UNIVERSITI PUTRA MALAYSIA

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

KHAIRUL MANAMI KAMARUDIN

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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

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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

By

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February 2017

Chairman : Professor Napsiah Ismail, PhD
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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

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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 Integration
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.

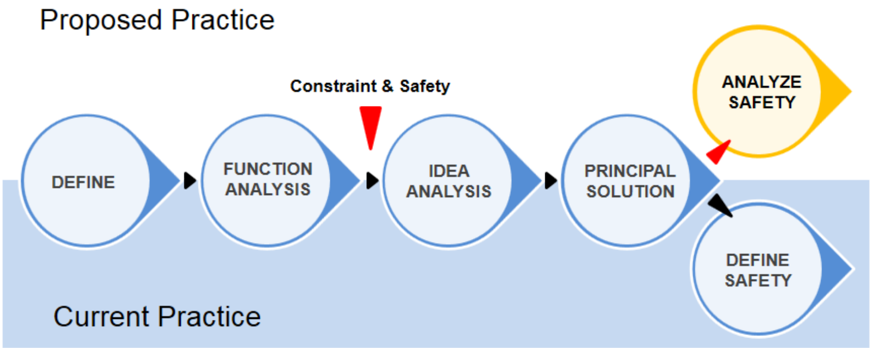

Figure 1.1: The process flow of proposed and current practice of conceptual design process

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.

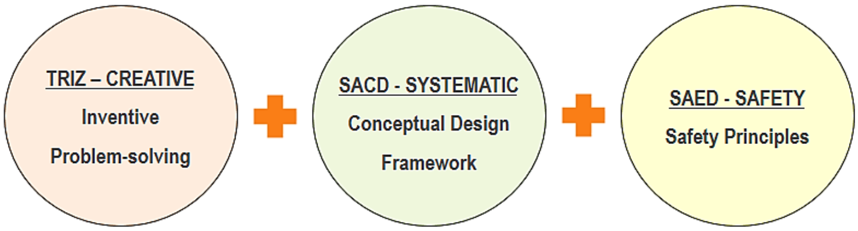

Figure 1.2: The research generic conceptual framework, where the TRIZ and SACD procedures, and SAED safety principles are merged

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.

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