g. grinding or cutting belt, magnet band etc. 2. Intensification of mixing processes 3. Orientation of moving objects e.g. via 180 degree rotation 4. Evolution of the Mobius band to the endless belts with different cross-sectional profiles: triangular, square, regular polygon, star-shaped etc	a. Transition: EFFECT -> BI-EFFECT, e.g. helix -> double helix b. Combination of two distinct effects or forms: EFFECT 1 + EFFECT 2 c. Combination of EFFECT with MOTION FORM d) Combination of geometrical FORM with a FILLING SUBSTANCE d. Combination of geometrical Effects or form (with or w/o

		filler) with physical or chemical effect
Ellipse & Ellipsoid	1. Ellipsoidal bodies for force and pressure transfer 2. Adjustment of contact stress and area by rotation of an ellipsoidal body 3. Excitation of oscillations 4. Generation of motion forms 5. Hydrodynamic amplification of flow in nozzles with ellipsoidal geometry 6. Focussing of optical (light, radiation) or acoustic (sonic waves) energy in focal points of ellipse	Application patterns of geometrical effects and forms: a. Transition: EFFECT -> BI-EFFECT, e.g. helix -> double helix b. Combination of two distinct effects or forms: EFFECT 1 + EFFECT 2 c. Combination of EFFECT with MOTION FORM d. Combination of geometrical FORM with a FILLING SUBSTANCE e. Combination of geometrical Effects or form (with or w/o filler) with physical or chemical effect
Hyperboloid & Paraboloid	1. Change of geometrical form in hyperboloid of one sheet 2. Supporting structures of buildings 3. Forming and profiling 4. Orientation and connection of objects 5. Transport roller with adjustable geometry 6. Grinding and polishing tools with adjustable geometry 7. Clamping and guiding devices 8. Throttling by changing the inside cross section of one sheet hyperboloids 9. Focussing of optical (light, radiation) or acoustic (sonic waves) energy with parabolic surfaces	Application patterns of geometrical effects and forms: a. Transition: EFFECT -> BI-EFFECT, e.g. helix -> double helix b. Combination of two distinct effects or forms: EFFECT 1 + EFFECT 2 c. Combination of EFFECT with MOTION FORM d. Combination of geometrical FORM with a FILLING SUBSTANCE e. Combination of geometrical Effects or form (with or w/o filler) with physical or chemical effect
Cycloids	1. Generation of motion forms with cycloids, epi- and hypocycloids 2. Cycloid gearing 3. Excitation of oscillations 4. Linear guideways with a cycloid cross section 5. Torque transmission in a coupling with a shaft of cycloidal cross-section 6. Application in rotary pumps, combustion engines 7. Crushing and grinding of substances	a. Application patterns of geometrical effects and forms: b. Transition: EFFECT -> BI-EFFECT, e.g. helix -> double helix c. Combination of two distinct effects or forms: EFFECT 1 + EFFECT 2 d. Combination of EFFECT with MOTION FORM e. Combination of geometrical FORM with a FILLING SUBSTANCE f. Combination of geometrical Effects or form (with or w/o

		filler) with physical or chemical effect
Application of Brushes	1. Orientation and guiding of moving objects 2. Vibration damping 3. Cleaning and treatment of surfaces 4. Flexible electric, magnetic or thermal contact element 5. Increase of the working surface, e.g. for heat exchange or absorption 6. Focussing and concentrating of mechanical, electrostatic or magnetic forces or fields 7. Pulverization of liquids 8. Temporary connection of objects 9. Hook and loop fastenings (Velcro)	a. Application patterns of geometrical effects and forms: b. Transition: EFFECT -> BI-EFFECT, e.g. helix -> double helix c. Combination of two distinct effects or forms: EFFECT 1 + EFFECT 2 d. Combination of EFFECT with MOTION FORM e. Combination of geometrical FORM with a FILLING SUBSTANCE f. Combination of geometrical Effects or form (with or w/o filler) with physical or chemical effect

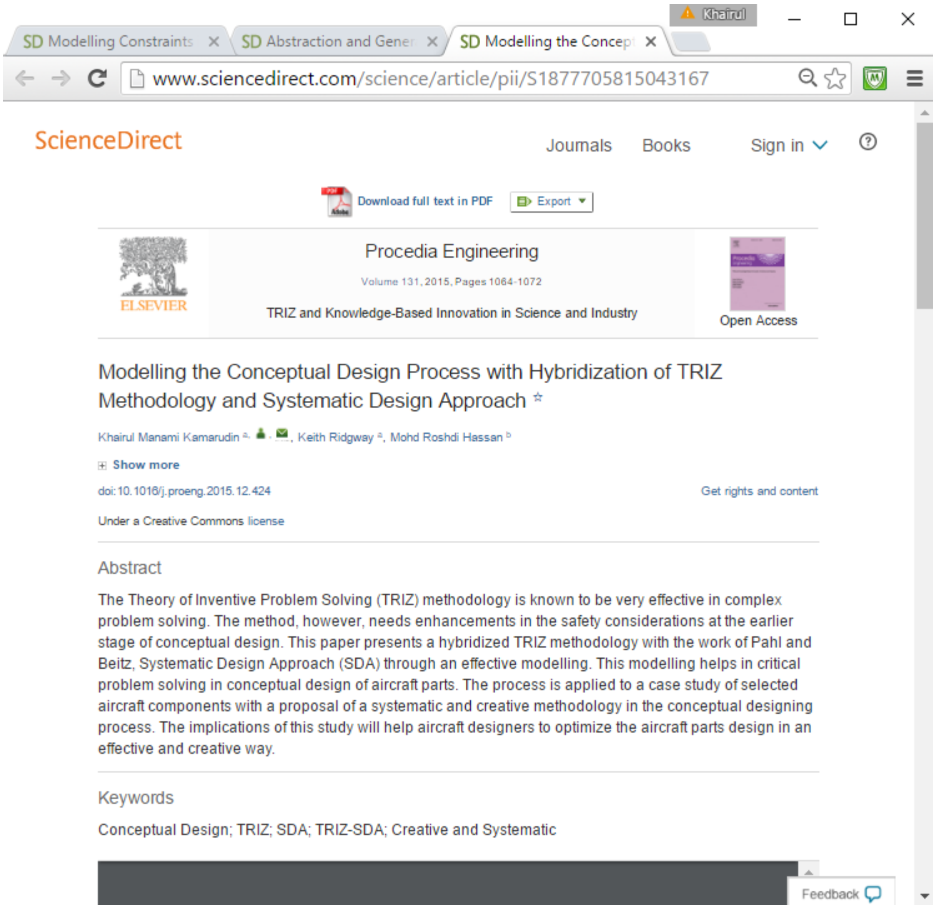
Action - Effect	
Change of Geometrical Properties: Length, Area, Volume, Form	1. Integration and nesting of objects 2. Telescopes, telescopic structures 3. Helix and spiral structures, double helix, telescopic helix tapes 4. Honeycombed structures 5. Collapsible structures, e.g. with two and three- dimensional concertinas 6. Application of geometrical bodies with variable cross section 7. Ellipsoidal adjustment elements 8. Variable side profile and internal cross section of one sheet hyperboloid 9. Mobius band with its modifications 10. Flexible three-dimensional forming with the help of pin matrix, sheet packages or brushes 11. Flexible three-dimensional forming with moulding sand or similar substances (with squeezing, sintering or vacuuming packaging) 12. Winding of objects 13. Application of brushes
Orientation and Connection of Objects	1. Orientation and connection by appropriate form 2. Torsion-loaded helix elements 3. Application of balls or rollers 4. Wedge, double wedge, tapered rings etc. 5. Temporary connection with squeezed sand, granules, balls etc. 6. Application of brushes, hook and loop fastenings (Velcro) 7. Application of sheet and spring packages 8. Changing the form of one sheet hyperboloid 9. Changing the centre of gravity or axis of rotation 10. Mobius band
Support and Transfer of Forces, Pressure, Vibration	1. Damping of mechanical vibration and shock waves with sand or other bulk substances 2. Application of balls and rollers with specific physical properties: density, elasticity, ductility, hardness etc. 3. Application of brushes for transmission of forces and vibration damping

	4. Application of sheet or spring packages 5. Application of cable, wire or string bundles 6. Belts with helical winding 7. Steel belt with arch-shaped cross-sectional 8. Elements with spherical or ellipsoidal form for force transmission 9. Adjustment of contact stress and area through rotation of an ellipsoidal body 10. Use of the micro-geometry of surfaces
Amplification and Focusing of Fields	1. Power gear transmission, thread mechanism, jack etc. 2. Generation of longitudinal forces in a strained cable by radial loading 3. Orientation of carbon or glass fibres in reinforced composite materials to optimise the mechanical properties of the components 4. Application of brushes to concentrate the mechanical, electrostatic or magnetic forces or fields 5. Focussing of optical (light, radiation) or acoustic (sonic waves) energy in focal points of spherical, elliptic or parabolic surfaces 6. Transition from point or line contact area of bodies or parts to surface or volume contact 7. Use of the micro-geometry of surfaces 8. Mobius band
Transformation of Movement and Oscillations	1. Helix, helical surface 2. Spirals 3. Helicoids, e.g. Archimedes water pump 4. Eccentrics and eccentricity 5. Mobius band and its modifications 6. Generation of motion with rolling curves of cycloids, epi- and hypocycloids 7. Generation of motion with ellipse and ellipsoids 8. Special three-dimensional curves, e.g. Frenet-pipe, Pinkall-pipe 9. Balls, rollers and ellipses as a medium for supporting or transforming motion 10. Application of transmissions and mechanisms for transformation of motion or its direction, speed, angular velocity, force, torque 11. Application of harmonic drive gear principle to transmit radial motion through hermetic walls

APPENDIX E

PROVE OF PUBLICATIONS

A. Journal in Procedia Engineering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Procedia Engineering
Volume 131, 2015, Pages 1064-1072
TRIZ and Knowledge-Based Innovation in Science and Industry
Open Access

Modelling the Conceptual Design Process with Hybridization of TRIZ Methodology and Systematic Design Approach ☆

Khairul Manami Kamarudin [a], Keith Ridgway [a], Mohd Roshdi Hassan [b]

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doi:10.1016/j.proeng.2015.12.424

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Abstract

The Theory of Inventive Problem Solving (TRIZ) methodology is known to be very effective in complex problem solving. The method, however, needs enhancements in the safety considerations at the earlier stage of conceptual design. This paper presents a hybridized TRIZ methodology with the work of Pahl and Beitz, Systematic Design Approach (SDA) through an effective modelling. This modelling helps in critical problem solving in conceptual design of aircraft parts. The process is applied to a case study of selected aircraft components with a proposal of a systematic and creative methodology in the conceptual designing process. The implications of this study will help aircraft designers to optimize the aircraft parts design in an effective and creative way.

Keywords

Conceptual Design; TRIZ; SDA; TRIZ-SDA; Creative and Systematic

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Volume 39, 2016, Pages 3-8

Structured Innovation with TRIZ in Science and Industry: Creating Value for Customers and Society

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Modelling Constraints in the Conceptual Design Process with TRIZ and F3 ☆

Khairul Manami Kamarudin [a, b], Keith Ridgway [a], Mohd Roshdi Hassan [b]

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doi:10.1016/j.procir.2016.01.034

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Abstract

Constraint stimulates creativity and is the key to understanding complexity. The benefit of the constraint-based problem is that it can spark ideas for new knowledge, new possibilities, and new opportunities. In every design, boundaries, controls and restraints exist. The constraint model in this paper shows the relationship among Form-Fit-Function (F3), Functional Analysis Model (FAM) and Su-Field. The constraint-based techniques improve problem solving in the preliminary design and satisfy ideal conceptual design. Constraints lift and improve creativity by reframing problems in a creative way. The best way to visualize constraints is by adopting design parameters and embedding them in the conceptual design stage, and continuously diagnosing them to ensure that the design does not violate the constraint requirements. This paper aims to model design constraints as a criterion for generating creative ideas and solutions, and suggest as a systematic entity in the conceptual design process. The model will be useful as a guide for developing an understanding of constraints in the conceptual design process.

Keywords

Constraints; modelling; F3; conceptual design; TRIZ.

Feedback

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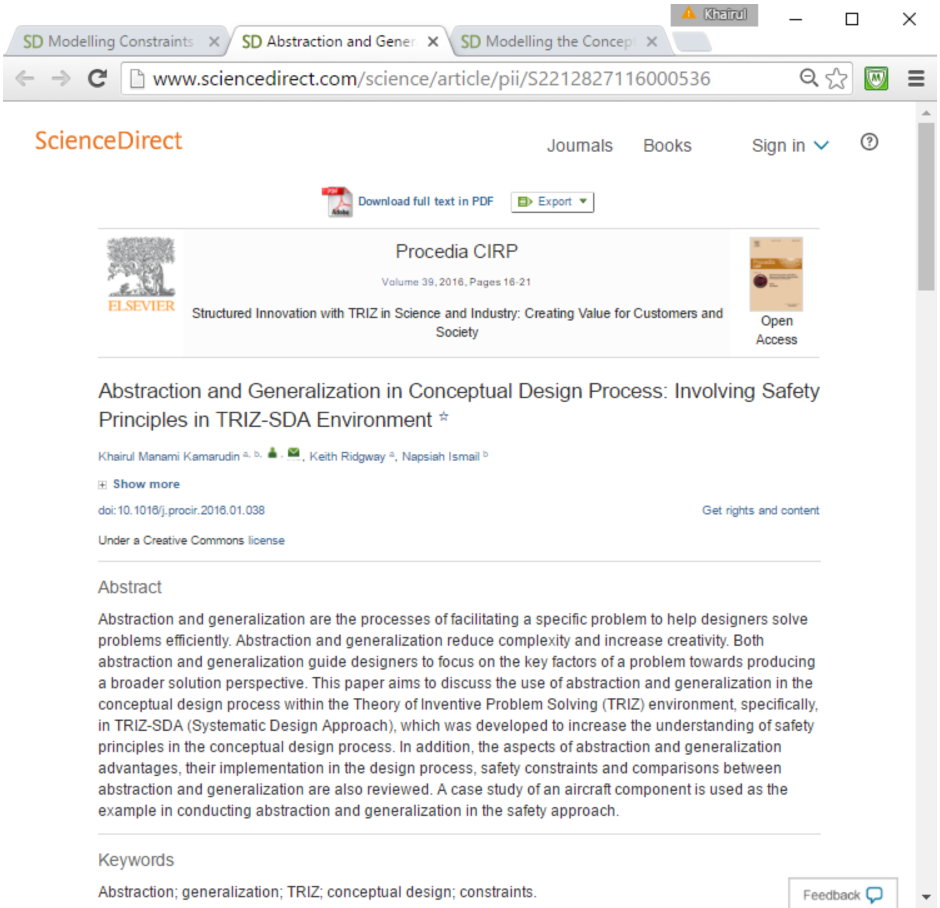

APPENDIX F

Formalities for Data Collection

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Tuan,

<u>KEBENARAN MENJALANKAN KAJIAN BERKAITAN REKABENTUK PESAWAT DI MIAT-UNIKL</u>

Perkara di atas dirujuk.

Saya, Khairul Manami Kamarudin, adalah pelajar kedoktoran *Jointly Awarded Research Degree* (JARD) di Jabatan Kejuruteraan Mekanikal dan Pembuatan, Fakulti Kejuruteraan, Universiti Putra Malaysia (UPM) dan *Advance Manufacturing Research Centre (AMRC) with Boeing, The University of Sheffield* (TUoS). Tujuan surat kebenaran ini adalah untuk mendapatkan persetujuan pihak tuan untuk saya menjalankan kajian di institusi tuan.

Saya sedang dalam proses mengumpul maklumat untuk kajian saya yang bertajuk *"Modelling the Conceptual Design Process with Hybridization of TRIZ Methodology and Systematic Design Approach"*, berkisar dengan rekabentuk *Landing Gear* pesawat. Saya diberi tugas oleh penyelia di AMRC, Prof. Keith Ridgway, untuk mengkaji komponen *landing gear* ini sebagai kajian kes menggunakan kaedah rekabentuk baharu (KRB). Ia adalah untuk mengkaji sejauh mana KRB ini berjaya menghasilkan rekabentuk baharu ke atas komponen yang kompleks. Kajian ini juga mendapat geran FRGS (*Fundamental Research Grant Scheme*).

Saya amat berbesar hati ke atas kesudian pihak tuan menyumbang ilmu, bahan kajian, fotografi, pengetahuan yang berkaitan dan juga idea untuk kajian saya ini. Saya dahulukan dengan ucapan ribuan terima kasih.

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Khairul Manami Binti Kamarudin obtained her Bachelor of Design (Industrial) from University of Technology MARA (UiTM) in 1999 and her Master of Science in Global Production Engineering (MSc.-Ing GPE) at the Technical University of Berlin in 2010. From 1999 to 2002, she worked as a Designer at Proper Link Sdn Bhd, an automotive company providing automotive manufacturing support. In 2002 up to 2007, she joined Perodua Manufacturing Sdn Bhd as a CAD Designer in the Research and Development department, focusing on Class-A Surface and geometric design for automotive design. From 2007 until recent, she is a tutor in the Industrial Design Department, Faculty of Design and Architecture, Universiti Putra Malaysia (UPM). She teach Computer Aided Design, Experimental Design Lab, and Ergonomics and Basic Technology. She had internship in Modern TRIZ Academy in Berlin in 2009 and actively involved in TRIZ in Malaysia and internationally, especially in Berlin and European TRIZ Association. In 2012, she joined the PhD of Jointly Awarded Research Degree between Universiti Putra Malaysia and Advanced Manufacturing Research Centre (AMRC) with Boeing, The University of Sheffield in the United Kingdom. She start her research in TRIZ methodology under supervision of Prof. Keith Ridgway (CBE) in AMRC and Prof. Datin Dr. Napsiah Ismail, Dr. Mohd Roshdi Hassan and Assoc. Prof. Dr. Azmin Shakrine Mohd Rafie in UPM.

LIST OF PUBLICATIONS

Kamarudin, K. M., Ridgway, K., & Hassan, M. R. (2015). Modelling the conceptual design process with hybridization of TRIZ methodology and systematic design approach. *Procedia Engineering*, *131,* 1064-1072.

Kamarudin, K. M., Ridgway, K., & Ismail, N. (2016). Abstraction and Generalization in Conceptual Design Process: Involving Safety Principles in TRIZ-SDA Environment. *Procedia CIRP*, *39,* 16-21.

Kamarudin, K. M., Ridgway, K., & Hassan, M. R. (2016). Modelling Constraints in the Conceptual Design Process with TRIZ and F3. *Procedia CIRP, 39,* 3-8.

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