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Système d'évaluation des concepts de solution générés en conception inventive

Discipline/ Spécialité : **Génie Industriel**

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This thesis is dedicated to my loving parents

Especially to my late father Yahya Khan

12-08-1957--- 11-03-2020

Though you never got to see this

you’re in every page

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Résumé en français suivi des mots-clés en français

En général, le processus de conception comporte trois étapes principales : la génération du concept, l'incarnation et la conception détaillée. La phase de génération du concept dans le processus de conception est la plus importante, car un échec à ce stade peut entraîner de longues dépenses de reconception et de modification, ainsi que des inconvénients tels qu'un retard dans le lancement des produits sur le marché.

Au cours des dernières décennies, les entreprises ont recherché en permanence des approches qui leur permettent de concevoir des produits innovants afin de se maintenir sur des marchés compétitifs. Ces approches sont principalement classées en deux catégories, à savoir les approches traditionnelles de la conception inventive et les approches systématiques de la conception inventive. Dans le cadre de la catégorie des approches de la conception inventive systématique, cette thèse se focalise sur la méthode de conception inventive basée sur la méthode TRIZ TRIZ (MCI-Triz ou IDM-Triz) (théorie de la résolution des problèmes inventifs). La méthode IDM basée sur TRIZ et d'autres approches de conception inventive génèrent plusieurs concepts de solution (SC) nécessaires pour résoudre le problème initial identifié. Cependant, les différentes approches n'offrent pas la possibilité d'évaluer rigoureusement les SC. En cas de manque de cadre d'évaluation pour ces CS générés, les concepteurs ou les décideurs ont généralement tendance à adopter des solutions conventionnelles.

Avant de répondre à ce point, il est préférable de lister les différentes approches de la conception inventive existantes et leurs limites en termes d'évaluation des CS. Premièrement, l'approche traditionnelle de la conception inventive associe la créativité à la pensée désordonnée et à la génération d'idées. Par exemple, le "brainstorming", qui est l'une des méthodes de créativité les plus répandues depuis plusieurs décennies, la technique du groupe nominal (NGT), le cahier collectif (CNB), le brainwriting Pool, la méthode SIL (Successive Intégration of Problème Eléments), le morphing des idées, la méthode des affinités, etc. sont quelques-unes des principales approches conventionnelles de la conception inventive. Deuxièmement, les approches systématiques de la conception

inventive permettent de générer des concepts de solutions, par exemple, la transformation des idées (Taguchi, GA/GP), SIT/ASIT, SCAMPER, la théorie CK, TRIZ et TRIZ-IDM, etc.

Les concepts de solutions résultant de ces processus de conception inventive sont généralement décrits de manière déclarative, ce qui empêche d'avoir une description formelle ou visuelle partageable entre les partenaires du projet. En outre, l'absence de modèle ne permet pas d'évaluer et de comparer des concepts concurrents. Dans ce contexte, il y a une lacune de recherche dans les approches méthodologiques dans la mesure où toutes les approches existantes manquent de méthodes rigoureuses pour évaluer les CS et cela explique pourquoi le thème de ma thèse est orienté vers ce sujet.

Parmi ces approches, cette thèse souligne l'approche systématique TRIZ-IDM qui constitue le domaine de recherche de notre équipe depuis plusieurs années. Il s'agit d'une méthode développée au cours de nombreuses années de recherche pour dépasser les limites de TRIZ et pour compléter son corpus de connaissances avec d'autres théories telles que la théorie de Pugh ou la théorie des graphes. Cette méthode comprend les quatre phases suivantes : 1) la phase d'analyse initiale, 2) la phase de formulation des contradictions, 3) la phase de synthèse des concepts de solution, et 4) la phase de sélection des concepts de solution. Ce Cette méthode constitue une amélioration par rapport à TRIZ mais elle souffre encore de certaines lacunes en termes d'évaluation des concepts de solution. L'IDM-TRIZ, identifie plusieurs SCs pour résoudre le problème initial. Cependant, après la génération des SCs, l'étape suivante pour évaluer les SCs et sélectionner la solution dépend de l'expertise humaine dans le département R&D ou la direction de l'entreprise. En outre, dans la phase initiale, il y a toujours un manque d'informations et de connaissances détaillées avec plus de risques de perte d'informations, D’où la nécessité d’avoir un moyen efficace pour représenter et 'évaluer les CS dans.

La plupart des méthodes d'évaluation des alternatives sont utilisées dans la sélection de la solution finale et elles sont simples, sans représentations des alternatives. Les méthodes d'évaluation sont les intrants les plus essentiels des méthodes de conception innovante, et il est également nécessaire de les rendre disponibles dans l'étape initiale des conceptions conceptuelles où il y a toujours un manque de représentation formelle et une perte d'informations. Les SCs de conception inventive sont considérés comme des structures capables de remplir les fonctions requises de l'artefact concu.Par conséquent, cette recherche se concentre sur le fait que les principales caractéristiques d'une SC peuvent être représentées par un ensemble de quelques caractéristiques fondamentales telles que les aspects fonction, comportement et structure (FBS). Nous adoptons l'approche de modélisation FBS de Gero dans notre méthode proposée de représentation et d'évaluation de la SC avec une étude de cas comme le montre la Figure A. Nous avons noté que les aspects fonctionnels et comportementaux des CSs n'ont pas fait l'objet d'une attention particulière dans la phase initiale des processus de conception inventive. Ainsi, les concepteurs doivent obtenir les CSs qui répondent aux exigences fonctionnelles, comportementales et structurelles dans la phase initiale du processus de conception. Le cadre d'évaluation des CSs que nous proposons se compose de 5 étapes principales. Étape 1- Collecte de données, Étape 2- Identification de la fonction, Étape 3- Décomposition fonctionnelle, Étape 4- Relation sémantique fonction-comportement et Étape 5- Relation fonction-comportement-structure.

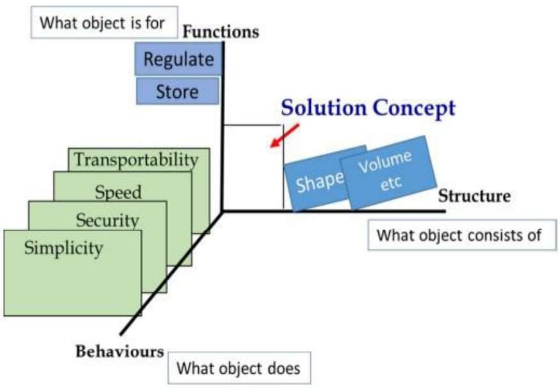

Figure A. l'approche FBS pour représenter les concepts de solutions

Dans les deux premières étapes, à partir de la collecte des données et de l'évaluation subjective des fonctions (jugement humain), le cadre d'évaluation aide à identifier les fonctions en utilisant l'échelle SD différentielle sémantique en mettant l'accent sur le concepteur, le client et les experts en gardant uniquement les fonctions essentielles.

Dans la troisième et la quatrième étape, la façon de relier les fonctions au comportement attendu est réalisée en introduisant l'approche de l'identification des caractéristiques fonctionnelles pour relier les fonctions identifiées au domaine du comportement. La cinquième étape principale consiste à utiliser le domaine du comportement comme un pont entre les fonctions et les domaines structurels possibles et à présenter les résultats finaux aux parties prenantes, au département R&D ou à la direction de l'entreprise afin de poursuivre la génération du concept final. Les résultats et les informations recueillis au cours de chaque étape sont également stockés dans une base de données pour être utilisés dans les étapes suivantes ou pour tout autre objectif connexe à l'avenir.

Le résultat de la méthode proposée offre pour les SCs évalués, une représentation formelle ou visuelle partageable entre les partenaires du projet. Le cadre d'évaluation permet au concepteur d'identifier les différents paramètres fonctionnels, comportementaux et structurels basés sur les caractéristiques / paramètres par une évaluation fonctionnelle subjective (implication du jugement humain). Le cadre d'évaluation fournit un indicateur au concepteur sur la façon de construire la relation fonction comportement, la relation comportement structure et l'utilisation du comportement comme un pont entre la fonction et la structure pour la sélection de la meilleure SC disponible pour développer une nouvelle conception de solution (solution structurelle). La faisabilité de notre méthode proposée est illustrée par un exemple d'étude de cas sur la faisabilité de la fonction des SCs générés par TRIZ-IDM. Ces travaux de recherche visent à faciliter et à rendre plus adaptable la conception inventive dans les entreprises. Lors de l'évaluation de SCs innovants, la satisfaction des exigences fonctionnelles est l'une des exigences principales. Pour y parvenir, les aspects FBS des CS doivent être explorés. Nous avons déjà présenté lors de la conférence (Yehya et al., 2021a) le schéma générique de la manière dont notre modélisation de concept de solution prend en compte les dimensions FBS. Le cadre d'évaluation principal, accompagné d'une étude de cas, a déjà été soumis à un journal à

facteur d'impact et le test technique initial a été approuvé et est en cours d'examen par les pairs avec le statut de premier examinateur (accepté).

Le défi futur consiste à intégrer cette méthode à d'autres processus de conception et à la rendre applicable avec les données de l'apprentissage automatique. Dans un premier temps, cette approche s'applique au domaine de la mécanique et, à plus long terme, après validation du modèle, nous travaillons à son déploiement dans d'autres domaines.

Mots clés :

Évaluation, conception inventive, prise de décision, conception conceptuelle, méthodologie de conception, résolution de problèmes, framework d'évaluation FBS.

Summary in English followed by key words in English

Generally, the design process has three main steps of concept generation, embodiment, and detailed design. The concept generation phase in the design process is most important as failure at this stage can result in a long time of redesign and rework expenses without any solution and facing disadvantages of delay in launching products into market. In recent decades, companies have continually sought approaches that help them to produce innovative artifacts as to survive in competitive markets. These approaches are mainly classified into two approaches i.e., traditional inventive design approaches and systematic inventive design approaches. Among these in the category of systematic inventive design approaches., my thesis concentrates on TRIZ (theory of inventive problem solving) based inventive design method IDM. The TRIZ based IDM, and other inventive design approaches identify several Solution Concepts (SC) that is very near to solve the initial identified problem. However, the different approaches do not offer the opportunity to rigorously evaluate SCs. When there is lack of evaluation framework for these generated SCs, usually designers or decision makers tend to opt conventional solutions.

Before answering this point, it would be better to list different inventive design approaches that exist for inventive design and their limitations in terms of evaluation of SCs. First the traditional inventive design approach connects creativity with disordered thinking and idea-generating e.g brainstorming which has been one of the most popular creativity methods for many decades, brainwriting nominal group technique (NGT), collective notebook (CNB), brainwriting Pool, Successive Integration of Problem Elements (SIL) Method, idea morphing, affinity method etc. are some prominent conventional inventive design approaches. Second the systematic inventive design approaches e.g., idea morphing (Taguchi, GA/GP) SIT/ASIT, SCAMPER, CK theory, TRIZ and IDM, etc.

The concepts of solutions resulting from these inventive design processes measures are. generally described in a declarative manner, which does not allow having a shareable formal or visual representation between partners of the project. In addition, the absence of a model does not allow the evaluation and compare competing concepts. With this in mind,

there is a research gap in methodological approaches that all the existing methods are lack of rigorous methods for evaluating SCs and this is why my PhD work is focused on this area.

Among these approaches this research highlights the systematic TRIZ-IDM approaches to creative thinking which has been the research domain of our institution from several years. It is a framework developed over many years of research to overcome the limitations of TRIZ and to complement its body of knowledge with other theories such as Pugh's theory or graph theory. This framework includes the four following phases: 1) Initial analysis phase, 2) Contradiction formulation phase, 3) Solution concept synthesis phase, and 4) Solution concept selection phase. This framework is considered an improvement over TRIZ but still suffers from some drawbacks in terms of the evaluation of solution concepts. The TRIZ based IDM identifies several Solution Concepts SCs that is very near to solve the initial identified problem. However, after generation of SCs, the next step to evaluate SCs and select solution depends on human expertise in R&D department or top management of the company. In this step, generally, designers or decision makers tend to opt conventional solutions when there is lack of evaluation framework for SCs. Also, in the initial phase there is always a lack of detailed information and knowledge with more chances of information loss, so there should be an efficient way to represent and evaluate SCs in such situations.

Mostly the methods for evaluation of alternatives are used in the final solution selection and are simple with no representation of alternatives. Evaluation methods are most essential inputs to innovative design methods, and it is also necessary to make it available in the initial step of concept designs where there is always lack and loss of information., The inventive design SCs considered as intangible structures capable of fulfilling required functions of required artifact. Therefore, in this research it is focused that main features of a SC may be represented by a set of few fundamental design domains such as function, behavior, and structure (FBS) aspects. We adopt and adapt FBS modelling approach by Gero in our proposed method of representation and evaluation of SC with a case study. We noted that there has not been much focus on functional and behavioral aspects of SCs in the initial phase of inventive design processes. By doing so, the designers have to get the SCs which fulfills the functional, behavioral, and structural requirements in the initial phase of design process. Our proposed framework of SC evaluation consists of 5 main steps. Step 1- Data collection, Step 2- Function identification Step 3- Functional decomposition, Step 4- Function-Behavior Semantic relationship and Step 5- Function-Behavior-Structure relationship.

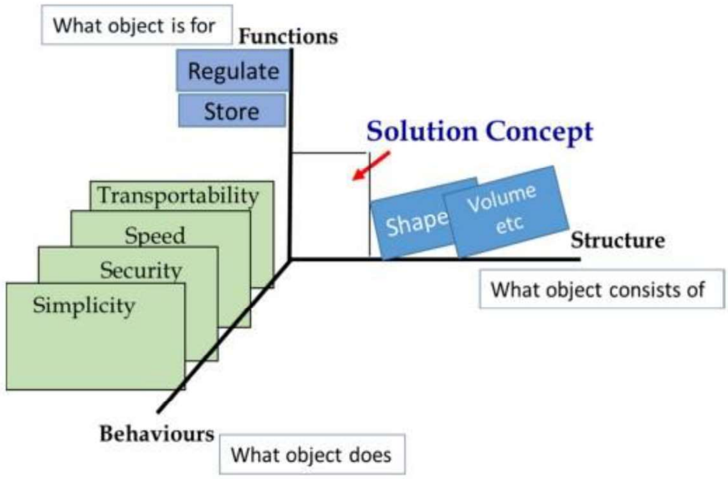

Figure A: FBS approach de solution concept representation

In the first two steps, starting from data collection and function evaluation subjectively (human judgement), the evaluation framework helps to identify functions by using semantic differential SD scale focusing designer, customer and experts by keeping only the essential functions.

In the third and fourth step, how to link functions to expected behavior is done by introducing approach of identification of functional characteristics to link the identified functions to behavior domain. As the fifth main step, using the behavior domain as a bridge between functions to possible structural domains and presenting the final outcomes to stakeholders, R&D department, or top management of the company for further towards final concept generation. The outcomes and information gathered during each step is also stored in database to be used in next steps or for any other related purposes in future.

The result of the proposed method offers for the evaluated SCs, a shareable formal or visual representation between partners of the project. The evaluation framework allows designers to identify various functions, functional behavioral, and structural parameters based on characteristic(s) / parameter(s) by functional evaluation subjectively (involvement of human judgment). The evaluation framework provides an indicator to designer how to build function behavior relationship, behavior structure relationship and using behavior as a bridge between function and structure for selection of best available SC to develop new solution design (structural solution). The feasibility of our proposed method is illustrated by a case study example on function realizability of SCs generated by TRIZ-IDM. This research works aims to facilitate and more adaptable inventive design in companies. When dealing with innovative SCs evaluation, satisfying functional requirements is one of the primary requirements. To achieve this, the FBS aspects of SCs need to be explored. We have already presented in conference about the generic schematic of how our solution concept modelling is concerned with FBS dimensions. The main evaluation framework with a case study has already been submitted in an impact factor journal and initially the technical test has been cleared and in process of peer review with status of first reviewer(s) (accepted).

The future challenge is how to integrate this method to other design processes and make it practicable along with inputs by machine learning. Initially this approach applies to the mechanical area and in future after validation of the model, we are working on it to expand it to other domains.

Keywords: evaluation, inventive design, decision making, conceptual design, design methodology, problem solving, FBS evaluation framework.

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NOMENCLATURE

Symbol	Description
TRIZ AFD	TRIZ Anticipatory Failure Determination
TRIZ IPS	TRIZ Inventive principles
AHP	Analytical Hierarchy Process
AP	Action Parameters
ARIZ	Analytical tools of TRIZ
ASIT	Advanced systematic inventive thinking
CK	Concept Knowledge theory
CNB	Collective Notebook
CNB	Collective Notebook
CW	Closed World
EP	Evaluation Parameters
FB	Function Behavior
FBS	Function Behavior Structure
FMEA	Failure Mode and Effect Analysis
IDM	Inventive Design Method
IPG	Inverse Problem Graph
LA-IDM	Lean-Agile Inventive Design
NGT	Nominal Group Technique
OTSM	General Theory on Powerful Thinking
PMI	Plus Minus Interesting
R&D	Research and Development
SC	Solution Concept
SCAMPER	Substitute Combine Adapt Magnify/Modify Put Eliminate Rearrange
SCs	Solution Concepts
SD	Semantic Differential
SIL	Successive Integration of Problem Elements
SIT	Systematic Inventive Thinking
TRIZ	Russian acronym for Theory of Innovative Problem Solving
TRIZ-IDM	TRIZ Based Inventive Design Method

1. INTRODUCTION

1.1. TECHNICAL CONTEXT

With the advancement in technology, market competition, and globalization there is an increase attraction in engineering design by designers' and researchers' more specifically towards inventive design approaches. Generally, engineering design process has three main steps of concept generation, embodiment, and detailed design (Nikander, Liikkanen, and Laakso 2014). The concept generation phase in the design process is most important for inventive designs as failure at this stage can result into long time of redesign and rework expenses without any solution and facing disadvantages of delay in launching products into market.

In past decades, researchers associated with academic as well as companies have continually developed approaches that help them in concept generation phase to produce inventive solutions to problems as to survive in competitive markets. These approaches are generally distinguished into two types i.e., first one is the traditional approach and second one is systematic approach. The traditional approach connects creativity with disordered thinking and idea-generating e.g., brainstorming which has been one of the most popular creativity methods for many decades, brainwriting nominal group technique (NGT), collective notebook (CNB), brainwriting Pool, Successive Integration of Problem Elements (SIL) Method, idea morphing, affinity method etc. are some prominent conventional inventive design approaches. The systematic inventive design approaches e.g., idea morphing (Taguchi, GA/GP) SIT/ASIT, SCAMPER, CK theory, TRIZ and IDM etc. (Gerhard Pahl et al. 2007; Shah, Kulkarni, and Vargas-Hernandez 2000).

These inventive design approaches identify several Solution Concepts (SC) that is very near to solve the initial identified problem. The SCs resulting from these inventive design processes measures are generally described in a declarative manner, which does not allow having a shareable formal or visual representation between partners of the project. In addition, the absence of a model in concept generation does not allow the evaluation and compare competing concepts. When there is lack of evaluation framework for these generated SCs, usually designers or decision makers tend to opt conventional solutions. With this in mind, there is a research gap in methodological approaches that all the existing approaches are lack of rigorous methods for representing and evaluating SCs and this is why this research work is focused on this area.

Among the inventive design approaches, in the category of systematic inventive design approaches., this research concentrates on TRIZ (theory of inventive problem solving) based inventive methods like Inventive Design Method (IDM). In next phase the research will be expended to other approaches as well.

TRIZ is logical and systematic ideation method based on contradiction resolution principles (Altshuller, Shulyak, and Rodman 40AD).The systematic TRIZ-IDM approach to creative thinking is a framework developed over many years of research to overcome the limitations of TRIZ and to complement its body of knowledge with other theories such as Pugh's theory or graph theory (Cavallucci and Strasbourg 2009). This framework includes the four following phases: 1) Initial analysis phase, 2) Contradiction formulation phase, 3) Solution concept synthesis phase, and 4) Solution concept selection phase. This framework is considered an improvement over TRIZ but still suffers from some drawbacks in terms of the evaluation of SCs. Like other inventive design approaches, the TRIZ-IDM, identify several SCs that is very near to solve the initial identified problem.

However, after generation of SCs, only list of generated SCs is provided and IDM stops here. The next step to evaluate SCs and generate concepts depends on human expertise in R&D department or top management of the company. When there is lack of evaluation framework for SCs in this step, generally, designers or decision makers tend to opt conventional solutions instead of focusing on generated SCs. Also, in the initial phase there is always a lack of detailed information, knowledge and formal representation with more chances of information loss, so there should be an efficient way to represent and evaluate SCs in such situations.

With the aim to increase inventiveness in problem solutions and increase the acceptability of SCs for inventive solutions this study proposes a general evaluation framework. In the current phase of our research, the proposed evaluation framework is applied on SCs generated in TRIZ-IDM. We focused on the generated SC by trying to both identify its areas of inefficiencies while attempting to save loss of information at initial steps of design process and provide the designer or partners of the project an evaluated result of SCs.

1.2. POSITION OF THE THESIS

This research position in the context of TRIZ-IDM and engineering design process is shown in Figure 1. In the third step, the key components of the contradictions are used as an input to generate Solution Concepts assisted by computer- based TRIZ techniques. Followed by a choice of the Solution Concepts to develop in Step 4. The main focus of this thesis relies on the framework for evaluation of Solution Concepts from Step 3 of IDM. The link between generated solution concepts and evaluation framework is developed by using FBS domain of SCs. Details of the evaluation approach presented in chapter 3. In coming sections, we describe our objectives. We end this section by describing the contribution of this thesis work

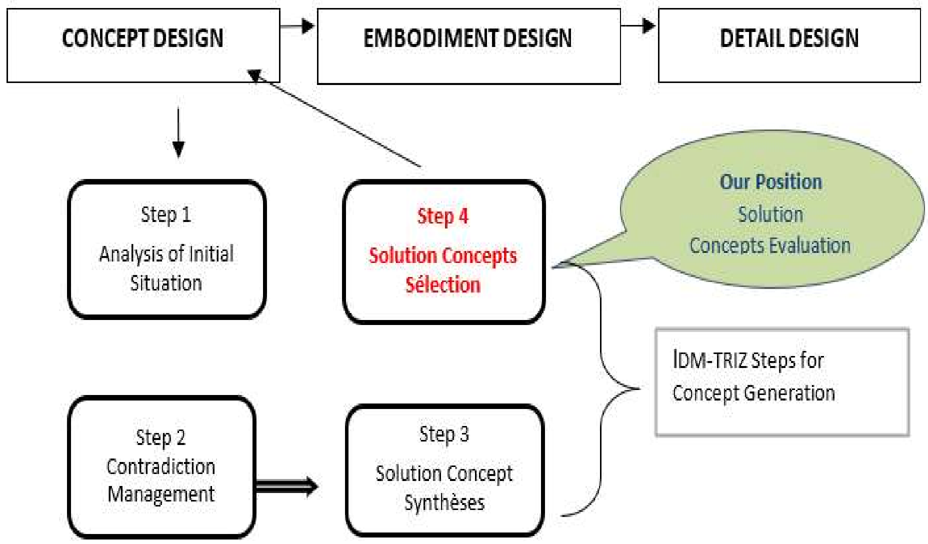


Figure 1. This research position in the first phase of concept design

1.3. RESEARCH OBJECTIVE

The title of this thesis focuses on the evaluation of solution concepts generate in inventive designs, but more precisely, for what? The main objectives are first to minimize the lack of required information and knowledge to propose a formal representation solution concept without information loss to be able to evaluate and select the optimal proposed solution concept. Second, to minimize, in the next phase of design process, from one side, the risk of developing a none-optimal SC. From the other side, to eliminate expensive modifications resulting from this not adapted SC.

1.4. THESIS CONTRIBUTION

The main contributions of this thesis are reflected in two aspects. First how to represent a SC which is not a product but just a rough idea with several elements. The second problem is how to build the evaluation framework in order to evaluate and compare important elements of SCs. From this development, we aim to increase the acceptability of SCs so that the designers or stake holders give more interests to consider these solution concept to produce inventive solutions instead of going with not fully adapted conventional solutions. Moreover, we propose to integrate evaluation framework within inventive design approaches more specifically in this part of study with TRIZ-IDM

1.5. THESIS STRUCTURE

The rest of the thesis is organized as follows. Chapter 2 presented a background and literature review about inventive design approaches and compared the inventive design approaches. Based on the literature review outcomes, we selected one of the prominent inventive design approaches i.e., TRIZ and its extension tool as IDM as our study focus in this research. In Chapter 3, based on the output of literature review, a FBS based framework proposed to evaluate solution concepts in the concept generation phase of engineering design process and applied on case studies. And we presented a method to integrate the evaluation framework to integrate in modern tool based TRIZ-IDM inventive design approaches. In Chapter 4, we present a case study to illustrate the applicability of our proposition. In Chapter 5, we present the implantation of our model into an informatic module integrable with the IDM informatic tools. In chapter 6, we presented the conclusion and future perspective by concluding the contribution of the study The end of this thesis reports the conclusion and suggestions for future work.

2. BACKGROUND AND LITERATURE REVIEW

The aim of this chapter to compare the different inventive design approaches to see if what are limitations in terms of SC evaluation or how SC are generated and how to evaluate them?

This chapter starts with section 2.1, types of engineering design in which the type of inventive design is our study focus. In 2.2, the main steps of engineering design are defined and from these main steps our study focuses on conceptual design step. Then section 2.3 focusses on the inventive design approaches and its classifications by identifying the limitations in terms of SC evaluation. In section 2.4 we compare these inventive design approaches. In section 2.5 we discuss the SCs representation. In section 2.6 focus on TRIZ-IDM and related approaches and in 2.7 we discuss TRIZ'S advantages and drawbacks then in 2.8 we present the -TRIZ-based inventive approaches. this chapter is discussed in section 2.9.

2.1. TYPES OF ENGINEERING DESIGN

The process of identifying and resolving engineering problems is known as engineering design, which can take various forms but shares a common feature of being a process. The primary types of engineering design include:

2.1.1. Inventive designs

Inventive design in certain cases, also known as original design, is employed. This approach involves creating a new and unique idea to fulfil a particular requirement or producing solutions. This could be through novel or new combinations of existing solutions. To achieve an inventive design, a one-of-a-kind solution is necessary, which often involves introducing new technologies that could have significant long-term impacts (Pahl and Beitz 2013).

To solve problems, and develop innovative artifacts, it is essential to generate inventive SCs. There are several inventive design approaches are known. These approaches are generally distinguished into two types i.e. first one is the intuitive approach and second one is systematic approach. These approaches are used in different steps of engineering design process for identification and solving engineering problems (Haik, Sivaloganathan, and Shahin 2015; McGill 2022; G Pahl et al. 2007; Pahl and Beitz 2013) .

2.1.2. Adaptive design

Adaptive design involves modifying an existing engineering solution to meet a different requirement. This type of design adheres to established principles of solution design and adjusts the implementation to accommodate the changed needs. It may be necessary to create original designs for specific components or assemblies. The focus of adaptive design is primarily on geometrical aspects such as strength and stiffness, as well as production and material concerns (Pahl and Beitz 2013).

2.1.3. Redesign

Redesign is an engineering design approach that aims to enhance an existing design. This type of design may involve expanding the product's service capabilities and functionality or reducing its manufacturing cost. Redesign may also be undertaken to modify the product's properties while maintaining its functionality and cost, even if the latter increases. For instance, redesigning a product to reduce its stress concentration by altering its shape is an example of this type of design.

2.1.4. Variant design

Variant design involves adjusting the sizes and arrangements of parts and assemblies within the boundaries established by previously designed product structures, such as size ranges and modular products. Only one original design effort is needed for variant design, and it typically does not pose significant design challenges for a specific order. This design approach may include modifying the dimensions of individual parts to meet a particular requirement, and it is sometimes referred to as principle design or design with fixed principles (G Pahl et al. 2007).

2.2. MAIN STEPS OF ENGINEERING DESIGN PROCESS

Engineering design is a multi-step process from requirements to creating a product Various approach to engineering design are proposed by different authors in the design field, depending on their understanding of engineering design and their specific objectives (Annarelli, Battistella, and Nonino 2016; Morelli 2006).The goal of engineering design is to integrate business models, products, and services throughout the entire life cycle, resulting in innovative value creation for the system (Vasantha et al. 2012). The existing engineering design process models mainly includes requirement management, concept development and evaluation, design embodiment and evaluation, detailed design, and testing (Cavalieri and Pezzotta 2012). This multi-step process is generally listed as Planning stage, Conceptual design Embodiment design, Detailed design, Prototype by (Pahl and Beitz 2013):

2.2.1. Planning

In this initial step of engineering design process all the tasks need to be clarified and requirements should be analyzed in detail based on either customer requirements or just to make some improvement on an existing product. As an output of this step, a list of requirements is generated and this list helpful as a reference for the conceptual design and following phases of design process.

2.2.2. Conceptual design

This step of design process is based on systematic design of Pahl and Beitz Beitz (G Pahl et al. 2007; Pahl and Beitz 1984, 2013). When it comes to real practice, the conceptual design process does not change with respect to problem complexity, novelty, experience of designer, uncertainty, and available resources etc. Therefore, without making related suitable changes/additions it is not suitable to apply for novel and evolutionary designs. The main change desired in systematic design process to make it suitable to novel/evolutionary design is the integration of different ideation methods.

At the end of this conceptual design process, a set of solution principles are obtained. Now, they need to be evaluated and inappropriate solution principles are eliminated. Once a finalized set of solution principles are obtained, we move on to a more concrete level of embodiment design.

2.2.3. Embodiment design:

From several alternatives generated in conceptual design the concepts are converted into structures and layouts. These layouts are analyzed to satisfy the technical and economic criteria. Embodiment stage has a higher information level as compared to conceptual design stage. After the detailed analysis one best layout is selected, and more ideas are incorporated on it.

2.2.4. Detailed design

As mentioned by Pahl and Beitz Beitz (G Pahl et al. 2007; Pahl and Beitz 1996, 2013), in this phase of the design process dimensions, forms, and other geometrical properties are identified, materials are specified, production possibilities are analyzed, and all the related documentation are produced. With the advancement of modern tools, like CAD modelling, the detailed design process is becoming more and more proficient day by day where maximum of the details can be specified and documented.

So, we have an overview of the different types and stages of engineering design process and their importance. It is also clear that the conceptual design process, which is focus of this research, is the most important phase since most of the important decisions are taken at this phase and it affects the whole process. It is evident that if a chosen solution concept for development fails, it would be difficult to make up for it during subsequent phases of advanced design and development due to the resulting extended periods of redesign and rework, which can be quite costly. According to research by S.R Daly (Daly et al. 2012) approximately 80% of the cost is incurred during the conceptual design selection phase, and it has been discovered that 80% of a product's manufacturing cost occurs during the product design process. This highlights the significance of conceptual design and emphasizes the need for an efficient and reliable conceptual design tool to assist designers in creating innovative design concepts.

2.3. TYPES OF INVENTIVE DESIGN APPROACHES

The inventive design approaches are generally distinguished into two main types i.e. first one is the traditional intuitive approach and second one is systematic approach. These approaches are different in terms of mechanism they used to generate SCs.

2.3.1. Traditional inventive design approaches

The traditional approach connects creativity with disordered thinking and idea-generating e.g brainstorming which has been one of the most popular creative methods for many decades (Osborn 1963), brainwriting (VanGundy 1984a) which is an alternative to brainstorming generally is referred to as brainwriting or idea writing. There are several brainwriting methods like Nominal Group Technique (NGT) (Gallagher et al. 1993), Collective NoteBook (CNB) (Haefele 1962), Brainwriting Pool (Geschka, Schaude, and Schlicksupp 1975), Pin Cards (VanGundy 1984a) and Battelle-Bildmappen-Brainwiiting (BBB) and Successive Integration of Problem Elements (SIL) Method etc. Synecticsc (Wilson, Greer, and Johnson 1973), Idea Morphing (Hsiao and Liu 2002), Affinity method etc. are also some prominent conventional ID methods.

2.3.2. Systematic inventive design approaches

Second the systematic inventive thinking and idea-focusing e.g., idea morphing (Taguchi, GA/GP) SIT/ASIT, SCAMPER, CK theory, TRIZ and IDM etc. As in this study we are concerned to concept generation step of design process. And secondly this study is also focusing on inventive design approaches on which modern tools have been applied. Following are some systematic inventive design approaches which are prominent in producing inventive solutions and are under focus of researchers and companies in last two decades like TRIZ and IDM which is also main part of this study.

In the following sections, we will see in more detail about the several solution concept/idea/solution generation approaches and compare them based on their methods and try to focus those inventive design approaches that are used in conceptual design.

2.4. COMPARISON of INVENTIVE DESIGN APPROACHES

There are many so called inventive design approaches available in scientific literature, in online platforms, and books etc. The exact number of these inventive design approaches is difficult to mention. Literature shows that there are more than 300 methods for inventive design approaches or inventive problem solving that exists as claimed by (Higgins 1994; Takahashi 2007). Initially during this research, the data collected identified more than 100 inventive design approaches shown in **Table 1**. To compare the inventive design approaches more closely, the inventive design approaches can be categorized in several types based on the methods and tools used under the categories given below.

1. Conditioning /organizing approaches.

These approaches create an environment that facilitates creativity by removing mental blocks and promoting natural creativity. This group includes techniques like the Napoleon technique and listening to music, as well as the use of helpful tools like notebooks, stickers, boards, and flip charts.

2. Randomization

These approaches help individuals to break free from their paradigms and make more random attempts to solve problems. Techniques like brainstorming fall under this category.

3. Focusing approaches

Approaches which are used to help individuals focus on one issue at a time and avoid frustration. Examples include attribute listing and random focusing.

4. Systems

Approaches which contain a set of focusing or random steps to be followed in a specific order. QFD is an example of a system.

5. Pointed approaches,

These approaches offer single or multi-step recommendations following a pre-determined direction, based on intuition, experience, or documented knowledge. Examples include problem reversal and ARIZ.

6. Evolutionary directed approaches

Approaches which offer directions based on fundamental patterns of evolution. The utilization of the TRIZ Patterns/Lines of Technological Evolution is an example of this category.

7. Innovation knowledge-based approaches

These approaches use structured knowledge derived from past human innovation experience. The Contradiction Table and 40 Innovation Principles fall under this category.

8. Modern tools applied approaches

In this category, the approaches on which modern tools have been applied are placed. Like the inventive design approach of TRIZ is used to develop many methods which are helpful in creating inventive solutions like STEPS, IPG. IDM etc.

Table 1. Comparison of inventive design approaches in state of the art

		Categories of comparison							
Sr.	**Approaches**	**1- Conditioning/organizing approaches**	**2-Randomization**	**3-Focusing approaches**	**4- Systems**	**5-Pointed approaches**	**6-Evolutionary directed approaches**	**7-Innovation knowledge-based approaches**	**8- Modern Tools**
1.	Random input (feature transfer, focused-objects technique, organized random search, picture or concrete stimulation) (Herring et al., 2009c)		✓	✓					
2.	Problem reversal				✓	✓			
3.	Questions Ask (Rhodes 1961)			✓	✓	✓			
4.	4.Question Summary			✓					
5.	Lateral Thinking (Thinking 1970)			✓	✓	✓			
6.	The Discontinuity Principle				✓				
7.	Thinkertoys (Fluk 2008)			✓	✓				
8.	Brainstorming (PUTMAN and PAULUS 2009)		✓		✓				
9.	Brainwriting (VanGundy 1984b)		✓						
10.	Forced Analogy (Huhns and Acosta 1988)		✓	✓					
11.	Nominal Group Technique NGT (Delbecq et al., 1975)	✓	✓						

12.	Attribute Listing (Crawford 1954)			✓					
13.	Morphological Forced Connections (Putri et al. 2019)				✓				
14.	Morphological Analysis (Zwicky 1969)				✓				
15.	Imitation					✓			
16.	Mind Maps * (Buzan and Griffiths 2013)			✓	✓				
17.	Storyboarding (Newman and Landay 2000)	✓		✓	✓				
18.	Synectics ** (Gordon 1961)			✓	✓	✓			
19.	Lotus Blossom Technique (Matsumura 1990)			✓	✓				
20.	Drawing and Visual Thinking (McKim 1972)	✓		✓					
21.	Camelot (Higgins, 1994)					✓			
22.	Checklists (Higgins, 1994)			✓					
23.	Limericks and parodies (Higgins, 1994)		✓						
24.	Role playing (Aldersey-Williams, Bound, and Coleman 1999)		✓						
25.	Workout/retreats/ incubate (Wallas 1926)	✓	✓						
26.	Kepner-Tregoe (Parker and Moseley 2008)			✓	✓				
27.	Draw a picture			✓					
28.	Experience kit			✓	✓				
29.	Fishbone diagram Liliana, 2016)			✓	✓	✓			
30.	King of the mountain		✓						
31.	Redefining a problem/opportunity [(Sirok and Likar 2015)		✓		✓				

32.	Squeeze and stretch			✓	✓	✓			
33.	What patterns exist?					✓			
34.	Why-why diagram (Kumar, Kataria, and Luthra 2020)			✓	✓	✓			
35.	Assumption reversal (Lavinsky 2009)					✓			
36.	Associations		✓						
37.	Circle of opportunity (Envick 2018)		✓						
38.	Deadlines	✓							
39.	Fresh eye	✓							
40.	Idea bits and racking (Gregory 1968)	✓							
41.	Idea notebook (BOO n.d.)	✓							
42.	Input-output (BOO n.d.)				✓				
43.	Listening to music (Chang & Liao, 2016)	✓							
44.	Name possible uses		✓						
45.	The Napoleon technique (Mattimore 1988)	✓							
46.	Product improvement checklist (VanGundy 1990)		✓						
47.	Relatedness		✓						
48.	Relational words		✓						
49.	Reversal – dereversal (Thomas, McDaniel Jr, and Dooris 1989)					✓			
50.	7x7 technique (Szewczak 1988)				✓	✓			
51.	Sleeping/dreaming on it	✓							
52.	The two-words technique		✓	✓		✓			
53.	Visualization		✓						
54.	What if?			✓					
55.	Gordon/Little			✓	✓	✓			

56.	Group decision support systems (Huber 1984)	✓							
57.	Idea board	✓							
58.	Idea triggers	✓							
59.	Innovation committee / Experts' opinion (Nielsen n.d.)	✓							
60.	Intercompany innovation groups / expert opinion (Nielsen n.d.)	✓							
61.	Lion's den	✓							
62.	Nominal group technique NGT (Delbecq, Van de Ven, and Gustafson 1975)	✓	✓		✓				
63.	Phillips 66 by Don Phillips	✓	✓		✓				
64.	Photo excursion		✓	✓					
65.	Scenario writing (Aldersey-Williams et al. 1999)		✓	✓					
66.	SIL method (combining) (VanGundy 1984b)		✓		✓	✓			
67.	TKJ (Similar to NHK)	✓	✓		✓				
68.	Delphi (Dull 1988)	✓			✓				
69.	Neuro-Linguistic Programming (NLP) (Dilts and Bandler 1980)	✓							
70.	Assumption Smashing					✓			
71.	DO IT [38] (Olson 1980)				✓				
72.	LARC (Williams and Stockmyer 1987)	✓							
73.	Unconscious Problem Solving (Spitz 1993)	✓							
74.	Basadur Simplex process				✓				

75.	Fuzzy Logic (Fuzzy Thinking) (McNeill and Freiberger 1994)				✓				
76.	SERENDIPITY	✓	✓						
77.	Wallas' model (Wallas, 1926)				✓				
78.	Rossman creativity model (Rossman 1964)								
79.	Working Paper: Models for the Creative Process (Plsek 1997)								
80.	Barron's Psychic Creation Model	✓			✓				
81.	Creative Problem Solving (CPS) Model (Treffinger 1995)				✓				
82.	Koberg and Bagnall"s Universal Traveler Model				✓				
83.	Robert Fritz's Process for creation (Fritz 1999)	✓			✓				
84.	Seven Steps by Roger von Oech				✓				
85.	SCAMPER (brainstorming) (Boonpracha 2023)	✓	✓	✓	✓				
86.	TRIZ (Mann 2001; Shulyak 2009; Webb 2002)	✓		✓	✓	✓	✓	✓	✓
87.	• TRIZ Contradiction Table and 40 Innovation Principles (Rousselot, Zanni-Merk, and Cavallucci 2012)	✓		✓	✓	✓	✓	✓	✓
88.	• TRIZ Ideality Concept	✓		✓	✓	✓	✓	✓	✓
89.	• TRIZ System Approach	✓		✓	✓	✓			✓
90.	• Ideation/TRIZ Patterns/Lines of Evolutions	✓		✓	✓	✓	✓	✓	
91.	• Ideation/TRIZ Problem Formulation	✓		✓	✓	✓			✓
92.	• Ideation/TRIZ ISQ	✓		✓	✓	✓			✓

93.	• Ideation/TRIZ ARIZ (Mishra 2013)	✓		✓	✓	✓	✓		✓
94.	• TRIZ Substance-Field Analysis	✓		✓	✓	✓			✓
95.	• TRIZ 76 Standard Solutions	✓		✓	✓	✓	✓	✓	✓
96.	• Ideation/TRIZ System of Operators	✓		✓	✓	✓	✓	✓	✓
97.	• Ideation/TRIZ IPS	✓		✓	✓	✓	✓	✓	✓
98.	• Ideation/TRIZ DE	✓		✓	✓	✓	✓	✓	✓
99.	• Ideation/TRIZ AFD	✓		✓	✓	✓	✓	✓	✓
100.	Subjective Objective System (SOS) (Ziv-Av and Reich 2005)								
101.	Six Thinking Hats (De Bono 2017)		✓		✓				
102.	SIT (Systematic Inventive Thinking) (Barak and Bedianashvili 2021)			✓	✓				✓
103.	C-K (Brunet 2013)	✓			✓	✓			

As mentioned earlier that this research is focused on SCs that generate by inventive design approaches in concept generation phase. So, during the study it identifies that many approaches were only useful in initial steps of problem solving before concept generation phase e.g Factorization(G Pahl et al. 2007) and PMI (plus, minus, interesting) approaches etc. are only useful in understanding the problem but not in ideas generating phase (De Bono 2006).Also, there were some approaches which were not clearly detailed about their implementation steps and there was no surety of usefulness of the approaches in idea generation phase like Prototyping (Herring, Jones, and Bailey 2009).

Thus, in the end, this study managed to narrow down he number of inventive design approaches to 25 or 30 shown in Figure 2, which have attracted the attention of researchers and organizations in the last two decades and are useful for generating SCs in the concept generation phase. Also, this study focuses on exploring the inventive approaches through which modern tools have been applied like TRIZ and its extensions such as IDM, IPG (Hanifi et al. 2021) etc.

In the following we will introduce some prominent inventive design approaches before going into details of TRIZ inventive design approach which is main focus of this study.

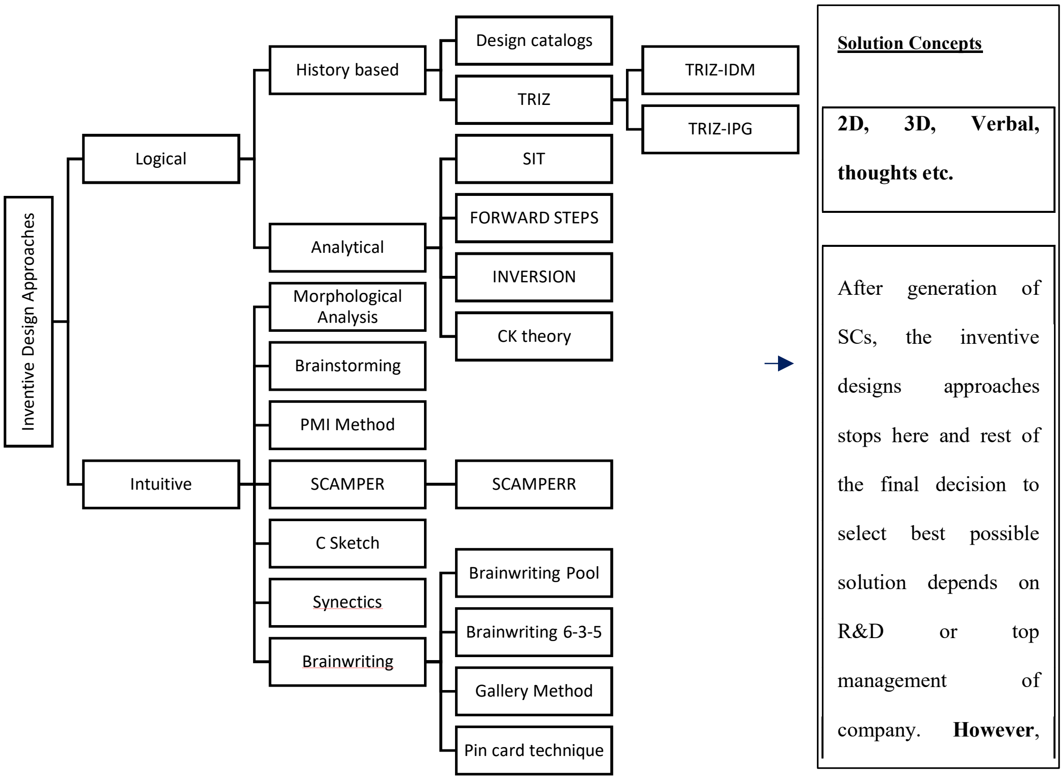


Figure 2. Classification of inventive design approaches

2.4.1. SIT/ASIT

The Systematic Inventive Thinking (SIT) methodology is a structured method for inventive idea generating by creation systematic manipulations. The SIT method (Barak and Bedianashvili 2021; Horowitz 2001) was derived from the TRIZ theory of inventive problem solving. SIT includes the following five principles or 'tools': • Subtraction: solving a problem by removing an object (with its main function) from the system; • Multiplication: solving a problem by introducing a slightly modified copy of an existing object into the current system; • Division: solving a problem by dividing or cutting an object or subsystem and reorganizing its parts; • Task Unification: solving a problem by assigning a new use or role to an existing object; and • Attribute Dependency Change: solving a problem by adding, removing or altering relationships between variables or attributes in a product or a system.

Advanced systematic inventive thinking (ASIT) is an advance version of SIT. The main central principle in SIT/ASIT is the `Closed World' (CW) principle, which insists that creative solutions of a problem depend on mainly on its neighboring environment(Barak n.d.).

2.4.2. SCAMPER

The SCAMPER brainstorming technique is an inventive design method. It can also turn a tired idea into something new and different. It is premiere version of systematic problem-solving (Osborn 1957) and follows set of directed questions to problem solutions. The acronyms that SCAMPER stands for are (Serrat 2017):S—Substitute (e.g., components, materials, people), C—Combine (e.g., mix, combine with other assemblies or services, integrate), A—Adapt (e.g., alter, change function, use part of another element), M—Magnify/Modify (e.g., increase or reduce in scale, change shape, modify attributes), P—Put to other uses , E—Eliminate (e.g., remove elements, simplify, reduce to core functionality), and R—Rearrange/Reverse (e.g., turn inside out or upside down).

2.4.3. CK Theory

C-K theory - or Concept-Knowledge theory - is an inventive design method presented by (Felk et al. 2011).C-K theory models the design process by integrating concept space C and the knowledge space K. A basic tool of this C-K theory is represented by the C-K map. Four kinds of operators can be used to model these two spaces expansions and interactions: K-C, C -K, C-C, and K-K (Le Masson, Weil, and Hatchuel 2010).

2.4.4. The theory of inventive problem solving TRI|Z

G. Altshuller developed TRIZ, also known as the theory of inventive problem solving, to aid engineers and scientists in solving problems by leveraging the knowledge of previous inventors (Altshuller, Al′tov, and Altov 1996). TRIZ provides a comprehensive toolbox for problem analysis and solving from various perspectives.

2.5. SOLUTION CONCEPT REPRESENTATION

After analysing the inventive design approaches, it was identified that the SCs resulting from these inventive design processes measures are usually described in a declarative manner or presented as 2D or 3D sketches or verbally, which does not allow for a formal or visual representation between project partners (three groups of peoples, i.e., an expert, designer, and top management of company or R&D) and with a lack of detailed info about SCs. Some examples of SCs generated by inventive design approaches are shown in Table 2. The inventive design approaches mostly have no inputs after generating SCs. The inventive design approaches do not offer precise and immediately applicable solutions, but rather rough ideas or solution concepts (Houssin et al. 2015). Additionally, it lacks the tools to focus on a standardized solution. The next step is to use these SCs to produce inventive solutions purely depending on R&D, project partners or top management of the company which often leads to less focus on these generated SCs and designer go for conventional solutions shown in Figure 3 and the results could be more successful if we apply rigorous evaluation at this phase. From this perspective, there is a research gap in methodological approaches that all the existing approaches lack rigorous methods for evaluating SCs, and thus this research work focuses on this area.

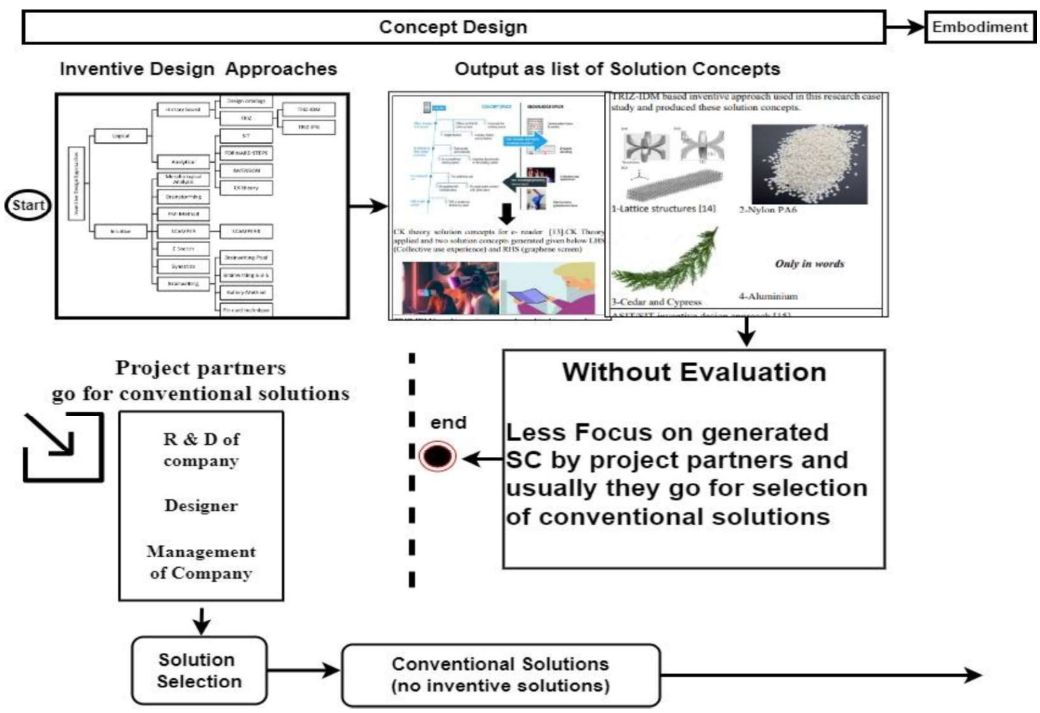
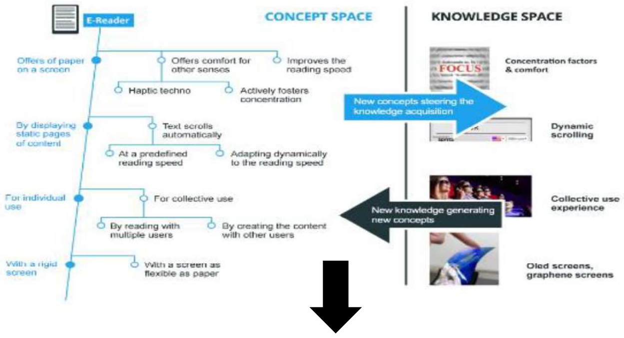


Figure 3. Schematic of solution concept evaluation gap

Table 2. Examples of solution concepts (SC) generated by inventive design approaches.

<table>
<tr><td>



CK theory solution concepts for e- reader (Anon n.d.).CK Theory applied and two solution concepts generated given below LHS (Collective use experience) and RHS (graphene screen)

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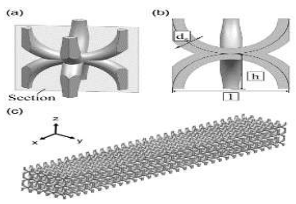
TRIZ-IDM based inventive approach used in this research case study and produced these solution concepts.



1-Lattice structures (Ding et al. 2020)

2-Nylon PA6

3-Cedar and Cypress

Only in words

4-Aluminium

</td></tr>
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ASIT/SIT inventive design approach (TRIZ Journal Editor n.d.)

A telecom company faced a docume ntation issue, and the SIT proposed two solution concepts.

1-The document collection process with the welcome visit,

2-The document verification executive should follow up with the franchisee for three days to complete the documentation and then collect even if the documentation is incomplete.

However, upon little analysis, these solution concepts needs more details (evaluation) to be useful for producing solutions.

</td></tr>
</table>

Among the inventive design approaches, in the category of systematic inventive design approaches, this research focuses on TRIZ (theory of inventive problem solving) based inventive approaches like Inventive Design Method (IDM). These inventive design approaches are helpful in the concept generation phase of inventive design processes which is focus of this study. In the following section, this study will detail the TRIZ approaches to produce SCs, and its limitations followed by a proposed evaluation framework in the next chapter. In the next phase, the research will be extended to other approaches as well.

2.6. TRIZ-IDM AND RELATED APPROACHES

Genrich Altshuller analyzed 400,000 patents in the 1950s and identified fundamental patterns that governed the generation of new ideas and creation of innovations. He used this analysis to develop the Theory of Inventive Problem Solving (TRIZ) with the aim of facilitating innovation (Altshuller 1984; Imoh M. Ilevbare, Probert, and Phaal 2013; Moehrle 2005). According to TRIZ any problem faced by designers may have already been solved by others (Altshuller 1984). The fundamental concept behind TRIZ is to provide a systematic approach for accessing a broad range of solutions that have been proposed by previous inventors (Mann 2001). This theory offers designers various tools and techniques that can be used to generate innovative ideas, instead of relying on traditional trial-and-error methods (Yang and Zhang 2000).

In TRIZ to solve the problem-, the real problem needs to convert into a conceptual one. Then, next to search the abstract solutions, helping to diverge thinking and generate practical solutions (Haines-Gadd 2016). Figure 4 showing the main TRIZ approach to solve a problem.

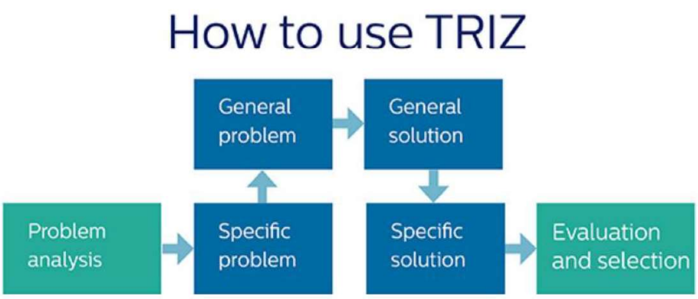


Figure 4. Basic TRIZ approach to solve problem.

2.6.1. TRIZ Notations

2.6.1.1. Contradictions

According to (Imoh M Ilevbare, Probert, and Phaal 2013), contradictions arise when desired characteristics within a system conflict with each other, leading to inventive problems. Solving technical problems that contain a contradiction often produce the most effective solutions (Shulyak 2009). However, due to their challenging nature, people tend to avoid these types of problems and go for conventional solutions (Haines-Gadd 2016). TRIZ seeks to provide solutions for resolving contradictions within a system, and there are three types of contradictions as identified by (Rousselot et al. 2012).

- Administrative contradiction:

An administrative contradiction refers to a situation where there is a desire to improve a system, but the direction for resolution is unclear. To address this type of contradiction, it should be transformed into a technical contradiction. Doing so can help to reduce ambiguity and clarify the problematic situation (Montecchi and Russo 2015).

- Technical contradiction:

A technical contradiction arises when the improvement of certain characteristics within a system leads to the deterioration of other characteristics within the same system. For example, increasing the size of an engine may improve the speed of a car, but it could also increase its weight, leading to a trade-off between the two characteristics (Imoh M Ilevbare et al. 2013). To facilitate the resolution of technical contradictions, TRIZ suggests using the matrix of contradictions, which consists of 39 features that are commonly used in the design process, as well as inventive principles. This matrix helps to identify the specific contradictions that need to be resolved and provides guidance on the principles that can be applied to find solutions (Yang and Zhang 2000). Technical contradictions can arise in various situations, including (Montecchi and Russo 2015):

  - The creation of a beneficial function in one subsystem to cause the emergence of a harmful function in another subsystem.

- Eliminating a harmful function in one subsystem may have a negative impact on a beneficial function in another subsystem.
- Enhancing the positive impact of a useful function or reducing the negative impact of a harmful function may result in an undesirable increase in complexity in other subsystems.

- Physical contradiction:

Physical contradiction occurs when one element of the system should have two opposite values simultaneously (Imoh M Ilevbare et al. 2013). For example, an umbrella should be small for user convenience but also large enough to provide adequate protection (Imoh M Ilevbare et al. 2013).

According to TRIZ, a contradiction involves three components: 1) an element, 2) parameters, and 3) values, as described by (Cavallucci, Rousselot, and Zanni 2009, 2011; Zanni-Merk, Cavallucci, and Rousselot 2009) :

1) Element, 2) Parameters, and 3) Values. The following sections will explain each component in detail.

- **Elements:**

The first component of a contradiction is the "element," which refers to the constituents of the system (Cavallucci et al. 2011; Zanni-Merk et al. 2009) . Elements can be described using nouns, names, or groups of names. The nature of an element can also change depending on the description provided (Cavallucci et al. 2009). For example, the statement "the hammer pushes the nail" can be rephrased as "the anvil drives the nail" by another expert (Cavallucci et al. 2011).

- **Parameters:**

Parameters provide specificity to the elements and reflect explicit knowledge of the observed field (Zanni-Merk et al. 2009). It is possible to use adverbs, names, or complements to object to express the parameters. The expression of parameters varies depending on the expert (Cavallucci et al., 2009). There are two categories of parameters, as described by (Rousselot et al. 2012):

- ***Action parameter:***

The parameter that depicts the designer's capacity to alter its states is called action parameter. Its value may be either positive or negative. When it has positive value (V), it means that it has a positive consequence on the other parameter and when its value is negative (-V) it means that it has a negative impact on the other parameter (Cavallucci et al. 2011; Rousselot et al. 2012). For example, the designer wants to change the weight of the hammers head, then in this case, Weight is an action parameter (Cavallucci et al. 2011).

- ***Evaluation Parameter:***

It is the parameter that evaluates both the aspects of the designer's decision i.e., positive as well as negative (Rousselot et al. 2012). In case of designing the head of hammer heavy to facilitate the driving of nail, the facility of driving is the evaluation parameter. (Zanni-Merk et al. 2009). One of the differences between the evaluation and action parameter is that the evaluation parameter has one logical direction whereas the action parameter has two logical directions (Cavallucci et al. 2009).

- **Values*:***

The attributes that are used to describe a parameter are called values (Cavallucci et al. 2011). In the decision of keeping the weight of the hammer high, high is regarded as a value that describes the weight.

- **Poly-contradiction**

When different parameters encounter each other there appears many contradictions so it is very important to show the relation between these contradictions. This can be possible by applying the poly contradiction template. It is a table in which the Action Parameter (AP) is located on the top of the table and all the related Evaluation Parameters (EP) are listed under the (AP).

- **Triz Tools**

TRIZ methodology comprises of several tools and techniques that are classified as the following (Yang and Zhang 2000):

- Analytical tools for problem analysis
- Knowledge base tools for system changing.

2.6.1.2. Analytical tools

Such as functional analysis and Su-field analysis contribute to articulating a problem (Imoh M Ilevbare et al. 2013). Below there is a description of each tool.

- **Function analysis:**

This tool helps to plot the components so that the problems can be draw out that are arising from the system function (Gadd 2011). Function is the incentive for the presence of a system (Cascini 2012) (Fey and Rivin 2005). The result of the action between a subject and the object in the system is basically the Function (Fiorineschi et al. 2018). The subject (tool) generates the action, and the object accepts that action (Fey and Rivin 2005).

- **Su-field analysis**

A TRIZ analytical tool that signify a graphical model of problems that are related to a technological system is called the Su -Field analysis (Terninko 2000). It is consisted of three components; a field named F and two substances named S1 and S2 (Chang 2005). In a system, a substance is considered as a tool if it generates an action and considered as a product if it receives the action produced by tool (Bultey, De Bertrand De Beuvron, and Rousselot 2007). Field is defined as an energy, being necessary for the interaction between two substances (Chen and Huang 2011).

2.6.1.3. Knowledge-based tools

Knowledge-based tools deliver information to change the systems. In this group, it is likely to remark the tools such as the inventive principles, 76 standard solutions and effects (Imoh M Ilevbare et al. 2013).

- **Inventive principles:**

The early TRIZ community had derived 40 ways to solve the contradictions after examining 40000 patents in different fields like mechanics, chemistry, electrical engineering and named them as the 40 incentive principles (Beckmann 2015). These principles are universal resolutions to perform an action in a system (Altshuller 2002). When these principles are applied to solve a problem, these allow the designers to generate several innovative and rare ideas (Beckmann 2015).

By using the contradiction matrix, problem-solvers can link to inventive principles. Additionally, they can rely on their personal intuition to identify the most suitable principle (Moehrle 2005). Altshuller developed the contradiction matrix as part of his research on patents, and it has since become one of the useful tools in TRIZ (Savransky 1997). The matrix consists of 39 columns and rows (Moehrle 2005). The horizontal rows contain the technical parameters to be enhanced, while the vertical columns signify the technical parameters that can be degraded as a result of improving the parameters (Nix, Sherrett, and Stone 2011). The intersection of the improved and degraded parameters contains the numbers that guide the designers to the inventive principles (Savransky 2000).

Three steps are involved in the application of contradiction matrix. 1) Step 1: The first step is the translation of the desired parameter into one of the technical parameters present in the rows. 2) Step 2: The second step is the changing of the harmful features into one of the parameters of the vertical columns. 3) Step 3: The final step is the extraction of one or several inventive principles from the joining of the parameters to solve the technical contradiction (Moehrle 2005).

- **76 standard solutions:**

To solve the inventive problems Altshuller and his associates developed the 76 standard solutions between 1975 and 1985 which is based on the laws of evolution of technological systems (Russo and Duci 2015; Yang and Zhang 2000) . Rendering to their objectives, the standards are classified into 5 classes and 18 groups (Livotov 2008; Terninko, Domb, and Miller 2000):

    - Class 1it comprises of 13 standard solutions that assist to progress the system with no or little modification.

- Class 2 contains 23 standard solutions that contribute to improving the system through its modification.
- Class 3 encompasses 6 standard solutions that help the system change.
- Class 4 includes 17 standards solutions applied in the measurement and recognition in the technical.
- Class 5 involves of 17 standard solutions used as approaches for upgrading and generalization.

The standards are generally employed as a step of ARIZ (Altshuller and Victory 1985). To apply these tools effectively, one must first identify the components and create a Su-Field model. This model can help in determining the class and finding a specific solution (Savransky 2000).

2.7. TRIZ'S ADVANTAGES AND DRAWBACKS

One of the advantages of TRIZ is its capability to discover the probable answers to the identified problems, while other practical procedures to problem solving, such as mind mapping, brainstorming, could only help to expose a problem, and its associated reasons. Furthermore, TRIZ could contribute to dropping the amount of time to expose an optimal solution and launch a new product. But there are numerous limitations involved in applying classical TRIZ in the R & D departments (Cavallucci 2014). The first is that it does not provide any means to express the problems in the early situations. Second, there is no means in TRIZ to lead its users to choose the best answers among the proposed ones. As the third limitation, TRIZ does not also provide a precise way to disclose a contradiction. Finally, there is not a complete explanation of its components and the relations between them in TRIZ's body of knowledge. To overwhelm these limitations, researchers have developed numerous frameworks such as Inventive Design Methodology (IDM).

2.8. TRIZ-BASED INVENTIVE DESIGN APPROCHES

After introduction of TRIZ, various frameworks have been developed to solve its drawbacks. Among them, it is possible to mention xTRIZ, OTSM-TRIZ and Inventive Design Methodology (IDM). Here, we briefly describe each framework and their related process.

2.8.1. xTRIZ

It is a problem-solving process that supports the application of TRIZ in Management and business. It was developed in seven stages (Souchkov 2007). These are:

1. Collection of the information: In this stage, the information about the problem is gathered. Additionally, restrictions, restrictions, and major targets, used as criteria to evaluate new ideas created in stage 5 of the process, are recognized (Souchkov, Hoeboer, and Zutphen 2006).

2. Decomposition of the problem: The second stage of stage xTRIZ process relates to the decomposition of the problem by applying the RCA+ (Souchkov 2007).

3. Identification of the contradiction: The thirds stage of the process relates to identify the contradictions that can benefit the designers to attain the expected results (Souchkov 2007).

4. Creation of a list of available resources: In the fourth stage, a list of the available resources within the contradictions' context is formed. The creation of this list should be achieved by considering classical TRIZ procedures (Souchkov et al. 2006).

5. Generation of inventive solutions: In the fifth step, the two TRIZ tools such as contradiction matrix and inventive principles are used to create new inventive solutions and remove the contradictions (Souchkov et al. 2006): The sixth stage concerns about generating a tree of generated solutions (Souchkov 2007).

6. Evaluation of the solutions: The seventh stage relates to the evaluation of the solutions by applying Multi-Criteria Decision Matrix. The purpose of this stage is to recognize the best solutions.

2.8.2. OTSM-TRIZ

It is the Russian abbreviation for General Theory of Powerful Thinking that make known to new method to describe complex problems, which is called Problem Flow Network (PFN) (Baldussu, Becattini, and Cascini 2011). The objective of OTSM-TRIZ is to accomplish interdisciplinary and complex problem (Nikulin et al. 2014, 2018). OTSM includes two main phases (Khomenko et al. 2007): 1) Construction of Networks, 2) Proposition of solution.

1. Construction of Networks phase: The first phase comprises on developing several networks by smearing OTSM's technologies. These networks are: 1) Network of Problems, 2) Contradiction Network, and 3) Parameter Network (Khomenko and De Guio 2007).

2. In the second phase, the process suggests applying the tools such inventive standards, inventive principles developing by classical TRIZ to answer the problems (Khomenko et al. 2007).

2.8.3. Inventive design method: IDM

The Inventive Design Method (IDM) is a framework that has been developed through years of research to address the limitations of TRIZ and complement its body of knowledge with other theories such as Pughs theory and graph theory (Cavallucci and Strasbourg 2009).

This IDM framework comprises the following four phases (Cavallucci and Strasbourg 2009).

1. Initial Analysis phase: In this phase, first, the designers should collect all the related knowledge, coming from internal documents and patent, tacit know-how of experts, and other related documents to the subject. Then, the gathered knowledge should be changed into a graphical model to facilitate decision-making (Cavallucci and Strasbourg 2009). For this purpose, it is possible to apply problem Graph.

2. Contradictions Formulation phase: In the second phase, the designers could apply numerous methods such as poly-contradiction template to express the contradictions, which are technical and physical issues in a system (Cavallucci 2014). These issues are considered as bottlenecks in the development of the system. Afterward, the extracted contradictions are used as an input point to apply TRIZ techniques and methods. The

purpose of this phase is to develop the contradictions that are utilized as inputs for the application of TRIZ tools (Chibane, Dubois, and De Guio 2021).

3. Solution Concept Synthesis phase: The designer applies different TRIZ tools to solve physical and technical flaws in the third phase (Cavallucci and Strasbourg 2009; Yan et al. 2018).

4. Solution Concept Selection phase: In the last phase, the experts should balance the concepts in order to degree the effect of each concept. To this end, they could apply an evaluation grid to select the most related concept (Cavallucci and Strasbourg 2009).

In this thesis, we focused on the SCs produced by IDM process. A concept of any product is a foretold representation of the shape of product, its working principles and technology. It is a well explained definition of product characteristics that specifies how the product will satisfy the customer requirements. The success of any product depends on the selection of best concept. Success here means the commercialization of a quality product. With reference to inventive design SC, the arrival of TRIZ and its allowance to IDM has been considered as a systematic methodology to produce set of SCs as compared to earlier formless methods.

After SCs are recognized and ranked using Pugh's matrix by the IDM. The next step is to assess SCs to select the suitable SC for the next phase. The evaluation phase of SC is the key trial for the designers, as well as the customers. Predominantly in SC selection phase qualitative methods are used to evaluate the produced solution concepts. Although, to enable the SC evaluation steps, there are many methodologies used by designers and customers (Chinkatham and Cavallucci 2015; Cross 2000; Stalnaker 1994). However, these methodologies are generally designated in a qualitative, declarative manner, which does not allow to choose the best solution concept neither to have a shareable formal or visual representation between partners of the project, like (Ulrich and Eppinger 2012) gives principally comparative judgements. Pahl & Beitz (Pahl and Beitz 2013) use multicriteria methods to differentiate technical and economical ethics. In IDM the process stops after standing of solution concepts and final selection of SC to develop depends on research and development (R&D) department or the top management of company. That is why, the time off of a self-assured model does not allow evaluation and compare challenging concepts thereby making a challenge for researchers and designers to develop a confident model for evaluation of SCs in IDM.

This framework is considered as an enhancement over TRIZ but still there are some drawbacks in terms of the evaluation of SCs. Like other inventive design approaches, the TRIZ-IDM identifies several SCs. However, after the generation of these SCs, only the list of generated SCs is provided and IDM stops there. The next step of evaluating SCs and generating concepts depends on human expertise of the R&D department or top management of the company. Also, in the initial phase there is always a lack of detailed information and knowledge, with more risks of information loss, so there should be an efficient way to represent and evaluate SCs in such situations.

2.8.4. Inventive design method IDM drawbacks

Evaluation methods are referred as methods which provide improved and more detailed knowledge for decision making steps. Mostly the methods for evaluation of alternatives are used in the final solution selection and are simple with no representation of alternatives. Evaluation methods are most essential inputs to innovative design methods, and it is also necessary to make it available in the initial step of concept designs where there is always lack and loss of information., The TRIZ inventive design SCs considered as intangible structures capable of fulfilling required functions of required artifact. This indicates that main features of a SC may be represented by a set of few fundamental design domains such as function, behavior, and structure (FBS) aspects. The literature shows that there has not been much focus on functional and behavioral aspects of SCs in inventive design approaches. Therefore, the proposed framework of evaluation for SCs is based on FBS domain of SCs. By doing so, the result is the evaluated SCs, with more confident data of SCs offering shareable formal or visual representation between partners of the project. This article outlines our approach for the development of this new evaluation framework.

2.9. DISCUSSION OF CHAPTER

The inventive design approaches which are useful in concept generation phase of engineering design are lack of evaluation frameworks. Based on the limitation of evaluation and knowing that generated SCs not only contain functional data, but also very likely to have data of behavioral and structural domains. So, we propose a FBS (Function Behavior Structure) SC modelling based on object-oriented modelling formalism. Because of the importance of function, behavior and structure, there have been countless definitions, descriptions, and discussions on them in the research community. The Function Behavior Structure FBS approach initially proposed by (Deng 2002a; Rosenman and Gero 1994; Umeda et al. 1996) forms part of the research area in functional, behavioral and structural modelling. A general idea is of SC representation with FBS is shown in Figure 6 .The FBS approach in TRIZ also used by some researchers by rewriting TRIZ principles based on FBS (Russo and Spreafico 2015), using FBS for device functions clarification or using FBS for TRIZ contradiction definitions (Chulvi and Vidal 2009). However, FBS has not been used for purpose of SCs evaluation in the initial design phase of inventive designs.

3. PROPOSITION OF SOLUTION CONCEPT EVALUATION FRAMEWORK BY FUNCTION, BEHAVIOR, AND STRUCTURE APPROACHES

3.1. LITERATURE REVIEW OUTCOMES

In the initial concept generation step of inventive design approaches, the approaches produce solution concepts (SCs). The inventive design solution concept SC is not a real product or solution/structure rather it is a rough idea of product which has the capability to guide project partners (designers, experts, R&D and top management of company etc.) to produce inventive solutions / product to problem(s) under consideration. It is a combination of different elements (i.e., functions, parameters, problems, contradictions, or requirements etc.). And how to generate an inventive solution from these elements is a big challenge because there are no methods for evaluation and comparison of these SCs at this stage. Due to these limitations the project partners usually go for conventional solutions instead of focusing on SCs to produce inventive solutions. From this perspective, there is a research gap in methodological approaches that all the existing inventive design approaches are lacking rigorous methods for evaluating SCs in the concept generation phase. The literature output and research gap are illustrated in the Figure 5.

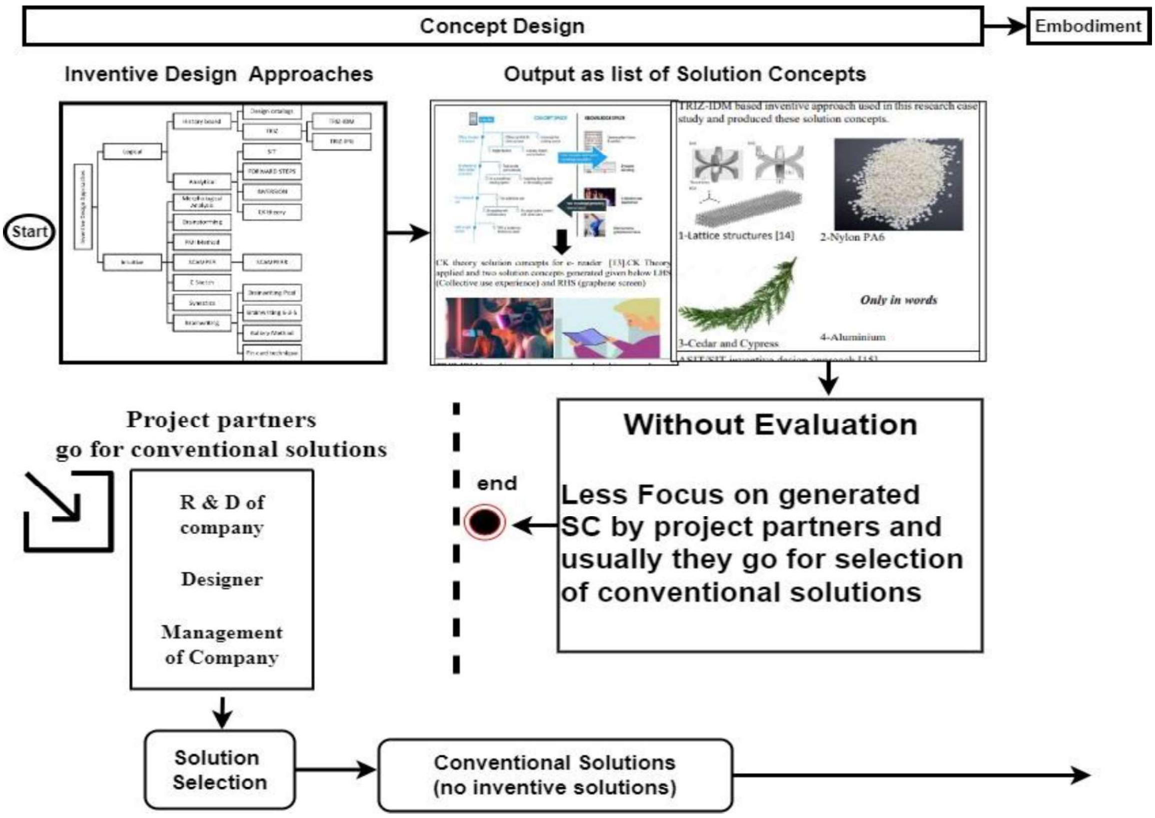


Figure 5. Schematic of research gap resulting more focus to conventional solution

To deal SCs in such situations there are two main problems to answer. First, how to represent a SC which is not a product but an idea with several elements. The second problem is how to build the evaluation framework in order to evaluate and compare important elements of SCs.

Therefore, to answer these problems, this study has proposed an evaluation framework for SCs in inventive design by combining different methods. We have combined methods in such a way to propose our own method of building a new evaluation framework that can allow us to compare two or more solution concepts. By doing so, this study will be contributing in terms of representation and evaluation of SCs.

3.2. SOLUTION CONCEPT REPRESENTATION

The inventive design SC is an idea that is not materialized in terms of a product, but capable of fulfilling intended functions of the expected product. This indicates that the main features of a SC may be represented by a set of few fundamental design domains such as functional, behavioural, and structural (FBS) domains. The literature review shows that there has not been much focus on functional and behavioural aspects of SCs in inventive design approaches. Therefore, for the formal representation of SC, this study says that a SC must fulfil certain functions and behaviors and fulfilling these functions and behaviors, SC could lead to a solution or structural solution, and it is formally expressed as:

$$f(F,B) \rightarrow S \quad (1)$$

The generic schematic of how SC representation modelling is concerned with FBS domains shown in Figure 6 is already presented in (Yehya et al. 2021) .

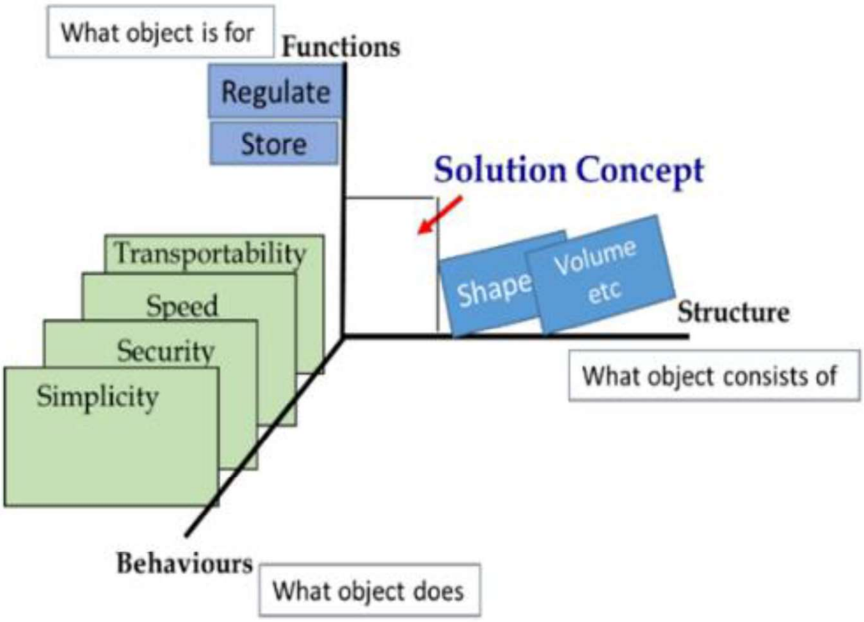


Figure 6. FBS aspects of solution concept representation

These basic findings of SC made possible to proposed evaluation framework which makes the idea that designer can evaluates a SC in each specific domain. The general proposed SC modeling approach focuses on evaluating the SC in expected functional, behavioral and structural dimensions.

The proposed framework of SC evaluation consists of 5 main steps. Step 1- Data collection, Step 2- Function identification Step 3- Functional decomposition, Step 4- Function-Behavior Semantic relationship and Step 5- Function-Behavior-Structure relationship shown in Figure **7**.These steps are detailed in section 3.2.

Main objective of using FBS modeling is to deal SC firstly by function evaluation through decomposition of functions subjectively (human judgement) and then by focusing on expected

FB relationship and further by using expected behavior as a bridge to link function and expected structure relationship providing designers an evaluated result of SCs to produce inventive solutions to problems.

Before going into detail of main steps, it is important to elaborate the term FBS in the perspective of this research. Because of the importance of function, behavior, and structure, in design processes, there have been countless definitions, descriptions, and discussions on them in the research community. The FBS initially defined by Gero (Deng 2002b; Rosenman and Gero 1994; Umeda et al. 1996) forms part of the research. When dealing with FBS there is confusion regarding function and behavior which often mixed each other (Proctor 2001). The terms function describes what it is for, behavior describes, what it does, and structure defines what an artifact is prescribed by Gero's (Hamraz et al. 2015) as shown in FBS aspect of SC Figure 6.In the following each term is elaborated.

3.2.1. Function

Many approaches proposed for function and function modeling (Baldwin, Clark, and Clark 2000; Chakrabarti and Blessing 1996; Khire and Messac 2008; Mukherjee and Liu 1995; Proctor 2001; Umeda et al. 1990). Functional requirements illustrate what an artifact should do for a possible solution. Some general examples of function initially provided by (Al′tšuller 1995) are separate, transfer, change, control, destroy, initiate, intensify, lower, modulate, raise, create, destroy, generate, accumulate, check, indicate, inspect, measure, setup, stabilize etc. Tomiyama (Tomiyama, Umeda, and Yoshikawa 1993) defined function as" a description of behavior abstracted by human through recognition of the behavior in order to utilize the behavior". Gero defined function as" the design intentions or purposes" (Dorst and Vermaas 2005; Gero, Tham, and Lee 1992).

Function of any system or artifact is very hard to define only objectively (without human opinion) because functions are requirements, intentions which are imagination of designers or customers based on Gero's definition of function. Take the example of a wooden table function, a designer can imagine one of its functions "to support items" and other designer "to provide cover during earthquake", even if the designers observe the same behavior" resists external loads". That is why function is related to both physical behavior and human perception of behavior i.e., objectively, and subjectively respectively.

In this study, function is used in two aspects as used by (Tomiyama et al. 1993) i.e., function symbolic representation illustrated by "to do something" proposed as value engineering (Miles 1962) with focus of design intentions and second one by functions semantic representation based on function behavior relationship (F-B relationship) (Coulibaly, Mutel, and Ait-Kadi 2007; Deng 2002a).

3.2.2. Behavior

Gero defined behavior as" how the structure of an artifact achieves its functions" (Gero et al. 1992).Behavior can be illustrated by physical states of an artifact and physical laws which shows that behavior can be defined objectively (without or not influenced by personal opinions or feelings) as changes of physical states. For example, take the behavior of a wooden table which could be to resists external load, reflection (color) and chemical and thermal reactions etc. with respect to the functions of that table.

In case of TRIZ based inventive SCs which is not a structural artifact rather it is a subset of required functional and behavioral domains, so it is very likely possible to see the behavioral aspects of SC as expected behavior for the expected structure solution. Some common examples of behavior are like chemical reactions, thermal reactions, resists impact load, reflection, friction, maintainability, durability etc. (Coulibaly, Houssin, and Mutel 2008; Raju et al. 2021).

3.2.3. Structure

Gero defined structure as" the component which makes an artefact and their relationships" (Gero et al. 1992). In structural the geometry, dimensions, topology, material, shape, location, and other physical properties are defined in connection to produce a technical solution (structural artefact) satisfying the required functional and behavioral aspects.

As this study is concerned with inventive design SCs which is related to concept generation step for producing innovative artifacts or solutions, so there is no structural design available. It could be useful to precise that in the phase of SC generation (after specification and before conceptual design) the structure is not defined yet and designer don't have much data, info about structure so the evaluation only identifies expected structural domain.

The globally known comprehensive framework for describing a product / artifact is based on its functions, behavior and structure FBS (Gero 1990; Thimm, Lee, and Ma 2006). The FBS framework encompasses all the critical aspects necessary for a successful artifact or solution. However, in the case of SCs, which are not fully realized as a product or solution, but it is very near to a solution or structure. It can provide a general idea or direction for creating an artifact or solution. Evaluating an SC across different domains of the FBS can be challenging due to the lack of evaluation models during the concept generation phase. Traditional methods of evaluating a product's reliability rely on statistical data from similar products, which may not be available for SCs in this case. To address this challenge, this study proposed a model based on the FBS framework that captures and analyses data and knowledge about SCs in the FBS domains. The model incorporates subjective evaluation of functions of SCs through human intention analysis, which helps to identify possible directions for the project partners to create innovative solutions with confidence by linking the expected behavioral and structural aspects. FBS are used in many fields like production, manufacturing, service, and software etc. How these domains can be related to our proposed model in terms of FBS is shown in Table 3.

Table 3. Different domains of design world

SC Domain	**Functions**	**Behavior**	**Form/Structure which fulfills required functions**
Mfg.	Product functional requirement	How structure fulfills required functions	Physical domain fulfilling functional requirement
Software	Output	How structure fulfills required functions	Algorithms and input variables
Materials	Required properties	How structure fulfills required functions	Microstructure
Systems	Systems functional requirement	How structure fulfills required functions	Machines or components and subcomponents

3.3. STEPS OF PROPOSED EVALUATION FRAMEWORK

In order to start this method, the Figure *7* illustrates steps of the proposed evaluation framework.

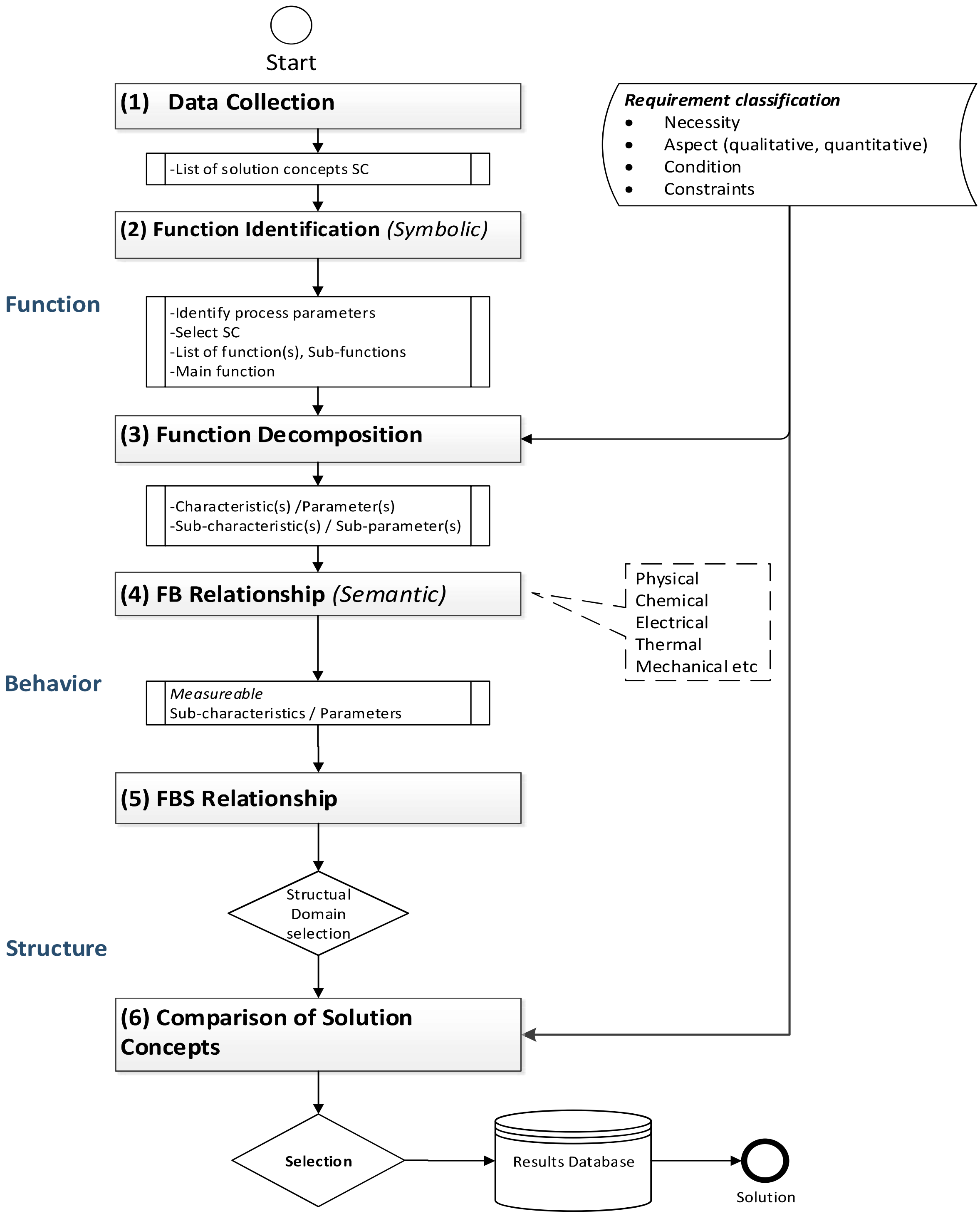


Figure 7. Proposed evaluation framework

This framework initiates by considering the acceptability of SC through functional evaluation subjectively. After generating and providing list of SCs in the concept generation phase, here a scientific question arise that which SC should be given focus before going to development phase. The designer has to use a model to evaluate the SCs and based on these evaluated results select the better SC for producing solutions. The generated SCs are analyzed using the proposed evaluation framework in the following steps.

3.3.1. Step 1- Data collection

First, we need list of SCs generated and all possible information related to initial problem and problem formulation to start the evaluation analysis. Only the list of SCs is very difficult to analyze. To do that, this study proposed step 1.

In this step the method initially helps to gather all the related information, data, technical drawings, documents about the SC(s). This related information includes the detail discussion with designers, customer and other experts involved in the initial problem formulation for the authentication of these data and to avoid loss of information. A List of generated SCs have to be provided in this step because the SCs are the main inputs of evaluation framework. Then next, a list of related functions is identified like transfer, change, control, destroy, initiate, intensify, lower, modulate etc. because functions are the fundamental procedures used to work with any artefact / solution design.

In next steps, each SC will be evaluated one by one with proposed steps which will give more confident data to designers to help producing inventive solutions.

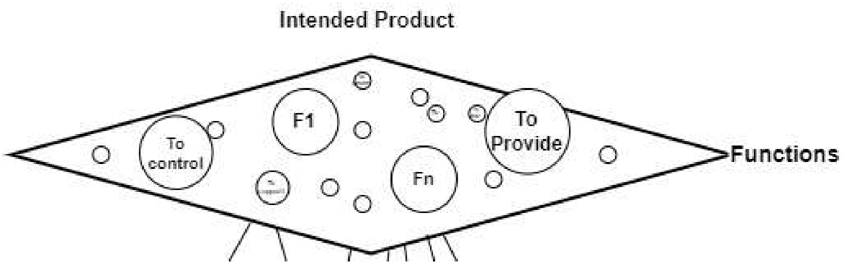
3.3.2. Step 2- Function identification

As our proposed framework is based on function, behavior and structural domains therefore following the information collected in first step, the second step is the identification of related functions and main function(s) of SCs to focus and present function(s) symbolically e.g., functions like “to support objects”, “to provide partition” and “to stop movement” etc. Here the list of related function(s) is identified with the involvement of designer, experts, and project partners. For reference a list of general functions presented to project partners which make them easy to identify the intended functions of SC. Lis of general functions is given in Table 4 . In future with the help of modern tool it is also possible to link already built function bases with inventive design approaches and evaluation framework to make the process more agile.

Table 4. List of general functions

Main category	Details
Branch	Cut, Branch, Separate, Count, Display, Filter, Remove, Distribute, Dissipate, Refine
Channel	Transmit, Transport, Import, Export, Guide, Stop, Transfer, Translate, Rotate, Allow DOF
Connect	Compare, Divide, Subtract, Switch, Connect, Mix, Pack, Add, Multiply, Valve, Mark, Couple
Change Magnitude	Crush, Process, Form, Coalesce, Change
Convert	Condense, Convert, Differentiate, Evaporate, Integrate, Liquefy, Solidify, Sense
Store/Supply	Release, Store, Supply, Stop, Hold
Information	Input Transducer, Decider, Internal transducer, Channel and Net, Decoder, Timer, Memory, Output Encoder, Transducer, Associator
Control magnitude	Actuate, Regulate, Change, Form, Condition
Support	Stabilize, Secure, Position, Translate, Rotate, Allow DOF, Stop, Provide
Signal	Sense, Indicate, Display, Measure
Provision	Store, Supply, Extract

Once intended functions are identified, these functions need to be analyzed. As discussed earlier that function of any system or artifact is very hard to define only objectively (without human opinion) because functions are requirements, intentions which are imagination of designers or customers based on Gero's definition of function. That is why in this study one of the known dimensionality reduction techniques Semantic Differential scales (SD scale) (Osgood, Suci, and Tannenbaum 1957) is suggested to use as quantifying chart. Why this study recommends this method, because this rating scale is highly rated quantifying method which allows individuals and organizations to measure stakeholder's view or attitude lies to a statement on a bipolar adjective scale (i.e., with opposite meanings), each representing a seven-point scale or five-point scale for function or function related characteristics, so that function is quantifiable. The SD scale chart can be used in any step where there feels necessary to narrow down or quantify the qualitative data. The use of such quantifying chart gives more detail information of human intentions.

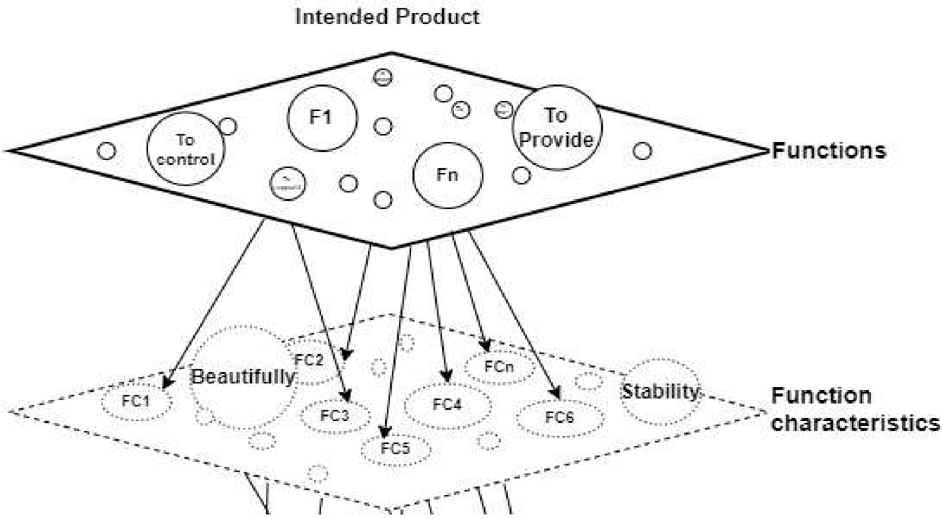


3.3.3. Step 3- Function decomposition

As discussed earlier that function is generally qualitative in nature and symbolically denotes with (to + verb). It is hard to scale function directly by using symbolic function. As we are using the FBS aspects for the evaluation of SCs, so next thing needs to elaborate function in such a way that it gives more details of the function and making way to link expected behavioural aspects easily with quantifiable data. Only function itself with symbolic representation is sometimes not possible to give all needed information. So, to cope with this challenge, we have proposed step 3 as "function decomposition" and it is done uniquely by decomposing function into related intended function "characteristics" by input of project partners and then identifying most important ones by using SD scale.

Additionally, one thing to mention here about final identification of important one by taking inputs of project partners which is three or more types of people. These different groups of people (i.e., designer, experts and top management of company) have different levels of knowledge but in same field. Despite of difference in level of knowledge, the final selection should be of that function or function characteristic(s) etc. which is highest rated by all the project partners.

If function itself is not easily linking to expected behavior of the SC, then function decomposition into function characteristics and then by using SD scale to narrow down most important characteristic(s) of function is very important to link function to expected behavior in next step.



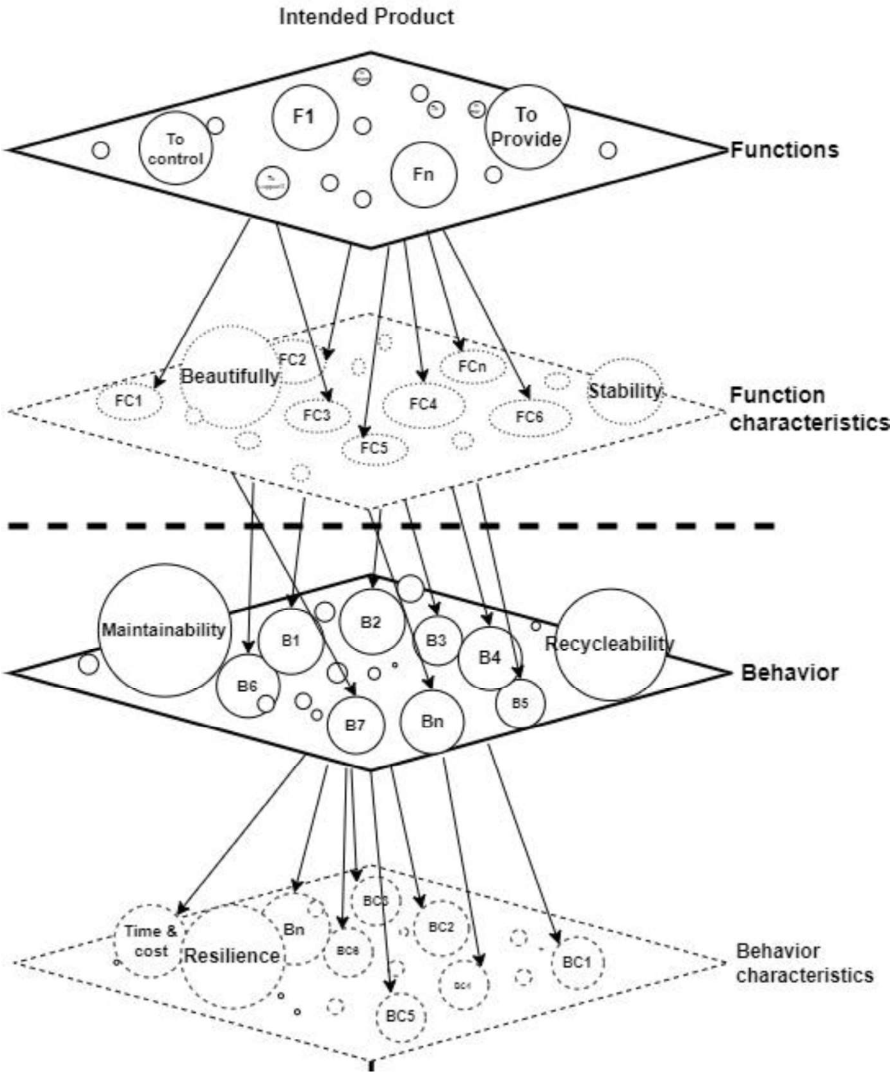
3.3.4. Step 4- FB semantic relationship

In step 4, after the function decomposition, based on all the information gathered from previous steps, the project partners now identify list of related expected behaviors of SC under consideration and identify most relevant behaviors. Moreover, before going to last step of expected structural domain, using expected function-behavior relationship with function also related behavioral parameters are identified which is most probably some characterizes which is very near to structural domain and having measurable units in most of the cases like mechanical properties.

At each step the result is stored in the main final table and also in the FBS analysis flow graph.

An example how FBS analysis flow graph and final table of comparison looks like is shown in section 4.2.1.6 and

Table **12**.

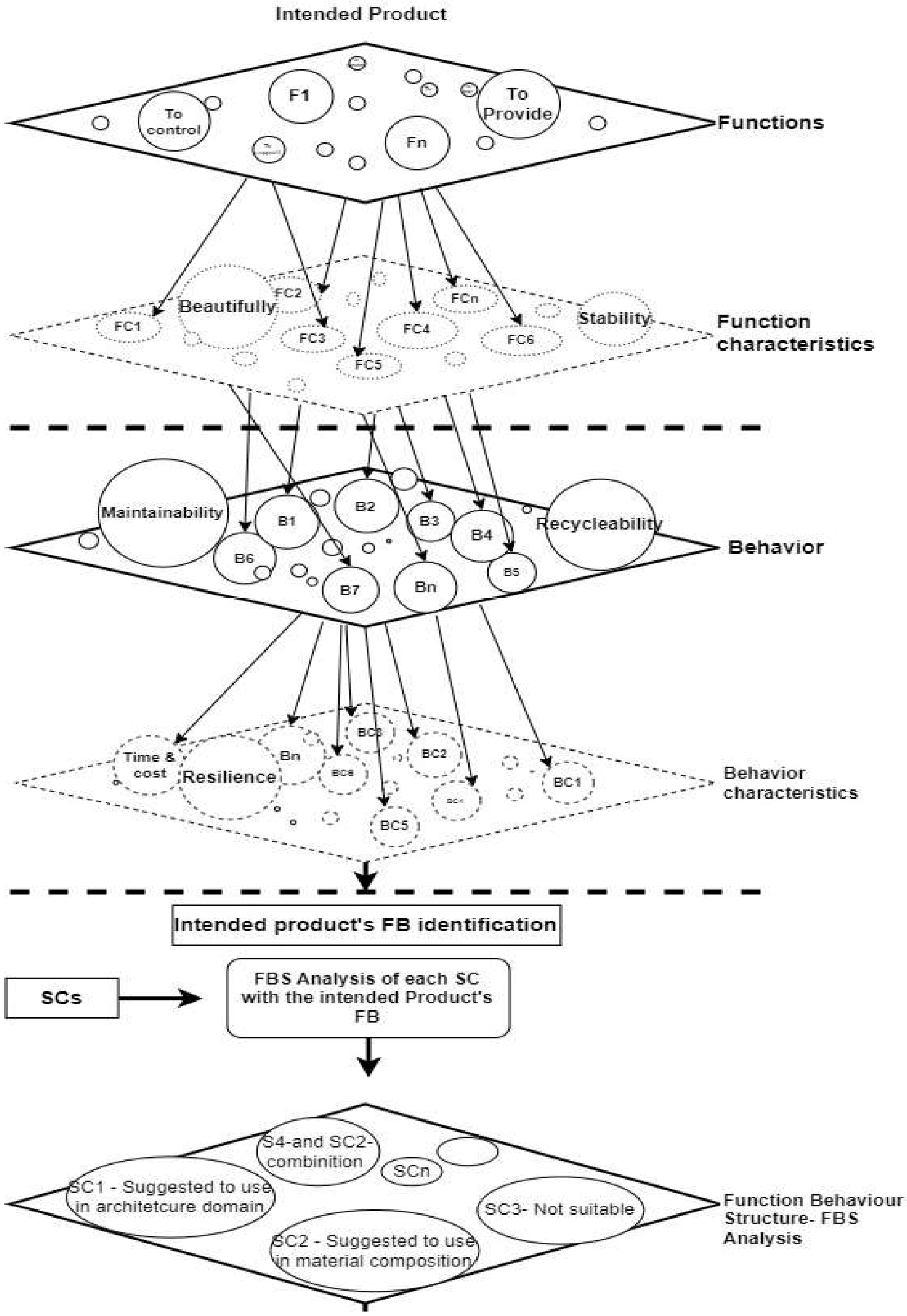


3.3.5. Step 5- FBS relationship

In this step of FBS relationship, the framework proposed to identify the expected structural domains of SC(s) and focusing upon which there are more chances of producing inventive solutions. The FBS relationship is an indication that if SC is selected to consider, then there is a strong possibility to produce inventive solution if designer give focus to the given suggestions mentioned in the final table of comparison as shown in

Table **12**. The designers will definitely keep this in mind and pay more attention during the generation of inventive solution(s).

Once one SC is evaluated following these steps, then similarly, all the remaining SCs are evaluated in the same way and results are stored and the final evaluation result is presented to stake holders or partners of the project for further to generate inventive solutions in accordance with the current situation and requirements.



3.3.6. Step 6- Comparison and selection of solution concepts

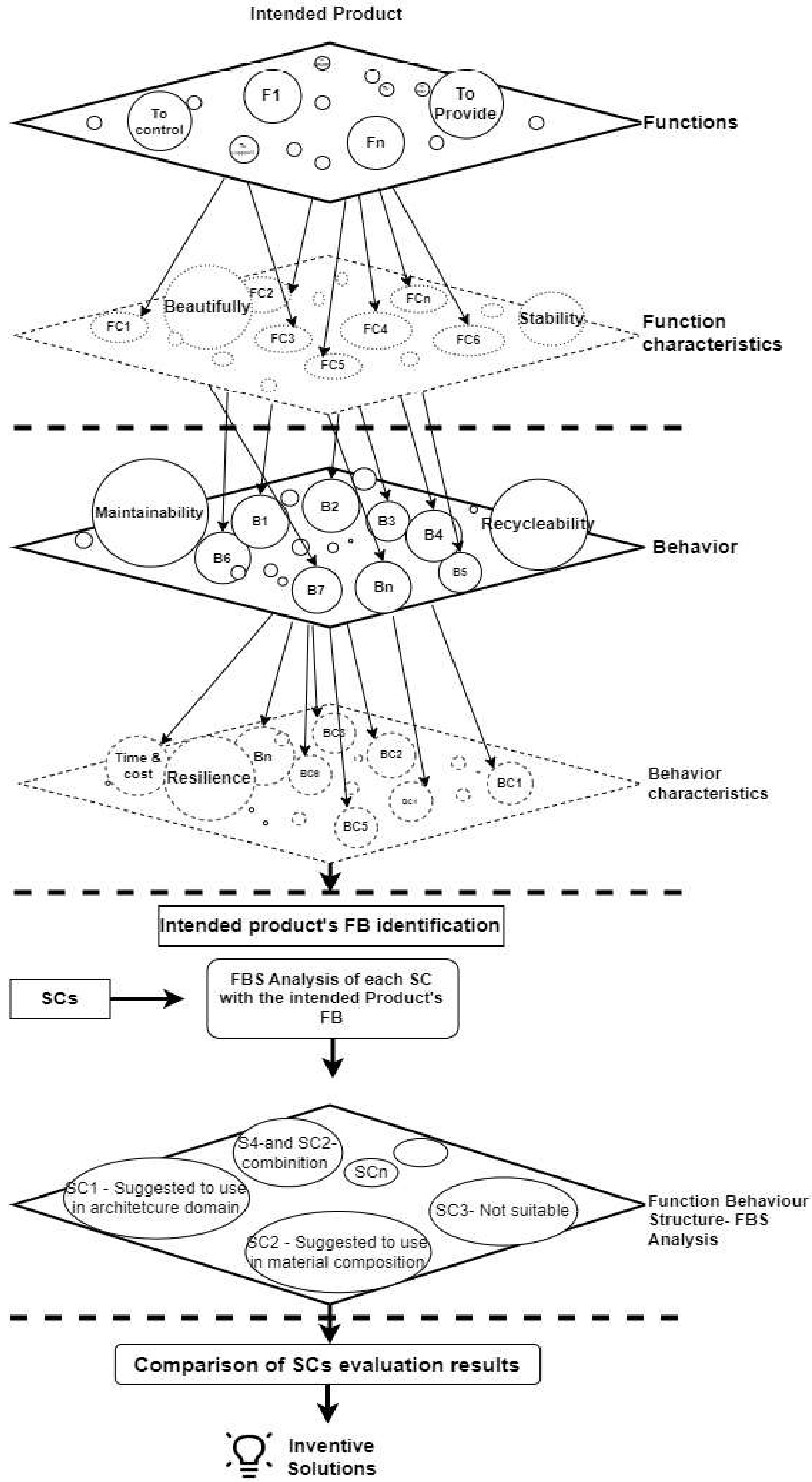
In this step, the final comparison of all the SCs is carried out based on the structural domain aspects, good points and bad points identified in the FBS relationship step.

For the comparison and final selection of SCs to propose inventive solutions, we have proposed in this step to identify main criteria upon which the final comparison is based. These criteria are main requirements which also reflects from the function, function characteristic, behavior and behavior characteristics identified during the FBS analysis process. the function, function characteristics, behavior, behavior characteristics.

The comparison of SCs based on the data of two Tables. The first one FBS analysis table which is extraction of FBS analysis graph and based on that analysis graph, the project partners have to identify the good and bad points of the SC under consideration. The good and bad points need to be identified keeping the information obtained throughout the FBS analysis process i.e., the initial problem, intended functions, expected behaviors and important information. Following Table 5 shows the main columns of the FBS analysis table.

Table 5. Contents of FBS analysis graph table

Solution concept	Function		Behavior		Structure	Analysis of FBS evaluation	
	Main intended Function	Function Characteristic	Expected Behavior	Behavior parameter / characteristic	Expected Solution/ Structure	Good Points	Bad point
SC 1							
SC 2							
SC 3							


Intended Product
To control
F1
Fn
To Provide
Functions
FC1
Beautifully
FC2
FC3
FC5
FC4
FCn
FC6
Stability
Function characteristics
Maintainability
B1
B2
B3
B4
B5
B6
B7
Bn
Recycleability
Behavior
Time & cost
Resilience
Bn
BC3
BC2
BC1
BC5
Behavior characteristics
Intended product's FB identification
SCs
FBS Analysis of each SC with the intended Product's FB
S4-and SC2-combinition
SCn
SC1 - Suggested to use in architetcure domain
SC3- Not suitable
SC2 - Suggested to use in material composition
Function Behaviour Structure- FBS Analysis
Comparison of SCs evaluation results
Inventive Solutions

3.4. SOLUTION CONCEPTS EVALUTION MODULE

In this section, we describe how to integrate the steps of the Solution Concept evaluation framework into inventive design software suite developed by CSIP team. In figures **Figure 8** and **Figure 9**, we show the UML class and Use Case diagrams we build applying object-oriented modeling to our proposed SC evaluation framework.

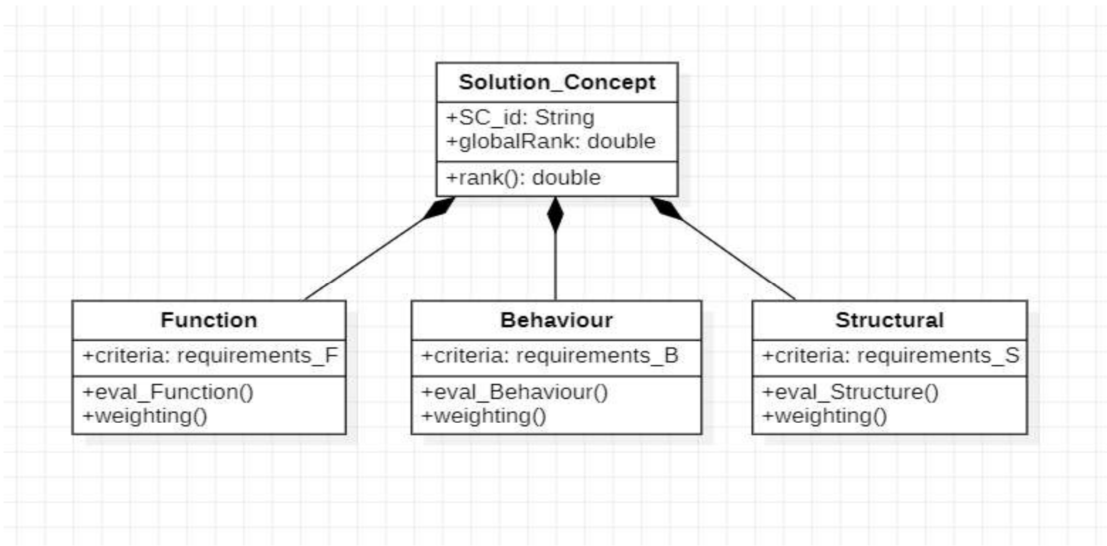


Figure 8. SC Evaluation class diagram

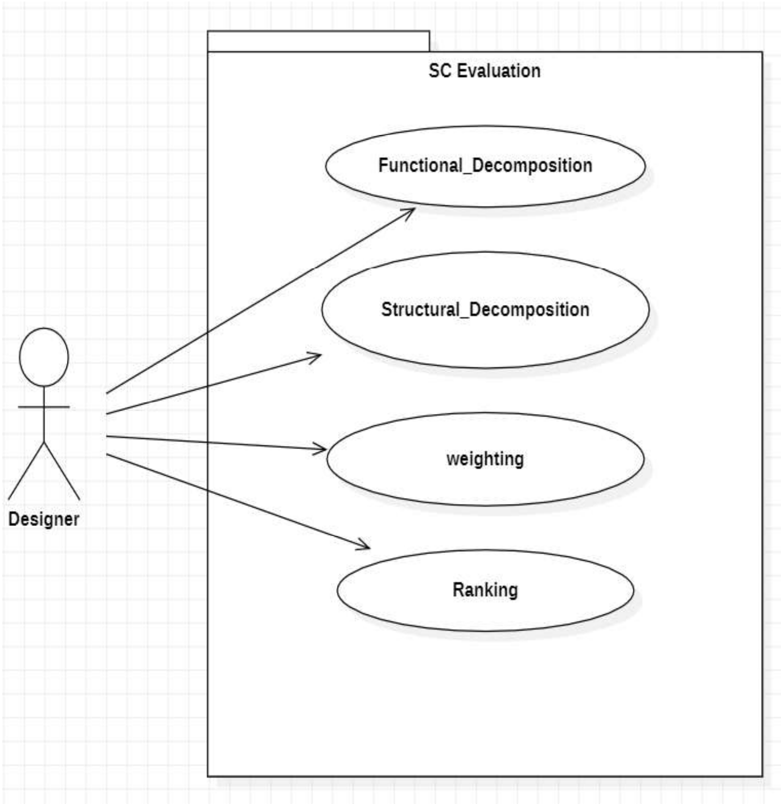


Figure 9. SC Evaluation Use Case diagram

The following tables **Table 6** , **Table 7** , **Table 8** and **Table 9** show the FBS based description of the data required to perform evaluation in a software.

Table 6. FBS description data for software evaluation

SC_id	F_rank	B_rank	S_rank	global_rank (weighting)
SC_1	2	1	2	2
SC_2	4	2	1	3
…				1
SC_n	i	j	k	k

Functional criteria

Table 7. FBS description data for software evaluation

F_id	Criteria_1	Criteria_2	…	Criteria_n
F_1	move	support		
F_2				
…				
F_n				

Behavioural criteria

Table 8. FBS description data for software evaluation

B_id	Criteria_1	Criteria_2	…	Criteria_n
	reliability	resistant		
B1				
B_2				
…				
B_n				

Structural criteria

Table 9. FBS description data for software evaluation

S_id	Criteria_1	Criteria_2	…	Criteria_n
	heavy	compact		
S_1				
S_2				
…				
S_n				

In chapter 5, we present the implementation of this module using the IPG approach which is under process and the initial steps have produced some successful promising results to implement the evaluation steps in software based IPG.

3.5. DISCUSSION OF CHAPTER

Based on the literature review and deep research of related inventive design approaches, this chapter introduced and proposed the use of FBS evaluation in the concept generation step of design process. Usually, evaluation methods are used in final step of solution selections and there has been not utilized evaluation methods in the initial step of concept generation in engineering design processes where there is always a need of systematic method to share and save loss of information. By proposing an evaluation framework for initial concept generation step, this study in its initial phase of research, will be contributing in terms of representation and evaluation of SCs in inventive design.

To deal SCs in such situations there are two main problems to answer. First, how to represent a SC which is not a product but just a rough idea with several elements. The second problem is how to build the evaluation framework in order to evaluate and compare important elements of

SCs in inventive designs. The application of proposed evaluation steps will be carried out in chapter 4 by a case study example.

4. CASE STUDY: A DRONE CAMERA BODY DESIGN PROBLEM

In this section, in order to illustrate the application of the proposed framework in a pedagogic way, we have chosen a project which is related to drones. Drones also commonly known as, unmanned aerial vehicles (UAVs), are flying robots that are functioned autonomously or remotely (M. Rouse n.d.). Drones are most often used in military services. However, in recent years, the drone has come into attention for several uses of weather monitoring, firefighting, search and rescue, surveillance, inspecting, external logistics, emergency deliveries, video recording, counting in inventory management, and traffic monitoring (Maghazei, Lewis, and Netland 2022)(Boon 2014) etc. This versatility in applications, with advancements in technology, have markedly propelled the markets for both commercial and recreational drones in recent years.

Due to its rapid advancement, there is an increasing trend of producing inventive solutions for design and fabrication of drone. With passage of time, in recent years, there has been extensive research on the utilization of advance design approaches for optimized and inventive design solutions and production of such product (Ahmed et al. 2022). Using inventive design approaches has distinct advantages for producing inventive solutions during design and development of drones. Inventive design approaches are a broad term of approaches which consists of various types of conventional and systematic inventive design approaches such as brainstorming, idea morphing, TRIZ, SCAMPER etc.

This chapter holds several key motivations. Firstly, we aim to validate and demonstrate the practical application of the proposed evaluation framework with a case study. Through a case study, we will examine how the evaluation framework contributes to inventive solution and problem-solving, and how it enhances the outcomes and potential impact of inventive design approaches.

Secondly, we seek to showcase the benefits of interdisciplinary collaboration, where theoretical frameworks and practical methodologies converge to create a more comprehensive and robust research approach. By bridging the gap between theory and practice, we can foster innovation and generate actionable knowledge that resonates with both academic and industry stakeholders. In this context, our research endeavors to use a case study with the method of

TRIZ-IDM based IPG which was developed by one of our lab fellows. This opportunity also enables us to go more in details of the TRIZ-IDM methods with the experience of the TRIZ_IDM based IPG experts. Details of how this method works can be found in the article (Hanifi et al. 2021).

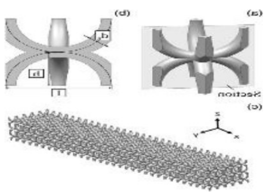
By combining our proposed framework with the insights and experience of our lab fellow through TRIZ- IDM bases IPG method, we aim to harness the power of collective intelligence and generate novel ideas that can drive transformative outcomes in our field of study.

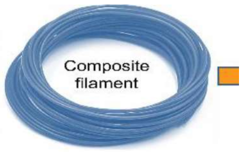
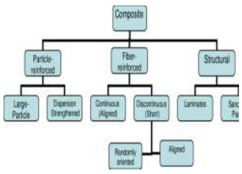
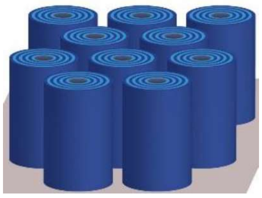
4.1. CONTEXT OF CASE STUDY

Keeping the challenges and current development in drone technologies, this case study is related to a project which is under development related to design a new drone which should address different problems. To suggest inventive solutions in designing the drone the designer has to take into consideration the main functions of “to transport” and “to carry weight”. The main issues to address are weight, strength, service time, durability, cost, rigidity, vibration, recyclability, time of fabrication, 3D fabrication, speed, height and stability.

Focusing the initial problem, with the help of TRIZ-IDM based IPG inventor, a list of SCs generated shown in Table 10 , which could be useful for producing inventive solutions for the problem under discussion.

Table 10. List of TRIZ generated solution concepts.

N°	Solution concepts	Images
1	The ARCH lattice structures have superior energy absorption and mechanical properties.	
2	They believed that the energy absorption capacity of rubber concrete could be accurately reflected using the normalized energy absorption value of compressive strength, which was 54–79% higher than that of ordinary concrete.	 Rubber

3	Combination of composites materials produced materials with strength, light weight, strength and stiffness etc.	 Composite Filament  Composite materials
4	'Safety Roller' are light weight, energy absorbing material.	
5	Nano Tube Array- It is light weight and absorbs energy	

But the next step of comparing these solution concepts and produce inventive solutions was a challenging task for designer due to non-availability of evaluation framework at this stage. Therefore, proposing an evaluation framework and applying the framework for its validation is core focus of this case study. To start the application of evaluation, after getting all the basic information of IPG steps involved to produce SCs, we identified the position of our proposed evaluation framework as shown in **Figure 10**.Detail of how IPG method works can be seen in the (Hanifi et al. 2021).

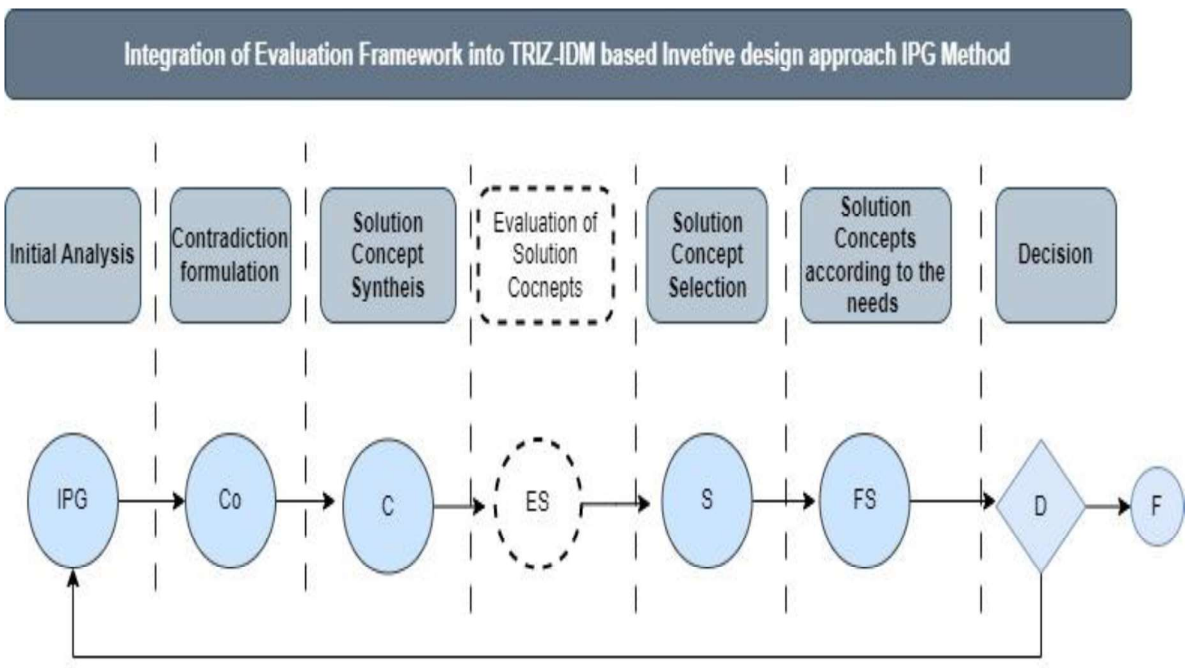


Figure 10. Application of proposed evaluation framework in TRIZ-IDM based IPG inventive design approach.

In the following we will showcase how the evaluation framework steps can effectively be helpful for the project partners in handling the SCs produced by inventive design approaches.

4.2. APPLICATION OF PROPOSED EVALUATION FRAMEWORK

To apply and understand the steps first we will select one of the SCs from list perform all the steps on the selected SC. The remaining SCs will be evaluated in same pattern and the final results will be presented in the final combine table to compare and selection for inventive solution.

The evaluation framework consists of the 5 steps given below:

4.2.1.1. Step 1: Data collection

The designer considered the list of SCs **Table 10** generated by ITRIZ_IDM as starting point for evaluation. All possible data collected and documented after meeting with project partners. The data includes information of the initial problem, problem formulation, project partner requirements etc.

Based on the data collection the project partners need to identify a reference point i.e., in this case a general system of drone with all the main functions, function characteristics, behavior and behavior characteristics that the final solution should contain. There is no structure available till this step, only the solution concepts are having sone functions and behaviors, and by focusing on those functions and behaviors the evaluation framework could lead us to a structural solution. As this is not a final product so based on the cases study context, the designer has identified a general part that artifact (drone).

In this case study we have made two types of reference point to start the evaluation. First a general schematic of the system (drone) with its main parts which is necessary part of all drones as shown in **Figure 11** . Second, a list of main intended function(s) and expected behaviors that is very important to be addressed in the final solution as shown in **Table 11**.

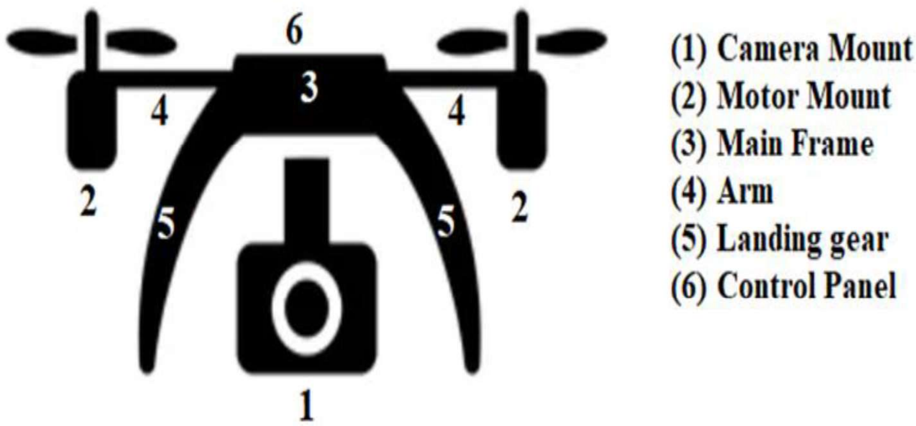


Figure 11. General main parts of a drone

Table 11. Main function and behavioral domains to be addressed in final solution.

Main Function of Drone	Functional Characteristics	Behavior	Behavior Characteristics

• To fly	• Maximum Height	• [m]	• Maneuverability	• Rotation, stability
	• Speed	• [Km/h]		
• To carry load (Camera)	• Acceleration	• [m/S^2]	• Rapidity	• Speed, acceleration
	• Speed of rotation	• [Rad/sec]		
	• Stability on fly	• [mm]	• Rigidity	• Elastic limit
	• Capacity to lift	• [mm]	• Battery autonomy	• Time
	• Camera weight.	• [kg]		
	• Time of battery operation (Flight time)	• [min]	• Shock absorption	• Energy absorbs
			• Vibration absorption	• Coefficient of dumping
			• Cost	• Time and cost
			• Easy fabrication	
			• Recyclable	• Environmental
			• Weight	• Packing
			• Transportability	

4.2.1.2. Step 2: Function identification

By applying the function identification step, taking the data collected in step 1 and using the list of general functions, the project partners were able to identify the main intended functions of final product under consideration with respect to the initial problem. The list of general functions is given in **Table 4** which gives some idea to the project partners in the identification of functions. The intended function(s) are identified with the help of project partners. After that the project partners selected the main function e.g., in this case study the main functions identified are “To transport “(fly) and “To carry load” (camera) etc. shown on **Table 11**. After the main function(s) identification, the evaluation of each SC is carried out one by one. Here in this case study in order to understand the process, we will show only one SC i.e., Lattice to do apply the next steps of evaluation. The main intended functions of SC “lattice” is listed in a FBS analysis graph **Figure 12** and proceed to next step.

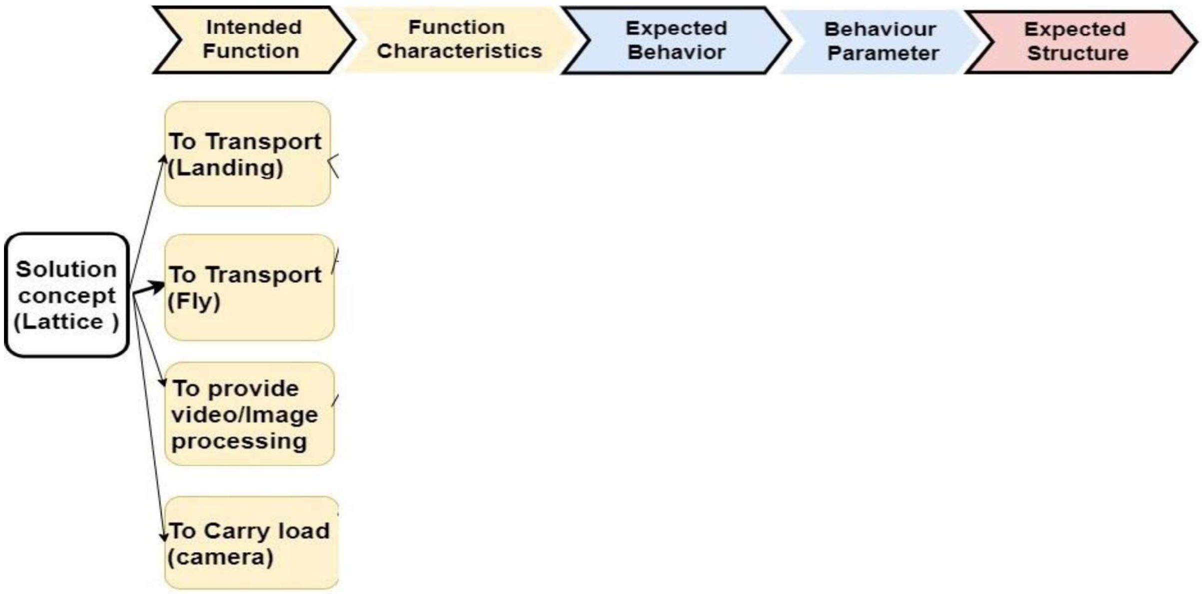


Figure 12. FBS analysis flow graph of SC

4.2.1.3. Step 3: Function decomposition

The step of function decomposition also carried to illustrate the function in more details. This step gives more in-depth of the functions and avoid loss of information or ambiguity between project partners. The selection of function and function characteristics are done with the input by project partners (i.e., designers, expert, and top management of company etc.). The output of this step is documented and highlighted as shown in **Figure 13**.The function characteristics identification is also based on the data collected in step 1.

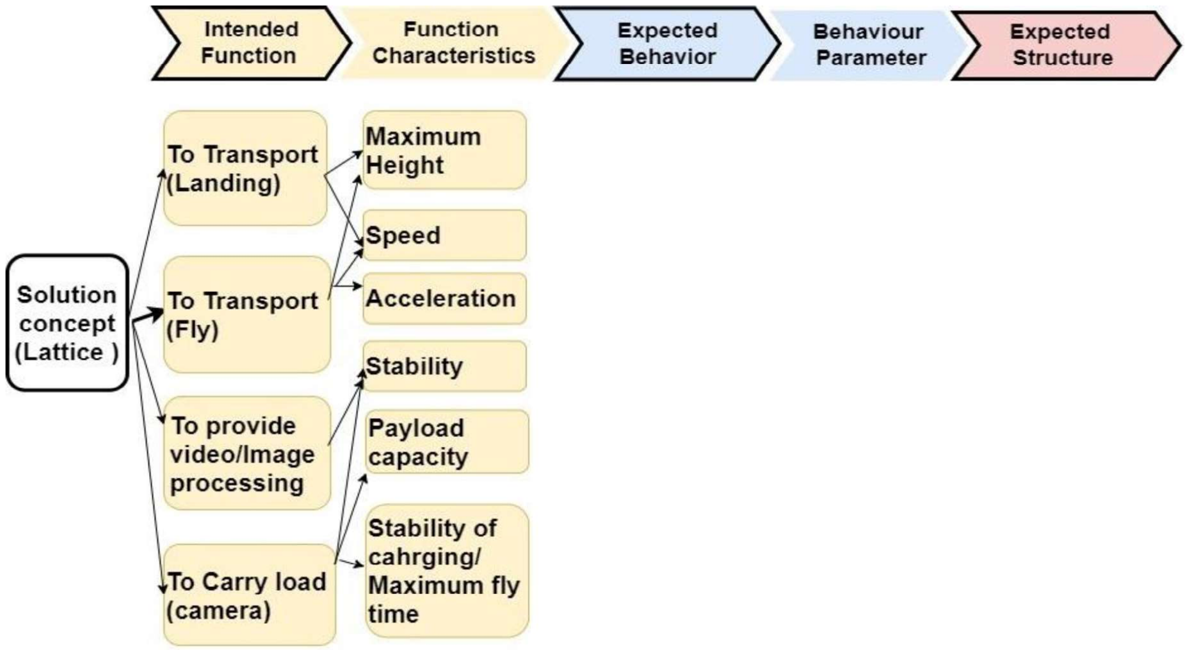


Figure 13. FBS analysis flow graph of SC

4.2.1.4. Step 4: FB relationship

After the function decomposition the next step to identify and update the FBS analysis list with expected behavior and behavior characteristics of SC under discussion. The function behavior relationship step carried out and the output of this step is shown in **Figure 14**.After the expected function behavior relationship identified, the next important thing to identify behavior characteristics or behavior parameters. This behavior characteristics is very important input for final comparison of requirements fulfillment and finding any deficiency need to address in this SC if it is selected. This can be seen in the columns good points and bad points of final table

Table 12. The initial three steps of data collection, function identification and behavior identification are almost applied to all SCs with same findings and all SCs will have almost same functions and behaviors in the FBS analysis flow graph. The main difference will be in the next step, where each SC will be analyzed based on these functions and behaviors to identify the expected structure domain in which each specific SC could be useful to produce final solution.

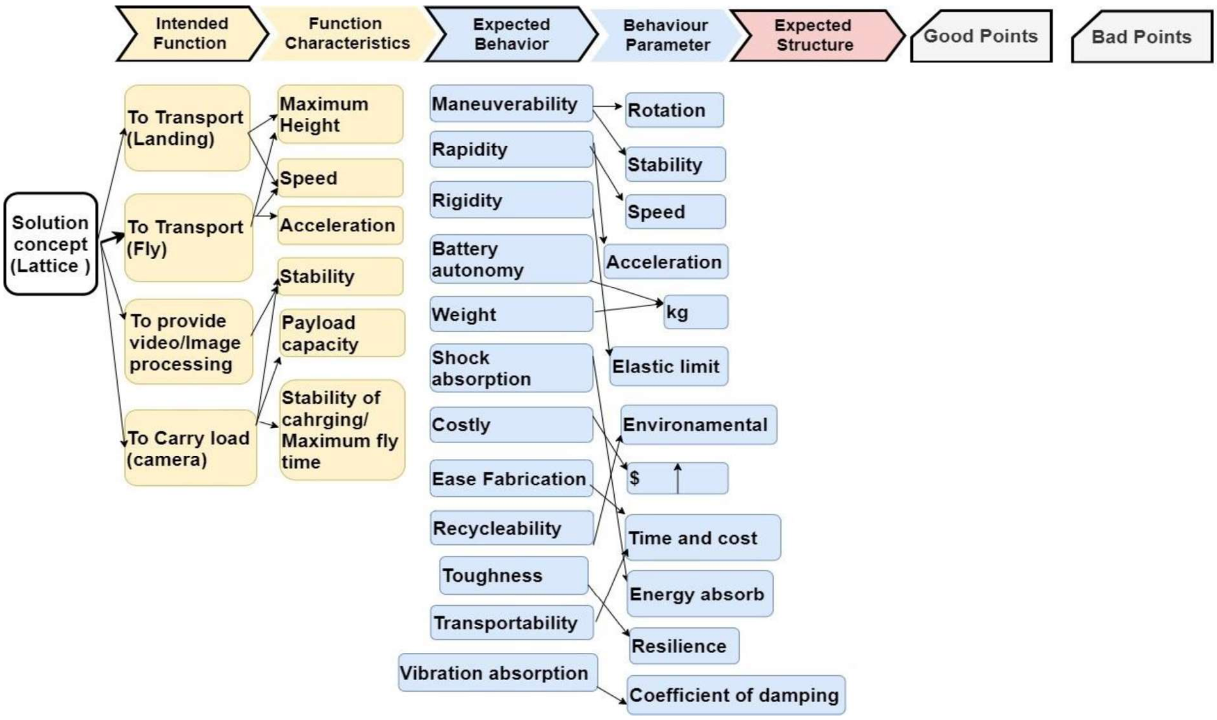


Figure 14. FBS analysis flow graph of SC

4.2.1.5. Step 5: FBS relationship

The final step of linking intended function of the SCs to expected structural domains using the expected behavioral domain as bridge is carried out. This final FBS step is most important as it identify capabilities each SCs with respect to Structure / solution of the final product. The structural domains of SC “Lattice” is identified by project partners shown in **Figure 15**.

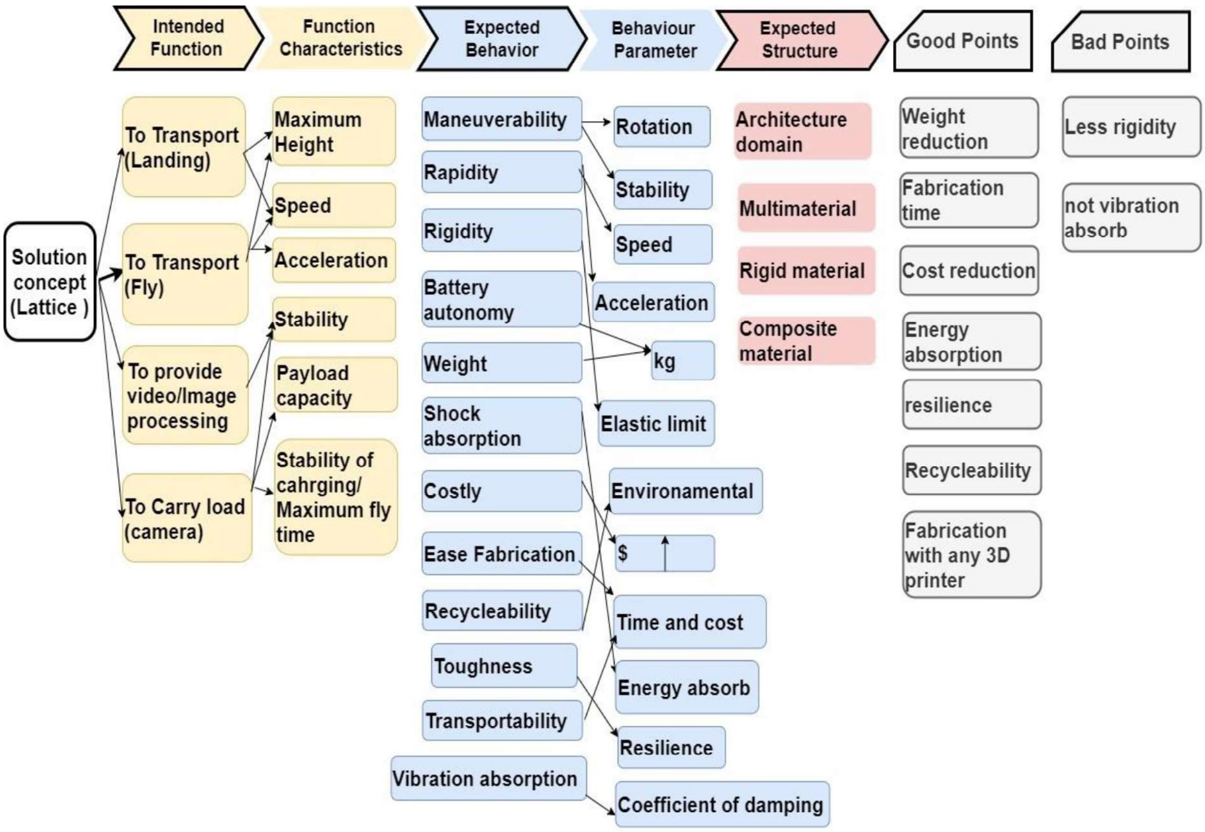


Figure 15. FBS analysis flow graph of SC

The identification of expected structural domains by project partners is done by taking into consideration of the general parts of product as in this case the general parts of" drone" shown in **Figure 11** and closely matching the SC with final product. The project partners identified that the SC" Lattice" in general is very close to be used in architecture of product and then also for the dame architecture it can be made rigid, it can be multilateral, and can also be of composite material.

Once the FBS graph is done, the analysis of FBS graph is carried out. In this analysis the project partners have to identify the good and bad points existing in this SC with respect to the related functions and behaviors identified earlier. The good and bad points of the SC "lattice" is identified and shown in **Figure 15**.

The same step repeated with all the SCs one by one, and the analysis results are documented and presented to project partners. In this case of SCs, all the remaining SCs are evaluated in same pattern and results are mentioned in the

Table 12.

The final FBS evaluation of SCs for the case study under consideration is completed and presented to project partners for comparison and selection of SCs in the next step.

4.2.1.6. Step 6. Comparison of solution concepts and final selection

Once the FBS evaluation is done and good and bad points are identified, the next most important step of comparison and selection of SCs is performed in this step.

In this comparison step, the general main part of final product is made as a reference point for comparison of SCs based on good and bad points. Also, this will indicate us where and which part of the product the particular SCs is helpful.

Table 12. FBS evaluation of solution concepts

Solution concept	**Function**		**Behavior**		**Structure**	**Analysis of FBS evaluation**	
	Main intended Function	**Function Characteristic**	**Expected Behavior**	**Behavior characteristic**	**Expected Solution/ Structure**	**Good Points**	**Bad point**
SC 1 **Lattice structure**	To Fly To carry load (camera)	Maximum height Speed Acceleration Stability Payload Stability of charging / Maximum fly time	Maneuverability Rapidity Rigidity Battery autonomy Weight Shock absorption Costly Ease Fabrication Recyclability Toughness Transportability Vibration absorption	Rotation Stability Speed Acceleration Kg Elastic limit Environmental $ Time and Cost Energy absorption Resilience Coefficient of damping	**Architecture** Multilateral Rigid material Composite	-Cost -Weight -Fabrication time -Energy absorption -Resilience -Recyclability -3D fabrication	-Not vibration absorb -No rigidity
SC 2 **Composite material**	To Fly To carry load (camera)	Maximum height Speed Acceleration Stability Payload Stability of charging / Maximum fly time	Maneuverability Rapidity Rigidity Battery autonomy Weight Shock absorption Costly Ease Fabrication Recyclability Toughness Transportability Vibration absorption	Rotation Stability Speed Acceleration Kg Elastic limit Environmental $ Time and Cost Energy absorption Resilience Coefficient of damping	**Composition of material** Long fiber Multilateral (glass, carbon etc.)	-Fabrication time -Rigidity	Recyclability Vibration absorb. Cost Energy absorb. Weight
SC 3 **Rubber**	To Fly To carry load (camera)	Maximum height Speed Acceleration Stability Payload Stability of charging / Maximum fly time	Maneuverability Rapidity Rigidity Battery autonomy Weight Shock absorption Costly Ease Fabrication Recyclability Toughness Transportability Vibration absorption	Rotation Stability Speed Acceleration Kg Elastic limit Environmental $ Time and Cost Energy absorption Resilience Coefficient of damping	**Flexible (elastomeric material)** Non-porous (block) Multilateral Flex material PP	-Energy absorption -Vibration absorption -Reversible deformation -Cost -3D fabrication	-Not rigid -Heavy / weight

SC 4 **Safety roller**	To Fly To carry load (camera)	Maximum height Speed Acceleration Stability Payload Stability of charging / Maximum fly time	Maneuverability Rapidity Rigidity Battery autonomy Weight Shock absorption Costly Ease Fabrication Recyclability Toughness Transportability Vibration absorption	Rotation Stability Speed Acceleration Kg Elastic limit Environmental $ Time and Cost Energy absorption Resilience Coefficient of damping	***Not suitable in any case*** ***Eliminate this SC***	Not applicable	Not applicable
SC 5 **Nano tube-arry**	To Fly To carry load (camera)	Maximum height Speed Acceleration Stability Payload Stability of charging / Maximum fly time	Maneuverability Rapidity Rigidity Battery autonomy Weight Shock absorption Costly Ease Fabrication Recyclability Toughness Transportability Vibration absorption	Rotation Stability Speed Acceleration Kg Elastic limit Environmental $ Time and Cost Energy absorption Resilience Coefficient of damping	***Not suitable in any case*** ***Eliminate this SC***	Not applicable	Not applicable

Taking the initial problem, we have produced SCs and evaluated those SCs on FBS aspects and identified the main characteristics of each SCs possible to help in producing the final solution. Now to find the final solution we need to compare the SCs and select best fit for designing the drone solution. To start the comparison and selection of SCs in **Figure 16** we presented a schematic of the drone and highlighted its main parts where we need problem solutions

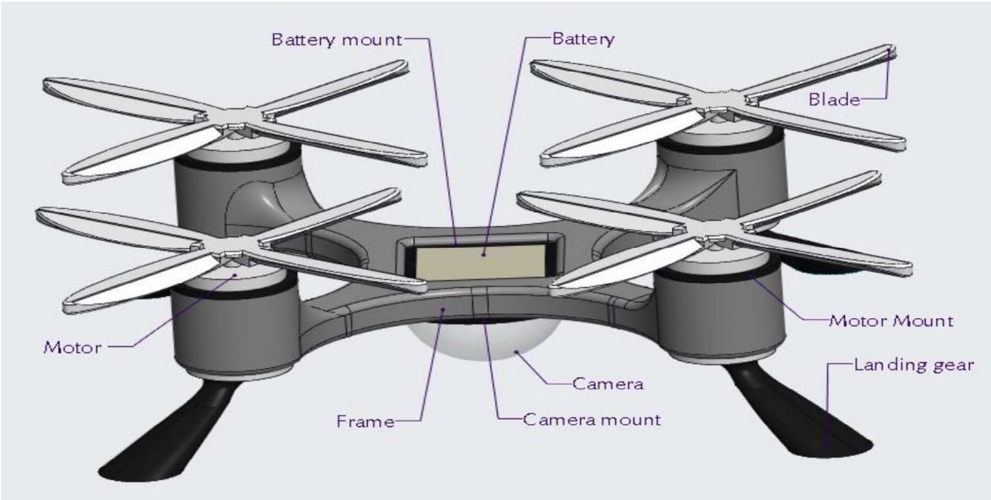


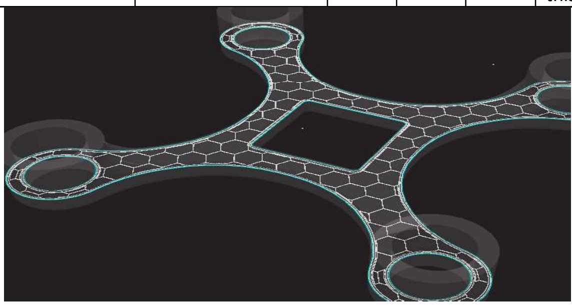
Figure 16. Main parts of drone to consider for solution

Table 13. Major issues related to main parts of drone.

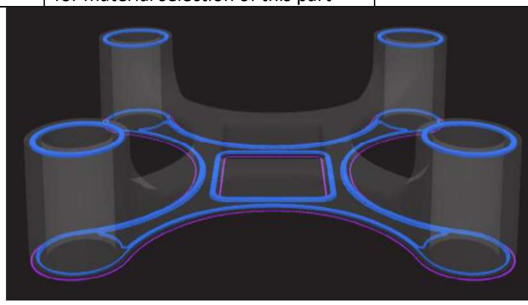
	Structure parts	Major Issues to address
1	Frame	Weight, Rigidity, recyclability, Cost
2	Camera mount	Stable, vibration and energy absorption, rigid, recyclability, Cost
3	Motor Mount	Vibration absorbs, rigid, weight, recyclability, Cost
4	Landing gear	Energy absorption, light weight, recyclability, Cost

4.2.1.6.1 Selection of solution concepts

Part 1 –Frame	**Main criteria**	**SC 1**	**SC 2**	**SC 3**	**Focus SC 1**	**Elimination of bad points**	**Remarks**
Major Issues with this part: **Weight, Rigidity, Recyclability, Cost**	-Cost	Yes	No	No			SC 1 “lattice structure” selected as architecture design of drone, and SC 2 of composites material to be used to increase the rigidity.
	-Weight	Yes	No	No			
	-Fabrication time	Yes	No	No			
	-Energy absorption	Yes	No	Yes			
	-Recyclability	Yes	No	Yes			
	-3D fabrication	Yes	Yes	Yes			
	-Vibration absorb	**No**	No	Yes	Does vibration absorb necessary for this part? **No**	Bad point eliminated-no need to focus on vibration issue	
	-Rigidity	**No**	Yes	No	Does rigidity necessary for this part? **Yes**	Make use of rigidity property of SC2 for material selection of this part	

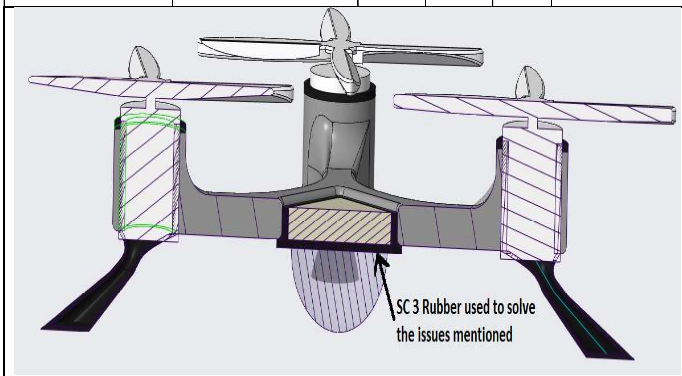


- For the issues related to the main frame, we selected the solution of lattice structure to be used in the architecture design of the drone. This solution has resolved the issues of **weight, cost** and **recyclability**. But one issue of rigidity still present.
- To solve the rigidity, issue the SC 2 is capable of fulfilling this issue, but if we use SC2 then another **issue of recyclability occurs** with it.



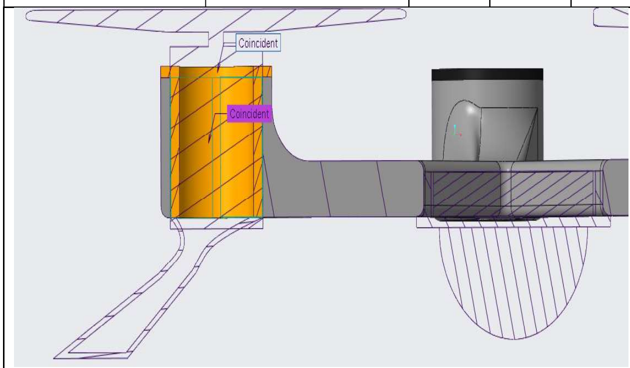
- For the **issue of recyclability**, we proposed to make a thin layer of the rigid material SC2 on the outer surface of the frame which solve the issue of less rigidity and it can also be easily removeable during the process of recycling. This addition of thin outer layer will make the frame rigid and at same time other maximum parts of the frame recyclable when it is needed.

Part 2 – Camera Mount	**Main criteria**	SC1	SC2	SC3	**Focus SC 1**	**Elimination of bad points**	**Remarks**
Major issues to with this part: **Stable, vibration and energy absorption, rigid, recyclability, Cost**	-Cost	Yes	No	No			SC3 which is rubber, selected for part 2 which is camera mount area. Using this SC3 to small portion, also eliminates the cost, weight and fabrication issues of SC 3, making it fit for selection after fulfilling all criteria
	-Weight	Yes	No	No			
	-Fabrication time	Yes	No	No			
	-Energy absorption	Yes	No	Yes			
	-Recyclability	Yes	No	Yes			
	-3D fabrication	Yes	Yes	Yes			
	-Vibration absorb	No	No	Yes	Does vibration absorb necessary for this part? **Yes**	SC1 and SC 2 already used for the camera mount frame. So	
	-Rigidity	No	Yes	No	Does rigidity necessary for this part? **Yes**	The part need rigidity when camera contacts with the mount area.	



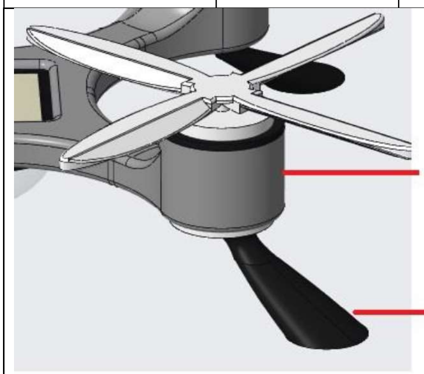
- For the issues related to the camera mount part, we already selected SC 1the solution of lattice structure to be used in the architecture design of the drone. This solution has resolved the issues of **weight, cost,** and **recyclability**. But one issue of rigidity still present.
- From the SCs, the SC3 has the capability of vibration absorb, which is required at this part of drone.
- Focusing on the issues, we proposed to use the SC3 only on specific portion where camera fits the motor mount part of the drone.
- By applying SC 3 on a small, required portions. This solution of using S3 made significant changes to solve the other 4 related issues i.e., cost, weight,and rigidity.
- The cost, weight and fabrication time issues solved with the used of less material, but for the issue of rigidity, we identified the inbuilt solution i.e., rigidity gained by pressing the SC3 between two surfaces .

Part 3 –Motor Mount	**Main criteria**	**SC1**	**SC2**	**SC3**	**Focus SC 3**	**Elimination of bad points**	**Remarks**
Major issue related to vibration when motor start.	-Cost	Yes	No	No			**SC3** which is rubber, selected for part 2 which is motor mount area. Using this **SC3** to small portion, also eliminates the cost, weight, and fabrication issues of SC 3, making it fit for selection after fulfilling all criteria
	-Weight	Yes	No	No			
	-Fabrication time	Yes	No	No			
	-Energy absorption	Yes	No	Yes			
	-Recyclability	Yes	No	Yes			
	-3D fabrication	Yes	Yes	Yes			
	-Vibration absorb	No	No	Yes	Does vibration absorb necessary for this part? **Yes**	Make use of SC3 for specific part only.	
	-Rigidity	No	Yes	No	Does rigidity necessary for this part? **Yes**	Pressing the material between two surfaces	



- The major issue identified related to this part is the vibration which occurs when the motor starts. Focusing to the SCs we noted that the mount areas is already made of SC1 during the frame design. So, there is need to focus on other SCs to eliminate the issue of vibration absorb.
- From the SCs, the SC3 has the capability of vibration absorb, which is required at this part of drone.
- Focusing on the issues, we proposed to use the SC3 only on specific portion where motor touches the motor mount part of the drone.
- By applying SC 3 on a small, required portions. This solution of using S3 made significant changes to solve the other 4 related issues i.e., cost, weight, fabrication time and rigidity.
- The cost, weight and fabrication time issues solved with the used of less material, but for the issue of rigidity, we identified the inbuilt solution i.e., rigidity gained by pressing the SC3 between two surfaces.

Part 4 –Landing gear	**Main criteria**	**SC1**	**SC2**	**SC3**	**Focus SC 3**	**Elimination of bad points**	**Remarks**
Major issued related to this part: Energy absorption, light weight, recyclability, Cost	-Cost	Yes	No	No			SC3 which is rubber, selected for part 4 area with minimum required amount. Using this SC3 to small portion, also eliminates the cost, weight and fabrication issues of SC3, making it fit for selection at specific parts.
	-Weight	Yes	No	No			
	-Fabrication time	Yes	No	No			
	-Energy absorption	Yes	No	Yes			
	-Recyclability	Yes	No	Yes			
	-3D fabrication	Yes	Yes	Yes			
	-Vibration absorb	No	No	Yes	Does vibration absorb necessary for this part? **Yes**	Make use of SC3 for specific part only.	
	-Rigidity	No	Yes	No	Does rigidity necessary for this part? **No**		



Landing gear to made with energy absorption material of rubber at outer part only

- From the previous steps it is now very easy to identify for the landing gear part requirement. The SC3 has been selected to apply on outer part of landing gear in order to solve the main issues.

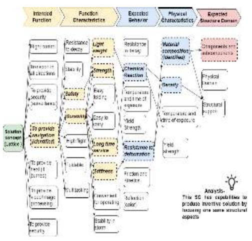
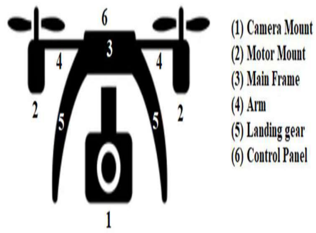
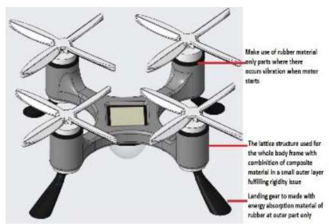
The designers based on the comparison table and SC selection charts, provided the suggested solutions with identified parts to project partners for further step of solution development.

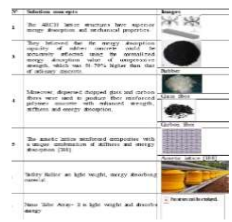
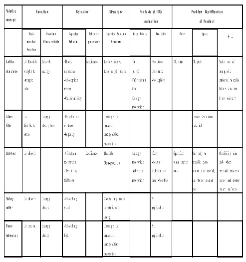
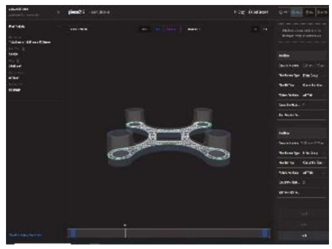
4.3. FINAL SOLUTION

We believe that the accuracy of the evaluation results and final selection of solution concepts still have the possibility to be improved with exploration to another domain other than FBS. The future research in this area will be carried out along with the testing and verification of current FBS framework with other inventive design approaches.

Based on the comparison and selection of SCs, the project partners utilized it and managed to find some inventive solutions. The inventive solutions suggested by the project partners gave encouraging results. The initial requirements of the problem which were weight reduction, safety, durability in terms of long service time with cost reduction, payload capacity all achieved significantly in the initial design and simulation test as compared to conventional solutions already exists. For an overview of the whole process, graphical abstract of evaluation framework position during inventive solutions is shown in **Table 14**.

Table 14. Graphical abstract of evaluation framework position during inventive solutions

Solution concepts →	**Evaluation of SCs** →	**Evaluation based inventive solutions** →	**Product concept**
Initial problem statement and list of SCs			

The purpose of the case study presented in this section is to validate the evaluation framework to produce inventive solutions for the problem mentioned in the start.

Based on the evaluation results and suggestion, we produced some inventive solutions for the problem under consideration shown in **Figure 17** .This final design of drone camera is in its final steps of development with the inventive solutions suggested in this case study.

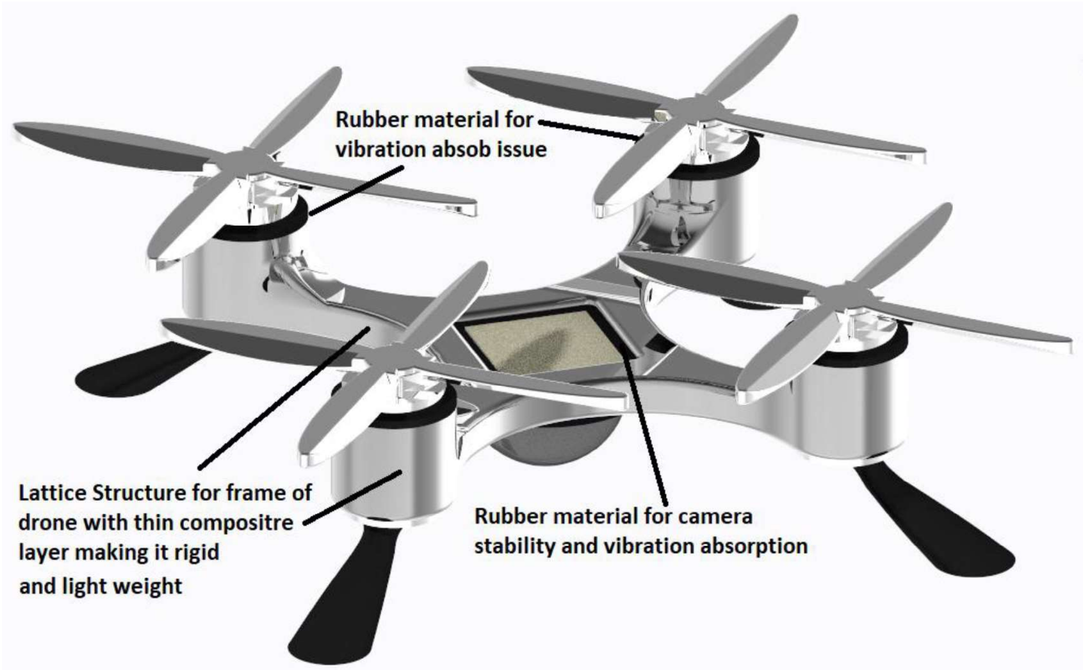


Figure 17. Final product with inventive solutions based on FBS evaluation of SCs in inventive design

Based on the design results and some initial simulations of the drone design, we have observed some good results as given below:

- More Weight savings: 55.99 %
- More Energy saving :
- Increased Flight time: from 20 minute to 28 minutes (estimated based on weight reduction)
- Aerodynamically less resistance.
- Less annual battery charging
- Increased rigidity
- Easily recyceable

4.4. MEASURING THE EFFICINCY OF SOLUTION CONCEPTS

The measurement of efficiency or effectiveness of SCs in inventive design involves two distinct areas that collectively contribute to the overall efficiency of the inventive design. These two areas are known as the use of SC for generating solution product (or artifact) and then level of inventiveness of solution.

The aim of assessing the efficiency of the (SC) in inventive design is to foster greater participation from project partners especially during the initial phase of concept generation in the design process. This leads to the creation of inventive solutions that can help businesses remain competitive in the marketplace. To achieve this objective, the first step is to gather design elements and parameters from various inventive design theories, which can then be used to configure the indicator. This article presents some of the results obtained from this process, specifically those associated with the SCs and inventive design approaches like TRIZ. The proposed efficiency assessment model is based on level of inventiveness of final solution. The assessment model consists of two integrated steps that evaluate the degree of inventiveness and acceptability of solution within framework of FBS evaluation, as shown in **Table 15**.In the assessment process, the initial stage relies on the five levels of the TRIZ theory to determine the creativity factors involved in resolving technical problems. Nonetheless, the first level, which entails standard issue resolution with a predictable outcome, does not apply to this assessment model. Moving onto the second step, the solution framework is scrutinized based on its intended purpose, anticipated performance, and projected structural characteristics to verify whether the end product conforms to these criteria.

<table>
<tr><th></th><th></th><th>Technical problem Solving</th><th>S</th><th>B</th><th>F</th><th>Efficiency of SC</th></tr>
<tr><td rowspan="5">Artefact</td><td>Solution</td><td>Level 1</td><td></td><td></td><td></td><td>No</td></tr>
<tr><td rowspan="4">Inventive Solution</td><td>Level 2</td><td></td><td></td><td></td><td>Yes</td></tr>
<tr><td>Level 3</td><td></td><td></td><td></td><td>Yes</td></tr>
<tr><td>Level 4</td><td></td><td></td><td></td><td>Yes</td></tr>
<tr><td>Level 5</td><td></td><td></td><td></td><td>Yes</td></tr>
</table>

Table 15. Assessment chart for inventive design solution concept efficiency

4.5. DISCUSSION

Evaluation methods are the most essential inputs to inventive design approaches. The evaluated results are effective in understanding and communicating ideas between partners of the project for decision making and also to minimize the loss of information, especially in the initial concept design steps. Although evaluation methods are useful in the solution selection steps, but it is also necessary to make it available in the initial step of concept designs where there is always lack and loss of information. This step is most important in new product development processes as failure at this stage can result into long time of redesign and rework expenses without any solution and facing disadvantages of delay in launching products in the market.

Considering the improvement of inventive design approaches and the importance of evaluated SCs for inventive design outcomes, this study proposed the use of the FBS approach in the initial concept generation stage of inventive design approaches.

The evaluation framework in the first part of its application was applied to one of the TRIZ-IDM inventive design approaches to produce inventive solutions for a drone project. After applying our proposed evaluation framework, the SCs got more focus from the project partners and produced some good results in form of final solution. As compared to the initial unevaluated list of SC(s), this evaluated result increased the attention of partners of the project to focus on these SCs and were able to produce some inventive solutions, indicating feasibility of our proposed framework and encouraging its application to other inventive design approaches in future research. The

Table 12 and the section 4.21.6.1 is the final summary of all the evaluated SCs and selected SCs after comparison.

5. INTEGRATION MODULE

5.1. PROPOSAL OF STEPS TO IMPLEMENNMENT EVALUATION FRAMEWORK INTO TRIZ-IDM BASED IPG

As we applied the evaluation framework on solution concepts generated by TRIZ based inventive design approaches. So, in this section, we have proposed steps for integration of evaluation framework into TRIZ based inventive design approaches. The integration framework is not complete but the initial proposed integration steps have successfully integrated the functional, behavioural and structural characteristic aspects of evaluation framework to the initial steps of TRIZ-IDM based inventive design approach of IPG (Hanifi et al. 2021).The IPG is the result of Lean Theory and its integration into IDM framework following which there is new proposed framework for inventive design called Lean-Agile Inventive Design Method (LA-IDM) Framework shown in Figure 18. This success of integration of initial steps of evaluation framework to inventive design approach if IPG has given us encouragement to make more focus in the next two steps in future to link the function evaluated solution concepts to expected behavioural and expected structural domains so that the FBS evaluation of SCs at initial step of concept generation become a useful framework to modern tool based inventive design approaches and we are working on same.

This current progress of integration module takes the assigned parameters of IPG which develop functional model and as output provides SCs. The first part related to this study serves as initial analysis of problem situation using Inverse Problem Graph IPG method. The Inverse Problem Graph method from LA-IDM helps to perform initial analysis of the problem situation. The second phase, our proposed method, refers to the formulation of the contradiction by applying the given parameters of the IPG step and defining functional model and desired characteristics of related function.

The proposed integration of evaluation framework consists of two main parts:

5.1.1. Identification of main steps involved (Steps 1 to 8):

In this part, we identified the main steps involved in the inventive design approaches. This identification of steps serves as a basis for the evaluation process and gives a way to see possible ways to integrate the evaluation framework into the inventive design approach. In order to identify the main steps, we first presented and overall view of the TRIZ-IDM based IPG method as shown in Figure 18. After this the need for the evaluation framework to this inventive design approach was identified and presented in Figure 19. After a thorough analysis with the pioneer researcher of this method, we identified 8 main steps of this IPG method shown in Figure 20.

5.1.2. Proposed integration steps (Step 9 to 15):

This part involves proposing a set of steps related to the integration of the evaluation framework based on FBS modelling approach, which are derived from the evaluation framework. The steps are identified by analyzing all steps involved in the inventive approach of IPG. The integration steps are then used in the concept generation phase of the inventive design approach. Figure 20 shows the outline of our proposed evaluation approach. The combination of the IPG method and the evaluation framework provides a systematic and comprehensive approach to evaluating solution concepts. This approach can help designers to generate more in detail solution concepts which can help the designers, experts or project partners to produce innovative solutions by focusing the evaluated SCs.

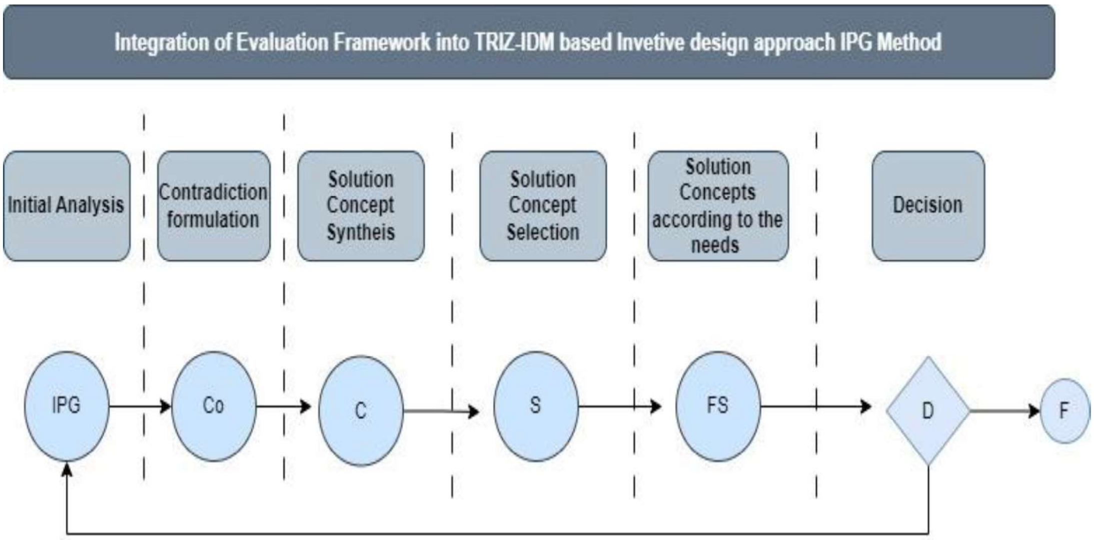


Figure 18. TRIZ-IDM based IPG for generation of solution concepts

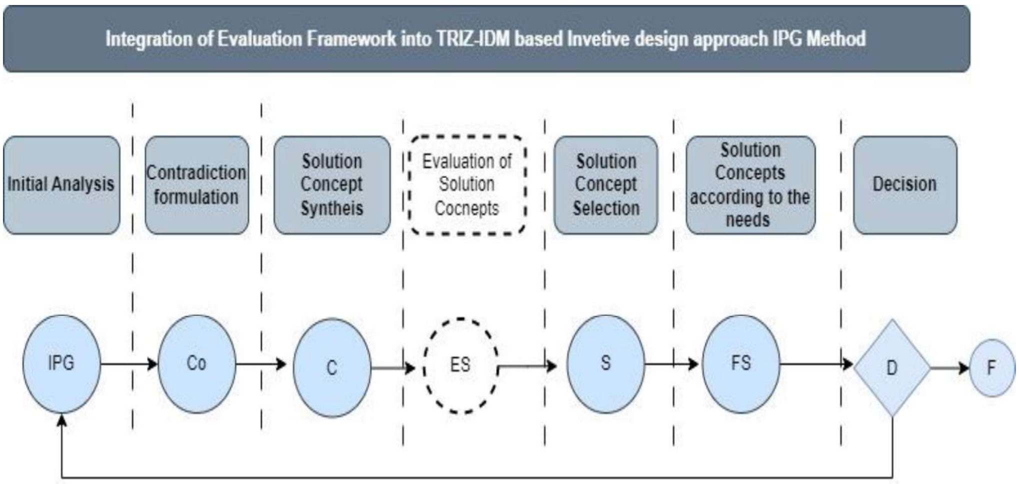


Figure 19. Integration of Evaluation framework to TRIZ-IDM based IPG framework

5.1.3. Methodology**:**

In this study contribution is integrated to the IPG in the second phase after step 7 of IPG starting step 8 to step 13.

Steps of TRIZ-IDM based inventive design approach IPG

1. Define objective of the Project
2. Define the initial problem of IPG
3. Find related problems to the initial problems
4. Grade problems in terms of importance
5. Determine the type of selected problem.
6. Extract the illustrate contradiction from the graph
7. Assign Appropriate parameters.
8. List of Solution Concepts

Following **Figure 20** shows an outline of the proposed steps for integration of the evaluation framework into inventive design approaches:

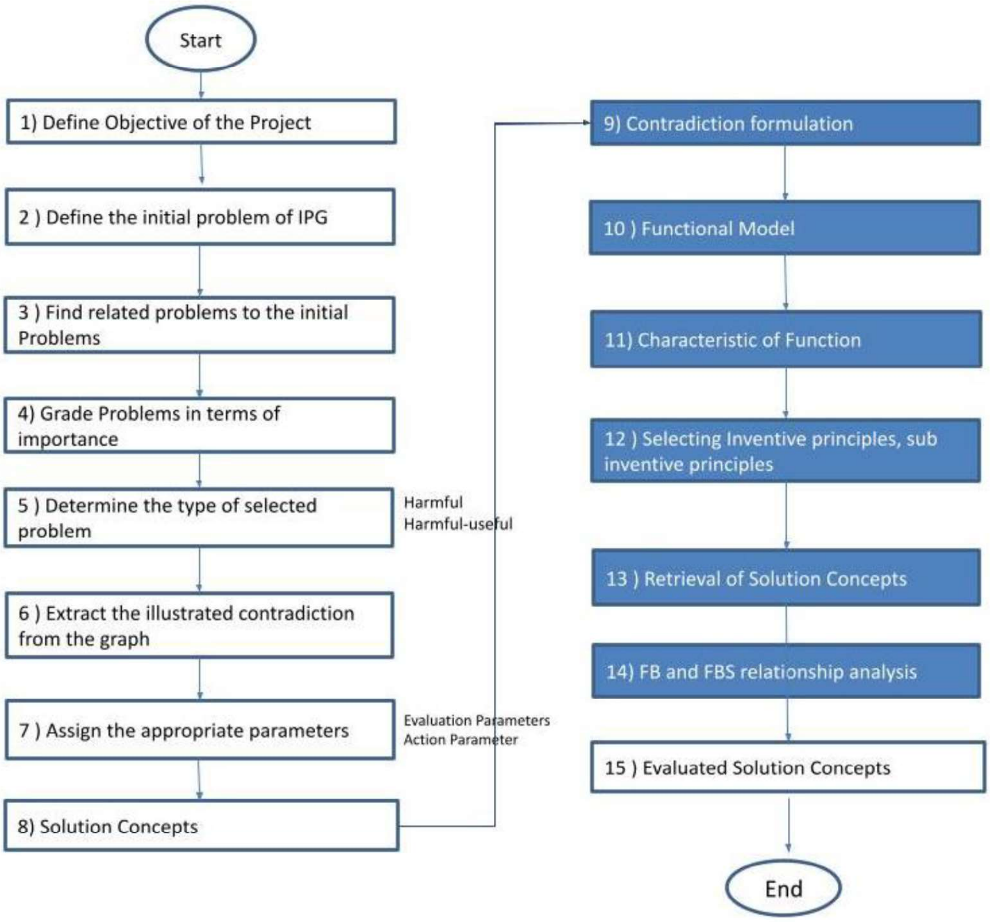


Figure 20. An approach to integrate evaluation framework to TRIZ based inventive design approach.

1. **Contradiction Formulation**

The integration steps start after Step 7. In this step of contradiction formulation, the designer first translates the assigned parameters of step 7 to TRIZ parameters and subsequently apply poly contradiction model.

2. **Functional model of selected contradiction**

In this step function model related to illustrated contradiction should be specified by the designer. This step allows to decompose the system into its components and to represent the functional relationship between them. There will be two functional model as left-hand side LHS and right-hand side RHS. The left-hand-side LHS that is existing function structure having problem or any reference functional model for which an innovative solution is required. The resulting transformation is then depicted as the right-hand side RHS. More simply that LHS is the problematic before and RHS is the proposed intended function model. In this step the functional modelling of expected solution identified and transformed into desired functional model.

The action parameter from step 7 is an input to identify the main function of the system. The LHS functional model at this step is then transformed to desired functional model as RHS as shown in Figure 26.

3. **Specify the desired characteristic of the function.**

In this step we need to specify the characteristics of the function identified in accordance with the function and process parameters identified focusing the desired characteristics. The desired Functional characteristics are also a representation of customer requirements or objective of project. The structure of this phrase could be as:

Function (characteristics of function).

4. **Selecting inventive principles, sub inventive principles**

This step consists of listing the inventive principles by applying TRIZ contradiction matrix and choosing one of them which is closest to our problem. Here while dealing with inventive principles or sub inventive principles, the function and characteristics identified in steps 9 and step 10 will be focused in selecting inventive principles.

5. **Retrieval of Solution Concepts**

This step specifies the retrieval of solution concepts from proposed design database by using the functional and the desired characteristics of function. By considering the functional model and characteristics extracted from the previous steps, list of solution concepts possible in 2d sketches, or 3d sketches are presented to the designer.

6. **FB and FBS relationship of solution concepts**

At this step, before this we have already generated the list of solution concepts with use of function and function characteristics which is one of the basic steps of our proposed evaluation framework. This function and functional characteristics identification makes the next step of expected function behavior and expected function behavior and structure domains to identify and present the evaluated solution concepts to the partners of the project. Our research is developing ways to integrate this step to some already developed databases of behaviors and structures from which we can rake expected behavior and structural aspects to complete the FBS evaluation.

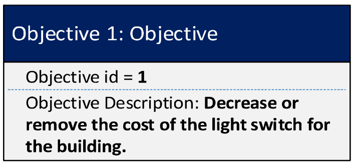
7. **Evaluated Solution Concept**

Evaluation of solution concepts based on generic function structure behavior model is the next proposed method for next phase i.e., evaluation step by using evaluation criteria.

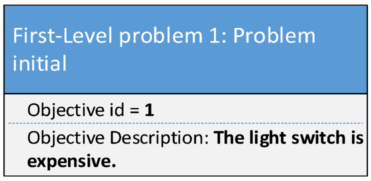
In the following, the development of our proposed integration steps is illustrated by a case study of a problem stated as:" *The user needs to move every time to change the status of the light switch".*

Based on the statement given above the objective of this research is to design an innovative solution for the switch and user. The development and implementation of our proposed method is integrated in Lean Agile inventive design method LA-IDM and consists of 6 steps. Following are these steps starting from the very beginning of step 1.

Step 1: Define the objective" Decrease or remove the cost of the light switch for the building".



Step 2: Based on objectives determine initial problem i.e "the light switch is expensive".



Step 3: Find related problem to initial problems.

The designer identifies the problems which cause the initial problem. Figure 21 shows these problems.

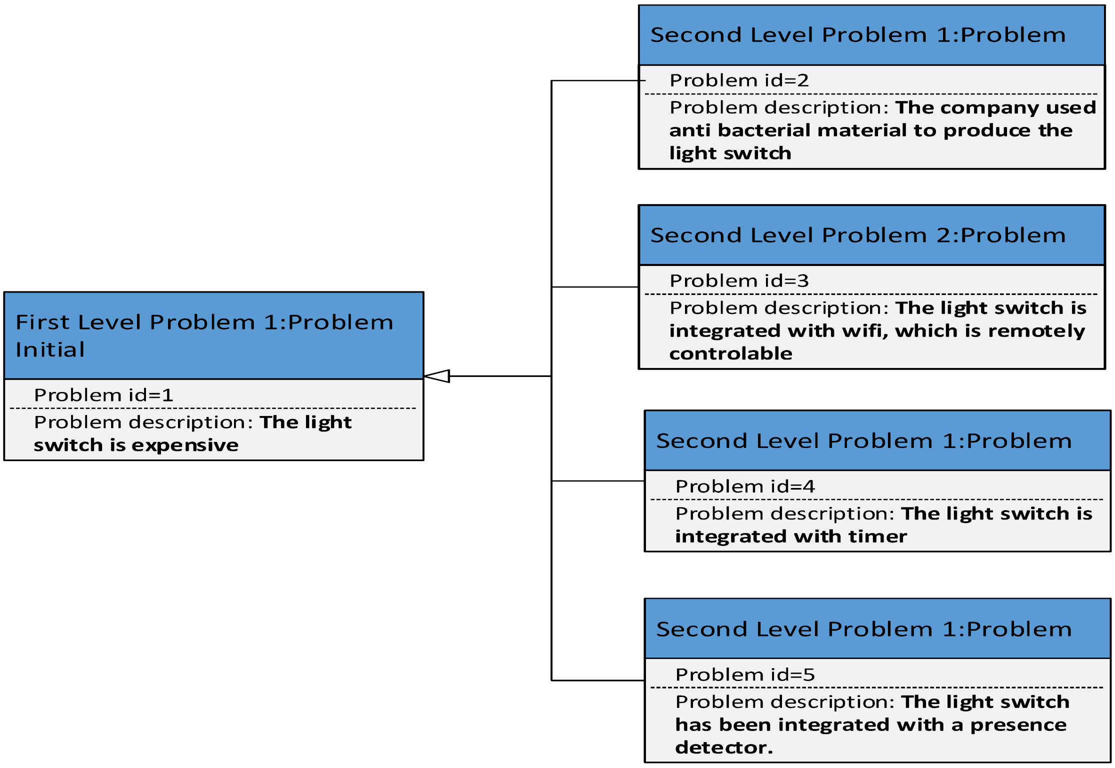


Figure 21. Different types of problems and levels

Step 4: Grading problems in terms of importance.

Designer verifies and decides the most important problem by considering answers to different questions, as the most important problem is highlighted shown in Figure 22 .

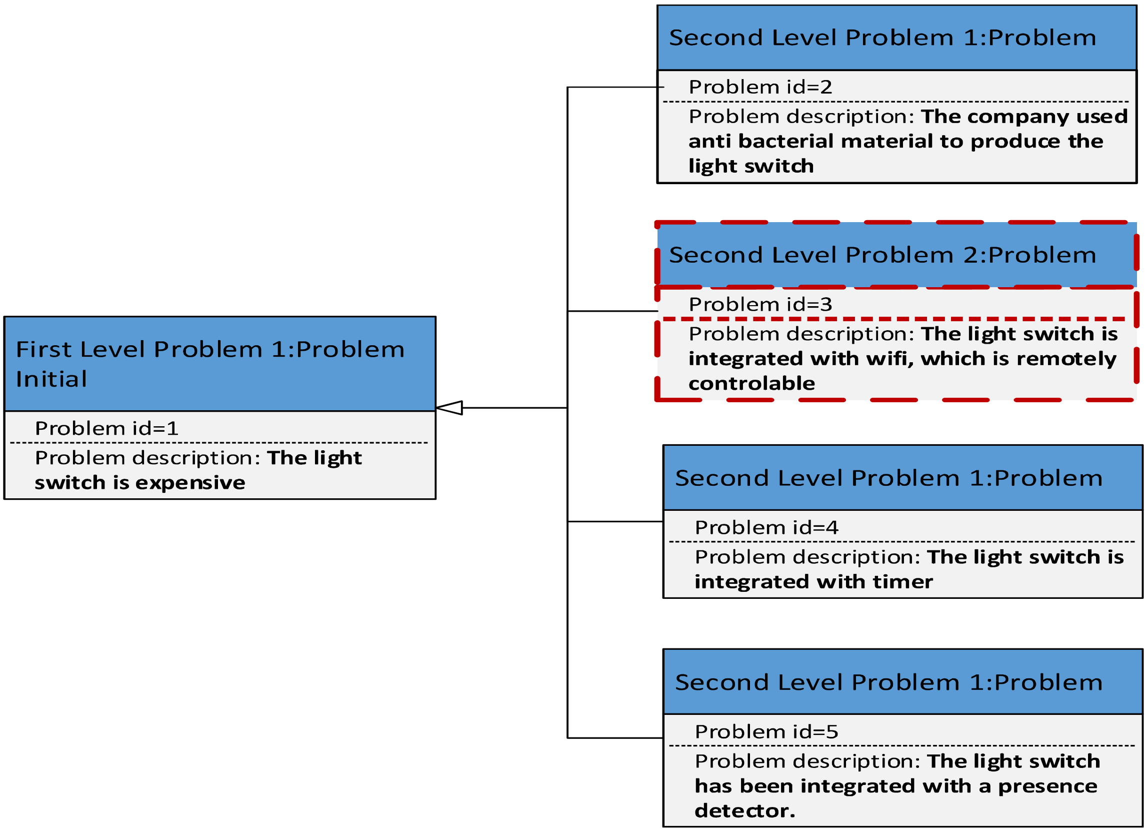


Figure 22. Problems grading interms of importance

Step 5: Determination of type of selected problem harmful or harmful-useful

By using the chosen problem from previous step, here the designer determines the type of the chosen problem by using the notions already given in the IPG structure i.e., Harmful and Harmful-Useful shown in Figure 23

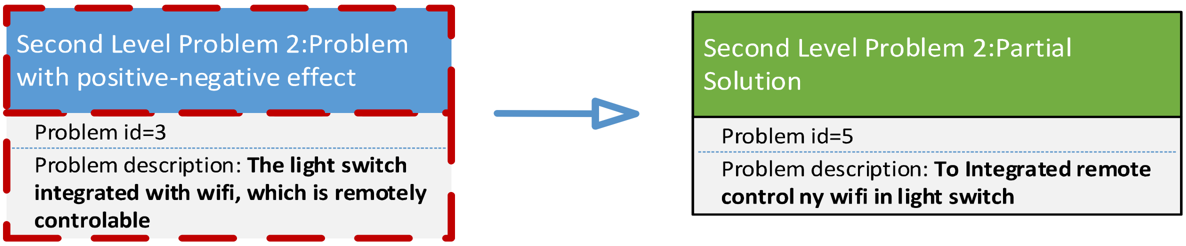


Figure 23. Conversion of the problem to partial solution

Step 6: Extraction of illustrated contradiction

In this step the designer extracts the illustrated contradiction of the selected problem from the IPG graph shown in Figure 24.

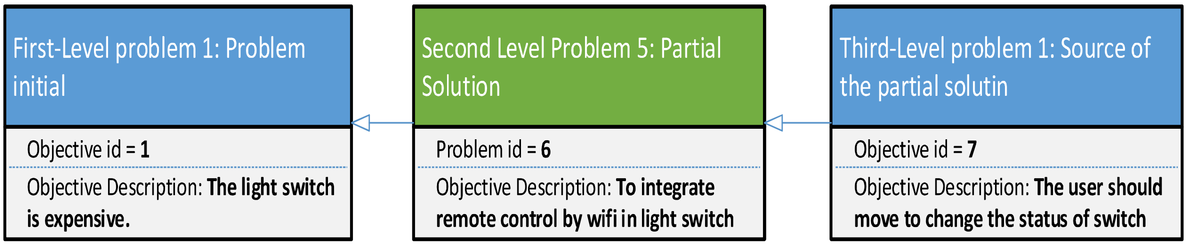


Figure 24. Extraction of contradiction

Step 7: Allocation of appropriate parameters

In this step problems and partial solution from the previous step are assigned the appropriate parameters. Figure 25 showing this assessment. The first parameter "Device complexity" was an evaluation parameter extracted from the problem "the light switch is expensive". Furthermore, "Using time by moving "selected as 2nd evaluation parameter from source of partial solution as "the user should move to change the status of switch" . correct parameter 2. to action parameter

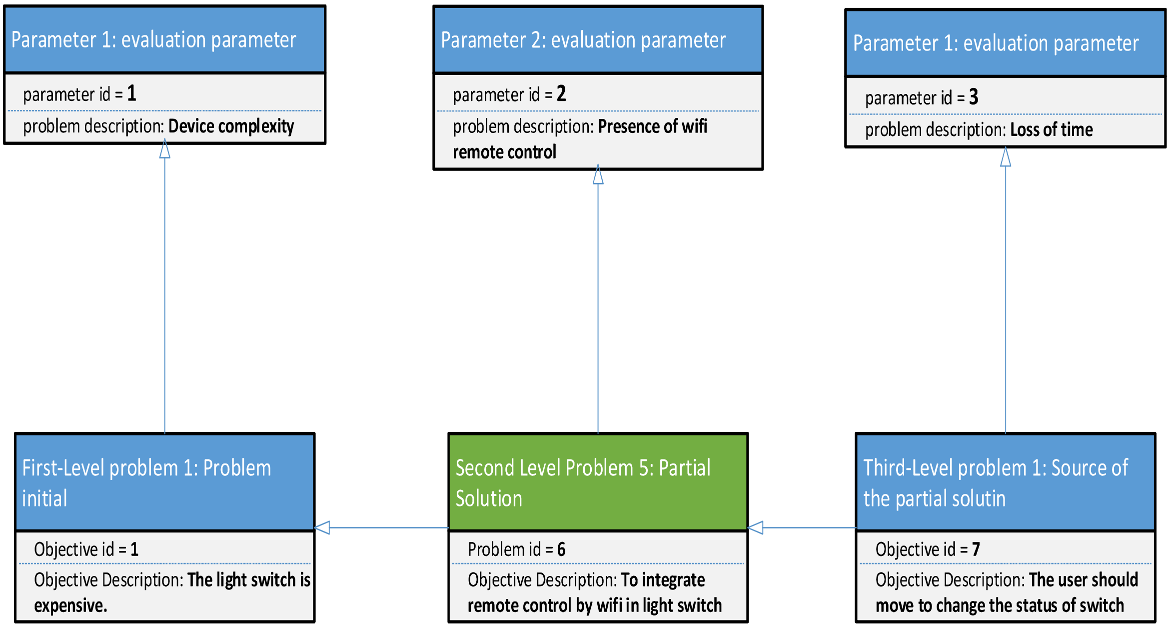


Figure 25. Allocation of the parameters

Phase 2

Step 09: Contradiction Formulation

In this step the assigned parameters from step7 are translated to TRIZ parameters. The first evaluation parameter was translated as it is as "Device complexity". Furthermore, the second evaluation parameter was also translated to "Use of time by moving". Subsequently the TRIZ parameters applied to construct a poly-contradiction model as shown in table 4. After the conversion of parameters to TRIZ parameters. These parameters (improving and worsening parameters are identified).

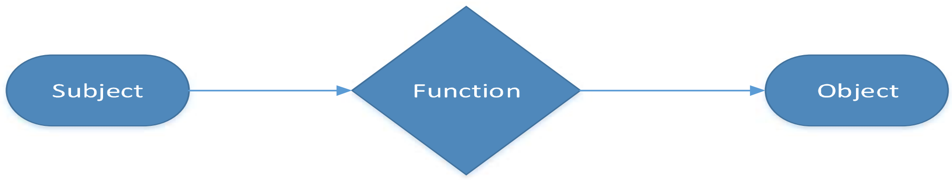
As shown in the step 7 that the first Evaluation parameter "the light switch is expensive" was translated to "Device complexity". Then the second evaluation parameter "the user should move to change the state of the switch" into "loss of time by moving". Subsequently we applied the TRIZ parameter to make poly-contradiction model as shown in table 4. the relationship between the parameters of the model when using a Wi-Fi remote-control system for the change of switch status occur a contradiction between two parameters. “Device complexity” and “loss of time”. This means that use of remote-control system, which,” could improve the time loss by moving of the user. However, it could worsen the device complexity of the system.

Step 10: Specify the functional model for the selected contradiction.

A function is the modification of the value of a parameter of a resource. The realization of the function modifies the parameter from an initial value into a final value. When there is a contradiction arise, which means one or several functions require that the parameter of a resource has one value, when another, or several others, functions require this parameter to have another value(Sébastien et al. 2005).

As mentioned in methodology of LHS and RHS functional model. Using the action parameters from step 7, the desired function is extracted from the action parameter. The functional modeling of this phenomenon is illustrated in Figure LHS. The incoming consists of the Current and Human hand, and the outgoing consists of the current to the device. The function that links the flow of material is “Regulate current or Control current”

Thus, the function connecting the human hand and current flow is “control current”. The desired function from the parameter step suggests the possibility of a signal-controlled approach. Instead of regulating the flow of current by human hand to change the status of switch an engineered solution could regulate by flow of signal, e.g., using some kind of a Wi-Fi control mechanism. Figure 26 illustrates example of control current of light switch as an input to the process as LHS functional model which in return the RHS a function model as an output with the desired functional model.



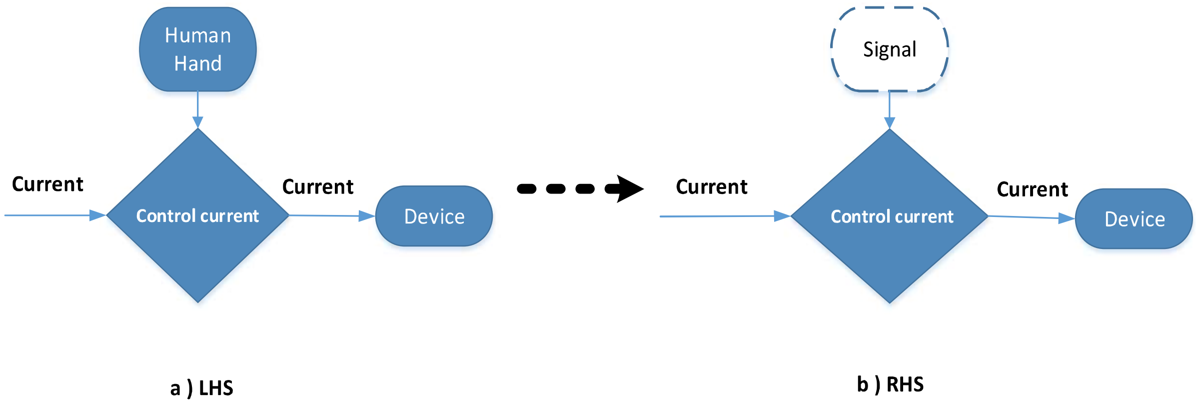


Figure 26. LHS an example of function control current with human hand functional model and RHS desired functional model

Function subgroup identification

In this step, the function identified in step 8 is further processed to extract the function subgroup from the new proposed database. As in step 8 the desired function identified was "Control" which is having sub group of desired functions "Actuate, change, regulate, condition ".

Function (Function sub group) → *Control (Actuate, change, regulate, condition)*

Step 11: Characteristic of Function

In this step after the specification of function model for the selected contradiction, in this step we specify the desired characteristics of the function based on process parameters. As in this case, the function "control" having desired characteristics "remotely". The desired functional characteristics are also a representation of customer requirements or objective of project. The structure of this phrase could be as:

Function	Characteristics
Control	Remotely

Characteristic subgroup Identification

In this step, the characteristic identified in step 9 is further processed to extract the characteristic subgroup from the new proposed database. As in step 9 the desired characteristic identified was “Remotely” which is having subgroup of desired characteristics “saving time, saving energy “.

Characteristic (Characteristic subgroup) → remotely (saving time, saving energy)

Step 12: Selecting Inventive Principles

Then in this step by applying the TRIZ contradiction matrix selection of inventive principles are done. It consists of listing the inventive principles, selecting inventive principles and then selecting sub inventive principles which is closest to our problem. The list below Table 16 shows the inventive principles obtained from the intersection of the parameters in the matrix.

Table 16. Selection of inventive principle

Principle	Proposed Actions
28 mechanics substitution	Replace a mechanical means with sensory means

Step 13: Retrieval of Solution Concepts

Once we get main function, sub functions, desired characteristics and sub characteristics of the system our purpose is to extract solution concepts from database of designs by using the desired functional model and desired characteristics. Inventive principles and sub inventive principles along with extracted applications from scientific papers database (i.e., mapping the inventive parameters and related suitable inventive principles and applications) making use of the applications and sub inventive principles basis. Once a function term is obtained, a basis set of the required function terms is defined. Then, the functional model is developed for the selected contradiction after that required characteristic are identified. Query generation and similarity ranking tools are then developed to query and retrieve the designs with the highest degree of relevance to the functional description of a given design problem with desired characteristics. Finally, the most relevant solution concepts results are presented to project partners as indicated in last column of **Table 17**.

Table 17. Functions, sub functions, characteristics, and sub characteristics

System	Characteristics	Sub Characteristics	Function	Sub Function	SCs
Light switch, Bulb Button, Device n	Manual	Use of energy by moving, loss of energy, loss of time,	Control	Actuate, Transform,	n
	Remotely	Save energy, save time, Device complexity	Control	Supply, Remove, regulate, convert	n
	Manual, Portable	Save energy, save time, durability	Control	Actuate, transform, control	n

Step 14: Expected FB and FBS relationship.

The study on steps to integrate FB and FBS related relationship is in progress as a next step of our research. With the help of current development to integrate in modern tool base inventive design approach, the function evaluation step has been integrated initially. Once those two evaluation steps will be completed then final evaluated solution concepts would be more agile and useful in producing inventive solutions to the initial identified problems.

Step 15: Evaluated Solution Concepts.

Final result of evaluated solution concepts could be in the form of table, sketches, verbal, picture etc like an example shown in **Table 18**.

Table 18. Future perspective of FBS evaluation framework integration

FBS	FB	System	Characteristics	Sub Characteristics	Function	Sub Function	SC
In progress		Light switch Bulb Button Device	Manual	Use of energy by moving, loss of energy, loss of time,	Control	Actuate, Transform	n
			Remotely	Save energy, save time, Device complexity	Control	Supply, Remove, regulate, convert	n
			Manual, Portable	Save energy, save time, durability	Control	Actuate, transform, control	n

6. CONCLUSIONS AND PERSPECTIVES

With the advancement of technological developments, companies have been seeking ways to find inventive design approaches to increase their chances of success in competitive markets. The purpose of these research work is to increase the acceptability and more focus to inventive design SCs to increase the process of finding inventive design solutions within companies contrary to the conventional solutions.

6.1. CONTRIBUTIONS

Our study is focused within the domain of concept generation step of inventive design approaches, and we have conducted an extensive analysis of existing literature on proposing an evaluation framework for SCs in inventive design approaches.

The SC is not a real product or solution/structure rather it is an idea of product which has the capability to guide project partners (designers, experts, R&D and top management of company etc. to produce inventive solutions to problem(s) under consideration. Next, how to generate an inventive solution from these elements is a big challenge because there is no method for evaluation and comparison of these SCs at this stage. From this perspective, there is a research gap in methodological approaches that all the existing inventive design approaches are lacking rigorous methods for evaluating SCs in the concept generation phase. To deal SCs in such situations there are two main problems to answer:

- First, how to represent a SC which is not a product but an idea with several elements.
- The second problem is how to build the evaluation framework in order to evaluate and compare important elements of SCs to produce inventive solutions.

Therefore, to answer these problems, this study has proposed a concept generation stage evaluation framework for SCs in inventive design by combining existing methods. It is not just a use of existing methods, but we have combined some existing methods in such a way to propose our own method of building a new evaluation framework that can allow us to compare two or more solution concepts. By doing so, this study will be contributing in terms of representation and evaluation of SCs in inventive design. A schematic of proposed evaluation framework contribution with inventive design approaches is shown in Figure 27.

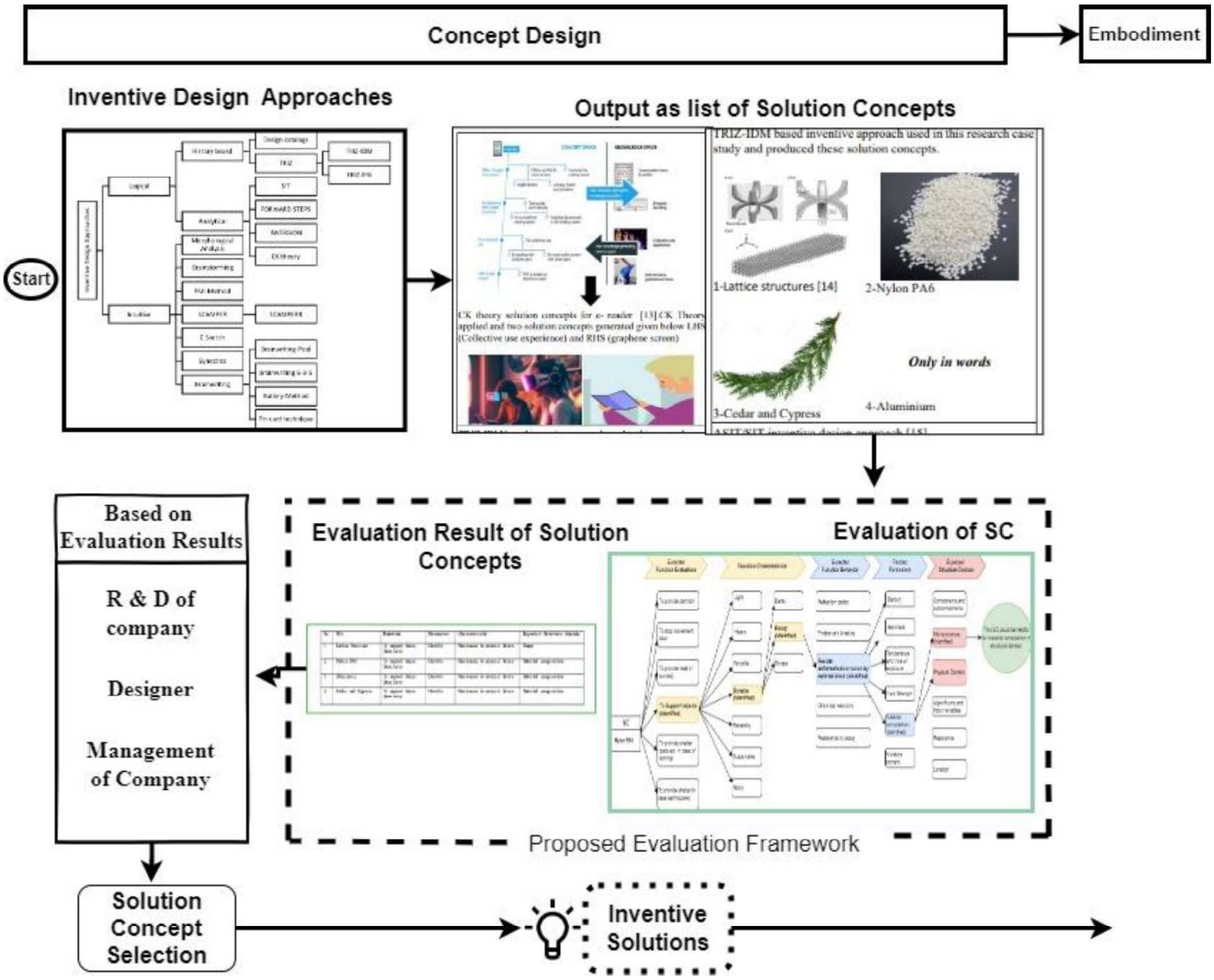


Figure 27. Schematic of inventive design approaches with evaluation framework

In the following sections, each chapter's research works are summarized, followed by an outline of the main contributions of this thesis. Finally, several future prospective points are suggested to enhance this research further.

6.1.1. Summarization of the chapters

In Chapter 1 of this thesis, we mentioned that one of the main limitations to the inventive design approaches is that these approaches generate rough idea, i.e., SCs, which can lead towards inventive solutions, but these rough ideas do not have the necessary detailed information to present for project partners resulting less focus. In order to increase the acceptability and efficiency of SC, we proposed “an evaluation framework by Considering FBS aspects.

Chapter 2 presented a background and literature review about inventive design approaches and compared the inventive design approaches. Based on the literature review outcomes, we selected one of the prominent inventive design approaches i.e., TRIZ and its extension tool as IDM as our study focus on this research. In the TRIZ part, we presented an introduction of TRIZ and the notions of TRIZ, such as technical and physical contradiction. Further, we introduced how TRIZ’s tools produce solution concepts and limitations in terms of evaluating those solution concepts. We provided an overview of xTRIZ, OTSM-TRIZ, and IDM frameworks.

In Chapter 3, based on the output of literature review, it was identified that to answer the research gap in terms of evaluation of SCs in concept generation phase we need two main problems to answer. First how to represent a SC and second ow to apply methods to evaluate the SCs. Then, a FBS based framework proposed to evaluate solution concepts in the concept generation phase of engineering design process.

I**n Chapter 4,** we applied the proposed evaluation framework to a case study. At the end of this chapter, we made a comparison how an evaluated SC could be possible inputs for producing inventive solutions. We also provided an efficiency measuring scale for the inventive design SCs.

In Chapter 5, we presented a method to integrate the evaluation in modern software based TRIZ-IDM inventive design approach. Subsequently, the proposal of the chapter was applied to integrate into initial concept generation steps of TRIZ-IDM based IPG method. Finally, we made a progress to find a way to integrate the evaluation framework into the TRIZ-IDM based IPG method and after integrating first three steps, we are working further to complete the integration module in future research.

In Chapter 6, we presented the conclusion and future perspective by concluding the two main contribution of the study as first, how to represent a SC which is not a product but just a rough idea with several elements. The second problem is how to build the evaluation framework in order to evaluate and compare important elements of SCs. To answer these problems, this study has proposed an evaluation framework for SCs in inventive design by combining already existing methods. It is not just a use of existing methods, but we have combined some existing methods in such a way to propose our own method of building a new evaluation framework that can allow us to compare two or more solution concepts. By doing so, this study will be contributing in terms of representation and evaluation of SCs.

The end of this thesis reports the conclusion and suggestions for future work.

6.2. LIMITATIONS

The evaluation framework aims to increase the acceptability of SCs to produce inventive solutions in the concept generation phase. However, it cannot completely do this task. In order to solve the limitations of inventive design SC synthesis, an evaluation framework proposed. The final result of these evaluation steps is SC evaluated in domains of function, expected behavior and expected structure by considering inputs of project partners. Nevertheless, this system has several limitations, as follows.

First of all, the success of the final result relies on the initial creation of the SCs by designers. Therefore, if they do not formulate a proper problem formulation etc., the evaluation result will not extract adequate results. One of the solutions for solving this drawback could be the presence of an evaluation framework integrated with inventive design approaches from the very beginning so that the data and information can be analyzed at each step and store data.

Secondly, the analysis of our case study related to the TRIZ-IDM based method reveals that absence of evaluation at initial steps of inventive design approaches reduce the chance of SCs acceptability. Therefore, further research is necessary to make availability of evaluation framework to other inventive design approaches.

6.3. PERSPECTIVES

In this thesis, a new evaluation approach for the initial concept generation phase of inventive design is introduced. This new approach needs future work to go beyond the limitations. The future challenge is how to integrate this method with other inventive design approaches, and we are working on this to extend the evaluation domains beyond FBS in future research. For this purpose, future research deals with the above limitations as follows. As the first, try to explore a general integration method of evaluation framework to inventive design approaches. Secondly, we could try to explore more domains of evaluation other than FBS aspects.

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APPENDICES

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Système d'évaluation des concepts de solution générés en conception inventive

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Résumé

Les concepts de solution issus des méthodes de conception inventive sont généralement décrits de manière déclarative, ce qui ne permet pas de disposer d'une représentation formelle ou visuelle partageable entre les partenaires du projet. En outre, l'absence de modèle ne permet pas d'évaluer et de comparer des concepts concurrents. Pour combler cette lacune, le cadre d'évaluation proposé dans cette thèse est basé sur le formalisme classique de modélisation de produits FBS de Gero. Le cœur du modèle consiste à évaluer les fonctions des concepts de solution sous deux aspects, à savoir symbolique et sémantique, suivis de la relation FB et de la relation FBS. Le cadre proposé pour l'évaluation de la CS se compose de cinq étapes principales. Étape 1 - Collecte des données, Étape 2 - Identification de la fonction, Étape 3 - Décomposition fonctionnelle, Étape 4 - Relation sémantique fonction-comportement et Étape 5 - Relation fonction-comportement-structure. Le résultat de la méthode proposée offre pour les CS évalués une représentation formelle ou visuelle partageable entre les partenaires du projet.

Résumé en anglais

The solution concepts which are outputs from inventive design methods are generally described in a declarative manner, which does not allow having a shareable formal or visual representation between partners of the project. In addition, the absence of a model does not allow evaluation and compare competing concepts. To fill this gape, the proposed evaluation framework in this thesis is based on the classical Gero's FBS product modeling formalism. The core of the model is to evaluate function(s) of solution concept(s) in two aspects i.e., symbolic, and semantic followed by FB relationship and FBS relationship. This proposed framework of SC evaluation consists of 5 main steps. Step 1- Data collection, Step 2- Function identification Step 3- Functional decomposition, Step 4- Function-Behavior Semantic relationship and Step 5- Function-Behavior-Structure relationship. The result of the proposed method offers for the evaluated SCs, a shareable formal or visual representation between partners of the project.