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Mathematical Modelling and Formalization of TRIZ: Trimming for Product Design

Chris Edward¹, Jane Labadin¹[0000-0003-0508-4277], Narayanan Kulathuramaiyer²[0000-0002-1278-8419]

¹ Faculty of Computer Science and Information Technology,

² Institute of Social Informatics and Technological Innovation,
Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia
chrised@sains.com.my, {ljane,nara}@unimas.my

Abstract. This work aims to formalize TRIZ modelling framework and trimming techniques through mathematical notations to lay the foundations for rigorous analysis of TRIZ as a Science of Innovation. Mathematical modelling has been employed to formalize the heuristic models of trimming. A case study was presented to demonstrate the use of the proposed modelling scheme. The paper has demonstrated the correlation of TRIZ modelling framework and trimming techniques with well-established mathematical fields such as Formal Logic, Set Theory and Graph Theory. It presents initial efforts in formalizing the functional analysis and trimming techniques as a rigorous formal approach. The acceptance of systematic innovation as a scientific discipline that can be supported by knowledge systems and can be connected to mathematical models remains a dream. This work provides directions for inquiry into this non-trivial endeavour. The value of this work will see future computational models for supporting systematic innovation. The real-life use case demonstrates the powers and gaps with regards to Genrich Altshuler's modelling of product innovation using heuristics.

Keywords: Data Dictionary, Graph Modelling, Trimming Principles, Trimming Iteration, Semantic Invariant, Formal Logic, Set Theory, Graph Theory.

1 Introduction

The *Theory of Inventive Problem Solving* (Russian acronym: TRIZ), an international exact science of creativity developed by G.S. Altshuller and his colleagues during the erstwhile U.S.S.R. reign circa 1946-1985, is a problem solving method based on logic and data – not intuition – which could potentially accelerate a project team's ability to solve problems creatively. Due to its systemic structural framework and algorithmic approach, TRIZ offers repeatability, predictability, and reliability. In contrast to brainstorming techniques which tend to rely on spontaneous and intuitive creativity of individuals or groups, the TRIZ methodologies rely on the study of the patterns¹ of problems and solutions – more than three million patents have been examined through empirical analysis in order to discover patterns behind the breakthrough solutions for various tough challenges. Altshuller's heuristic mental model proposed that *there exists a set of fundamental universal principles of creativity that form the basis for all creative innovations*. In addressing this imperfect knowledge, there is a need to translate the knowledge into a formalized model as we hypothesize that if *all* of these fundamental principles could be identified *completely* and codified *consistently*, they could be taught to anyone to make the creative process more systematic and predictable. A similar aim was discussed by Lau [1] on his proposed framework for developing a TRIZ implementation model in China. His empirical approach towards adopting TRIZ has given insights to properly formalizing existing TRIZ principles and techniques. In contrast, our study employs an analytical approach in formalizing TRIZ modelling specifically on trimming principles via the use of graph theory.

There are other research in similar pursuit such as the work of Nordlund [2] who provided case studies concerning the applications of Axiomatic Design theory towards a manufacturing process, micro and nano product design, software design, and socioeconomic systems design. The theory prescribes nominative rules to adhere in a design process. Efimov-Soini & Chechurin [3] introduces a new ranking method for component-function-component duplet chain structures in a system. Overall, their proposed method is better than the classical method of ranking and Miao Li's linear convolution method of ranking. Just like previous functional model ranking methods, the proposed method is intended to aid in trimming using existing TRIZ trimming rules by proposing candidate duplet chains to be trimmed based on their low rankings. The same authors then in [4] presented an innovative approach to objectively rank functions (between components) in a dynamic system model.

Motivated by [1] – [4] and as highlighted in [5], there is a need to formalize TRIZ in some ways and to eliminate ambiguity in interpretations where it is deemed necessary. This paper, therefore, presents a formalization of TRIZ trimming principles, of which is chosen amongst others due to it being canon in classical TRIZ literature, so that it be (mathematically) defined formally, and the trimming process, based on the rigorous trimming principles

¹ Dr. Keith Devlin, emeritus mathematician at Stanford University and director of the Stanford Mathematics Outreach Project [6], referred Mathematics as the science of patterns [7]. Interestingly, there seems to be massive overlaps and parallels between Mathematics and TRIZ; just as TRIZ explores patterns of problems and solutions.

definition, reflects iterative and algorithmic nature. This paper focuses on Device Trimming which is an important instrument particularly in the area such as product design and patent circumvention [13]. Trimming is an analytical tool that can eliminate one or more components in a system while still maintaining the main useful functionality.

2 Model Formulation

Contrasting from TRIZ diagram-based modelling approach, we introduce a novel algebraic notation and graph modelling, based on Graph Theory, that could be considered a shorthand notation to the existing TRIZ modelling techniques without compromising the conceptual and logical integrity. Additionally, once the algebraic notation graph modelling approach are defined, we introduce six new trimming principles as well as the formal mathematical formulation of the new principles using the acquainted algebraic notation.

Before introducing the algebraic notation, we first introduce the corresponding data dictionary (cf. Table 1) which provides a brief definition of m components and n functions found within a systems model [8], where $m, n \in \mathbb{N}$.

Table 1. Generic example of Data Dictionary.

Components	Functions
c_1 : component ₁	f_1 : function ₁
c_2 : component ₂	f_2 : function ₂
...	...
c_m : component _m	f_n : function _n

For example, the data dictionary for a “playing ball” system constitute two components namely “hand” and “ball” with two functions “hold” and “push”, and they can be defined as shown in Table 2. We notated the sub-components within the indices of the component.

Table 2. Playing Ball Data Dictionary.

Components	Functions
c_1 : hand	f_1 : hold
$c_{1.1}$: thumb	f_2 : push
$c_{1.2}$: index finger	
$c_{1.3}$: middle finger	
$c_{1.4}$: ring finger	
$c_{1.5}$: little finger	
c_2 : ball	

Based on the “Playing Ball” data dictionary on Table 2, the function model for “hand hold ball” can be notated as the following mathematical construct:

$$c_1 \xrightarrow{f_1(c_2)} c_2 \quad (1)$$

$$c_1 \left\{ \begin{array}{l} c_{1.1} \\ c_{1.2} \\ c_{1.3} \\ c_{1.4} \\ c_{1.5} \end{array} \right\} \xrightarrow{f_1(c_2)} c_2 \quad (2)$$

As defined in Table 2, the “hand” component consists of sub-components thumb, index finger, middle finger, ring finger and little finger. These sub-components are encapsulated in braces as shown in equation (2). Here, the function model still reads “hand hold ball” as all the sub-components of the hand are contributing to the function called ‘hold.’ If one of the sub-component performs a function to another component, then the sub-component must be stated before the function and separated by a colon (:). For instance,

$$c_1 \left\{ \begin{array}{l} c_{1.1} \\ c_{1.2} \\ c_{1.3} \\ c_{1.4} \\ c_{1.5} \end{array} \right\} \xrightarrow{c_{1.2} : f_2(c_2)} c_2 \quad (3)$$

which reads “index finger push ball”. Notice in the above, a function corresponds to an edge or an arrow, indicating that an edge must have a function and vice versa.

2.1 Trimming Principles

Let V be the set of components and sub-components in the data dictionary, F be the set of functions in the data dictionary, and $g_1, g_2, \dots,$ and g_i be the set of ordered pairs $((a, b), f_1), ((a, b), f_2), \dots, ((a, b), f_i)$ such that $f_1 = g_1((a, b)), f_2 = g_2((a, b)), \dots,$ and $f_i = g_i((a, b))$ respectively, where $a, b \in V$ and $i \in \mathbb{N}$. Here,

$$\begin{aligned} g_1 &= \{((a, b), f_1) \text{ if and only if } a \text{ function}_1 b\}, \\ g_2 &= \{((a, b), f_2) \text{ if and only if } a \text{ function}_2 b\}, \\ &\dots \\ g_i &= \{((a, b), f_i) \text{ if and only if } a \text{ function}_i b\} \end{aligned}$$

Define the relation, E as the union of the set of ordered pairs g_1, g_2, \dots, g_i , that is $E = \{g_1 \cup g_2 \cup \dots \cup g_i\}$. Now let each element in E be called e_1, e_2, \dots, e_n , therefore we have $V = \{c_1, c_2, \dots, c_m\}, E = \{e_1, e_2, \dots, e_n\}$ and $F = \{f_1, f_2, \dots, f_i\}$ where $i, m, n \in \mathbb{N}$. Finally, let $G = (V, E)$ be a graph, and define the trim function and append function as $\text{trim}(x, y): x \notin y$ and $\text{append}(x, y): x \in y$ respectively. Based on these algebraic notations and the definitions of trim and append functions, together with graph theory, the following principles are defined.

Principle 1 (Non-functionality). *If $\exists c \in V$ such that $\deg(c) = 0 \Rightarrow \text{trim}(c, V)$*

Meaning: “If a node in the graph does not execute or receive any function to or from another node nor itself, then trim the node.”

Principle 2 (Redundancy). *If $c_1, c_2, c_3 \in V, f \in F$ and $((c_1, c_3), f), ((c_2, c_3), f) \in E \Rightarrow \text{trim}(((c_1, c_3), f), E)$*

Meaning: “If two nodes in the graph also execute the same function to the same node, then trim one of the edges.”

Principle 3 (Transitivity). *If $c_1, c_2, c_3 \in V, f \in F$ and $((c_1, c_2), f), ((c_2, c_3), f) \in E \Rightarrow \text{trim}(((c_1, c_2), f), E), \text{trim}(((c_2, c_3), f), E), \text{append}(((c_1, c_3), f), E)$*

Meaning: “If two nodes in the graph also execute the same function to the next node in the 3-node chain, then trim each edges in the chain and append the edge from the first node to the last node.”

Principle 4 (Obsolescence). *If $c_1, c_2 \in V, f \notin F$ and $((c_1, c_2), f) \in E \Rightarrow \text{trim}(((c_1, c_2), f), E)$*

Meaning: “If a function in the graph becomes obsolete, then trim all the edges having the obsolete function in the graph.”

Principle 5 (Transfer). $\text{Transfer}(e_1, e_2): \text{trim}(e_1, E), \text{append}(e_2, E)$ where $e_1, e_2 \in E$

Meaning: “Transferring one function between a pair of nodes to another pair of nodes in the graph is permissible; trim the edge between a pair of nodes then append the edge to another pair of nodes.”

Principle 6 (Generalisation). *Let $f_1, f_2, \dots, f_i \in F$ where $i \in \mathbb{N}$. If $f_1 = g$ in context $y_1, f_2 = g$ in context $y_2, \dots,$ and $f_i = g$ in context y_i regardless if $g \in F$, define a piecewise function called g . Thus,*

$$g = \begin{cases} f_1 & \text{if } y_1 \\ \dots & \\ f_i & \text{if } y_i \end{cases}$$

Then, substitute f_1 in context y_1, f_2 in context $y_2, \dots,$ and f_i in context y_i with g .

Meaning: “If at least two different functions in some context are equivalent to some function, then each of the functions can be generalised by that same function.”

To illustrate the principles 1 – 6, we consider a system with a data dictionary defined as in Table 3.

Table 3. Illustration Data Dictionary.

Component	Function
c_1 : left hand	f_1 : grip
c_2 : right hand	f_2 : deform
c_3 : plier	f_3 : hang
c_4 : string	f_4 : levitate
c_5 : blower	Φ : other functions performed by the node
c_6 : ping pong ball	

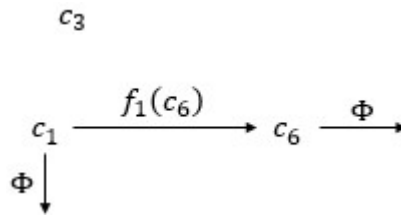


Fig. 1. Example of a graph model construct of three components in a system where principle 1 can be applied.

Fig. 1 depicts a graph model of the components “plier” and function model of “left hand grip ping pong ball”. Here, $\text{deg}(c_3) = 0$ while the degree of the other nodes (i.e. components c_1 and c_6) are non-zero. We may apply principle 1 and thus trim c_3 .

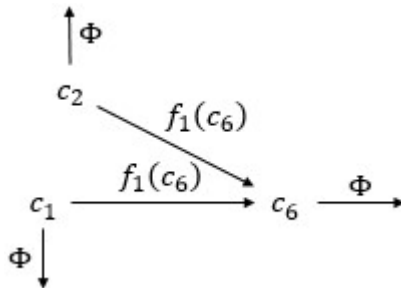


Fig. 2. Example of a graph model construct of three components in a system where principle 2 can be applied.

A function model for “left hand and right hand grip ping-pong ball” is formulated into a graph shown in Fig. 2 where the edges $((c_1, c_6), f_1)$ and $((c_2, c_6), f_1)$ are executing the same function, f_1 , to the same node, c_6 . We can then apply principle 2, and thus trim either one of the edges.

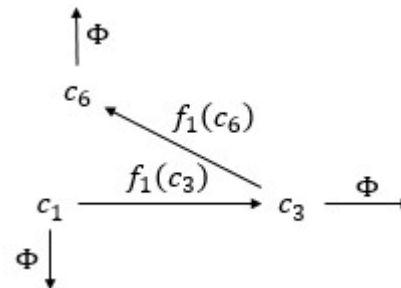


Fig. 3. Example of a graph model construct of three components in a system where principle 3 can be applied.

“left hand grip plier and plier grip ping-pong ball” formed a graph as in Fig. 3 which illustrates the nodes c_1 , c_3 and c_6 forming a 3-node chain with edges $((c_1, c_3), f_1)$ and $((c_3, c_6), f_1)$ and are executing the same function to the next node in the chain. Therefore, based on Principle 3, we can trim both edges and append edge $((c_1, c_6), f_1)$.

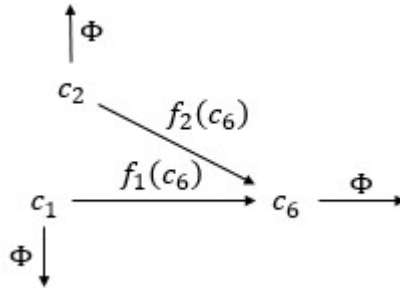


Fig. 4. Example of a graph model construct of three components in a system where principle 4 can be applied.

Consider in Fig. 4 where the function f_2 becomes obsolete and thus $f_2 \notin F$. We may apply principle 4, and thus trim edge $((c_2, c_6), f_2)$ and all other edges with f_2 .

Fig. 5 depicts a graph showing three functions acting on the same component. Here, we want to trim edge $((c_4, c_6), f_3)$ but node c_6 must receive function f_3 . Hence, we apply principle 5 and trim edge $((c_4, c_6), f_3)$ between the pair of nodes c_4 and c_6 , then append another edge $((c_3, c_6), f_3)$ between the pair of nodes c_3 and c_6 .

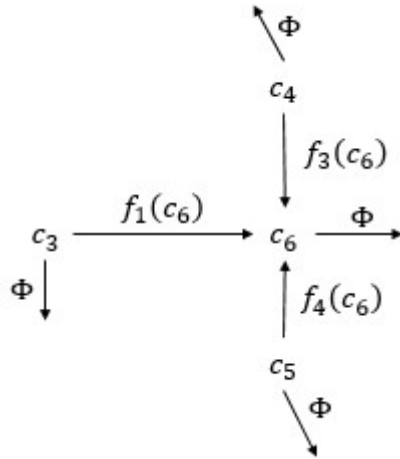


Fig. 5. Example of a graph model construct of four components in a system where principle 5 can be applied.

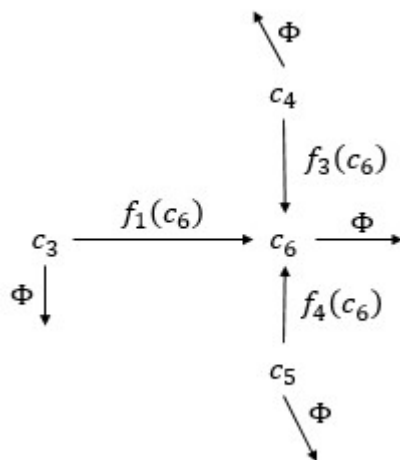


Fig. 6. Example of a graph model construct of four components in a system where principle 6 can be applied.

Fig. 6 depicts functions f_1 , f_3 and f_4 which are similar. Therefore, we apply principle 6 and generalised the functions by the same function, g : hold. Thus substituting the functions f_1 , f_3 and f_4 with g then we get a ubiquitous case of redundancy. We then may apply principle 1 and trim the relevant edges in the graph.

3 Case Study

To further illustrate the algebraic notation, graph modelling and the trimming principles in practice, we consider a case study on face mask.

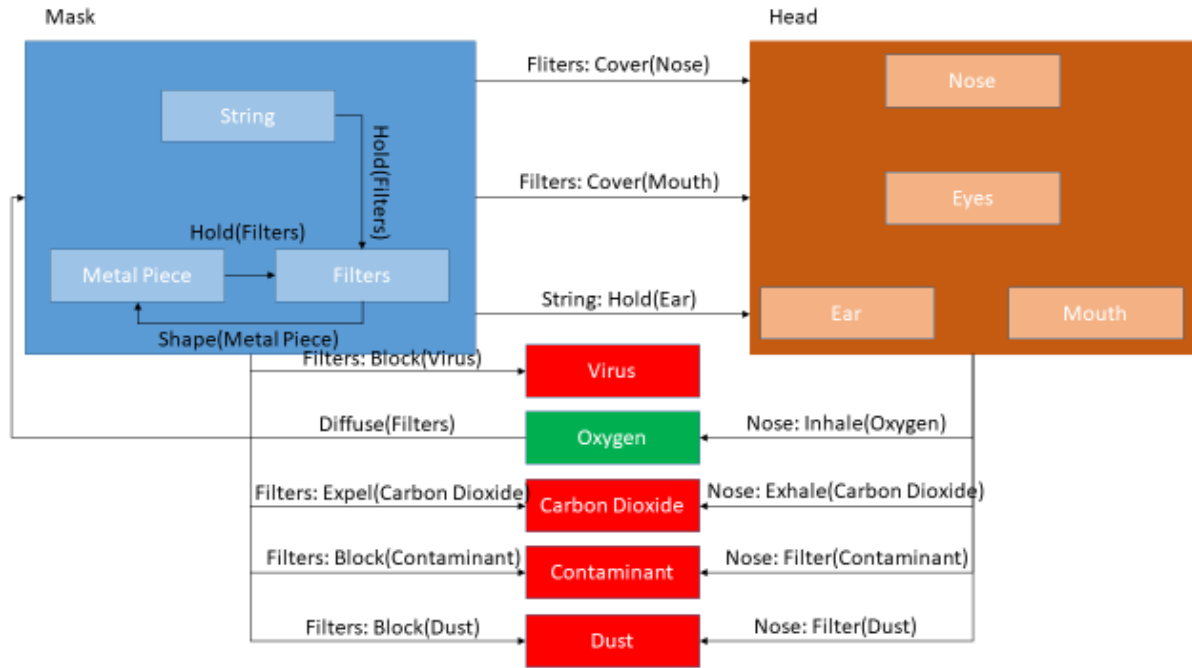


Fig. 7. Face mask system using TRIZ function model.

Fig. 7 shows the face mask system modelled using TRIZ function model. Following our defined algebraic notations and graph modelling, the function model of the face mask system shown in Fig. 7 can be represented into a graph model shown in Fig. 8. As formulated earlier, the data dictionary for the face mask system can be defined as in Table 4.

Table 4. Face Mask System Data Dictionary.

Components	Functions
c_1 : mask	f_1 : hold
$c_{1.1}$: string	f_2 : grip
$c_{1.2}$: filters	f_3 : block
$c_{1.3}$: metal piece	f_4 : diffuse
c_2 : head	f_5 : shape
$c_{2.1}$: nose	f_6 : cover
$c_{2.2}$: mouth	f_7 : inhale
$c_{2.3}$: ear	f_8 : exhale
$c_{2.4}$: eyes	f_9 : expel
v_0 : virus	f_{10} : filter
a_1 : Oxygen (O_2)	

a_2 : Carbon Dioxide (CO ₂)	
a_3 : contaminant	
a_4 : dust	

Based on the data dictionary in Table 4, let V_1 be the set of components and sub-components found in the data dictionary, F_1 be the set of functions found in the data dictionary, p_1, p_2, \dots, p_{10} be the set of ordered pairs $((a, b), f_i)$, $((a, b), f_2), \dots, ((a, b), f_{10})$, such that $f_1 = p_1((a, b))$, $f_2 = p_2((a, b))$, ..., and $f_{10} = p_{10}((a, b))$ respectively, where $a, b \in V_1$. Here,

$$p_1 = \{((a, b), f_1) \text{ if and only if } a \text{ function}_1 b\},$$

$$p_2 = \{((a, b), f_2) \text{ if and only if } a \text{ function}_2 b\},$$

...

$$p_{10} = \{((a, b), f_{10}) \text{ if and only if } a \text{ function}_{10} b\}$$

Define the relation E_1 as the union of the set of ordered pairs p_1, p_2, \dots, p_{10} , thus $E_1 = \{p_1 \cup p_2 \cup \dots \cup p_{10}\}$. Now let each element in E_1 be called $e_{1.1}, e_{1.2}, \dots, e_{1.15}$, therefore we have $V_1 = \{c_1, c_{1.1}, c_{1.2}, c_{1.3}, c_2, c_{2.1}, c_{2.2}, c_{2.3}, c_{2.4}, v_0, a_1, a_2, a_3, a_4\}$, $E_1 = \{e_{1.1}, e_{1.2}, \dots, e_{1.15}\}$ and $F_1 = \{f_1, f_2, \dots, f_{10}\}$. Lastly, let $G_1 = (V_1, E_1)$ be a graph of the face mask systems, and $\xi_1 = \{V_1 \cup F_1\}$ representing the type of nodes and edges found within the face mask systems.

Before any trimming iterations are done, i , the initial state of the face mask system graph is set to $i = 0$ and is depicted in Fig. 8.

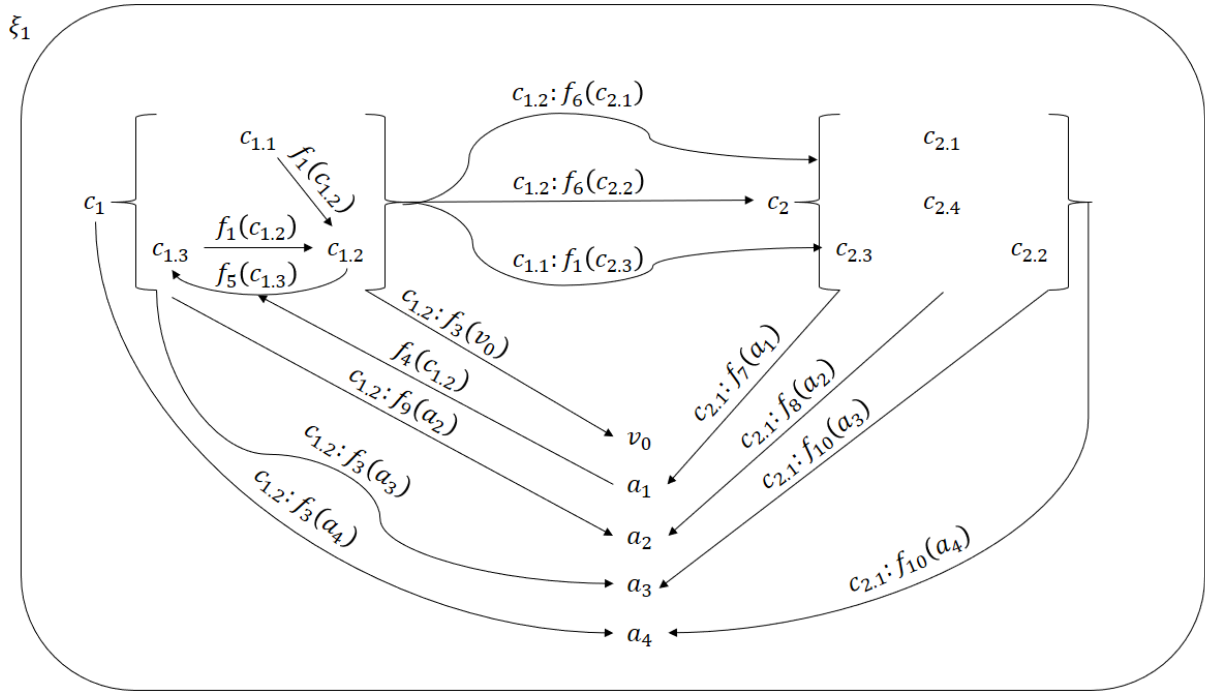


Fig. 8. Face Mask System Graph, with $i = 0$.

Once the initial state of the face mask graph is set, we now apply the trimming principles. We apply principle 1 to node $c_{2.4}$ because $\text{deg}(c_{2.4}) = 0$. Nodes $c_{1.1}, c_{1.2}$ and $c_{1.3}$, and edges $((c_{1.1}, c_{1.2}), f_1)$ and $((c_{1.3}, c_{1.2}), f_1)$ form the redundancy case as in principle 2. We decide to trim edge $((c_{1.3}, c_{1.2}), f_1)$. The graph now has been trimmed neatly as shown in Fig. 9.

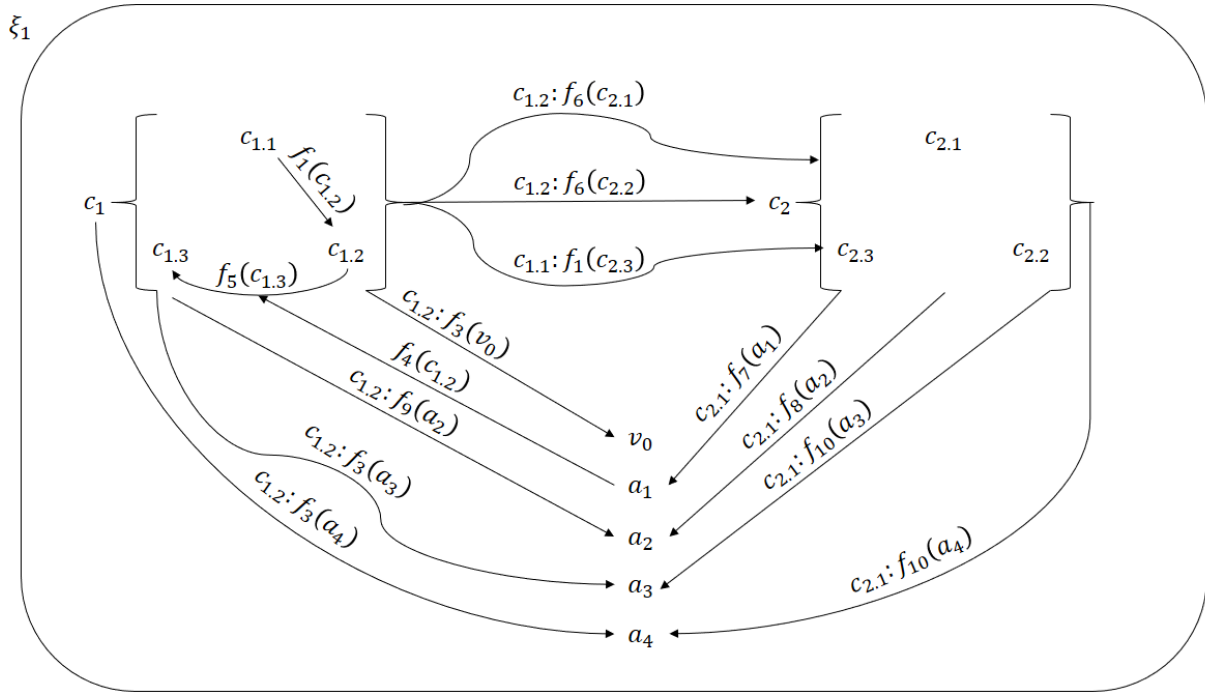


Fig. 9. Face Mask Graph after trimming, $i = 1$.

4 Analysis and Discussion

Inspired by Formal Logic, Set Theory and Graph Theory, advantage of the TRIZ Mathematical formalization, algebraic notation and novel TRIZ graph modelling includes: invariant of a semantic interpretations, open to one-to-many interpretation, simpler and quicker modelling, and such proper mathematical formalization enables TRIZ concepts to be programmable.

Unlike standard TRIZ model which declares an instance of an object that comprise of components (including subcomponents) and interactions between components (functions) which are tagged based on nouns and verbs, the proposed graph-based modelling does not declare an instance of such object and is invariant of what that component or function actually is. It is more concerned with which component it is and how the components interacts with each other (function).

The use of logical formalisms is not new in the field of Artificial Intelligence. The expressive capacity of logic, augmented by the structuring capability of semantic networks (a form of graph-representation) has been adopted widely by AI researchers. However, the proposed formal models have the advantage of providing a formalism for the formulation of ideal models based on a principled approach to trimming. The proposed framework also mainly suggests structural features as means of selecting trimming conditions.

5 Results

For the sake of completeness, we map existing TRIZ trimming rules to our trimming principles. We chose the term ‘principle’ as nomenclature to describe our graph-based trimming techniques, despite the fact it has no difference with the word ‘rule’ in Mathematics and Physics [11], purely for distinction purposes only. Unlike TRIZ trimming rules which is derived from empirical research of 200,000 over patents and real-world physical systems, our trimming principles are based on the mathematical study of networks and discrete structures [9], thus it is entirely structure-based.

Table 5. Comparing the Fundamental TRIZ Trimming Rules, A, B and C, to the Trimming Principles.

No.	Trimming Rules	Trimming Principle
1	Rule A: The functions (thus its carrier) can be trimmed if the object of the function is trimmed [10, 12].	Non-functionality
		Redundancy
		Transitivity

		Obsolescence
		Transfer
		Generalisation
2	Rule B: The functions carrier can be trimmed if the object of the function can perform the useful function by itself [10, 12].	Non-functionality
		Redundancy
		Transitivity
		Obsolescence
		Transfer
		Generalisation
3	Rule C: The functions carrier can be trimmed if another existing component in the system or super system can perform the useful function by the current function carrier [10, 12].	Non-functionality
		Redundancy
		Transitivity
		Obsolescence
		Transfer
		Generalisation

	Highly Comparable		Slightly Comparable		Least Comparable
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Table 6. Comparing the Extended TRIZ Trimming Rules, X, D and E, to the Trimming Principles.

No.	Trimming Rules	Trimming Principle
1	Rule X: The functions carrier can be trimmed if its useful function is trimmed or not needed [10].	Non-functionality
		Redundancy
		Transitivity
		Obsolescence
		Transfer
		Generalisation
2	Rule D: Function carrier can be trimmed if a new or niche market can be identified for the trimmed product [10].	Non-functionality
		Redundancy
		Transitivity
		Obsolescence
		Transfer
		Generalisation
3	Rule E: Function carrier can be trimmed if the function can be performed better by a new/improved part providing enhanced performance or other benefits [10].	Non-functionality
		Redundancy
		Transitivity
		Obsolescence
		Transfer

		Generalisation
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	Highly Comparable		Slightly Comparable		Least Comparable
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Based on the above table, we can observe that, in general, there are more than one trimming principle of ours that correspond to each existing TRIZ trimming rules because the rule exhibits at least some elements of the principles. This suggest perhaps the existing fundamental and extended trimming rules may not be sufficiently fundamental to be considered the basis trimming techniques in TRIZ as some – e.g., Rule D – is based on an external factor – e.g., ‘new/niche market’ – that is arguably subjective in nature. For TRIZ to become a hard science of innovation, we want to minimize as much as possible assumptions and fuzzy human factors to allow for rigorous, objective-based analysis.

6 Conclusion

The efforts to formalize TRIZ to turn it into the hard science of innovation calls for frameworks based on the adoption of rigorous mathematical models. In this paper, we have introduced the data dictionary, algebraic notation, graph modelling and trimming principles which are attempts to mathematically formalize TRIZ models in general and the trimming model. Trimming is seen as a valuable tool not only for its ability to retain functionality with a much more compact (or minimal) system design, but also trimming provides a way of thinking whereby product innovation triggers can be identified by suggesting a component(s) to trim.

The case study presented via mathematical modelling, applying Formal Logic, Set Theory and Graph Theory, is just a starting point in this direction. Our proposed framework in mapping TRIZ trimming rules to the formulated trimming principles, is seen to be an important contribution. In future works we will explore the formalization of other tools which includes process trimming.

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