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Modelling Constraints in the Conceptual Design Process with TRIZ and F3

Khairul Manami Kamarudin^{a,b,*}, Keith Ridgway^a, Mohd Roshdi Hassan^b

^aAdvance Manufacturing Research Centre with Boeing, The University of Sheffield, Advance Manufacturing Park, Wallis Way, Catcliffe, Rotherham, England, S10 1GZ
^bDepartment of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

* Corresponding author. Tel.: +603-8946 4096 ; E-mail address: manami@upm.edu.my

Abstract

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

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1. Introduction

Among the copious information gathered for the conceptual design process, constraints should be the first to be studied. Constraints carry the designer into an environment where permissible design requirements and the limitations of the function work together. Inappropriate constraint management in conceptual design can cause catastrophic failure while removing it will result in a chaotic system [1]. When developing a conceptual design, the designer must consider a multitude of constraints and the best way to handle them is by determining which constraint is the top priority and then to sequence them until reaching the lowest priority.

Constraints stimulate creativity and create an opportunity for exploring disadvantages within a problem and enabling the relationships among the design parameters to be explored within the system boundaries. Design constraints are necessary because significant innovations happen in spite of the inadequacy of resources and various design limitations. Indeed, the lack of resources can be the catalyst for the creation of

greater innovation and a better conceptual design than one with abundant access to resources.

The development of the constraint model uses several TRIZ tools to make the model more robust in F3 perspective. The aim of this paper is to give suggestion to another method of modelling, as an alternative to many existing constraint model. The model itself and its process expects to help designers understand and differentiate the constraints applied in the design process. This paper also aims to gather constraints and design data together to understand a system's behaviour. Section 2 of this paper consists of the background of the constraints, TRIZ tools and F3, while section 3 elaborates upon the study of the constraints and the modelling. Section 4 is the discussion section, together with the conclusion.

Nomenclature

Prototype	Current design
Artefact	New concept design
SDA	Systematic Design Approach

F3	Form-Fit-Function
LG	Landing gear
IFR	Ideal Final Result
40-IP	40 Inventive Principles
39-P	39 Parameters

2. Background

2.1. Definitions

According to [2], the definition of constraint means a limitation or restriction, while [3] defines constraint as “a factor that restricts an entity or system from achieving its higher level of output with reference to its goals”. Another definition of constraint by [4] is “the state of being checked, restricted, or compelled to avoid or perform some action”. The keywords boundary, control, force, and restraint are suitable for the understanding of constraints in the context of conceptual design activity. Several studies regarding constraints in the abstraction process were made by [5, 6, 7], but there is still room for improvement for constraint modelling studies. Much of the literature suggests that constraint-based techniques improve problem-solving for preliminary design [8, 9, 10, 11].

2.2. Types of constraints

There are four distinguished types of design constraint: functional, topologic, geometric and quantitative [12, 13]. According to both author, the functional constraint is the requirement for functionality of the prototype, topologic constraints are the relationships between entities, geometric constraints are about geometric dimensions, and quantitative constraints are the parameter measures. It is important to monitor constantly and diagnose constraints in the conceptual design process to ensure the performance of the product in terms of it working properly and functioning correctly [14, 15]. Several researchers have built many models of constraint to ease the understanding of constraint in design, especially conceptual design [11].

Leffingwell and Widrig [16] interestingly compiled a list of the characteristics of constraints according to the three sources of design constraints, as elaborated in Table 1. Although the scope of their constraint analysis is for software management, it can be applied to design field as well. In this paper, the focus on constraints pertains to the first and second sources from Table 1, and, specifically for the constraints of the LG sub-part, side strut.

Table 1. Three sources of constraints [16].

Constraint Sources	Details	Types of Constraint
Design Options	<ul style="list-style-type: none"> A degree of flexibility and development freedom has been lost due to design constraint, Mostly internal constraints. 	Functional, technology, time, material, motion, aesthetic, health and safety.

Conditions Imposed on the Development Process	Requirements imposed on the process of design, for examples: <ul style="list-style-type: none"> Compatibility with existing/current systems, Application standards, Corporate best practices and standards, Mostly external constraints. 	Manufacturing, inspectability, quality sustainability, life-cycle.
Standards and Regulations	The body of regulations and standards related to the prototype to be designed, <ul style="list-style-type: none"> Examples of design standards and regulations: German Industrial Standard (DIN) for mechanical parts, EASA & FAA (for Aviation), etc., External constraints 	Economic, environmental, social, legality, ethical

2.3. Constraint characteristics

Constraints promote creativity by reframing problems creatively. Here, the reframing of problems is through modelling to clarify the design process involving multiple constraints. Constraints in conceptual design are usually defined according to the design parameters and choice of parameter values.

A prototype’s constraint is categorized into two: inherent and imposed [17]. The inherent constraint is usually about the laws of nature of the design problem, the capability of the material, the sturdiness of the shape and its lifecycle. The inherent constraints are unavoidable. Imposed constraints factor in when the component receives energy, receives loads or external functions, and interactions when in motion. Design regulations, customer requirements, and design standards also falls into the imposed constraints category. An artefact will not give an ideal design solution if the constraints are too controlled and will become inefficient if too loose. Designing an artefact creatively with constraints requires the skill of critical thinking and a content expertise.

On the characteristics of constraint, a single product has several constraint characters:

- The constraint which is not allowed to perform exceeding its limitation, restrained from performing more than permissible range. Question of “What risk will arise if the performance reaches more than the permissible limit?” arises. Usually, factors regarding danger, hazard or emergency situation to others would be the concern.
- The constraint which cannot perform after reaching its limit, that is, after the limitation is reached the product cannot perform anymore – the end of its performance. Question of “What is the risk after performance limit?” arises.
- Constraints which forbid the product to touch or in contact with other product to avoid risk in performance.
- Constraints pertaining the supply of a certain energy, load, force, tension.
- The product’s reaction to certain application, contact or performance action, performance environment.
- The constraint frequency – where the input frequency is 1, the sub-component frequency might be more than 1, with a limitation of certain frequency quantity.

A combination of two or more products will experience more quantity and multiple types of constraint.

In TRIZ, the term *contradiction* complements constraint. But, contradiction in TRIZ understanding is something that is able to be eliminated, while in general, constraints can be the existing characteristics of the component (inherited). It can only be reduced or optimized. Some constraint in the prototype are not contradicting to the “improving parameter” but limiting its performance. These constraints can create the opportunity to get signs of ideas to the problem, and suggests potential solutions. For example, the LG side strut contradiction has component complexity but have high design durability. But there are other constraints inside the side strut in terms of length and material, and the imposed influences (super-system) such as loads, aerodynamics, and heavy weather could not be totally eliminated. Another constraint is related to the design itself especially safety constraint which should not be omitted in its redesign process.

2.4. Reasons for modelling constraints

Constraints can promote creativity, possibility to many inventive solutions by reframing problems creatively. Here, the reframing of problems is through modelling, not just to clarify the design process involving multiple constraints but to find potential radical solution ideas. Constraints are usually defined according to the parameters and choice of parameter values. By modelling parameter constraints, it is possible to describe how individual components behave and to inform us about a system’s behaviour. Visualizing parameter constraints is easier through the model representation; whether on the relationships of the parameters (between weight, size, material type, and the quantity of components, joints), how they interact, and work with each other, or the possibilities to add or reduce components.

In TRIZ, 39-P of a prototype is set out for the use of contradicting parameters. Modelling constraints can increase the understanding of the overall design process. According to Medland et al. [18], initially, the constraints are not all known and usually viewed in set-theoretic terms. Constraint modelling helps designers adjust the values of the design parameters, adding or removing constraints. One strategy for improving designs with constraints is to begin with a model of a prototype system. To start, [19] recommends obtaining the list of components and the respective position and pivot points inside the overall system. The data may be incomplete or incorrect but with proper mapping, the visibility of the actual size of the prototype network becomes clearer.

2.5. TRIZ and constraints

At the highest level, TRIZ has a simple tool for determining the constraints at the outset of the problem-solving process. The tool is the *If-Then-But Rule*. The tool is dedicated to finding the contradiction of a problem, where the user requires to find one *improving parameter* (the current problem advantage) and one *worsening parameter* (the constraint or disadvantage). Yeoh [19] constructed a structure that is simple and makes it easy to understand the relevance of the If-then-but rule; Table 2 represents the structure of the tool. This tool is beneficial for identifying the parameters used for the selection of 40-IP through the TRIZ Contradiction Matrix. The

responding variables, a contradicting parameters, is the first constraint identified in the problem-solving process of TRIZ. Later, EC comes in.

Table 2: The TRIZ *If-Then-But Rule* structure [19].

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

The offset of EC and PC contradiction formulations is that it only formulates single constraint. Multiple constraints need multiple contradiction formulations and may lead to scattering 40-IP solutions and sometimes hard to relate to each other.

2.6. Form-Fit-Function (F3)

Segmenting the system and structure of a prototype into F3 can help designers plan and organize resources, such as technology concept, incorporation of new materials and time taken to develop the system pertaining to the constraints. Below are descriptions of form, fit and functions [20]:

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

This paper suggests that the viewpoint of the design constraint model is with the F3 representation.

3. The constraint modelling

The best way to understand constraints within a problem is to simplify and model multiple constraint characteristics. Proposed here is a constraint model with the F3 structure to ease the understanding and the differentiation of constraint types for the purpose of conceptual design. Reformulating or eliminating unnecessary imposed constraints further elevates the new solution in terms of concept design. The constraints should be monitored and continuously be diagnosed to ensure that the artefact development does not violate certain design limitations.

3.1. Gather information

A basic framework of the constraint model with F3 divisions is shown in Fig. 1. The term “Form” here can be a single part (eg: P1, P2 or P3) or an assembly; a group of components (PG). The form is the initial step, bringing the selected component (form) for further the investigation of its sub-component fit and function. The “Fit” is the relationship between sub-component, their locations and the function associations between them. Then, the “Function” division shows the performance between each other when in work - what functions do, accomplish and what are the constraints involved inside their functions. This framework should indicate the inherited and imposed constraints, and the parameters involved in order to show a visible picture of the constraint network.

The model in Fig. 1 indicates the min-max propositions; C_{ideal} shows ideal or IFR constraint, $< C_{ideal}R$ is the risk probability of a performance less than the IFR. C_{max} is representing maximum constraint, while, $C_{max}R$, is the risk probability when exceeding the maximum permitted constraints. Often designers will create worst case scenario of a part’s performance and failures ($C_{max}R$), and find C_{ideal} .

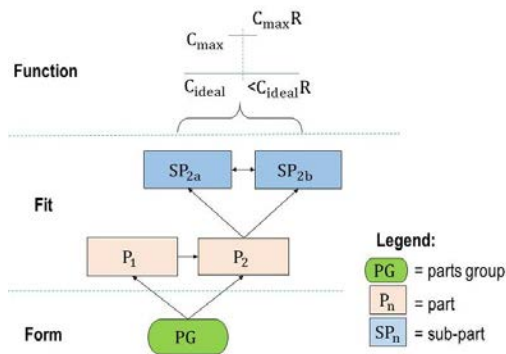


Figure 1. The FAM is segmented into F3 divisions. The divisions made are to help designers to further understand the *Fit* characteristics and to identify potential design changes.

At the beginning of the problem solving and design process, a component-specific FAM model is constructed. During system modelling, it is important to identify the constraint (both inherited and imposed) of each prototype and its boundary around the whole system [21]. The focus of constraint study will be on the component inside the chosen boundary. Fig. 2 shows the FAM of a typical commercial aircraft’s LG side strut. The FAM here indicates several group components inside a boundary lines.

An inventory tool from ARIZ, *Substance and Field Resources* (SFR) [22] can help exhibits and determines the constraints characteristics, as shown in Table 3. The use of the SFR table absolutely aids in identifying the characters of constraints inherited in the prototype.

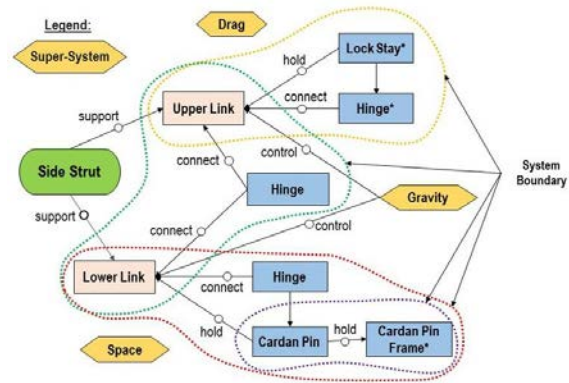


Figure 2. The FAM of the LG side strut [23]. Shown are several PG boundaries. Items marked with * are connected to the main strut.

When the SFR adequate list is obtained, the designer will organize the constraints from the resources, substances, and parameter fields from the highest priority to the lowest, the ones that have little possibility of change down to total changes.

Table 3: The SFR table of side strut and its affiliates.

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

The “fields” column in the SFR table (Table 2) consists of the mechanical (Me), chemical (Ch), and gravitational (G). Other field includes thermal (T), acoustic (A), electrical (E), magnetic (M) and more. Note that the “Tool: side strut” inherited the mechanical field. Although it is from the mechanical field, it should not be limited to only mechanical solutions but can adapt ideas from a different field as well.

3.2. The modelling

The next step is to further expand the FAM of the side strut focus part so that the understanding of constraint variables within the prototypes’ system is extended. The FAM shown in Fig. 3 is about the upper link of LG, added with more particular details and the constraints of the part. The constraints information is obtained from the parameters listed in Table 3, and should also take into account other possible imposed constraints, such as force direction, magnitude, drag, loads, and retractable LG door movement clearances, that may be important for further design consideration or constraint elimination. Here, the designer can find what the appropriate technology is or the suitable design changes for a possible new concept design.

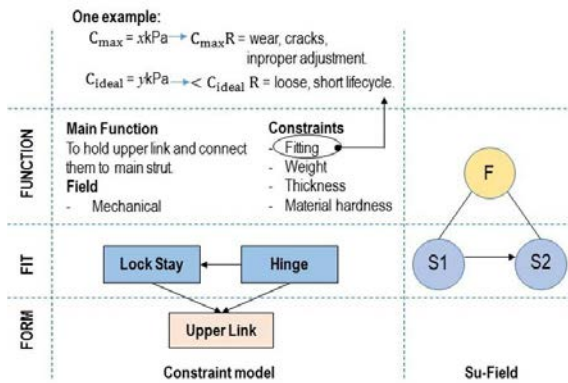


Figure 3. The side strut constraint model with several parameters from the lock stay and hinge combination. Shown here is the example of fitting constraint values and the risk possibilities of exceeding the permitted values.

The constraint and risk possibilities here are for both lock stay and hinge, where both have different inherited constraint characteristics yet rely on each other when functioning. Main function of each part are examined, the field is identified and the constraints are tabulated in a single F3 model. The model is simpler and helps in better understanding the “fit” characteristics and constraints when there is a need to change the prototype into a new artefact.

The structure of the constraint model is inspired by TRIZ Su-Field model [24], where the *field* terms is broadened to not just only engineering fields but also prototype’s main function, performance outcome, and constraints’ values.

3.3. Multiple constraints

Multiple constraints on the LG side strut upper link are also much easier to visualize with a constraint network model. The design IFR should be the increasing value of C_{max} of the side strut so that the flexibility range is becoming bigger. The second design IFR is to reduce the numbers of imposed constraint (design parameters) than the current prototype so that the possibility of the design change is higher. The *fitting mechanism*, of the lock stay and hinge, is discovered to be one of the major constraints, due to the criticality of its potential failures. Designers should focus on the problem-solving and new design development of the current fitting to replace other means of better fitting. The ideas for new fitting efficiency might include the use of flexible materials such as fibre coating, rubber, silicon, or combining two types of flexible material. This way it increases the maximum value of flexibility constraint, and, at the same time, can reduce the risk of wear, crack and improper adjustment due to heavy landing impact. A suggestion of using *LaGrange Multipliers* for finding min and max of a multiple constraints network are useful too. The C_{ideal} and C_{max} constraint calculation should also relate to number of cycles (frequency constraints), in accordance with the maintenance procedures of life limit cycles, where for as high as 75,000 cycles [25], both parts must be re-evaluated for a replacement.

4. Discussion and conclusion

4.1. Discussion

The external constraints are actually the ones that drive the innovation of new design. They influence the decision for change and innovation into a new conceptual design, and for the replacement of parts with more sophisticated materials and technology; therefore, improving the design constraints until they achieve more manageable design limitations. Designers should engage with the external constraints characteristics and translate them into a more creative idea, further into a better solution.

Although there are selected tools, not in-sequence, from TRIZ and ARIZ used in the constraint modelling method, it is only for the constraint modelling guidance and not intended to change TRIZ procedures. Sometimes the designers experience psychological inertia when resolving design constraints where the constraints are unknown and unorganized. By doing constraint modelling, it is hoped it will ease the initial analysis part of the conceptual design process.

4.2. Conclusion

The constraint model should be a friendly tool for designers who work with multiple constraint characteristics prototype. It is hoped that the constraint model will inspire designers to innovate and initiate the search for new technologies to supplement or replace the existing technology of the prototype efficiently. This study also anticipates to encourage designers to perform a conceptual design for a more complex prototype system. The combined methodology of TRIZ with the constraint-based approach sanguinely increases the capability to design with constraint management. In future, the authors hope to further the constraint model dedicated as one of TRIZ tool.

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