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QFD and TRIZ integration in product development: a Model for Systematic Optimization of Engineering Requirements

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Abstract

Paper aims: Proposal of a Model for Systematic Optimization of Engineering Requirements applied to product concept development and based on a two-level integration of the methods Quality Function Deployment (QFD) and Theory of Inventive Problem Solving (TRIZ).

Originality: Requirements extraction directly from patent documents in order to identity the most relevant user requirements as well as the technical requirements interactions through a QFD matrix. Then, TRIZ Contradiction Matrix is used to withdraw the requirements contradictions through inventive principles in order to enable the product conception.

Research method: Case Study which enables the Model construction inductively through its application on the development of a mortar ammunition concept.

Main findings: A product concept comprising innovative features which reflect the laws of technology evolution from TRIZ.

Implications for theory and practice: The product concept definition points to the academic relevance of an integration model which identify the technical requirements objectively from patent documents.

Keywords
Product requirements. Technical contradictions. Technology evolution. Customer needs.

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1. Introduction

The New Product Development (NPD) is usually defined as a set of activities that start with the perception of a market opportunity and end with the production, sale and delivery of a product. It is a knowledge-driven activity in which requirements and constraints are transformed into a product description.

The NPD requires the definition of the features needed by the functions the product is planned to perform. Such features are expressed by requirements which reflects not only the user whishes, but also the evolutionary trends of the product underlying technology. The difficult arrives when attempting to meet one constraint make another one unattainable, which leads to the adoption of compromise solutions with partial fulfilment of each parameter. Rarely engineers can claim that the best trade-off was selected, and that the entire design space was examined. As a rule, many products are designed with less than optimal performance.

Therefore, this paper proposes a Model for Systematic Optimization of Engineering Requirements to achieve next generation products based on a two-level integration of the methods Quality Function Deployment (QFD) and Theory of Inventive Problem Solving (TRIZ). At the first level, the prospective capacity of TRIZ grounds the requirements extraction from patent documents. The user and technical requirements are inserted in a QFD matrix in order to identity the most relevant user requirements as well as the technical requirements interactions. At the second level, the Contradiction Matrix is used to withdraw the technical contradictions between requirements through the proposition of solutions based on inventive principles in order to enable the product conception. Finally, the Model is deployed to the development of a new mortar ammunition concept.

QFD is used to transform subjective user demands into objective parameters, leading to the identification of engineering characteristics which may be relevant, and assigning priorities for system requirements. On the other hand, TRIZ is used to surpass suboptimal design through the elimination of systems conflicts without achieving a balanced solution between two desirable but incompatible features. Also, TRIZ is used to predict the product technical evolution towards an increasing degree of ideality, since it states that the evolution of technical systems is not random, but ruled by laws. Therefore, as technical systems follow repeatable patterns in the long term, these patterns can be applied to the systematic development of products.

This paper is organized in seven sections: the first section with an introduction that allows the reader to figure the main disciplines involved in this paper and how they are used; the second section with the main features of the research methodology; the third section with a brief description about TRIZ and QFD, as well as their integration; the fourth section with the Model for Systematic Optimization of Engineering Requirements; the fifth section with an example of mortar ammunition development through the deployment of the Model; finally, the sixth and seventh sections respectively with the discussion of results and conclusion remarks.

2. Research methodology

The research methodology comprises a Case Study which enables the model construction inductively through its application on the development of a mortar ammunition concept by a Brazilian weaponry manufacturing company. In this sense, the real context of a mortar ammunition development allows the improvement of the NPD theory, specially the QFD/TRIZ integration, since it can be structured through the collected information and have its limits defined in the specific case (Cauchick Miguel & Sousa, 2012).

The theoretical framework drove the systematic literature review from which 122 papers were retrieved from CAPES and Science Direct databases. The search strategy matched through the Boolean connective "AND" the words QFD, TRIZ, Product, Requirements, Evolution and Contradiction located at the titles (Leite & Silva, 2013). The papers published less than 10 years ago were selected through the analysis of two filters enabling the choice of papers which encompass tools exclusively from methods QFD or TRIZ applied only to product development. The elimination of duplicated papers selected papers which encompass QFD tools either to product development or theoretical approach and TRIZ tools either to contradiction elimination or technical trends identification, as well as QFD and TRIZ tools simultaneously. However, only the TRIZ tools for technical contradiction removal are used to solve conflicts arising from the integration of user-valued requirements. Therefore, no case of integration between QFD and TRIZ methods using the TRIZ prospective capacity was identified. Thus, the systematic literature review points to the academic relevance of an integration model which identify the technical and user requirements objectively from patent documents, such requirements thereafter submitted to user evaluation and their contradictions eliminated by Contradiction Matrix.

The patent search was conducted in order to identify and select potential patents followed by the extraction of relevant technical and user requirements from them. The patent documents were extracted from United States Patent and Trade Office (USPTO) and European Patent Office (EPO) databases, since both are the most important patent databases worldwide (Trott, 2012). Also, USPTO represents a useful source of information due to the impartiality of the criteria and procedures for obtaining patent registrations, as well as incentives for companies to get industrial property protection (Tidd & Bessant, 2015).

Finally, the QFD matrix allowed to identify the most relevant user requirements which were evaluated by 18 Brazilian Army officers. The relationship between user and technical requirements were ranked and evaluated and the TRIZ inventive principles were used to solve the contradictions and enable the establishment of the product concept.

3. Market and technology integration in new product development

3.1. Theory of Inventive Problem Solving (TRIZ)

The Theory of Inventive Problem Solving (TRIZ) was created by Genrich Altshuller after the Second World War through the analysis of inventive solutions provided by thousands of patents of the former Soviet Union. Altshuller (2005) states that the systematic process of innovation can be structured with basic principles of inventiveness which allow the elimination of technical contradictions based on the concept of ideal solution, which means technological systems tend to evolve towards ideal systems through the overcoming of contradictions and project commitments. As patents typically feature innovative solutions to contradictions, these solutions often represent identifiable points along lines of evolution, so TRIZ considers that specific patterns of evolution in designs can be followed to solve problems.

These patterns of evolution were originally called as general laws of dialectics, or laws of the development of technical systems, an effective "soft" technology for solving inventive problems, so their application in product development results in regularity in design evolution and recurring principles to find innovative solutions (Fey & Rivin, 2005).

There is a very common pattern of evolution with the shape of an S-curve, a graphical representation of the life cycle of technical systems permitting evaluate the maturity level of a product. This allows the designer to choose the best development strategy: the improvement of existing products or the search for fundamentally new solutions to envision a new product (Labouriau & Naveiro, 2015).

TRIZ seeks to emphasize both the positive (useful functions) as the negative relationships (harmful functions) between the components of a system and, more importantly, to use the function analysis as a means of identifying the contradictions, in-effective, excessive and harmful relationships in and around a system (Mann, 2007).

3.1.1. Contradictions

The contradictions are trade-offs assumed in designs. A contradiction emerges when a designer must choose between two different characteristics in conflict one with each another. They are called technical contradictions when a design parameter is achieved at the expense of another parameter and physical contradictions when opposite states must be present simultaneously in a product (Gadd, 2011).

The inventive solution enables the elimination of contradictions without establishing any kind of compromise between feasible alternatives, which means that the inventive solution arrives when it provides simultaneous satisfaction of conflicting parameters. The inventive solution provided by is an effective method for generating ideas and is based on the application of Inventive Principles and the concept of Engineering Parameters (Altshuller, 2005).

The Inventive Principles are suggestions of possible solutions for solving a given problem. These principles were obtained from the generalization and grouping of solutions repeatedly used in the creation, development and improvement of technical systems of different areas. Altshuller (2005) proposed 40 inventive principles for technical innovation as shown in Table 1.

Table 1. Inventive principles.

Nº	Inventive Principle	Nº	Inventive Principle
1	Segmentation	21	Rushing Through
2	Extraction	22	Convert Harm Into Benefit
3	Local Quality	23	Feedback
4	Asymmetry	24	Mediator
5	Consolidation	25	Self-service
6	Universality	26	Copying
7	Nesting	27	Dispose
8	Counterweight	28	Replacement of Mechanical System
9	Prior Counteraction	29	Pneumatic or Hydraulic Construction
10	Prior Action	30	Flexible Membranes or Thin Films
11	Cushion in Advance	31	Porous Material
12	Equipotentiality	32	Changing the Color
13	Do It in Reverse	33	Homogeneity
14	Spheroidality	34	Rejecting and Regenerating Parts
15	Dynamicity	35	Transformation of Properties
16	Partial or Excessive Action	36	Phase Transition
17	Transition Into a New Dimension	37	Thermal Expansion
18	Mechanical Vibration	38	Accelerated Oxidation
19	Periodic Action	39	Inert Environment
20	Continuity of Useful Action	40	Composite Materials

The Engineering Parameters are the physical quantities involved in technical problems which shall be maximized, minimized or kept around a target value depending on the problem. Altshuller (2005) proposed 39 technical parameters to describe features and/or functions of engineering systems as shown in Table 2.

Table 2. Engineering parameters.

Nº	Engineering Parameters	Nº	Engineering Parameters
1	Weight of a mobile object	21	Power
2	Weight of a stationary object	22	Loss of energy
3	Length of a mobile object	23	Loss of substance
4	Length of a stationary object	24	Loss of information
5	Area of a mobile object	25	Loss of time
6	Area of a stationary object	26	Amount of substance
7	Volume of a mobile object	27	Reliability
8	Volume of a stationary object	28	Accuracy of measurement
9	Speed	29	Accuracy of manufacturing
10	Force	30	Harmful factors acting on an object from outside
11	Tension / Pressure		
12	Shape	31	Harmful factor developed by an object
13	Stability of composition	32	Manufacturability
14	Strength	33	Convenience of use
15	Time of action of a moving object	34	Repairability
16	Time of action of a stationary object	35	Adaptability
17	Temperature	36	Complexity of a device
18	Brightness	37	Complexity of control
19	Energy spent by a moving object	38	Level of automation
20	Energy spent by a stationary object	39	Capacity / Productivity

The Contradiction Matrix is used to surpass design conflicts when technical contradictions are involved, and is probably the best known TRIZ tool. It is used to compare the improving parameter with those which get worse in order to identify the most appropriate inventive principles to solve a technical contradiction and find out a solution that enables both parameters to be satisfied, what eliminates the need of a compromise solution. The Contradiction Matrix is a 39 x 39 matrix made up of 39 engineering parameters which guide the choice of which of the forty inventive principles solve the particular technical contradiction. In a given situation, there is a parameter to be improved on the vertical axis and another parameter on the horizontal axis which shall not get worse (Gadd, 2011). Figure 1 shows a scheme of the Contradiction Matrix adapted from Altshuller (2005).

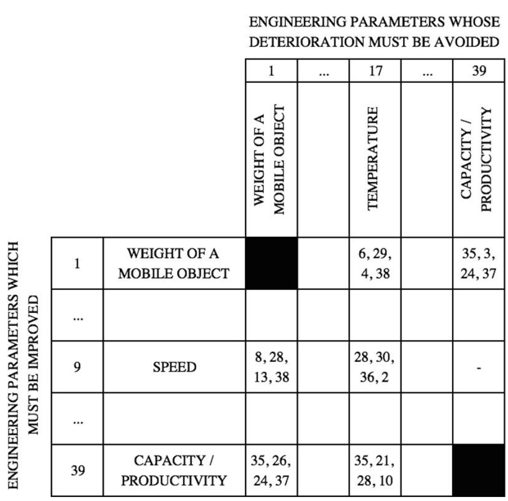


Figure 1. Scheme of the contradiction matrix.

3.1.2. TRIZ laws (or patterns) of evolution

The Theory of Inventive Problem Solving (TRIZ) states that the evolution of technological systems follows objective laws. Thus, despite the apparent randomness of technological evolution, it is possible to identify, in the long run, the directions by which systems evolve (Clausing & Fey, 2004). The laws of technological system evolution describe significant, stable, and repeatable interactions between elements of the system, and between the system and its environment in the process of its evolution (Fey & Rivin, 2005).

The following laws of technical systems development were identified in the detailed work made by Altshuller (1984) with patents and comprises a program for solving inventive problems:

1. Evolution in stages or by the transition to a higher-level system;
2. Evolution towards increasing degree of ideality;
3. Evolution towards increased dynamism and controllability;
4. Increased complexity then simplification (reduction);
5. Evolution toward micro level and increased use of fields;
6. Synchronization and desynchronization, or symmetry and asymmetry;
7. Non uniform development of system elements;
8. Automation or evolution toward decreased human involvement.

The trends of evolution can play two relevant roles in the technical field, one as a strategic tool for predicting system evolution and the other as a problem solving tool (Mann, 2007).

3.2. Quality Function Deployment (QFD)

3.2.1. Customer needs

Quality Function Deployment (QFD) is a visual and systematic method by which a design team deploys from the voice of the customers to manufacturing operations. The word deployment signifies a combination of translation from one language to another, as well as team decision making, in order to arrive to sound design decisions. The introduction of the quality function in the early stages of the design process ensures the desired quality at the production stage (Clausing, 1994). Thus, vague and unmeasurable customer wishes about product quality and production features are translated into measurable technical characteristics deployed to all stages of the product development process. Also, QFD can be used only for the early stages of product development process or it can be used on subsequent subsystem issues in design progression.

Ahmed & Amagoh (2010) argue that QFD is a mechanism capable of inserting the customer's voice into the product development process, from the conceptual design phase to manufacturing. It is therefore the systematic transformation of customer expectations into measurable product parameters that "[...] helps the company to focus on what customers perceive as important" (Ahmed & Amagoh, 2010).

The voice of the customer converted into technical characteristics results in a product with the expected quality which fulfil the performance requirements established by the market (Cheng & Melo Filho, 2007).

3.2.2. House of Quality

The expectations of the user regarding the product are subjective, qualitative and non-technical. Their deployment in product requirements, which are essentially objective, quantitative and technical, is performed through a matrix diagram called House of Quality. The House of Quality is a matrix diagram formed by lines in which the external information is inserted, and columns, from which the results referring to this information are extracted, i.e. lines contain information from the customers and columns contain the characteristics that are expected to be achieved in the new product. Such method not only reduces the time of development, but also increases the customer's satisfaction with the product (Clausing, 1994). Figure 2 shows a diagram with the main features of the House of Quality matrix adapted from Clausing (1994).

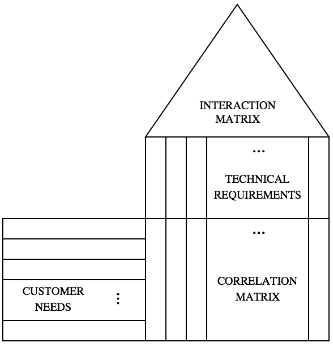


Figure 2. House of Quality diagram matrix.

The field of customer needs receives the information about the expectations regarding the product, i.e. what customers expect the product to do or what characteristics customers expect to be in the product. The customer needs must also be rated according to the degree of importance of each one to the client. A numerical scale ranging from 1 to 5 is normally used, in which concept 5 corresponds to the one of the greater relevance (Yeh et al., 2011).

The connection between customers needs and technical requirements is made through the correlation matrix. This strength can be represented by symbols to denote strong, moderate or weak relationship providing a quick visual impression of the overall relationships strengths of the technical requirements and the customers needs (Clausing, 1994).

The interaction matrix shows the positive or negative interactions between the technical requirements in order to enable early planning to overcome inherent conflicts. (Clausing, 1994).

3.3. QFD/TRIZ integration

3.3.1. Conceptual design

The concept development phase of NPD generates and evaluate a broad set of conceptual product alternatives in order to select one or more concepts for further development. The initial alternatives are generated from the identification of opportunities that match the strategic objectives of the organization and the concepts come from specific technological knowledge or market demand (Ulrich & Eppinger, 2012).

The conceptual selection aims at the technological systems with greater potential for success for later development, which is relevant in a context of resources constraints. This process starts with the concepts that have been generated in response to the customer needs in the House of Quality. The concepts are entered to a concept selection matrix as the column headings and one of them is selected to be the reference concept to which the other concepts will be compared. The designer uses a three level rating scale to evaluate how a concept satisfy the requirements compared to the reference concept: better (+), worse (-), similar (=) (Clausing & Fey, 2004). Figure 3 shows a concept selection matrix scheme adapted from Clausing & Fey (2004).

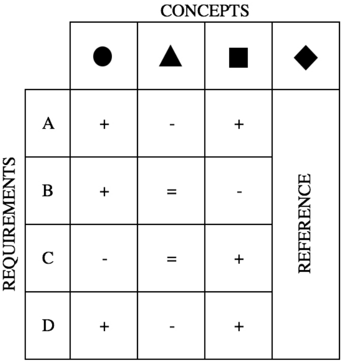


Figure 3. Concept selection matrix scheme.

The conceptual selection matrix allows the generation of new concepts from the combination of original concepts, deriving in the defining of a new reference concept which is used to run the matrix again. After completing a certain number of runs the participants will have acquired a greater understanding of the potential solutions, leading to better concepts (Clausing & Fey, 2004).

Depending upon the complexity of the project, it is not untypical to carry out five or six evaluations and comparisons before a single concept emerges, which is them carried out through the final design with a strong concept that will stand when exposed to competitive pressure.

3.3.2. QFD/TRIZ synergy

The innovation strategy can be based on market needs and known potential technologies (Clausing & Fey, 2004). The identification of the market demands, whether implicit or explicit, is a market-pull innovation strategy that establishes which products should be offered to satisfy the customers. On the other hand, the development of disruptive technologies aims to meet latent demands, until unknown by the market itself, which constitutes a technology-push innovation strategy. In the "technology-push" approach innovations are based on new technologies, which are able to create new products, as well as redefining the competitive standard (Maicon et al., 2012).

The balance between market-pull and technology-push innovation strategies is currently a major challenge for organizations, since both require different and complementary development processes. However, business sustainability depends on the coexistence of such strategies, which makes it imperative to integrate methods that meet both demands (Maicon et al., 2012).

The commercial and technological perspectives reflect the type of innovation strategy to be developed by the organization, i.e. if it is focused on incremental or on disruptive innovation. According to Christensen (2003), incremental innovations offer improvement of products in use by existing customers, while disruptive innovations offer improvements beyond demand, creating new markets that may eventually encompass the existing market. However, Christensen (2003) argues that the apprehension of the customer needs by the organization may be harmful to the activity of technological innovation once it limits the search for solutions not identified by its current customers.

Many business publications argue market research as the most reliable way to assess the market viability of emerging innovations. While various market research techniques prove to be very useful for incremental improvements, they often mislead when used to appraise breakthrough innovations. Clausing & Fey (2004) agree on the need for new approaches once they argue that methods generally used for the evaluation of potential market for new products do not fit when dealing with disruptive innovation.

The integration between QFD and TRIZ allows the efficient prospection of market needs and potential directions of technological evolution that lead to new products, thus considering the commercial and technological perspectives of innovation. The combination of both prospective capabilities therefore allows not only the satisfaction of the demands directly or indirectly invoked by users, but also the design of solutions based on technological systems that provide entirely new experiences of use.

Gadd (2011) reinforces the predictive capacity of TRIZ in searching for the next generation products and technologies. As TRIZ is based on laws of technological evolution, this allows the anticipation of market demands. Thus, the perception of the life curve of technological systems allows identifying the evolutionary potential of a certain product or technology, as well as the difference between the current stage and the final stage in a line of evolution.

QFD and TRIZ have complementary approaches and different temporal perspectives to seek the apprehension of market needs; while QFD identifies present needs, TRIZ identifies future needs through the identification of technological evolutionary patterns. Figure 4 shows a table adapted from Terninko et al. (1998) with a set of factors in the first row and the impact of QFD and TRIZ related to them.

	QFD	TRIZ
CUSTOMER SATISFACTION	⊙	○
PRODUCT QUALITY	⊙	⊙
PROFITS	⊙	⊙
MARKET SHARE	⊙	⊙
INNOVATION	•	⊙
FAILURES ANTECIPATION		⊙
INTELLECTUAL CAPITAL PROTECTION		⊙
TECHNOLOGICAL PROSPECTION		⊙

○ WEAK IMPACT
• MEDIUM IMPACT
⊙ STRONG IMPACT

Figure 4. QFD/TRIZ synergy.

As already stressed in this paper, product development involves problem solving in which constraints and requirements must be satisfied. Then, a contradiction emerges when a designer must choose between two different characteristics in conflict one with each other, which sometimes leads to adopt compromise solutions with partial fulfilment of each parameter. The inventive solution occurs when contradictions are surpassed without establishing any kind of compromise between feasible alternatives. TRIZ provides a systematic procedure of conflict resolution by the use of a matrix of correlation in which engineering parameters are associated to technical requirements and solution principles. Thus, TRIZ inventive principles may be integrated to QFD in order to withdraw the conflicts raised from the functions integration. Also, TRIZ predictive tools arisen from evolution laws may be integrated to QFD through the selection of user and technical requirements directly from patent documents.

4. Model for Systematic Optimization of Engineering Requirements

In this paper it is proposed a prescriptive Model for Systematic Optimization of Engineering Requirements based on QFD/TRIZ integration. The first building block of the model is the definition of requirements corresponding to the possible trends of technological evolution. This is done by selection of relevant patents, which is achieved by the definition of the research terms which describe the technological system, as well as the selection criteria based on specific filters. Such criteria must ensure the technological delimitation of the system itself, so neither it encompass the super-system in which it is embedded, nor it is limited to specific subsystems.

The innovations revealed in the selected patent documents allow the establishment of technical requirements and user requirements. The last one points out characteristics and functionality that the system presents, permitting users to evaluate them accordingly to their relevance to the technical system. Users can rate their degree of relevance by a numerical scale ranging from 1 to 5, in which concept 5 corresponds to the one of the greater relevance.

The relationship between technical requirements and user requirements are established through QFD matrix; the influence of one or more technical requirements on the satisfaction of each user requirement can be represented by the “weight” of each relationship. This is represented by a set of numbers (1, 3, and 9) that indicates, respectively, weak, medium and strong dependency relations. In addition, the matrix presents, in its upper portion, the interactions between the various technical requirements through the symbols + and -, which indicate, respectively, cases of positive and negative interaction.

While, in the case of a positive interaction, the relationship between two technical requirements promote the mutual increase of their effects, in the case of negative interaction there is a conflict between the requirements, either because they cannot coexist physically in the same system, or because the increase in the effect caused by one of the requirements leads to deterioration of the effect caused by the other.

Technical requirements whose negative interactions are contradictory, i.e. which constitute technical contradictions, must lead to the choice of engineering parameters, so the functional feature of each technical requirement is associated with the engineering parameter that best reflects it. Then, the chosen parameters are inserted in the Contradiction Matrix, in which the lines indicate the parameters to be improved and the columns indicate the parameters whose deterioration should be avoided. The separation of the links between two parameters enables the solution for the contradiction by the identification of the inventive principles accordingly. Each cell in the matrix is filled out with the solution principle number.

The inventive principles provide solutions capable of changing the configuration of requirements in order to overcome the existing technical contradictions. Such solutions should be expressed through new technical product requirements, which are then integrated into a reference concept. The comparison between the solutions provided by the original technical requirements and the reference concept is carried out through the elaboration of a conceptual selection matrix which oppose the user requirements to the original technical requirements in order to compare the satisfaction of user requirements promoted by the reference concept against the satisfaction promoted by the integration of the reference concept with each technical requirement.

At this stage, a positive signal is associated to the technical requirements whose integration to the reference concept increases the satisfaction of a certain user demand, and the negative signal is assigned to technical requirements whose integration to the reference concept reduces the satisfaction of a certain user demand. An equal signal is assigned to the technical requirements used to generate the reference concept. Finally, the technical requirements to which the positive signal has been assigned are used to set out the product concept from the reference concept.

The Model is structured through the six steps embodied in the protocol presented in Figure 5, with each step encompassing a given set of actions. Thus, the actions defined by the protocol make it possible to obtain the product concept through the extraction of requirements from patent documents.

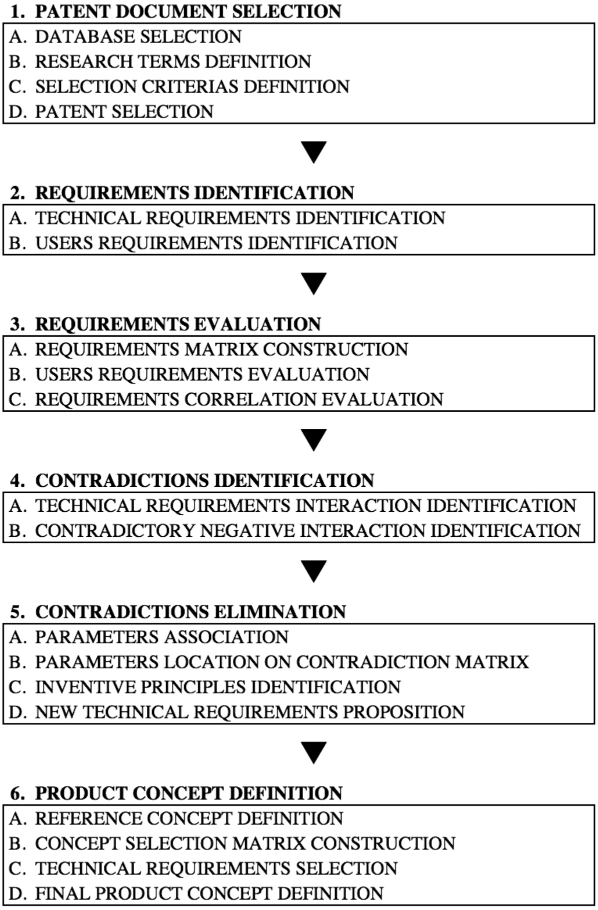


Figure 5. QFD/TRIZ integration model protocol.

The first four steps of the protocol correspond to the first level of integration of the Model, in which technical requirements are identified and valued through the correlations established with the user requirements. In addition, the first level of integration ends up with the identification of technical contradictions between technical requirements.

The last two steps of the protocol correspond to the second level of integration of the Model, in which technical contradictions are eliminated through the solutions proposed by the inventive principles. Such solutions are then integrated to define the reference concept and, then, the product concept itself.

5. Mortar ammunition concept development

This topic presents the use of the former concepts on QFD and TRIZ, as well as the Model for Systematic Optimization of Engineering Requirements embedded in an example of mortar ammunition.

In order to carry on a survey of patents related to this artifact, the terms ‘ammunition’ and ‘mortar’ were defined, respectively, from the keywords that describe the system of interest. Thus, such terms were conjugated in USPTO and EPO databases through the Boolean connective AND, within the scope of patent abstracts, in order to generate the desired results. The terms ‘projectile’, ‘shell’ and ‘grenade’ were not used because they limit the achievement of results, since they refer to specific subsystems. In the same sense, the terms ‘weapon’ and ‘gun’ were not used because they refer to the supersystem.

The selection of patent documents was done through two filters. The first filter selects the patent documents for mortar, thus excluding any possible results relative to other systems. The second filter selects the documents related to the system defined by the ammunition, including its subsystems, but not the supersystem where it is inserted into. The mortar ammunition system encompasses ammunitions containing active components, so it does not enclose inert ammunitions intended for training purposes.

In addition, such system only considers ammunition which is loaded by the front of the weapon tube, which excludes ammunitions configured to be fired by rods or the ones whose loading is carried out by the breech of the armament. Finally, the system considered covers only ammunition subject to axial and non-rotational acceleration, since rotation, although increases the stability of the projectile, depends on the adaptation of the ammunition to weapon tubes with internal helical streaks imparting such rotation. It should also be noted that no distinction was made regarding the caliber of the mortar ammunition in the selection of patent documents.

Table 3 shows the terms searched in the USPTO and EPO databases, as well as the results provided by each filter.

Table 3. Patent documents selected.

Database	1º Term	2º Term	Total	1º Filter	2º Filter
USPTO	Mortar	Ammunition	18	18	3
EPO	Mortar	Ammunition	127	101	29

The search selected 32 patent documents from which 33 technical and 12 user requirements were extracted. The technical requirements were extracted from the technical innovations brought by the patent documents and the user requirements were extracted from the improved effects provided by such innovations. These requirements are shown in Tables 4 and 5 with their reference indexes, respectively, RT for technical requirement and RU for user requirement.

Although each patent document brought at least one technical innovation which lead to the technical requirements shown in Table 4, the different effects provided by the technical innovations were gathered in groups of related effects which generated the 12 user requirements shown in Table 5. The 12 user requirements were evaluated by 18 Brazilian Army officers in order to identify the most important technical requirements through the numerical scale ranging from 1 to 5. The average ratings are also shown in Table 5.

Table 4. Technical requirements.

Index	Technical Requirement
RT01	The projectile shall contain a thermally actionable luminescent chemical marker
RT02	The propulsion subsystem shall be disconnected from the projectile right after firing
RT03	The additional propulsion charges cases shall be arranged longitudinally along the axis of the charge-carrying tube
RT04	The additional propulsion charges cases shall be covered by impermeable nitrocellulose film
RT05	The propellant charges must contain modified pyroxylin powder with low dependence on the combustion rate related to the pressure
RT06	The initial propulsion charge shall be contained in cylindrical cartridge with a length to diameter ratio of 5.5 / 6.5
RT07	The initial propulsion cartridge shall be inserted in a metal tube with a perforation to surface ratio of 0.030 / 0.035
RT08	The initial propulsion cartridge shall contain a primer igniter with black powder at the rate of 5.0 / 5.5% by weight related to the initial propulsion load
RT09	The projectile shall contain an additional propulsion charge inside the grenade with delayed trigger mechanism with an exclusive igniter
RT10	The projectile shall contain articulated aerodynamic fins which open after firing fixed to the grenade by means of a rod
RT11	The grenade shall contain a fuze in its lower part with a pyrotechnic device for delayed trigger mechanism composed by a transmission charge with low burning rate
RT12	The grenade shall have protrusions on its inner surface which prevent the movement of the main explosive charge
RT13	The grenade shall have a previously fragmented coating with lower tensile strength
RT14	The fins shall be made of lightweight metal alloy
RT15	The fins shall be coupled to an ejectable propulsion device containing grooves on its outer surface capable of preventing the exhaust of the propulsion gases during firing
RT16	The fins shall comprise retractable stabilizing flaps holded by an ejection device containing grooves on its outer surface capable of preventing the escape of the propulsion gases during the firing
RT17	The projectile shall have a diametrically opposite pair of side fins located at the rear of the shell body in addition to the stabilizing fins
RT18	The projectile shall have the tip angle formed by the fuze and the shell body up to its maximum diameter between 4° and 20°
RT19	The projectile shall contain a self-propelled charge with exclusive igniter with delayed trigger mechanism coupled to an ejectable propulsion device
RT20	The stabilization fins shall have oblique radial edge and a parallel axial edge related to the longitudinal axis of the ammunition in order to deflect the air against the side face of the fins
RT21	The grenade shall have a metal skirt at its rear that allows the ammunition to fall through the tube of the weapon and whose end can be expanded by the propulsion gases in order to retain them inside the tube during firing
RT22	The fuze must contain a delaying mechanism adjustable by external key
RT23	The stabilization fins shall have rectangular plates coupled transversely to their respective rear edges

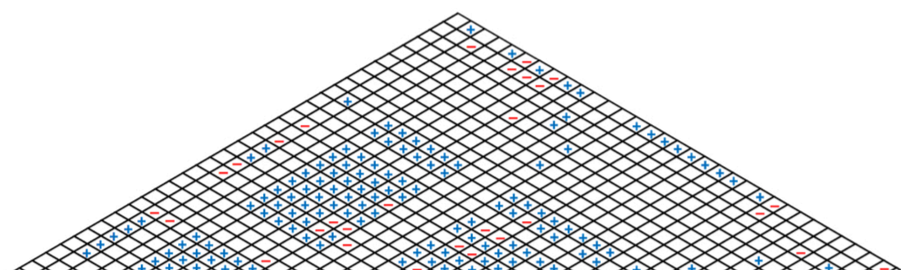
Table 4. Continued...

Index	Technical Requirement
RT24	The initial propulsion cartridge shall consist of a tube containing the propellant charge with the top end closed and the bottom end connected to the base containing the igniter being both parts made of synthetic polymer
RT25	The initial propulsion cartridge shall consist of a tube containing the propellant charge with the top end closed and the bottom end connected to the base containing the igniter through grooves and protrusions
RT26	The initial propulsion cartridge shall be fixed within the fins axial tube by a deformable polymer flange
RT27	The grenade shall have spherical steel projectiles stored inside the wall
RT28	The fuze shall have a safety mechanism which allows the alignment of the explosive chain after firing through a retractable fin which opens due to the air resistance
RT29	The main explosive charge shall be PETN
RT30	The fuze shall have an explosive chain consisting of a sequence of explosives with a decreasing sensitivity up to the main charge with a density change of 1.2 to 1.7 g/cm^3
RT31	The fuze shall have deformable side sections linked to axial bores capable of conveying oblique impact
RT32	The propulsion cartridge shall have an initial charge in the longitudinal axis of the ammunition and additional concentric charges parallel to the first axis and triggered by the initial charge through selective holes
RT33	The initial propulsion cartridge shall have two igniters located at opposite ends connected by axial tube in order to trigger the projection charge located on the side of the cartridge in a downward direction

Table 5. User requirements and respective average ratings.

Index	User Requirement	Average Rating
RU01	The initial propulsion charge shall remain fixed during storage and transport of the ammunition	3.6
RU02	The additional propulsion charges shall not be damaged during storage and transport of ammunition	3.9
RU03	The projectile shall not detonate before firing	5.0
RU04	The projectile shall not detonate right after firing	5.0
RU05	The projectile detonation shall be delayed from the moment of impact	2.7
RU06	The projectile detonation shall not fail	4.3
RU07	The projectile trajectory shall be visually marked	2.6
RU08	The shot range shall be maximum	3.7
RU09	The shot range shall be changeable	4.2
RU10	The shot accuracy shall be maximum	4.3
RU11	The projectile lethality shall be maximum	3.8
RU12	The ammunition shall be used against ballistic armor	3.6

In the QFD matrix shown in Figure 6 there are cells assigned with values 1, 3 or 9 depending on the influence of a technical requirement on satisfying a user requirement. Also, the positive and negative interactions between technical requirements are identified through positive and negative signs in the matrix upper portion.



	RT 01	RT 02	RT 03	RT 04	RT 05	RT 06	RT 07	RT 08	RT 09	RT 10	RT 11	RT 12	RT 13	RT 14	RT 15	RT 16	RT 17	RT 18	RT 19	RT 20	RT 21	RT 22	RT 23	RT 24	RT 25	RT 26	RT 27	RT 28	RT 29	RT 30	RT 31	RT 32	RT 33
RU01																									3	3							
RU02				3																													
RU03																												9					
RU04												3																					
RU05																						9											
RU06											9																			9	1		
RU07	9																																
RU08		3			1	1	1	1	9	3				9	9	3	3	1	9	1	3		1	3									1
RU09			9																													1	
RU10										3						1	3	3		1			1										
RU11													1														1		9				
RU12																													1				

Figure 6. QFD Matrix.

There were identified 29 negative interactions, from which 18 are not contradictory, i.e. interactions whose pairs of technical requirements cannot be simultaneously applied to the system, even though they produce the same effect. Once the same effect is provided, the better technical solution shall be selected.

The other 11 negative interactions are contradictory, i.e. interactions whose pairs of technical requirements cannot be simultaneously applied to the system, but they provide different effects. Thus, each negative interaction demands a decision to surpass trade-off situations in order to provide simultaneous satisfaction of conflicting parameters. The 11 technical contradictions are shown in Table 6 with the respective pair of effects provided by the conflicting technical requirements and the respective derived technical requirements, which represents the solutions provided by Contradiction Matrix.

Table 6. Originals and derived technical requirements.

1st Original Technical Requirement	2nd Original Technical Requirement	1st Effect	2nd Effect	Derived Technical Requirement
RT02	RT10	Range	Precision	RT34
RT03	RT10	Variation	Precision	RT35
RT09	RT29	Range	Lethality	RT36
RT09	RT11	Range	Effectiveness	RT37
RT15	RT11	Range	Effectiveness	RT38 / RT39
RT28	RT31	Safety	Effectiveness	RT40
RT32	RT06	Variation	Range	RT41
RT32	RT07	Variation	Range	RT41
RT32	RT08	Variation	Range	RT41
RT32	RT24	Variation	Range	RT41
RT32	RT33	Variation	Range	RT41

The 11 technical contradictions may be expressed by 7 pair of engineering parameters, since the 5 technical contradictions encompassing RT32 oppose the same effects and have the same solution. Table 7 shows the technical contradictions between the effects expressed by the contradictory negative interactions as well as their correspondent engineering parameters and inventive principles used for their solutions.

Table 7. Technical contradictions and Inventive Principles.

1º Effect	2º Effect	1º Parameter	2º Parameter	Inventive Principle
Range	Precision	Loss of substance	Reliability	Prior Action / Transformation of Properties
Variation	Precision	Adaptability	Reliability	Mediator
Range	Lethality	Time of action of a moving object	Volume of a mobile object	Extraction / Prior Action
Range	Effectiveness	Time of action of a moving object	Reliability	Extraction / Do It in Reverse
Range	Effectiveness	Loss of substance / Tension or Pressure	Reliability	Do It in Reverse / Prior Action
Safety	Effectiveness	Area of a mobile object	Reliability	Prior Counteraction
Variation	Range	Adaptability	Force	Transition Into a New Dimension

The reference concept is generated by the integration of the derived technical requirements RT34, RT35, RT36, RT37, RT38, RT39, RT40 and RT41, i.e. the solutions enabled by the inventive principles, once they fully satisfy their related user requirements without any compromise between any of them. The derived technical requirements are shown in Table 8.

Table 8. Derived technical requirements.

Index	Technical Requirement
RT34	The projectile shall have retractable aerodynamic wings for longitudinal rotation and attached to the grenade through a rod connected to an ejectable propulsion subsystem
RT35	The projectile shall have retractable aerodynamic fins attached to the grenade through a rod connected to an ejectable propulsion subsystem containing additional propulsion removable charges disposed longitudinally along its axis
RT36	The projectile shall have grenade filled with PETN with external rod containing additional propulsion charge connected to an ejectable propulsion subsystem
RT37	The projectile shall have an external rod containing a fuze with a delayed trigger mechanism on its front and an additional propulsion charge on its inner rear part connected to an ejectable propulsion subsystem
RT38	The projectile shall have a rear fuze with an exclusive delayed trigger mechanism within an ejection propulsion subsystem with reverse propellant charge, which is triggered by the propulsion gases through radial holes as well as the delayed trigger mechanism
RT39	The ejectable propulsion subsystem shall have an upper flange with an external diameter equal to the caliber of the ammunition and the external surface containing a pair of parallel grooves
RT40	The projectile shall have a front fuze with a retractable flap that aligns the explosive chain when opened by air flow as well as rear fuze with a pyrotechnic delayed trigger mechanism composed by low burning rate charge
RT41	The propulsion subsystem shall have removable additional propulsion charges longitudinally along its axis with an initial propulsion pyrotechnic charge connected to a impact igniter

The product concept is generated by the comparison of the solutions brought by the original technical requirements with the reference concept enabled by the inventive principles through a concept selection matrix shown in Figure 7. The solutions which improve the reference concept receive a positive sign and are added to the concept, while the solutions which worsen the reference concept receive a negative sign and are rejected. Also, the solutions brought by the original technical requirements used to generate the reference concept receive an equal sign, since they are already integrated in the concept.

	RT 01	RT 02	RT 03	RT 04	RT 05	RT 06	RT 07	RT 08	RT 09	RT 10	RT 11	RT 12	RT 13	RT 14	RT 15	RT 16	RT 17	RT 18	RT 19	RT 20	RT 21	RT 22	RT 23	RT 24	RT 25	RT 26	RT 27	RT 28	RT 29	RT 30	RT 31	RT 32	RT 33
RU01																									+	+							
RU02				+																													
RU03																												=					
RU04												+																					
RU05																						+											
RU06											=																			+	-		
RU07	+																																
RU08		=			+	+	+	+	=	=				+	=	-	+	-	=	+	-		-	+									-
RU09			=																													-	
RU10										=						-	+	-		+			-										
RU11													-														-		=				
RU12																													=				

Figure 7. Concept Selection Matrix.

The extraction of requirements from patent documents enabled the development of a new concept of mortar ammunition, as shown through its external and internal views respectively in Figures 8 and 9.

Figure 8 shows the external view of the mortar ammunition concept with detailed retractable wings.

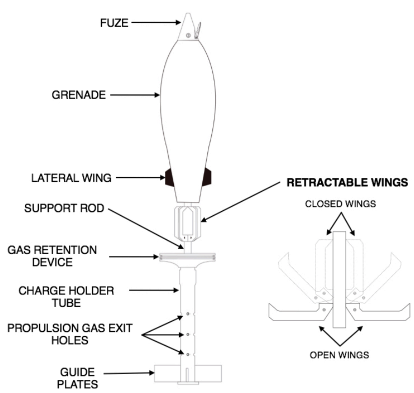


Figure 8. External view of mortar ammunition concept.

Figure 9 shows the internal view of the mortar ammunition concept with detailed fuzes and ejection charge.

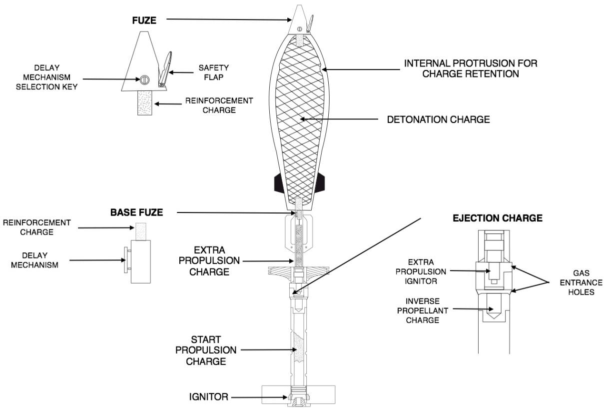


Figure 9. Internal view of mortar ammunition concept.

6. Discussions

The concept integrates solutions associated to several product demands and expresses, directly or indirectly, 23 out of 33 technical requirements initially identified. The Model is an innovation driver, since the solution of technical contradictions required the formulation of new technical requirements, nevertheless derived from the original technical requirements.

The artifact constitutes an entirely novel solution of mortar ammunition that was reached with the aid of the systematic deployment of the inventive principles, and shall be submitted to a patent registration. This is corroborated by the identification of the technical laws of evolution satisfied by the new product concept.

The law of **increase of ideality** is testified by the satisfaction of different user requirements through the integration of the corresponding technical requirements, which has increased the functionality of the artifact. For example, the increase of the ammunition range is expressed by a large number of requirements integrated into the product concept. The law of **non-uniform development of elements** is demonstrated by the difference between the number of requirements related to the ammunition range, and the ones related to other demands such as lethality.

In the case of the law of **increase of complexity followed by simplification**, the integration of the additional propulsion leads to a great increase in functionality, but also a significant increase in system complexity, which is reduced by the ejection solution of the propulsion subsystem. Furthermore, the integration of the range variation solution through removable additional propulsion charges, and the switching solution for the delay mechanism, reflects the application of the law of **increase of dynamism and controllability.** In addition, the increased flexibility can be seen in the aerodynamic stabilization subsystem composed of retractable fins.

The law of **evolution towards micro level and increased use of fields** is expressed in the ejection capacity of the propulsion subsystem, which is separated from the projectile after firing. Finally, the law of the **synchronization and desynchronization** is embodied in the integration of the requirements in the overall product concept.

The user requirements evaluation was considered for product concept generation, since the most relevant needs are satisfied, like the safety concern expressed by RU03 and RU04, while the less relevant were rejected, like RU07 whose technical requirement RT01 significantly increases the complexity of the system.

7. Conclusions

Product development is a complex activity in which constraints satisfaction is a hard goal to achieve. This paper showed with an example that it is possible to integrate QFD and TRIZ, utilizing QFD to identify and quantify engineering parameters and TRIZ inventive principles to achieve solutions.

In this paper it was emphasized the analytical power of TRIZ. The solutions and innovation principles extracted from patent documents are the essence of TRIZ's prospective capacity. This feature enables the extraction of requirements from patent documents in order to identify solutions whose integration promotes the evolution of a technological system. This is evidenced by the features of the product conceived which reflect the action of the laws of technological evolution.

The House of Quality is a strong graphical tool to identify relationships among requirements and interactions between the technical requirements of the product. However, the implementation of the TRIZ Contradiction Matrix overcame the main disadvantage of the QFD method with regard to the solution of conflicts that arise from the integration of the various functionalities prescribed by technical requirements

The inventive principles effectively eliminate the technical contradictions, once they led to the systemic integration of the solutions presented by the technical requirements whose interactions were identified as negative and contradictory.

Moreover, the conceptual selection matrix allowed the integration of other technical requirements which added value to the product concept, excluding only the technical requirements whose integration was not feasible, given the configuration of the system and whose demands have been met by other solutions.

The proposed Model is applicable to the conceptual development of products in general, as well as a useful method to the innovation process. Further developments of the model should comprise other QFD deployments in order to define technical requirements needed to the complete development of the product, as well as data mining methods should be used to optimize the search of patent documents.

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