A TRIZ-based Behavioral Modeling of Technological Systems

Victor Fey

The TRIZ Group, LLC, West Bloomfield, MI, 48322, USA
fey@trizgroup.com

Abstract. The paper describes a novel TRIZ-based method for automated modeling and simulation of technological systems. The method involves capturing all of system's interactions – both normative and faulty – in a behavioral model. The behavioral model contains the functional and physical interactions among the system's components and among these components and those of adjacent systems and the system's physical environment. Overall system behavior is represented as a sum total of functional "streams," as well as "streams" of energy and materials (i.e., physical/chemical phenomena) that "flow" through its components. The system's components and physical/chemical phenomena are represented as transfer functions assembled into cause-effect chains. These chains allow for automated modeling and simulation of various system's behaviors.

The method is applicable to different types of analyses used in TRIZ-based projects: function modeling, cause-effect analysis, and automated FMEA. The method has been implemented in a software application that will also be discussed.

Keywords: Behavior model, Failure analysis, Automated FMEA, System modeling, System simulation, Functional modeling, Cause-effect analysis

1 Introduction

1.1 Problems with existing function and physics modeling tools

A properly run TRIZ project involves extensive modeling of functional and physical interactions of the modified system. Various types of analysis – structural, functional, substance-field, cause-effect, and failure – are used to model and examine both normative and faulty system's behaviors. The effective application of these tools requires in-depth understanding of the modified system and therefore it is often time-consuming. The tools are most adequately applied to comparatively simple systems that contain several parts and components.

However, in a complex system (e.g., an automobile or an assembly line), hundreds of functions are performed, thousands failures may occur, and a comprehensive functional and failure analysis may take months to perform, even by a team of experienced specialists. The outcome depends heavily on the personal qualifications of these specialists. The complexity of the situation is also greatly exacerbated by the integrative nature of modern systems, which often incorporate highly diverse components based on mechanical, electronic, thermal, chemical, and other principles. Such diversity makes it extraordinarily difficult for system designers, most of whom are narrow subject matter experts, to effectively communicate with each other during the both conceptual design and FMEA stages in a system's development process. This may result in sub-optimal system designs as well as incomplete FMEAs and, consequently, often leads to major system failures.

Another shortcoming of prevailing practices in the application of these modeling and analysis tools is their poor coordination and the necessity to translate standard engineering terms into a TRIZ lingo [1].

The need to effectively and efficiently perform functional and failure analysis of complex systems can be met if there is a unified approach that combines the tools. This approach would become even more helpful if it is incorporated in a software application.

1.2 Overview of the proposed approach

The proposed approach (tentatively dubbed Joint Function and Physics Modeling, JFPM) is a blend of three effective methods for analyzing the behavior of physical systems: qualitative physics, functional modeling, and substance-field analysis. While both functional modeling and substance-field analysis are well-known in the TRIZ world, qualitative physics warrants a synopsis.

Qualitative physics is concerned with qualitative simulation of the behavior of physical systems [2-5]. Qualitative physics offers various representations and reasoning methods for modeling with incomplete information or incomplete knowledge. It bases its model specifications on qualitative descriptions that are derived from known qualitative system properties. A system model in qualitative physics is generated by assembling context-free behavior (functional) models of system components ("no-function-in-structure" principle [2]).

JFPM involves capturing all of system's interactions – both useful and potentially harmful (failures) – in a behavioral model. The behavioral model contains the functional and physical interactions among the system's components and among these components and those of adjacent systems and the system's physical environment. Overall system behavior is then represented as a sum total of functional "streams," as well as "streams" of energy and materials (i.e., physical and chemical phenomena) that "flow" through its components. Both the system's components and physical/chemical phenomena are represented as transfer functions (or, models of physical and chemical phenomena). These transfer functions are assembled into cause-effect chains that allow for modeling and simulation of various system's behaviors. The behavioral model reveals energy and material propagation paths along all of the hierarchical levels of the system's structure. This allows for performing two types of functional and physical analysis: a) assign an output (e.g., a failure) first and then determine its potential cause(s), and b) simulate various modes of the system's operation (by assigning various inputs to different system's components) and reveal normative, as well as potentially harmful physical and chemical phenomena in the system (i.e., failures).

JFPM was extensively tested in various consulting projects [6, 7].

2 Modeling of parts and physical/chemical phenomena

2.1 Modeling of parts

Fig. 1 shows the general functional model of a part (component). It includes a part which transforms an input function (Function 1) into an output function (Function 2).

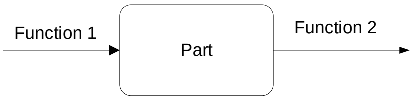


Fig. 1. General functional model of a part.

Fig. 2 shows a simplified functional model of a piezo igniter used in gas lighters. It includes a piezo igniter, which transfers the input function ("hit") into an output function ("ignite").

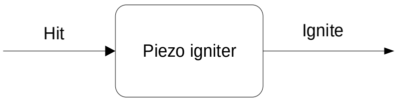


Fig. 2. Simplified functional model of a piezo igniter.

For each part, its own state, as well as a set of functional inputs (A = {FI_1, FI_2,…,FI_N}) uniquely defines a set of functional outputs (B = {FO_1, FO_2,…,FO_N}). Each functional input and functional output, as well as the part, is in a certain qualitative state (e.g., present, absent, excessive, insufficient, intermittent, slow, fast, etc.), which is characterized by a qualifier Qi (i.e., Qi can assume the value of "present," "absent," "excessive," "insufficient," "intermittent," "slow," "fast," etc.; see Fig. 3).

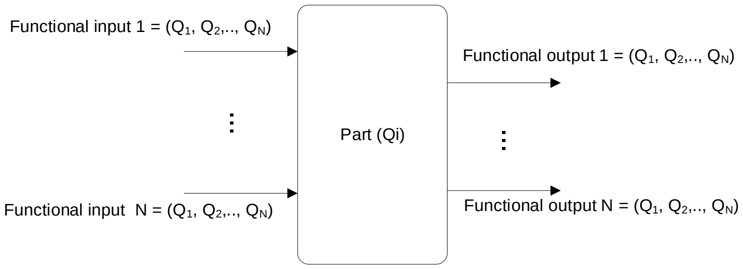


Fig. 3. A part as a function conversion module.

One can easily imagine a graph showing functional relationships between the part in Fig. 3 and some other parts, all of them being components of the same technological system (e.g., a product). In such a graph, functional inputs of the part are functional outputs of some other part(s), and the functional inputs of the part are functional outputs of some other part(s). Since each part exists to deliver certain functional outputs, each functional output can be charatcerized by at least one qualifier having a nominal value. Any deviation of this qualifier from its nominal value can be considered the part's failure, which, in turn, is caused by the deviation of at least one of the input qualifiers and/or the deviation of the part qualifier from their respective nominal values.

For each part, one can define Boolean relationships between input and output qualifiers (both for intended and failure behaviors):

If (input qualifiers $Q^i_{1},\dots Q^i_{n}$), *then* (output qualifiers $Q^o_{1},\dots Q^0_{m}$). (1)

2.2 Modeling of physical chemical phenomena

Natural phenomena are the basis for all technological systems. To perform a function, certain natural phenomena should be appropriately arranged in space and time [8].

Fig. 4 shows a general model of a natural phenomenon. It includes a substance (or a specific group of two or more substances) that transforms certain physical inputs (i.e., energies (fields) and/or substances and/or attributes (e.g., shape, dimensions, position in space, etc.)) into other physical outputs (i.e., energies (fields) and/or substances**,** and attributes).

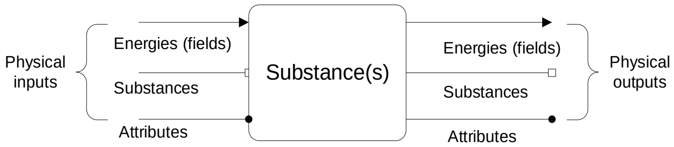


Fig. 4. General model of a physical/chemical phenomenon.

For each substance (or a specific group of substances), a set of physical inputs (C = {PI_1, …, PI_N }) uniquely defines both a set of physical outputs (D = {PO_1, …, PO_N }). Each physical input and physical output is in a certain qualitative state (e.g., present, absent, excessive, insufficient, intermittent, slow, fast, etc.) that is characterized by a qualifier Qi (i.e., Qi can assume the value of “present,” “absent,” “excessive,” “insufficient,” “intermittent,” “slow,” “fast,” etc.; see Fig. 5).

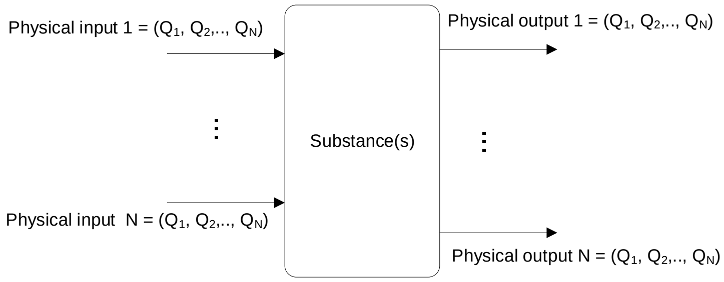


Fig. 5. A substance as a phenomena conversion module.

For each natural phenomenon, one can define Boolean relationships between input and output qualifiers:

If (input qualifiers $Q^i_{1},\ldots Q^i_{n}$), *then* (output qualifiers $Q^o_{1},\ldots Q^0_{m}$). (2)

Fig. 6 shows an example of modeling of applying a friction force to a solid body. The physical outputs in this case are heat and vibrations (energies, fields), wear particles (substances), and two attributes: wear and thermal expansion.

Fig. 7 shows a model of a chemical reaction of neutralization, in which an acid is mixed with a base, and, as a result, both water and a salt are produced.

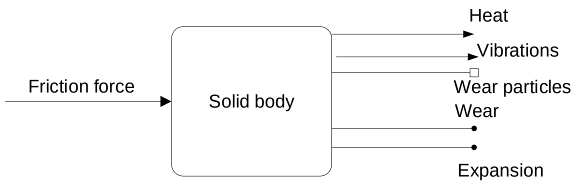


Fig. 6. Modeling of applying a friction force to a solid body.

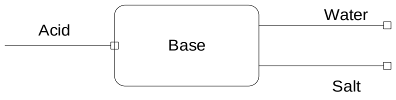


Fig. 7. Modeling the reaction of neutralization.

Links

In cases, when a natural phenomenon involves two or more interacting substances, they are connected by links. The latter define a type of physical connection between substances. For example, a link "touch" defines a kinematically unrestricted contact along at least one chosen direction (e.g., a sliding contact); a link "joint" is placed between substances that are riveted, glued, welded, soldered, or otherwise permanently connected; a link "gap" defines an unoccupied space between two substances.

Different links transmit different fields and substances (Fig. 8). For example, a link "gap" can transmit a magnetic field and moisture, but it will not transmit a mechanical load. Since substances can be connected in different ways, many types of links can be introduced.

TOUCH	Kinematically unrestricted contact (e.g., a wineglass on a table; a teaspoon in a teacup).
JOINT	Parts that are riveted, glued, welded, soldered, or otherwise permanently connected (e.g., circuit traces on a PCB; a bimetal strip).
ENCLOSURE	A fluid (gas or liquid) or solid in a sealed vessel (e.g., water in a closed teapot; gun powder in a barrel).
CONTAINING	A fluid or solid (stationary or moving) in an open vessel or conduit (e.g., coffee in a cup; billiard balls on a pool table; a liquid in a chute).
MIX	A mixture of fluids and/or solids (e.g., a mixture of gases; dust or moisture in the air; a blend of different powders).
GAP	Space between two parts.

Fig. 8. Different types of links between substances.

Fig. 9 shows a model of the phenomenon of galvanic corrosion, in which two metals are in contact with an electrolyte. These three substances are connected by links "touch.” The physical outputs in this model are an electric voltage (energy or field) and galvanic corrosion (attribute).

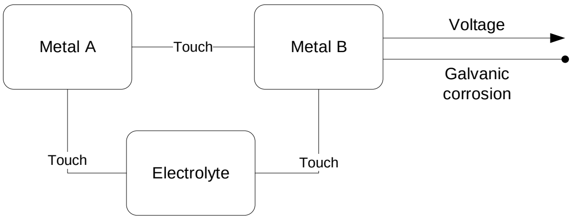


Fig. 9. Modeling the phenomenon of galvanic corrosion.

2.3 Function failure as a phycal phenomenon

As stated above, functions performed by parts and components of technological systems can be reduced to natural phenomena. This implies that many functional failures are, in fact, physocal phenomena. A part's failure is either a deviation of its intended function(s) from the prescribed value(s) or the generation of a new – unintented – harmful function(s). Or, in the language of physcs, a part’s failure is either

either a deviation of its intended physocal parameters from the prescribed values or the generation of new – unintented – “harmful” physical phenomena.

Fig. 10 shows a simplified functional model of a generic incandescent bulb, in which a function ("power") is appled to the bulb, which, in turn, performs a function ("emit (light)").

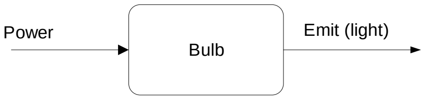


Fig. 10. Simplified functional model of the bulb.

A functional failure of the bulb is shown in Fig. 11: The function ("emit light") is assigned a qualifier "absent."

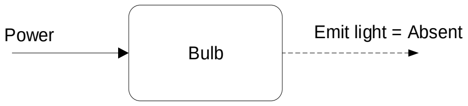


Fig. 11. Functional failure of the bulb.

Fig. 12 shows a physical model of the failure: a physical input ("voltage"), applied to a metal (filament), does not result in a physical output ("light"). This failure may have various causes, e.g.,evaporation of the filament (hence a qualifier "absent" is assigned to the metal).

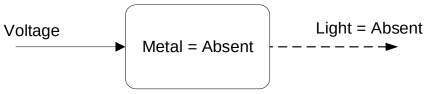


Fig. 12. Physics of the bulb failure.

Fig. 13 shows the generation of an unintended harmful function ("heat") by the bulb. The flow of electric current through the metallic fillament causes the emission of light**,** as well as generation of heat, which causes heating of the inert gas inside the bulb, which, in turn, causes heating of the glass (at that, consecutively, can cause one to burn one's fingers).

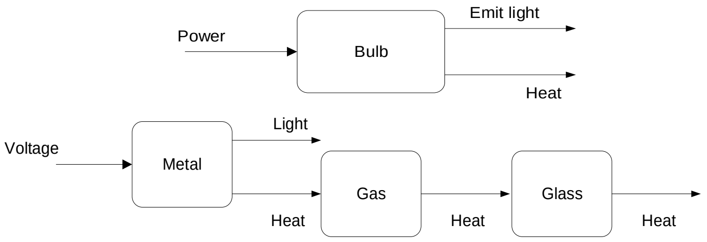


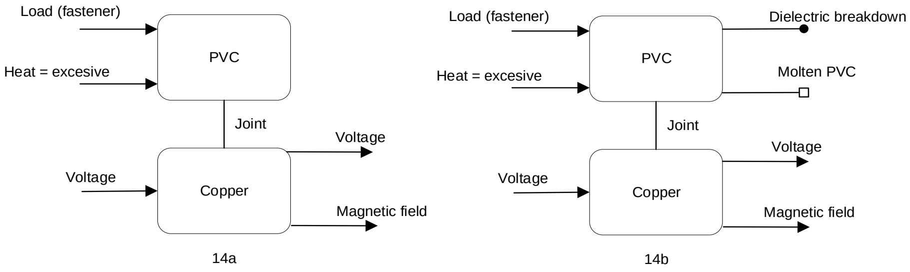
Fig. 13. Physics of generating heat by the bulb.

2.4 Part models combining functions and physics

To combine both functional and physical representtions of a part in one model, the part’s material(s)/substance(s) should be specifically identified.

Fig. 14a shows a simplified model of a generic wire that consists of two substances: copper and PVC (insulation). The wire receives three fields – voltage, ambient heat, and a fastener load – and generates three fields (voltage, a magnetic field, and Joule heat).

Fig. 14b shows a typical failure mode: if ambient heat is excessive, then a dielectric breakdown may occur, and the PVC insulation may melt (i.e., the insulaion goes through solid-to-liquid transition; the resultant polymeric liquid may “propagate” through the system and affect both the environment, adjacents and remote parts).



14a

14b

Fig. 14. Normative and faulty behaviors of a generic wire.

3 Software rendering of JFPM

The described approach was incorporated into a software package for automed discovery of failure modes and failure causes dubbed TechScan. The software outline is presented below.

TechScan contains three main modules: a knowledgebase of part models, a knowledgebase of physical/chemical phenomena models, and and an analysis engine (Fig. 15). Each part or phenomenon model includes a graphical repesentation similar to the ones in Figs. 3 and 14, and 6, 7, and 9, respectively. Each model also includes a set of rules (see Boolean expressions (1) in section 2.1 and (2) in section 2.2, respectively) that define the normative and faulty relationsphips between the model's inputs and outputs. Both knowledgbases are fully user-editable.

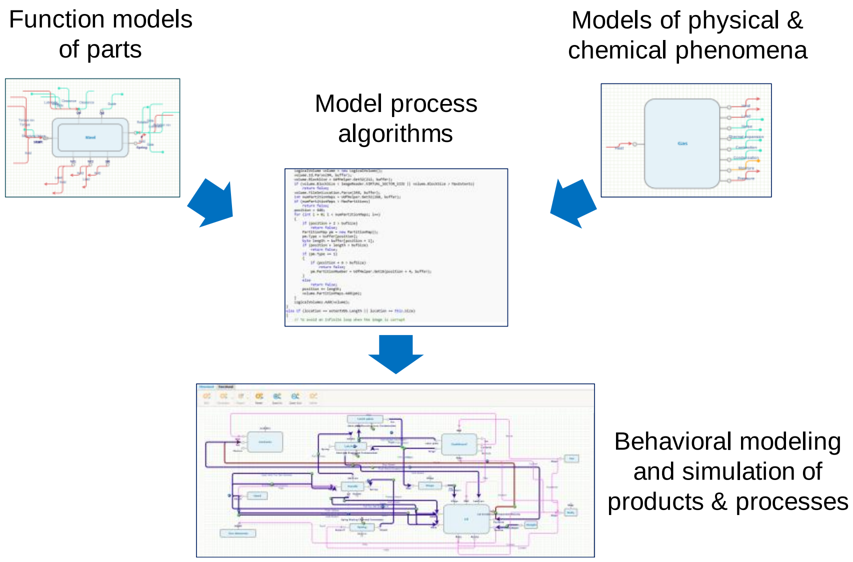


Fig. 15. The structure of the JFPM based software application (TechScan).

Analysis begins with constructing a structural model that includes major parts of the system. Each part is connected with other parts via specific links (see Fig. 8 above). Then, functions performed by each part are specified.

TechScan has a library of typical functions (e.g., "Move," "Stop," Turn on," Turn off," "Control," etc.). Each function is associated with a specific physical input. For example, the function "Control" can be associated with the physical input "DC voltage." The user can rename this function in an arbitrary way (e.g., rename "Control" to "Control XYZ," where XYZ is the part's name), as well as associate it with any physical input available in the phenomenon knowledgebase (e.g., they can replace "DC voltage" with "AC voltage"). The direct association between a function and its physical input enables the conversion of functions into physical inputs/outputs that propagate through the system via the links.

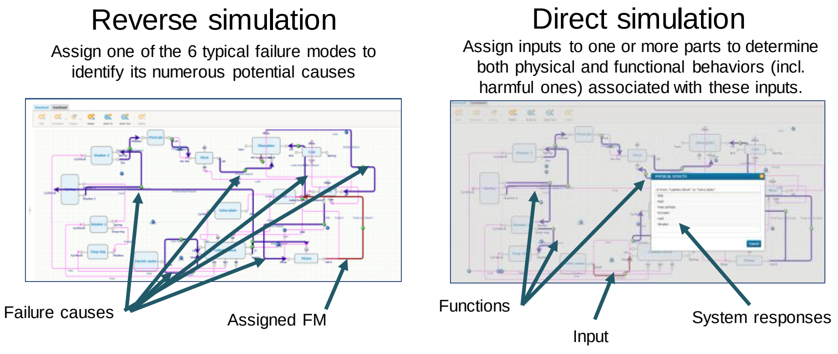
Next, either a direct or reverse simulation is run (Fig. 16).

For the former, different inputs (e.g., function values) are assigned to one or more parts (Fig. 16b). The analysis engine processes the inputs and generates functional and physical outputs for each part in the system. Some of these outputs are normative functions and others are faulty ones.

To run a reverse simulation (Fig. 16a), one of the six standard failure modes (absent, insufficient, excessive, random, slow, and fast) is assigned to the selected function. The analysis engine processes the input and identifies all potential causes (cause-effect chains) for this failure mode.

A user-customizable FMEA report is automatically generated for each type of simulation.

TechScan can analyze complex systems comprising dozens and even hundreds of parts. To this end, multicomponent systems are represented as single assemblies. This approach allows for finding out how a change in one part of a complex system might affect other, remote parts.


Reverse simulation

Assign one of the 6 typical failure modes to identify its numerous potential causes

Direct simulation

Assign inputs to one or more parts to determine both physical and functional behaviors (incl. harmful ones) associated with these inputs.

16a.

16b.

Fig. 16. Direct and reverse simulations.

4 Conclusions

A novel approach for functional and physical modeling and analysis of technological systems has been developed. This approach combines function analyses, qualitative modeling, and substance-field analysis. The latter is enhanced by the introduction of a new element – link – that transmits specific energies (fields) and substances between parts.

The developed approach allows for capturing a much more comprehensive array of a system’s normative and faulty behaviors than any other modeling method used in TRIZ processes. It was incorporated into the first of its kind software application that enables the automated discovery of potential failure modes and failure causes of complex product and process systems.

Specifically, this software application enables the following functionality:

- Comprehensive functional and physical modeling of technological systems of any degree of complexity (consisting of hundreds and even thousands of parts)
- Automated identification of failure modes and failure causes at all level of the system's hierarchy (part – component – assembly – system)
- Rapid "what-if" testing of conceptual and design modifications (any proposed change can be quickly modeled, and its effect on the system's parts, as well as on the system's environment, can be rapidly simulated and analyzed).

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