Computers & Industrial Engineering 149 (2020) 106785

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

# The evaluation of conceptual design through dynamic simulation: A proposal based on TRIZ and system Dynamics

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A R T I C L E I N F O

*Keywords:*
Conceptual design
System dynamics simulation
Substance-field analysis
TRIZ

A B S T R A C T

Conceptual design is a decisive stage in the new product development process and responsible for the originality and uniqueness of a product. Also, it is in this stage where technical feasibility becomes a critical issue in time. Simultaneously, there is an increasing pressure for developing new products faster, which demands more original, practical, and faster solutions from the conceptual design stage. This article demonstrates that the combination of the Theory of Inventive Problem Solving (TRIZ) with the System Dynamics Simulation can face this challenge. Results underline the following advantages: (1) The ability to assist the decision making process; (2) The capacity to identify the critical problem to solve; (3) The evaluation and simulation of conceptual design.

## 1. Introduction

Conceptual design plays a critical role in the new product development process. It is a challenging stage with complex requirements and a profound impact and repercussions in the overall design process (Liu et al., 2019). Conceptual design is responsible for the originality and uniqueness of a product (Hartson & Pyla, 2012), (Pokojski, Oleksiński, & Pruszyński, 2019), and more important yet, it is in this step of the design process where the technical feasibility becomes a critical issue in time (Vuletic et al., 2018). Simultaneously, there is an increasing pressure for developing new products faster, which demands more original and effective solutions form the conceptual design stage at a higher rate (Riesener, Rebentisch, Doelle, Kuhn, & Brockmann, 2019; Roy & Reidel, 1997; Vezzoli, Ceschin, Diehl, & Kohtala, 2015). Thus, conceptual design as a creative process faces several challenges (Pokojski et al., 2019):

(1) The conceptual design calls for new approaches to systematically explore the frontiers of a product, without neglecting the feasibility of a concept.
(2) It is essential to evaluate in advance the effect of an idea or a potential solution to accelerate the design process.
(3) It is necessary to conceive a method to manage the information that emerges when there are multiple design alternatives. This information produces valuable insight.

The above challenges are also some research opportunities. This article describes and demonstrates the feasibility of combining the Theory of Inventive Problem Solving (TRIZ) with the System Dynamics (SD) Simulation tools to assist the conceptual design stage. The combination of TRIZ, and more specifically, the Substance-Field Analysis (SFA) with the System Dynamics produces a tool capable of addressing inventive problems and model conflicts through a set of dynamic relationships, which are useful to several purposes: (1) To explore how a system changes in time; (2) To identify what are the more relevant conflicts in a system, and (3) To evaluate the impact of potential solutions.

This work envelops five sections: Section two describes the background and some characteristics of SFA and SD, revealing that the interaction between both approaches is a research opportunity. Subsequently, the combination of tools is explored, generating a new methodological proposal. Section four shows the combination of SFA and SD (SFA + SD) applied to a case study and discusses SFA + SD integration. Finally, the last section offers the conclusion and future work of this

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https://doi.org/10.1016/j.cie.2020.106785
Received 20 January 2020; Received in revised form 10 July 2020; Accepted 24 August 2020
Available online 31 August 2020
0360-8352/

article.

## 2. Background

### 2.1. The Substance-Field analysis (SFA)

The Theory of Inventive Problem Solving (TRIZ) is currently a well-accepted approach for problem-solving in the academic and industrial fields. Among the problems that TRIZ can deal, some of the more frequent are (1) situations where technical or physical contradictions occur; (2) the analysis of the trends of evolution in a system (ToE), and (3) problems that involve the interaction of functions, mainly through the Substance-Field Analysis (SFA), which is crucial in this article. According to (Altshuller, 1999), every system performs at least one useful function, which involves substances and fields. The term "substance" describes an object of any degree of complexity. Substances represent material, physical, or system objects in an indistinct manner (Altshuller, 1984). The means of the interaction of substances are called a "field". The concept of "field" has different definitions (Altshuller, 1984; Salamatov, 1999; Savransky, 2000). According to (Bultey, Yan, & Zanni, 2015), the term 'field' is not defined by its intention (set of formal attributes) but by its extension (set of formal objects: mechanical, chemical, thermal, electrical, gravitational and magnetic field). The Substance-Field Modeling (SFM) consists of one or more oriented graphs describing how each component's functions gave shape to a system. According to (Altshuller, 1999), the creation of a fundamental Substance-Field model involves two substances and one field or two fields and one substance. The SFA formulate problems via one function or through the interaction of multiple functions. Sometimes, the function describes a problem where the knowledge available does not lead to a satisfactory solution, produces an impasse, or simply there is a lack of knowledge to accomplish the desired result. With the goal to deal with these situations, there is a set of generic rules called the 76 standard solutions. A standard solution allows the user to find a potential route to deal with the problem more efficiently.

The creation of an SF Model demands four stages: (1) the identification of the components; (2) the construction of the model; (3) the identification of the correlation of the model with at least one of the 76 standard solutions, and (4) the development of at least one solution concept validating its feasibility (Terninko, Zusman, & Zlotin, 1998) and (Helfman, Reich, & Greenberg, 2015). The SFA has several advantages over other inventive tools: (1) the creation of simple knowledge-based models; (2) the representation of complex systems through simple modeling; (3) the construction of models through functions; (4) It shows the user the relationship between substances and fields, and (5) The SFA establishes a straight relation between one problem and one solving strategy, which considerably delimits the solution space.

These advantages are the central topic of different research and some of the reason for the extensive use of TRIZ in design activities in several domains, for instance, (Baldussu & Cascini, 2015; Bogatyrev & Bogatyreva, 2015; Helfman et al., 2015) apply TRIZ in the field of biomimetics imitating living systems and replicating them in designs implemented for engineering. The work of (Labuda, 2015) and (Nazidizaji, Tome, & Regateiro, 2015) use the SFA to solve inventive problems during architectural design, which results in the creation of new approaches in architecture. The works of (Lopez, Negny, Belaud, & Le Lann, 2015; Manami, Ridgway, & Roshdi, 2015) and (Saverio, Fiorineschi, & Cascini, 2015) Propose the application of SFA in the conceptual design process. The main contribution of these works is the overcoming of limitations that occur in the conceptual design phase, using SFA in combination with other TRIZ tools, software specialized in CAD, collective intelligence, and the systematic design approach (SDA).

On the other hand, (Bultey et al., 2015) faces the lack of standardization and the empirical use of the 76 standard solutions during the SFA process (Yan, Zanni-Merk, Rousselot, Cavalucci, & Collet, 2013). Propose in their research a strategy to choose a physical effect depending on the context of the inventive problem (Nazidizaji et al., 2015). Show in their research a significant contribution to the architecture based on the SFA (Chen & Huang, 2011). Presents an eco-innovative design methodology to support designers in developing product-service systems (PSS) with the SFA (Feng, Tai-yong, & Hui-juan, 2006). Propose to use SFA in the conceptual design of complex mechanical systems. The logic of SFA is also crucial in the work of Ko (2017), which offers the conception of a tool for modeling inventive problems in the conceptual design stage. The work of (Chakroun, Gogu, Pacaud, & Thirion, 2014) Underlines that the logic of TRIZ has a positive effect on the conceptual design process and envisages the use of the SFA for solving environmental problems. According to (Lim, Chung, Tan, & Teoh, 2015), the SFA is a pragmatic tool for developing new alternatives in the conceptual design of new soldering processes. The work of (Hmina, Sallaou, Arbaoui, & Lasri, 2018) Corresponds to the use of the TRIZ logic in preliminary design, which is also a creative stage. The authors propose the use of the SFA logic to impel creativity and accelerate preliminary design (Goel & Singh, 1998). Make a review of different methods to impel the idea generation phase. This work underlines the potential of the TRIZ logic to accelerate this process.

Despite the usefulness of the SFA, it has some limitations: (1) The tool cannot model conflicts and analyze the relationships between their variables, taking into account the temporal dimension (Delgado-Maciel, Cortés-Robles, Jiménez, Sánchez-Ramírez, & García-Alcaraz, 2017). Also, it cannot solve problems simultaneously. This situation generates a limitation to address complex problems (Terninko et al., 1998). (2) The SFA operates according to the logic of TRIZ: it solves problems sequentially, and with this, the current methodology does not allow to help the solver to discern which conflict is the most important. This condition increases the complexity of the decision-making process, and (3) The current resolution process of TRIZ does not have any technique that allows evaluating, which is the problem with the most significant positive or negative impact within the system. For the above reasons and under the current SFA state, it is not possible to carry out an analysis of the changes that occur within the system over time, nor to discern among several potential solutions (Delgado-Maciel et al., 2017). However, there is a tool capable of dealing with the lack of dynamism of TRIZ and also able to explore the causality among different elements and conditions within a system: System Dynamics (SD). The next paragraph offers a brief perspective of the System Dynamics advantages and objectives.

### 2.2. The System Dynamics

The System Dynamics (SD) is a more mature modeling approach if compared with the SFA. According to the System Dynamics Society, SD is a computer-aided approach to policy analysis and design. SD provides some tools to model a system and an interface to generate a simulation model of the functions that a system encompasses. In this process, the simulation provides the tools to observe the effect of each of the problems in a system. Consequently, a dynamic simulation model can explore the complex relations that exist among different problems in a system to select the right conflict to solve. Also, the simulation model is useful for evaluating the impact of a potential solution or, in other words, evaluating the impact of a Standard Solution of the SFA. A System Dynamics simulation produces information that assists in the decision-making process and produces new information about the non-evident interactions that affect the conceptual design process. The work of Park, Wang, Yeo, and Ng (2014) offers a broad perspective of the repercussions that have the selection of the right infrastructure in a naval transportation system. This work provides information to evaluate the conceptual design of a service. According to (Marquez & Blanchar, 2006), dynamic simulation can evaluate the effect of a decision-making process that has an impact on the structure of a service that changes rapidly on the market; such is the case of high-technology business (Geum, Lee, & Park, 2014). Follow a similar direction. The authors propose a dynamic simulation model to organize scenarios that are valuable to evaluate the conceptual design of a car-sharing service. The work of Onggo (2009) explores the importance of a conceptual model in a simulation project, including a system dynamics simulation. The author emphasizes the importance of a good conceptual model and its role in the success or failure of a simulation project (De França & Travassos, 2016). Focus their attention on a relevant observation: Software engineering has a lack of data about the results of dynamic simulation models, specifically in the conceptual software design (i.e., process simulation software, project management, software development, among others). The authors advance a set of elementary guidelines to deploy a simulation-based study for software engineering. It is interesting to notice that most of the reported cases of SD in conceptual design belong to the service design domain or more related to the process analysis (Demczuk & Domingos, 2017; Hsieh & Chou, 2018; Lee, Han, & Park, 2015). Despite the usefulness of both techniques to assist conceptual design (Franco, 2019; Kamarudin, Ridgway, & Hassan, 2015; Noor, Sapuan, Ishak, & Sultan, 2018), the search for some references reporting the combined use of these techniques did not produce a positive result, a condition that emphasizes the originality of this article. Thus, this article combines the capacity to model and solve problems of TRIZ through the Substance-Field Analysis with the System Dynamics Simulation. Results show, not only that the combination is feasible, but that new resources for problem-solving emerge that have the potential to accelerate the conceptual design stage. Simultaneously, the TRIZ theory and the System Dynamics produce a synergy in which both approaches acquire new capabilities in the conceptual design development. Table 1 synthesizes the analysis of state of the art.

Table 1 shows a comparison between different works focused on the development of the conceptual design. These works involve different types of software for system modeling. (Delgado-Maciel, Cortés-Robles, Alor-Hernández, Alcaráz, & Negny, 2018) and (Li, Wang, & Li, 2014) use Vensim ® software for modeling the causal relationships among variables or creating the simulation model. At the same time, (Franco, 2019) uses Dynaplan ® Smia, a software developed by Dynaplan AG that allows modelers to build simulation models through some interfaces and output graphs. Both pieces of software are focused on dynamic simulation. This type of simulation has an advantage over traditional simulation because it allows the analysis of variables over time and the evaluation of the temporal impact between variables (Sterman, 2000).

### 2.3. The product development process

From an industrial perspective, product development is the process that companies employ to compete in a particular market. This process includes the creation of new goods or services, the update to previous products, or the total modification of available products in the market. Thus, product development lies in the research and design of goods or services focused on satisfying the market's needs. Several trends affect the product development process in recent years, and according to (Riesener et al., 2019), one of the most relevant trends is a shorter life cycle of products due to their increasing complexity (OECD, 2008). For this reason, the concept of agile product development is increasingly important in the manufacturing industry (Schuh et al., 2018), a condition that produces an increasing pressure in the first stage of the product development process: the conceptual design stage and also in the techniques focused on it.

**Table 1**
Work comparison.

| Authors | Simulation | TRIZ | SFA | SD | System modeling |
|---|---|---|---|---|---|
| (Franco, 2019) | X | – | – | X | X |
| (Noor et al., 2018) | – | X | – | – | X |
| (Delgado-Maciel, Cortés-Robles, Alor-Hernández, García & Negny, 2018) | – | X | – | X | X |
| (Nazidizaji et al., 2015) | . | X | X | – | X |
| (Li et al., 2014) | X | – | – | X | X |
| (Wu, 2011) | – | X | X | – | X |

There are many techniques focused on the development of conceptual designs: The trial–error method (Petroski, 1991), the design thinking (García-Manilla, Delgado-Maciel, Tlapa-Mendoza, Báez-López, & Riverda-Cadavid, 2019), the brainstorming method (Bonnardel & Didier, 2020), biomimetic design (Cheong & Shu, 2013), among other techniques. However, these tools have some critical limitations when they are implemented in the development of conceptual designs:

1. These methods lack or have a little mathematical basis.
2. It is challenging to analyze the causal relationship among the system variables.
3. There are no specific guidelines that generate strategies to resolve inventive conflicts.

The works of Nazidizaji et al. (2015), and Wu (2011) shown in Table 1, present an advantage over conventional techniques for developing conceptual designs. Both approaches use the modeling capacity of functions that SFA possesses, and (Franco, 2019) follows a similar logic, but using the causal analysis among variables through SD. These works search to overcome the three limitations of the classic techniques typically used in the conceptual design stage.

Table 1 also underlines a research opportunity in the integration of the TRIZ theory with SD. This literature review shows that there are gaps in TRIZ and SD. Each of these techniques has limitations that the other technique can overcome. Therefore, a combination of both techniques represents an excellent opportunity for improving the inventive problem-solving process through a composed analysis based on System Dynamics and the Substance Field approach. The next section describes the methodology to combine SFA + SD and proposes some essential activities to face an inventive problem.

## 3. Methodological approach

The analysis of both approaches shows that SFA is a tool useful for modeling a conflict in a system via the interaction of several functions. Once the solver has a problem model, it is possible to link it with one specific solving strategy from a set called the 76 Standard Solutions (Altshuller, 1999; Salamatov, 1999). On the other hand, SD can model and simulate the system behavior to observe the effect of a possible change in the system (Sterman, 2000). However, in the context of conceptual design, SD provides the tools for modeling a system, and in this effort, the solver can observe the inherent conflicts of the design process, but SD does not offer any guideline or tool for problem-solving, neither for proposing inventive solutions. Hence, the design process's continuity depends on the solver's experience (Franco, 2019). The proposed synergy between SFA and SD assists the user in the decision-making process by analyzing the system over time and produces some unique advantages that other tools do not possess. SFA and SD have diagrams inside their toolbox capable of modeling systems that involve complex relations between variables. This characteristic is of utmost importance because it implies some compatibility between both techniques. The SFA allows the modeling of an inventive conflict and allows the user to analyze variables through functions. According to (Terninko et al., 1998), a field often represents a form of energy, force, or reaction to produce an effect. This cause-effect relationship has some similarities with the diagram used in SD to represent causal relationships: The Causal Loop Diagram (CLD). This diagram uses dynamic hypotheses to assess causality among variables (Sterman, 2000) and consists of some ideas about what structure might be capable of generating a potential behavior in a system.

A synergy between the two approaches gives a new dimension to the understanding of inventive problems: (1) The SFA approach acquires the ability to model and evaluate the simultaneous impact of multiple conflicts. This new feature is the result of the fundamental mathematical analysis necessary to build a simulation model in the SD. (2) Simulation offers many advantages to the analysis and solution of inventive problems. A simulation model from the Discrete Simulation (DS) or the System Dynamics (SD) point of view demands a graphical interface to evaluate a model's behavior. These characteristics benefit the inventive problem-solving process, presenting a great opportunity capable of generating conceptual designs.

Table 2 shows a brief comparison between Discrete Simulation (DS), Substance-Field Analysis (SFA), System Dynamics (SD), and the combinations of the Substance-Field Analysis and System Dynamics (SFA + SD).

The integration of the SFA modeling processes with the SD approach consents some advantages: (1) it allows the modeling of an inventive problem as the interaction of some functions. (2) The functions that interact in the system produce enough information to generate a Causal-Model Diagram and a simulation model. (3) Once there is a causal-model of the functions, it is possible to identify the system's conflicts. Each conflict has an associated strategy to transform an undesirable state of a function into something useful.

The central methodology in this article is based on the work of (Forrester, 1968; Salamatov, 1999; Terninko et al., 1998), and (Sterman, 2000). This methodology represents an original approach for solving inventive problems, which is the main contribution of this work. Table 3 shows the four phases and the most significant activities.

The work of (Sterman, 2000) has a broad application domain. It is useful in production systems (Alamerew & Brissaud, 2020), manufacturing (Adane, Bianchi, Archenti, & Nicolescu, 2019), logistics processes (Zenezini & De Marco, 2020) to mention only a few. The methodology proposed in this work (Table 3) acquires this versatility and is applicable to multiple dynamic systems as it is based on the studies by (Forrester, 1968) and (Sterman, 2000). Therefore, the methodology is original and represents an emergent research area for solving inventive problems. A case study describes a situation that illustrates how these advantages are useful to propose a potential solution and a mechanism to evaluate a conceptual design through a dynamic simulation model. The next section shows a case study that involves the analysis of an object in which there are inventive conflicts: a dry-erase marker. The case deploys the methodology proposed in Table 3 and discusses its potential use as an approach to assist conceptual design.

## 4. Case study: context and results

A local entrepreneur offers us a case related to the use of a typical dry-erase marker. This object has several problems. Their useful function is to create a temporal register over a surface easy to clean, which means that the register will not remain for a long period. Table 4 synthesizes the results of a brainstorming session and underlines the advantages and drawbacks of the object.

After this brief analysis, a research team focuses their attention on solving the most significant problem: how to increase the useful life of the object without affecting as possible the present configuration? The research question is relevant because the object preserves all their physical attributes when the main useful function cannot be provided anymore, also to avoid changes in the production process. The next points describe the application of the methodology proposed in Table 3.

**Table 2**
Comparison of different approaches.

| Advantage | DS | SFA | SD | SFA + SD |
|---|---|---|---|---|
| Modeling simultaneous problems | – | – | X | X |
| Modeling complex systems | X | X | X | X |
| Based on functions | – | X | – | X |
| Solution of inventive problems | – | X | – | X |
| Use of simulation tools | X | – | X | X |
| Based on mathematical models | X | – | X | X |

**Table 3**
The methodology SFA + SD.

| Phase 1<br>Description:<br>Identify elements | Phase 2<br>Formulation:<br>Making diagrams | Phase 3<br>Evaluation: Build simulation models | Phase 4<br>Application:<br>Find solutions |
|---|---|---|---|
| 1) Define the purpose of the model. | 1) Develop the Forrester diagram. | 1) Simulate the model to observe conflicts and test the relationships of the CLD and SFM. | 1) Develop at least one solution. |
| 2) Identify critical variables. | 2) Build the SF Model (SFM) | 2) Test the model under different assumptions. | 2) Observation and analysis of the model under different scenarios. |
| 3) Establish relationships among variables and develop the Causal-Loop Diagram. | 3) Comparison and verification of the SFM and Forrester diagram to secure the compatibility of both models. | 3) Consider solutions from the 76 Standard Solutions. | 3) Validate the solution. |
| 4) Identify the substances and field, interacting inside the model. | | | 4) Recommend the best alternative. |

**Table 4**
Opportunities for developing a new product.

| | Advantages | Drawbacks |
|---|---|---|
| 1 | Non-expensive object | Only one color in the object. Thus it is necessary to have different colors |
| 2 | A portable object | Only one size in the point |
| 3 | Easy to use | Non-ergonomics |
| 4 | | Some people find the smell disagreeable |
| 5 | | The object has a negative impact on the environment due to its short useful life |
| 6 | | At the end of its useful life, the object has no physical damages |

### *4.1. Phase 1 description*

During phase 1, the user must understand the relationships of the causal type among the system variables. This analysis produces the design of a Causal Loop Diagram (CLD). Also, this phase enables the identification of the Substance-Field Model (SFM) components. The necessary steps are:

(1) **Define the purpose of the model**: The purpose of the model is to resolve conflicts and propose at least one inventive solution to improve the object and to increase its useful life without affecting as possible the present configuration.
(2) **Identify critical variables**: The analysis of the object requires the identification of two different types of variables: physical and functional. The first involves the physical part of the system components. The dry-erase marker has some components such as the plug, the case (object's body), the absorbent medium, the gripper, some information (the written text on the surface available), and the blocker (Fig. 1). These components determine some physical variables such as weight, volume, surface, shape, to mention the most relevant. The functional variables of the model have a more abstract meaning related to the effect: profitability, cost, customer preference, duration of the main useful

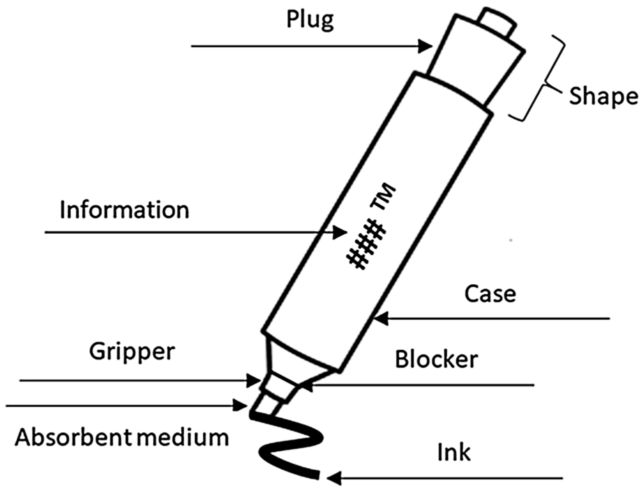



**Fig. 1.** Physical parts of a dry-erase marker.

function (making several ink records throughout the useful life of the object), environmental damage, and odor to mention the most relevant. Fig. 1 shows the basic object components. The technical terminology is available in the patent US006048121A (Carver, 2000).

(3) **Establish relationships among variables and develop the Causal-Loop Diagram:** A CLD consists of a graph-oriented where each of the arrows represents a causal relationship that connects the variables. Each link has a polarity that shows if it is a positive or negative implication. The polarity of the causal relationship can be positive or negative. Being positive implies that if variable *A* increases, then the variable *B* will do so too. Else, if the variable *A* decreases, so will do the variable *B*. On the other hand, in a negative influence: if the variable *A* increases, then the variable *B* decreases, and if the variable *A* decreases, thus the variable *B* increases. The oriented graphics allow the identification of system feedback and balancing loops. Balancing loops allow the stabilization of the system. Vensim © is a software capable of representing CLD and making dynamic simulation models. Fig. 2 shows the CLD of the dry-erase marker.

A brief explanation of each loop is:

B1: An increase in the case dimensions expands the volume of the object, but it reduces its portability. Simultaneously, a bigger case can hold a bigger absorbent medium, which can store a larger amount of ink, that at its time, it increases the duration of the useful function and, thus, has lower environmental damage.
B2: The variables of B2 are immersed in B1. However, there is an additional variable: Absorbent medium. A larger absorbent medium can store more ink and, thus, to provide the user with an object that lasts longer. However, if the portability decreases, it generates a reduction in the client's preference.

There is a particular situation that deserves a more detailed analysis: If the duration of the main function increases, similarly, the customer preference does, generating higher demand. A higher demand produces an interesting condition. If the market demands more product, then the environmental damage increases. However, if the product has a longer useful function, then the user will consume a lower quantity of dry-erase markers in a certain period, which will reduce the product demand. Fig. 2 captures this complex relation.

The CLD allows the user to determine the most important variables within the system. According to Fig. 2, portability and volume are fundamental variables in the design process, and their relations with other variables gave shape to the loops B1 and B2. The descriptions of the loops B1 and B2 generate the dynamic hypothesis. Dynamic hypothesis are part of the systemic approach proposed by (Forrester, 1961). Dynamic hypothesis explain what will be the impact on the system if one variable increases or decreases. Also, dynamic hypothesis allow the design of various scenarios that provide the ability to evaluate multiple solution strategies. Loops B1 and B2 graphically represent the system dynamic behavior.

(4) Identify the substances and field, interacting inside the model:
- There are two fields in the system: mechanical ($F_M$) and gravitational ($F_G$)

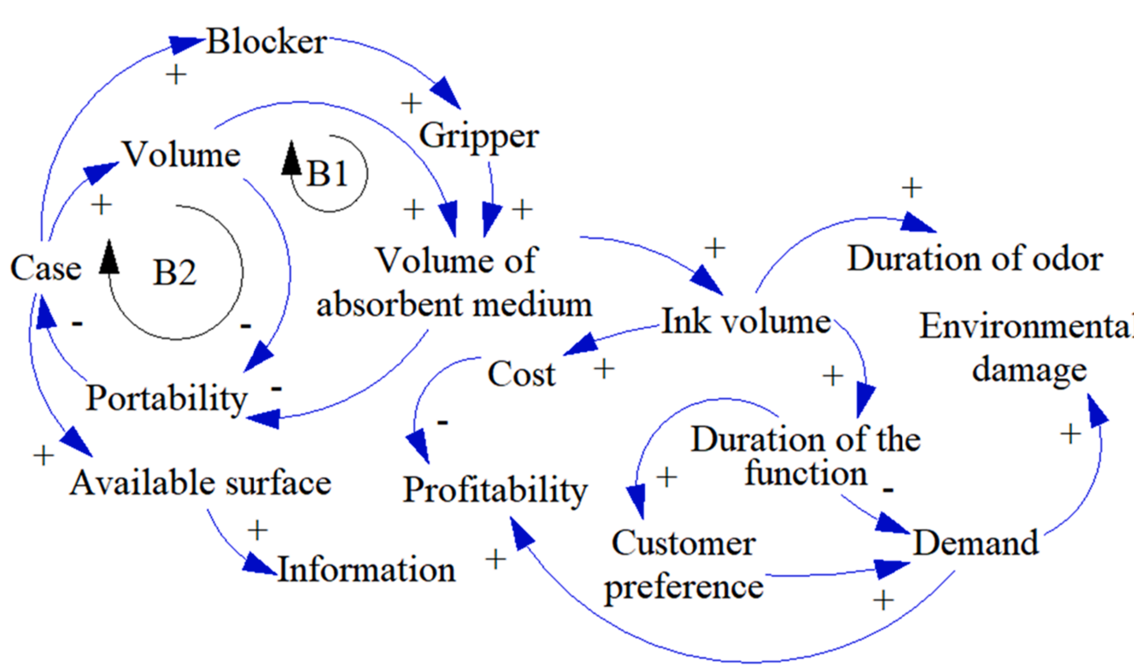



**Fig. 2.** Causal-Loop Diagram.

- Several components represent the substance in the model: the ink ($S_1$), the absorbent medium ($S_2$), the case ($S_3$), the plug ($S_4$), and the surface that receives the function of the object ($S_5$).

The interaction among substances and the mechanisms or processes to transform the fields into something useful inside the system produce some inventive conflicts. The solving process needs to model and formulate these conflicts to determine the most desirable solving path.

### 4.2. Phase 2 formulation

The phase 2 consists of the construction of diagrams corresponding to the SD and SFA approaches. Each of them provides information about the conflicts in the system.

(1) **Develop the Forrester diagram**: The information displayed on the CLD becomes a Forrester Diagram (FD) using dynamic simulation software: Stella ©. The components and functional variables are converted into flows, level variables, and auxiliary variables. FD allows the introduction of some variables that do not appear in the original CLD, such as demand, quantity, capacity medium, necessary text, use, limit, to mention but a few. These variables contribute to completing the missing information in the model. Fig. 3 shows the FD.

Level variables such as ink quantity, duration of the function, information, volume, and profitability generate differential equations measured over time. In the case study of this article, the most important equation is the volume, since it involves the amount of ink (level) and the absorbent medium of the object.

$$V(t) = V(t_0) + \int_0^t (A - Q)dt \quad (1)$$

In the above equation, $V(t)$ = Volume of the object in an instant of time, $V(t_0)$ = Initial volume, $A$ = The size of the absorbent medium and $Q$ = Quantity of ink. The capacity of the absorbent medium and the volume determine the amount of ink inside. The volume of the object is then closely related to its portability.

(2) **Build the SF Model (SFM)**: Once the FD is available, the next step is to build the SFM. Table 5 shows the nomenclature used in SFM. Each arrow has a different meaning inside the model.

Fig. 4 depicts the model of the dry-erase marker. Some elements, such as the gripper, the blocker, and the information (Fig. 1), which are part of the case, are not explicitly inserted in the diagram to facilitate the comprehension of the model. Following points describe the fields and the substances:

**Table 5**
Nomenclature used in SFM (Delgado-Maciel et al., 2018).

| Analysis | Nomenclature |
|---|---|
| 1) Application |  |
| 2) Desired effect |  |
| 3) Insufficient desired effect |  |
| 4) Excessive |  |
| 5) Harmful effect |  |
| 6) Inexistent effect |  |
| 7) Transformation of the model |  |
| 8) Uncontrolled effect |  |

- Fields: there are two fields in the diagram: mechanical ($F_M$) and gravitational ($F_G$)
- Substances: the ink ($S_1$) which is contained by the absorbent medium, the absorbent medium ($S_2$) that stores a certain amount of ink and has a tip in the end that interacts with a surface, the case ($S_3$) that contain the absorbent medium and the ink, it holds the blocker, and has a shape that facilitates the insertion of the plug, the plug ($S_4$) that covers the tip of the absorbent medium to avoid damages and to reduce the volatility of the ink. Finally, it is the surface that receives the function of the object ($S_5$) through the interaction with the absorbent medium tip.

With this information, it is possible to model the main useful function of the object. Fig. 4 explains that a temporal register on a surface, which is the main useful function, results from the interaction of the absorbent medium ($S_2$) with the surface ($S_5$) through a mechanical field ($F_M$).

Fig. 4 also shows that all components in the system collaborate with at least one function in the system. The diagram explains that the absorbent medium ($S_2$) interacts with the ink ($S_1$) through a gravitational field ($F_G$). The absorbent medium captures a certain amount of ink by capillarity, and this relation determines the durability of the useful function. The case ($S_3$) holds, via a mechanical field ($F_M$), the absorbent medium ($S_2$). This relation is crucial to determine the volume of the object and then, its portability. The case ($S_3$) holds via a mechanical field ($F_M$) the plug ($S_4$). Fig. 4 is a representation of the system in its present state. However, the problem describes that it is necessary to increase the object durability (main useful function). To accomplish this objective is

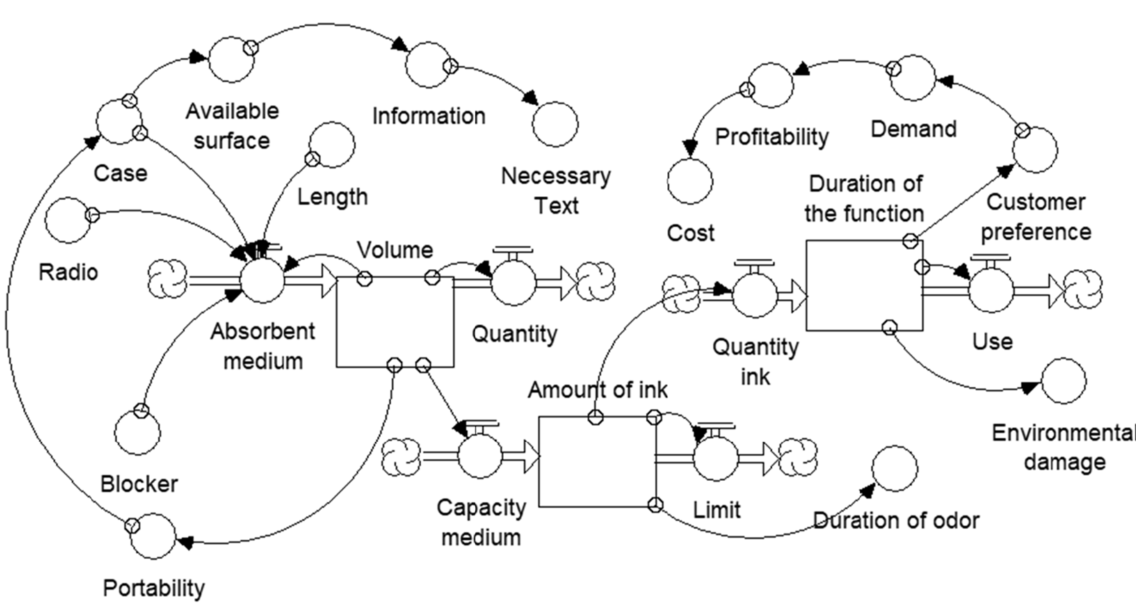



**Fig. 3.** Forrester diagram.

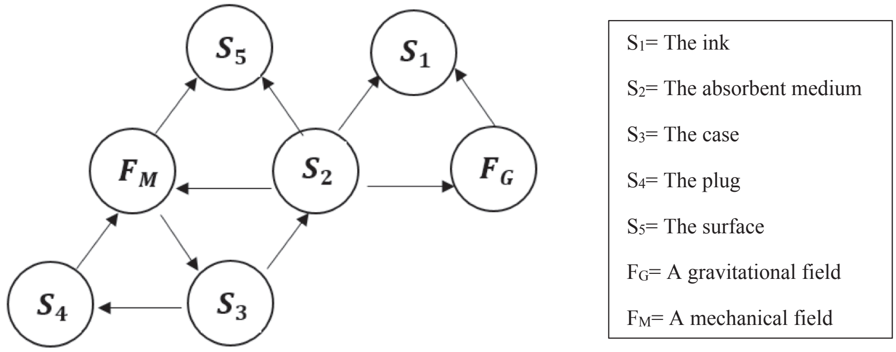



**Fig. 4.** The main useful function of the object.

necessary to increase the capacity of the absorbent medium ($S_2$) or replace the amount of ink that gets out from the system when the main useful function is served. These initiatives generate a negative impact on the system. Any augmentation in the size of the absorbent medium ($S_2$) affects the case ($S_3$). If the volume of ink ($S_1$) overcomes the saturation point of the absorbent medium ($S_2$), the risk of spill out appears. If the object is not in use, and there is an excessive volume of ink ($S_1$), the plug ($S_4$) will store the excess. If the case ($S_3$) becomes easy to disassemble, then the risk of leakage of ink ($S_1$) will appear. Fig. 5 depicts these conflicts.

Fig. 5 allows representing the inventive problems found in step 4 through the CLD. Some inventive problems in the system involve the absorbent medium, the ink spill, the length of the object, and the volume of ink. Table 6 describes some problems that emerge when the variables that have a positive effect on the duration of the function increases (see Fig. 2).

**(3) Comparison and verification of the SFM and Forrester diagram to secure the compatibility of both models**: According to the SD approach, the CLD is the basis for generating an FD (Sterman, 2000). The CLD and FD variables (Figs. 2 and 3) are equivalent to those presented in the SFM (Fig. 5). The causal relationships in the FD and their functions in the SFM that represent the system involve the same variables. The components and functional variables are similar, a condition that increases the compatibility between both approaches.

### 4.3. Phase 3 evaluation

Phase 3 uses the FD to simulate the programmed variables. In this section, the sensitivity analysis applies the 76 standard solutions.

**(1) Simulate the model to observe conflicts and test the relationships of the CLD and the SFM**: The Stella interface allows the creation of useful graphics to analyze the system. An example of this is Fig. 6, which represents the system in the current state. A dry-erase marker initially weighs 22 g and descends to 15 g once it is empty (7 g approximately 7 ml of ink considering a density close to the density of water). According to experimental results, the volume of ink used per hour is 0.2 ml. It is interesting to notice that in Mexico, an elementary school teacher dedicates 800 hr/year and works more than 200 days. Something similar happens in the high school where a teacher works 1,047 hr/year, which produces an average use of 4.6 hr/day and

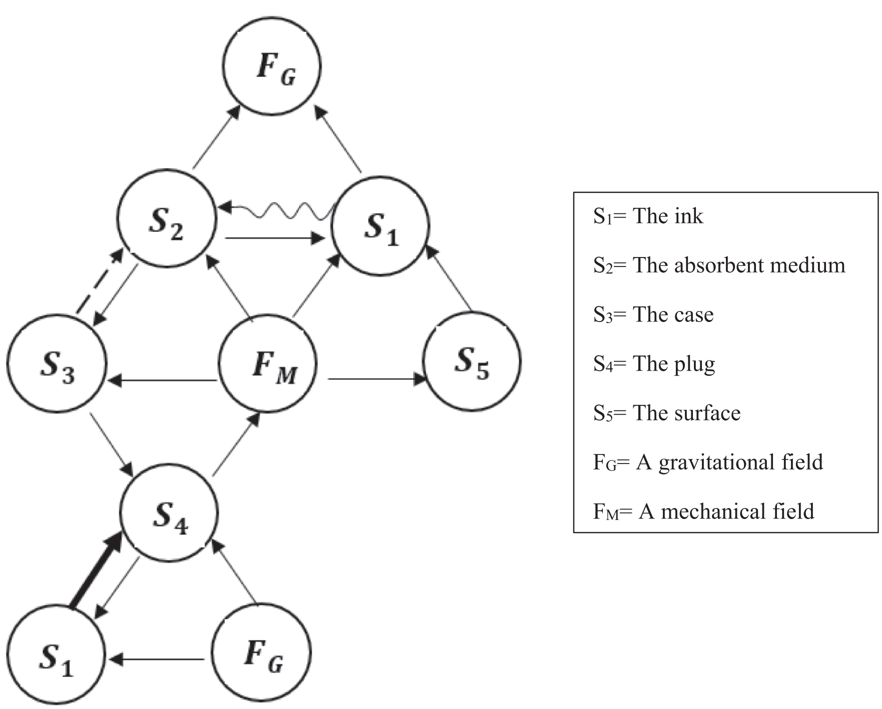
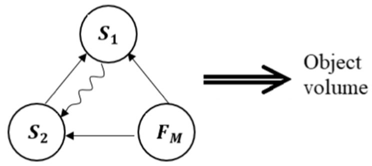
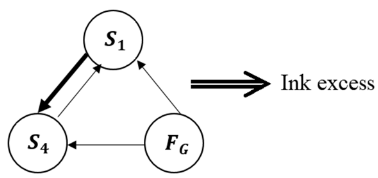
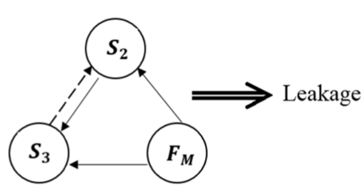



**Fig. 5.** The inventive problems in the system.

**Table 6**
Conflicts and SFM.

| Conflict | Diagram | Inventive problem |
|---|---|---|
| Conflict 1 |   | A bigger absorbent medium ($S_2$) will have a greater capacity to contain a large amount of ink ($S_1$), but increases the dimensions of the object, reducing the portability. Hence, it is necessary to increase the amount of ink without the addition of other kinds of matter. |
| Conflict 2 |   | An increase in the amount of ink ($S_1$) also increases the duration of the useful action. However, if it is excessive, then it causes the ink to spill out of the case and get stored in the plug ($S_4$) when the dry-eraser is not in use and upside down. If such condition arrives, then the ink will flow outside the case. Thus, it is necessary to propose a mechanism to replace the right amount of ink to avoid an excess of liquid. |
| Conflict 3 |   | If the case ($S_3$) becomes easy to disassemble to renovate the amount of ink in the absorbent medium ($S_2$), then it is not possible to assure the hermetic seal of the case. |

maximal use of six to eight hours (Indicators, 2014). These statistics are crucial to estimate the time of use of the dry-erase marker. Consequently, the usage rate moves between 0.2 ml and 1.2 ml daily approximately, which corresponds with an arbitrary classification of moderate use (1 hr/day), regular use (3 hr/day), and intensive use (6hr/day). Fig. 6 shows how the use affects the ink volume over time, considering the use from one to six hours per day, and the (Indicators, 2014) average use. The intensive use runs out of ink approximately at day 10. Moderate use exceeds day 35.

In this stage, the user can modify the variables programmed through the Stella © interface. These modifications produce new information about the relevance of the CLD and the dynamic simulation model. It is in this step where the user can observe the effect that each problem has on the system and then, to decide what is the first problem to solve. Table 6 concentrates on the most significant conflicts that become visible in the CLD and the SFM. The amount of ink in the object determines the extent of the main useful function (see Fig. 2 or the CLD diagram). Thus, to modify the volume of ink in the system is necessary to intervene in the absorbent medium. The SFM explains that the mechanisms to affect the absorbent medium operates through two fields: mechanical ($F_M$) and gravitational ($F_G$) and two substances the case ($S_3$) and the ink ($S_1$). These relations help to identify the most significant problem: A bigger absorbent medium ($S_2$) will have a greater capacity to contain a large amount of ink ($S_1$), but increases the dimensions of the object (the case $S_3$) reducing the portability. Hence, it is necessary to increase or replace the amount of ink without modifying the case. This is the first conflict listed in Table 6 and, thus, the most relevant problem. The CLD and the SFM depict that conflict 2 in Table 6 has some particular conditions. For instance, the SFM highlight that there is no physical contact between the absorbent medium and the plug. This relation is also explained in the CLD (Fig. 2), which shows no effect between the plug and the absorbent medium. The effect over the absorbent medium passes through the case, which mechanically holds the plug. This conflict has slightly less relevance than the first one. Thus it is the second relevant problem. This initial classification determines the importance of the last conflict in Table 6.

(2) **Test the model under different assumptions**: After verifying the CLD and SFM assumptions, the next phase involves a simulation of the model to test different scenarios. This step produces more information to solve the conflicts described in Table 6. Nevertheless, the creation of a scenario is a creative process, and two TRIZ concepts are helpful in this step: the ideal system and the use of resources. The next points describe the ideal state to the design problem:

(A) It is necessary to increase or replace the amount of ink without affecting the present object configuration. Thus the marker by itself replaces the right amount of ink to assure its useful function or the volume of the marker adapts by itself to the user requirements and use.
(B) Without the addition of another component, the marker uses its available resources to replace the right amount of ink.

(3) **Consider solutions from the 76 Standard Solutions**: The 76 standard solutions are useful to create different scenarios because they are a set of strategies to transform the system modeled. Each conflict in Table 6 has a match with an archetype in the 76 Standard Solutions, and each conflict proposes one solving strategy. The matching process follows the (Savransky, 2000) algorithm, and also (Salamatov, 1999) offer a description of the general structure of these solving strategies and a useful explanation of how to apply each solution standard. Table 7 connects each conflict with one standard solution:

### 4.4. *Phase 4 application: developing potential solutions*

To propose at least one solution, the solver or the team working in a project needs to adapt the Standard Solution to satisfy the problem requirements. It is in this stage where a creative effort is crucial. The 76 Standard Solutions is a set of abstractions that the solver needs to adapt in a particular context to materialize a specific solution. The role of Standard Solutions is to reduce the solution space and to offer a previously validated solving strategy. The logic behind the solution process of an SFM explains that if a function (problem to solve) matches a particular model, then its associated solving strategy could be transferred to the problem to solve.

(1) **Develop at least one solution:** The adaptation of each standard solution to the conflicts listed in Table 7 produces the next potential solutions.

Conceptual design 1: The first inventive problem arises from the need to replace the amount of ink in the object to extend the main useful function. It is important to notice that, generally, when the useful function of the object ends, there are no physical damages. Hence, if the object provides its useful function for a longer period, then its environmental impact decreases. It is essential to emphasize that the

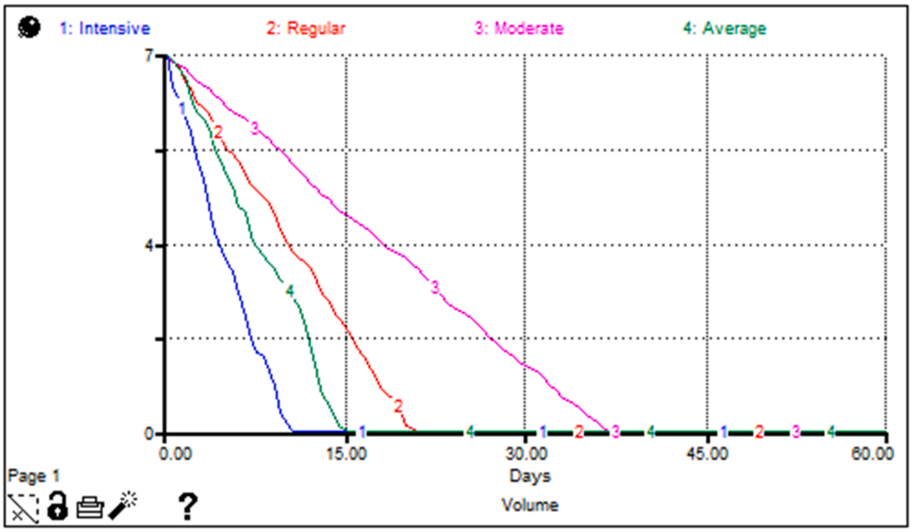



**Fig. 6.** The typical use of the object.

evaluation of the environmental impact of the object in the case study is out of the scope of this article.

According to Table 7, the standard solution 5-1-1-3 can solve the first conflict. This standard solution states that “If it is necessary to introduce a substance in the system, and it is not allowed, an external additive can be used instead of an internal one.” Thus, an external element can accomplish the desired result. The first solving scenario consists of a set of small containers with different ink colors to form a charging base. The user places in the corresponding spaces a dry-erase marker. The tip has a physical contact with the liquid, so that the ink level of the object is increased by capillarity while it is not in use (see Fig. 7).

The object in Fig. 7 allows the user to reload the ink level when the dry-erase marker is not in use. According to Fig. 8, the ink level (7 ml) goes down by daily use. In a simulation period of 30 days, the user reloads the object by choice four times (one time per week) near to the maximum load level (approximately 7 ml, calculated by the difference in weight between a new and an empty object). The experimental results show that the capillarity of the object allows recharging at a rate of 0.2 ml per minute. Therefore, the recovery of the ink level is a rapid process that increases the useful life of the object compared to the graph in Fig. 6 (see only the intensive use curve). Another aspect to consider is the fact that each ink refill (made on days 13, 19, and 28 of the simulation period), fails to reload the object to its original level (7 ml). This is due to the normal mechanical wear of the object, mainly in the absorbent medium.

Also, Fig. 9 shows the behavior of the ink level over a period between 50 and 60 days. In an approximate period of two months, the tip of the absorbent medium (responsible for conducting the ink to a surface) is sufficiently worn so that the user needs to dispose of the object.

Conceptual design 2: The second scenario involves the same inventive problem of extending the useful life of the object, but it faces conflict 2. According to Table 7, a possible standard solution to solve the second conflict is 5-1-1-1: “If it is necessary to introduce a substance in the system, and it is not allowed, a “void” can be used instead of the substance”. A “void” is usually gaseous substance, like air, or empty space formed in a solid object. In some cases, a ”void“ may be formed by other substances, such as liquids (foam) or loose bodies.” The second design is to take advantage of the space available inside the plug to insert an ink security stock (Fig. 10). The dry-erase marker increases its ink level thanks to the dispenser composed of a sponge and covered with a membrane to prevent the ink spill.

The dimensions shown in Fig. 11 allow the ink stock to be calculated from the volume of a truncated cone (equation (2)) and a cylinder (equation (3)).

$$V(r,R,h) = \frac{1}{3}\pi h(R^2 + r^2 + Rr) \tag{2}$$

$$V(r,h) = \pi r^2 \mathrm{h} \tag{3}$$

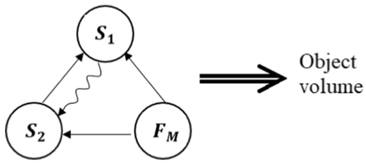
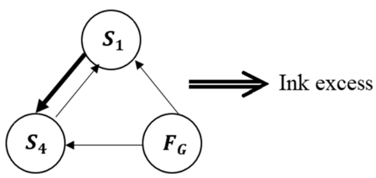
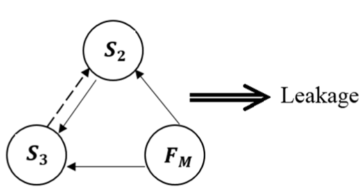
Fig. 11 shows the diameters (0.8 cm, 1.7 cm, and 1.8 cm) and the heights (1.1 cm and 0.4 cm) of the ink security stock. It is necessary to underline that equations (2) and (3) need the radius. Hence, the total volume is: $2.64\ \mathrm{cm}^3 + 0.201\ \mathrm{cm}^3 = 2.841\ \mathrm{cm}^3 = 2.841$ ml (considering a density close to the density of water).

The graphic of the second conceptual design has different behavior if compared to the previous design. This is because the object is automatically loaded while it is not in use. Thus, the ink stock does not descend in one work session. For this scenario, the user employs the object daily at a rate of 0.2 ml per hour (0.00334 ml per minute). According to experimental results, the capillarity of the object allows recharging at a rate of 0.2 ml per minute. Fig. 12 shows the variation of the ink stock in the second conceptual design. The simulation horizon corresponds to 6 h (360 min). It is crucial to notice that this simulation uses hours instead of days due to the recharge speed. If we use days as the same time scale, the consumption curve is not visible. Thus, the simulation in hours make it more understandable the ink load and the consumption rate in the dry-erase marker.

After using the dry-erase marker, the ink security stock (located in the plug) recharges the ink level near to the original level (7 ml). The user recharges the object multiple times during the 6 h period. The usage rate is 0.00334 ml per minute, which implies that the necessary volume is 1.2024 ml for 6 h. According to equations (2) and (3), the ink security stock (2.841 ml) is sufficient to satisfy the requirements of use in 6 h (1.2024 ml). The volume of ink security stock (2.841 ml) is sufficient to satisfy approximately 14 h of use. The object continues its normal wear once the extra volume of the ink security stock ends, considering the average normal use rate of 0.2 ml per minute (see Fig. 13) until it reaches approximately to zero and is thrown away after 72 h of continual use (12 days of use with six hours of use per day). This conceptual design allows extending the period of life of the object by approximately two extra days.

Conceptual design 3: A third conceptual design allows the possibility of having a stock of ink available to give a second life to the object. This design proposal is a possible solution to conflict 3 (Table 7) because it involves the quantity of the substance and the duration of the main function (the useful life of the object). A possible standard solution to solve the third conflict is 5-1-1-1 defined in the second scenario. Then a small spherical capsule placed at the end of the case allows having a

**Table 7**
SF Models and their corresponding Standard Solution.

| Conflict | Diagram | Standard solution |
|---|---|---|
| Conflict 1 |  | This SFM can be solved using class 5: Helpers, particularly the group 5-1 (introductions of substances under restricted conditions). A potential solution is the standard solution 5-1-1-3: "If it is necessary to introduce a substance in the system, and it is not allowed, an external additive can be used instead of an internal one". |
| Conflict 2 |  | This SFM can be solved using class 5: Helpers, through two solutions from group 5-1 (introduction of substances under restricted conditions). The first potential standard solution is 5-1-1-1: "If it is necessary to introduce a substance in the system, and it is not allowed, a "void" can be used instead of the substance". A "void" is usually gaseous substance, like air, or empty space formed in a solid object. In some cases, a "void" may be formed by other substances, such as liquids (foam) or loose bodies. Another potential standard solution is 5-1-1-2: "If it is necessary to introduce a substance in the system, and it is not allowed, a field can be introduced instead of the substance". |
| Conflict 3 |  | The Standard Solution to solve conflict 3 can use a similar solution of conflict 2 (5-1-1-1): "If it is necessary to introduce a substance in the system, and it is not allowed, a "void" can be used instead of the substance". |

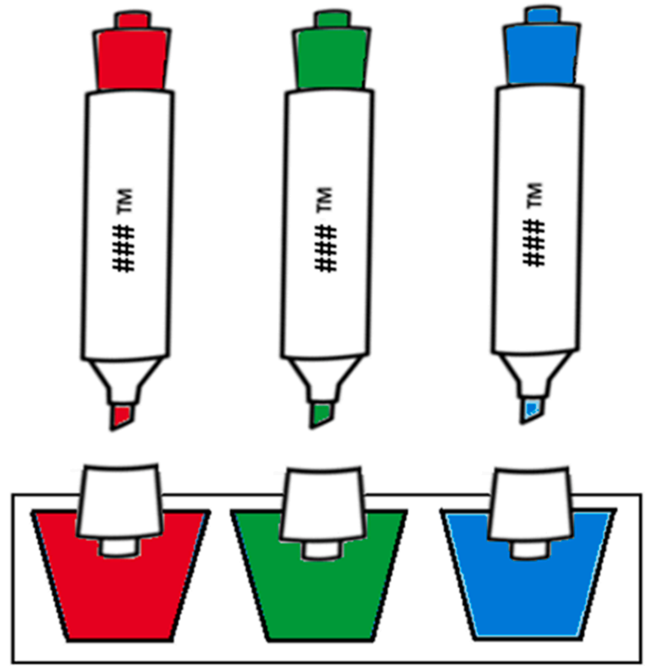



**Fig. 7.** First conceptual design.

reserve of ink to be used when the original ink level decreases. The user breaks the spherical capsule (Through a manual turn on the dotted line). The absorbent medium absorbs the additional ink by capillary action (see Fig. 14).

The radius of the spherical capsule measures approximately 0.62 cm. The mathematical formula for calculating spherical volume is:

$$V(r) = \frac{4}{3}\pi r^3 \tag{4}$$

Equation (4) estimates volume in 0.99 ml. The volume of the spherical capsule (1 ml) represents approximately five extra hours of use (considering the rate as mentioned above of 0.2 ml per hour). Fig. 15 represents the average level of ink of a dry-erase marker (7 ml) and how it decreases until the end of its useful life (approximately ten days using the dry erase marker for 6 h each day). The life span increases by breaking the additional ink stock (spherical capsule), which recharges the stock approximately 8.3% of the original level. Hence, the object works for the second (and last) occasion and then can be discarded (see Fig. 15).

Fig. 15 shows the ink refill on day 7. This increase in ink level makes it possible to prolong the life of the object by approximately an additional day.

(2) Observation and analysis of the model under different scenarios: The Stella © interface allows the evaluation of different simultaneous scenarios to compare various design alternatives. The user can analyze any variable within the FD and evaluate any scenario according to the input parameters that it inserts in the interface. Fig. 16 allows the simultaneous observation of each conceptual design in 30 days, taking into account an intensive use of six hours in all cases. The visual tools of Stella © facilitate the analysis of the scenarios that include the sensitivity analysis, which is a way to observe the impact produced by any change in the variables.

According to Fig. 16, the first conceptual design extends the duration of the dry-eraser marker more than the other two alternatives. However, the first conceptual design involves the production of another object, which demands a new business model that needs to prove its economic feasibility. An advantage of the first conceptual design is that it does not perturb the production system nor affects any physical attribute of the dry-erase marker. Simultaneously, the first conceptual design exposes a

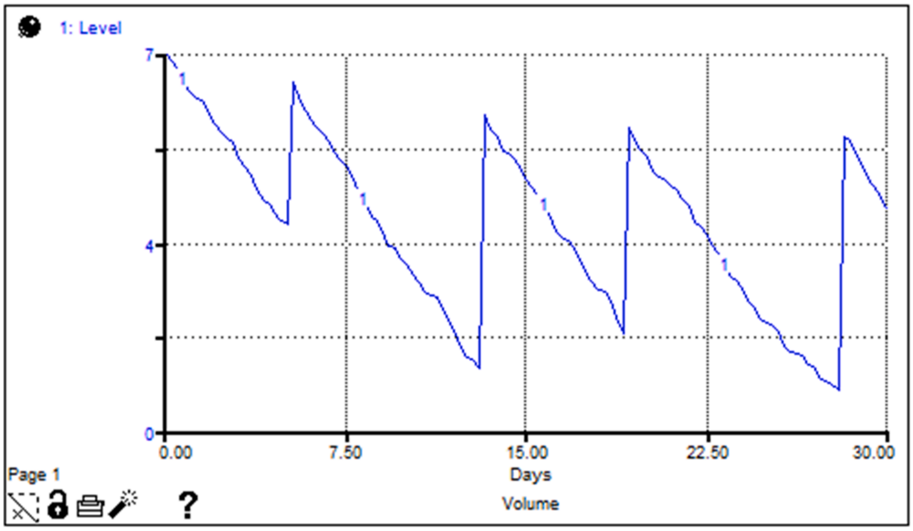



**Fig. 8.** The ink consumption in the first conceptual design (first scenario).

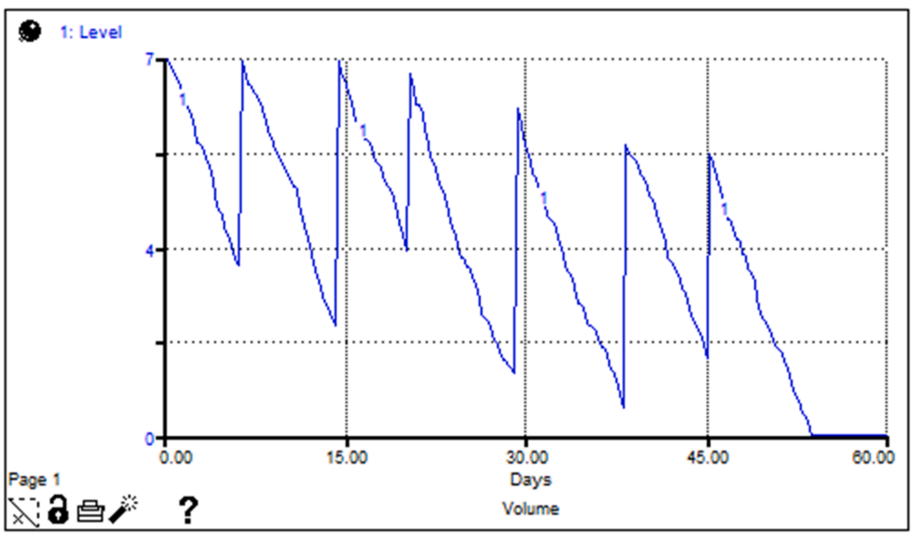



**Fig. 9.** The limit of ink consumption in the first conceptual design (first scenario).

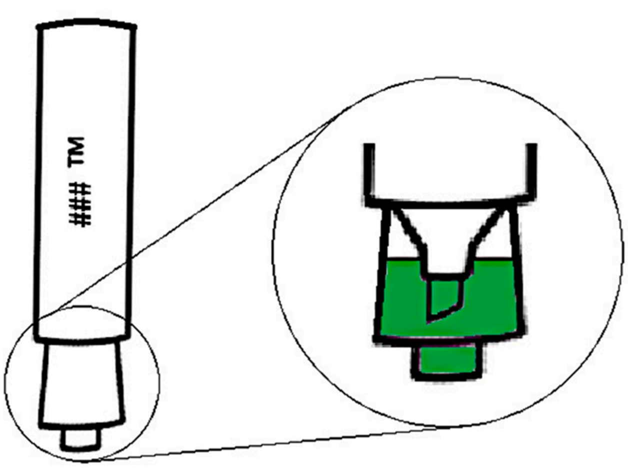



**Fig. 10.** Second conceptual design.

challenge because the object should be flexible enough to adapt its main useful function to other dry-erase markers available in the market. The second and third conceptual designs extend the useful life of the object without the need to add any external components such as the first design, but they involve minor changes in the dry-erase marker. The second conceptual design has a better performance than the third scenario. Also, it only affects the plug, which is an object that is not attached permanently to the dry-erase marker.

In that sense, the plug is considered as an independent object. Thus, this conceptual design does not perturb the production system of the dry-erase marker, and the solution takes place after the object is produced. Nevertheless, the second scenario adds other activities to the production of the object, activities that increase the production cost. The third conceptual design demands a small modification in the dry-erase marker because the solution is implemented inside the case. Therefore, it is indispensable to evaluate the necessary changes in the production system. The third scenario then denotes a more complicated implementation. Also, the sensitivity analysis is important to evaluate different scenarios in a single graph and leads to a more intuitive strategy to observe the impact of a potential solution. The information about the comparison of scenarios is useful in the physical construction

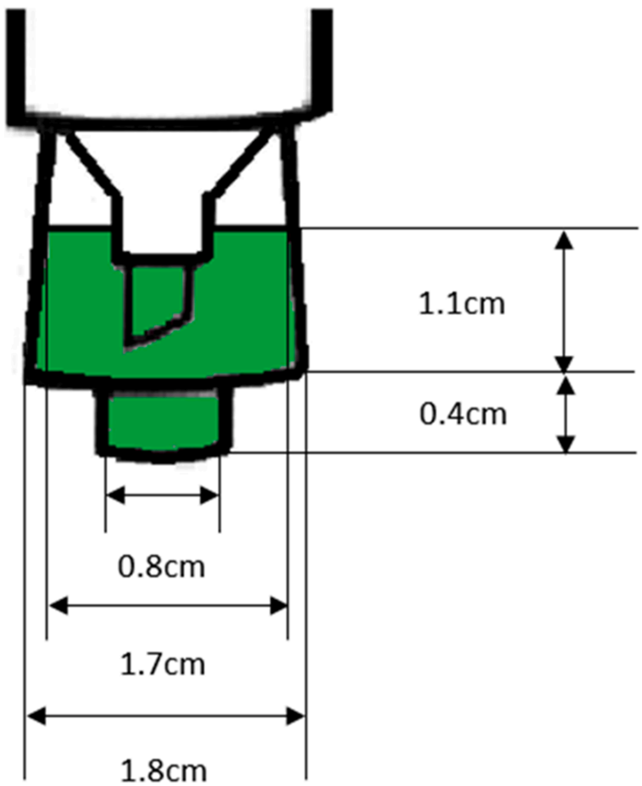



**Fig. 11.** Dimensions of the ink security stock.

of prototypes. This step considers the physical elaboration of prototypes, which is useful to validate several technical parameters and produces feedback for the design process. However, the simulation allows the visual and mathematical analysis of the best conceptual designs. Finally, it is inevitable to obtain a feedback and return of experiences useful to improve the design process, the conceptual design, or to identify new opportunities. The feedback leads to an interesting question: It is possible to combine the conceptual design two and three? What is the effect on the system? Fig. 17 shows the implementation of the second and third scenarios to create a product with a longer duration.

The final conceptual design generates a new graphic (Fig. 18). According to Fig. 18, the object obtains a continuous recharge the first few days due to the use of the ink security stock (Fig. 11) and an additional recharge on day 7 due to the use of the ink stored in the spherical capsule. Under these conditions, the dry-erase marker reaches almost 15 days of use, as Fig. 18 depicts.

Fig. 18 shows how the ink-filled up the object during the first 3 days through the ink stock security described in the second conceptual design. Later, the object acquires an extra amount of ink on day 7 through the spherical capsule. The combination of both solutions extends the useful life of the object by approximately 4–5 days compared to those shown in Fig. 6.

(3) Validate the solution: An effective strategy to validate the solution is to enter the new data in the Stella © interface and simulate the effect of any conceptual design. It is necessary to validate if the adaptation of the Standard Solution for the SFM has the expected result. However, the statistical validation is also possible. The student's paired *t*-test allows making a comparison between the data of the physical prototype built from the final conceptual design ($X_j$) with the data obtained from the simulation model ($Y_j$). From the value t-statistical and the analysis of variance, the test generates intervals that validate whether the data obtained from the simulation model are statistically valid to represent the reality of the system. Table 8 and equations (5) and (6) show the development of the student's paired *t*-test. This test allows the comparison of the ink level between the actual prototype and the simulation results.

According to Table 8, the arithmetic mean for $Z_j$ is 0.05297 ($Z_m$). This value is necessary to calculate the sum of squares of the difference between $Z_j$ and its arithmetic mean ($Z_m$), and subsequently, the arithmetic means of these operations (Table 9).

Equation (5) and (6) shows the equations to calculate the variance (equation (5)) and the confidence interval (equation (6)). The value t-statistical for a 90% confidence interval is $\mathbf{t}_{15,\,0.05} = 1.753$ ($\mathbf{t}_{n-1,\,1-\alpha/2}$)

$$Var(Z_m) = \frac{\sum_{i=1}^{n}[Z_i - Z_m]^2}{n(n-1)} \tag{5}$$

$$Z_m \pm t_{n-1,1-\frac{\alpha}{2}}\sqrt{Var(Z_m)} \tag{6}$$

According to Equation (5), the variance is:

$$Var(Z_m) = \frac{\sum_{i=1}^{n}[Z_i - Z_m]^2}{n(n-1)} = \frac{0.4435}{16(16-1)} = 0.001847$$

According to Equation (6), the confidence interval is:

$Z_m \pm t_{n-1,1-\frac{\alpha}{2}}\sqrt{Var(Z_m)} = 0.05297 \pm (1.753)\sqrt{0.001847} = 0.05287 \pm 0.07533$, which produces a confidence interval: (−0.0224, 0.1282) that includes the value of zero. Thus, the simulation model has a reliability of

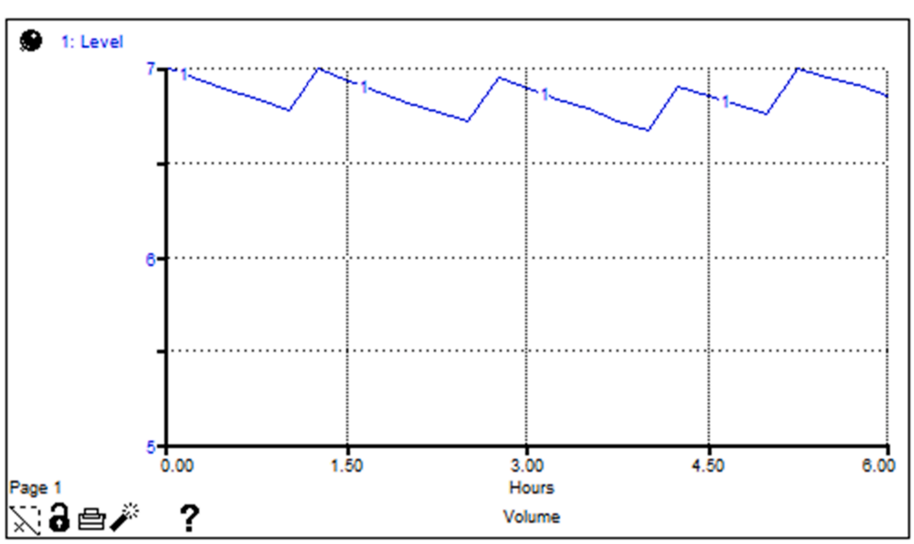



**Fig. 12.** The ink consumption in the second conceptual design (second scenario).

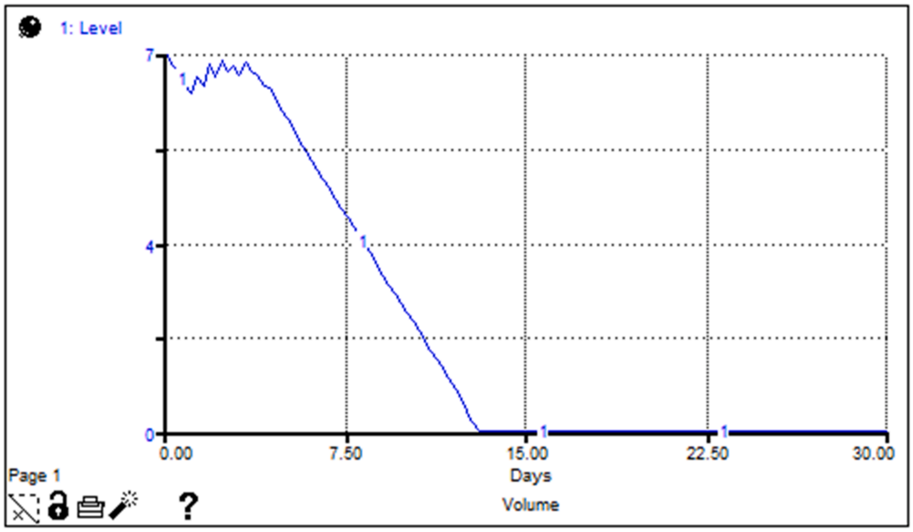



**Fig. 13.** The limit of ink consumption in the second conceptual design (second scenario).

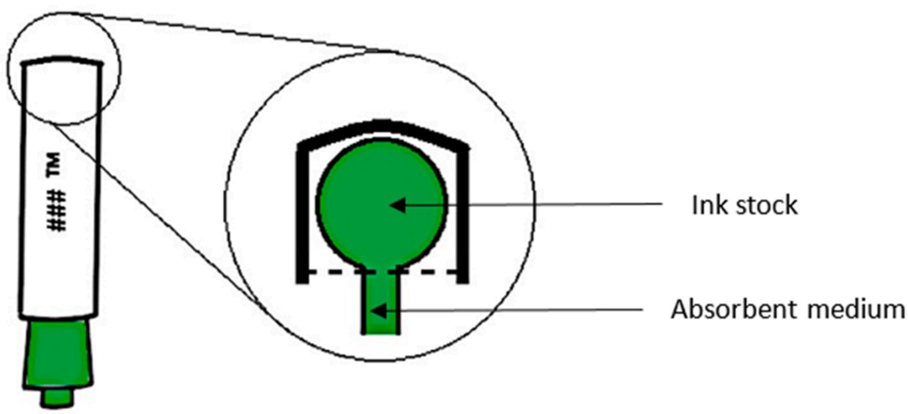



**Fig. 14.** Third conceptual design.

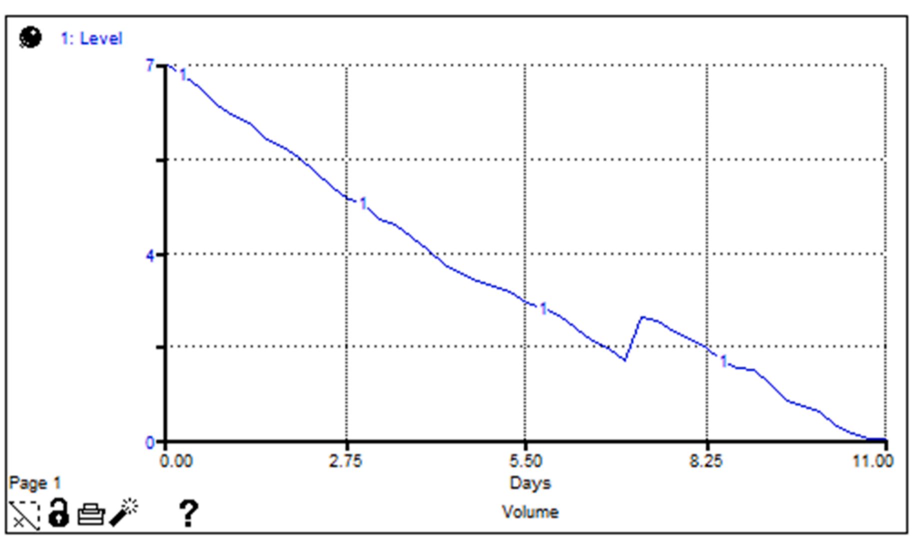



**Fig. 15.** The ink consumption in the third conceptual design (third scenario).

90% and is statistically valid.

(4) Recommend the best alternative: The comparison of the proposed scenarios allows the user to evaluate the alternatives. The first scenario is the best alternative if the production system or the object itself represents a restriction. If it is not possible to modify the object or the production system, then the first scenario is feasible. However, it is

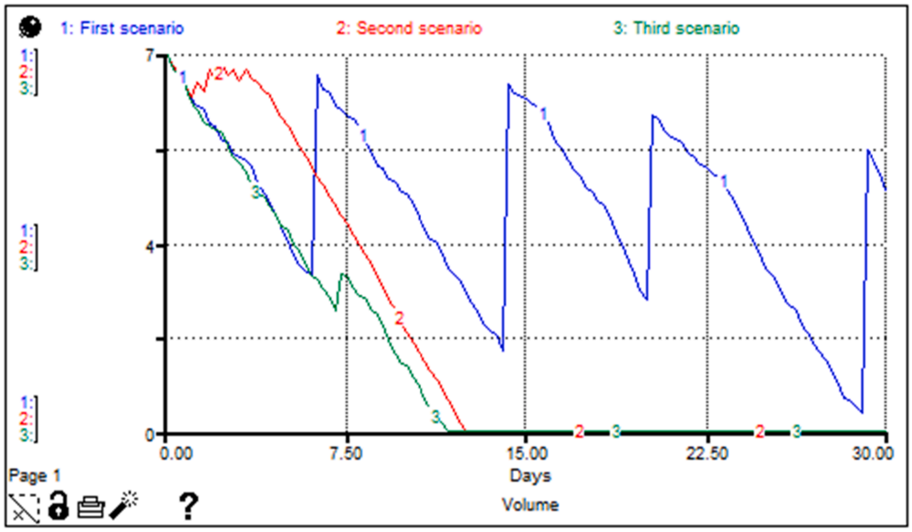



**Fig. 16.** Comparison of conceptual designs (three scenarios).

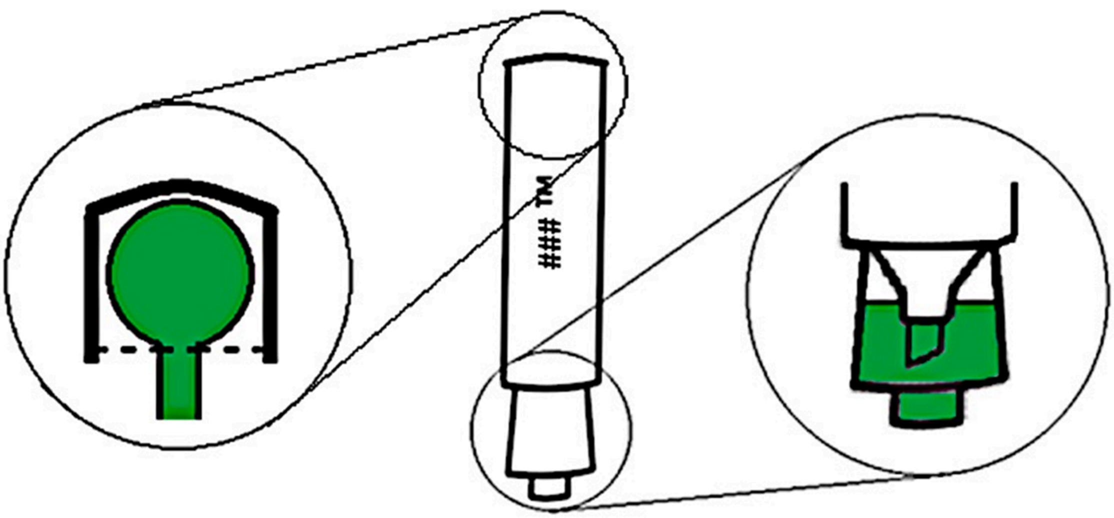



**Fig. 17.** A combined conceptual design.

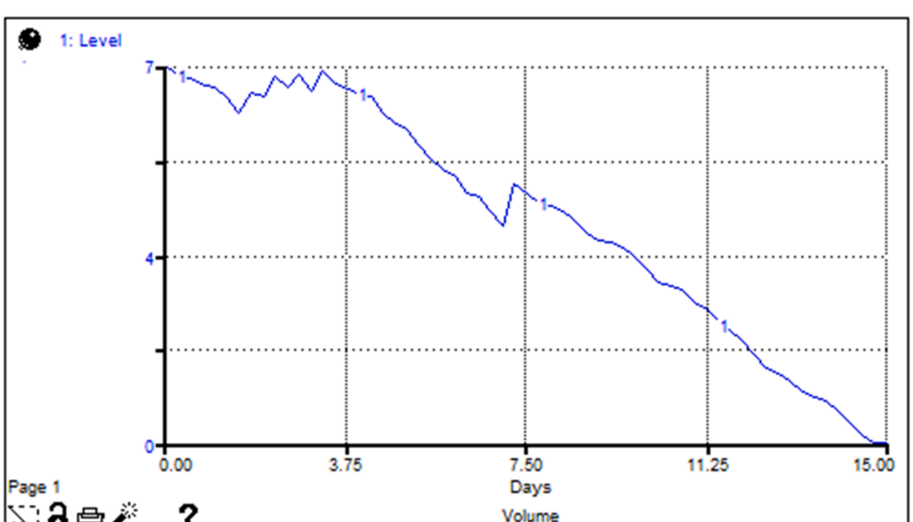



**Fig. 18.** The ink stock in the combined conceptual design.

**Table 8**
Student's paired *t*-test (part 1).

| Day | $X_j$ | $Y_j$ | $Z_j = X_j - Y_j$ | Day | $X_j$ | $Y_j$ | $Z_j = X_j - Y_j$ |
|---|---|---|---|---|---|---|---|
| 0 | 7.00 | 7.00 | 0.00 | 9 | 3.77 | 3.81 | −0.04 |
| 1 | 6.96 | 6.38 | 0.58 | 10 | 3.24 | 3.20 | 0.04 |
| 2 | 6.81 | 6.75 | 0.06 | 11 | 2.32 | 2.43 | −0.11 |
| 3 | 6.91 | 6.76 | 0.16 | 12 | 1.75 | 1.71 | 0.04 |
| 4 | 6.40 | 6.36 | 0.04 | 13 | 0.98 | 1.06 | −0.08 |
| 5 | 5.73 | 5.76 | −0.03 | 14 | 0.47 | 0.42 | 0.05 |
| 6 | 5.15 | 4.96 | 0.20 | 15 | 0.11 | 0.00 | 0.11 |
| 7 | 5.06 | 5.28 | −0.22 | | | | |
| 8 | 4.40 | 4.36 | 0.04 | Arithmetic mean for $Z_j$ ($Z_m$): | | | 0.05297 |

necessary to produce a completely new accessory for the dry-erase marker. If minor changes are possible, the second scenario is interesting, because all necessary changes can take place when the object is a finished product. Thus, this solution can be applied to other similar products. The last scenario and the combination of scenario 2 and 3 demand modifications in the production system and the object, but these scenarios do not affect the complexity of the product portfolio of the enterprise.

## 5. Discussion

The science of the 21st century faces daily challenges that involve complex systems analysis (Bar-Yam, 2003). A complex system consists of some elements or components that interact with each other through non-linear relationships (Jacobson et al., 2017). Thus, the problem-solving process asks for methodologies, techniques, or tools to acquire knowledge that facilitate the analysis of non-linear relations or simply to gain valuable information to propose effective solutions. Also, in a system, there are some hidden interactions that, when combined, create new patterns at a higher level that are necessary to understand to incorporate this information into the solving process. Consequently, and according to the System Dynamics point of view, the combination of variables leads to positive or negative feedback. Feedback influences each component of the system, causing small variations in the system, leading to significant changes. The information about the system interactions produces valuable insight into the system behavior, which leads to a new understanding of the system. Hence, the information of the system interactions enables new solving resources that have the potential to facilitate the solving process. Also, the solver needs a mechanism to observe the impact of a practical solution, or some mechanism when he does not know how to materialize a function, even if the expected result is clear. Hence, the solver or user relies on his experience and past events to deal with a problem. Thus, a single approach cannot deal with all these challenges, and a combined approach is the best alternative. This section discusses the proposal to combine the SFA approach, which is a problem-solving tool of the TRIZ theory with the System Dynamics approach through three points: (1) the ability to identify critical problems, (2) the advantages of the results of evaluation and simulation, and (3) the ability to support the decision-making process.

### *5.1. The ability to identify critical problems*

The incorporation of the causal analysis approach (CLD) into TRIZ, contributes significantly to improving the ability to identify critical problems (Delgado-Maciel et al., 2018). A CLD represents each of the variables involved in a system and analyzes causal relationships among them (Cosenz & Noto, 2018). An increase or decrease in one variable will directly or indirectly impact another due to the causal relationship that links them. Also, the dynamic hypothesis (see 3.1 Phase 1 Description section) allows the user to evaluate the effect one variable has on another since they reflect the system's causal reality. Consequently, the CLD allows the visualization of relevant connections among crucial variables in a single diagram, which according to (Papachristos, 2019) "can be transferred into quantitative simulation models for further study". The CLD capabilities enhance the TRIZ's inventive analysis, which positively benefits the inventive problem-solving process. On the other hand, despite the SFA capacity to model conflicts, this approach cannot simultaneously assess the effect among variables or the impact of a potential solution. Therefore, the implementation of the CLD allows the user to identify critical problems and analyze the impact that one variable will have on another through causal analysis. It is essential to underline that both modeling approaches have a complementary perspective: the CLD explores how some variables interact, while the SFA depicts how some components or subsystems produce at least one useful function. Even if both approaches have a different modeling logic, they identify the same conflicts in a system, which produce a broad perspective in the problem-solving process. This advantage is part of the case study in Section 4.

### *5.2. The advantages of the results of evaluation and simulation*

According to (Savransky, 2000), the complexity of the systems during the modeling process of inventive problems is not related to the number of variables in the model, but to the relations among components, the number of conflicts, the nature of the conflict, and the need to propose trade-off solutions. The case study shows the feasibility of creating a synergy between the SD and SFM tools. Both techniques have different approaches to model conflicts and a complementary perspective that produces a different problem-solving process. The methodology (SFM + SD) represents a research opportunity due to the ability to cover two different areas of knowledge through a single framework. This new approach provides a new tool for solving certain types of complex systems: conflicts that involve an inventive situation and evolves in time. Each of the phases in Table 3 shows the compatibility between both techniques, which can propose a new problem-solving approach.

The results of this integration generate a valuable contribution for a solver since it allows to model and simulates an inventive problem. The first stage of the SFM + SD methodology gives the user the ability to analyze the system variables' relationships. This step produces valuable information for modeling inventive problems. This information satisfies the requirements of SFA and SD. Probably, the most important part of phase one is the conceptualization of the CLD. This initial diagram is the support for the Forrester diagram and the SFM. The CLD and the SFM

**Table 9**
Student's paired *t*-test (part 2).

| Day | $X_j$ | $Y_j$ | $Z_j = X_j - Y_j$ | $Z_j - Z_m$ | Day | $X_j$ | $Y_j$ | $Z_j = X_j - Y_j$ | $Z_j - Z_m$ |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 7.00 | 7.00 | 0.00 | 0.0028 | 9 | 3.77 | 3.81 | −0.04 | 0.0086 |
| 1 | 6.96 | 6.38 | 0.58 | 0.2751 | 10 | 3.24 | 3.20 | 0.04 | 0.0002 |
| 2 | 6.81 | 6.75 | 0.06 | 0.0001 | 11 | 2.32 | 2.43 | −0.11 | 0.0250 |
| 3 | 6.91 | 6.76 | 0.16 | 0.0104 | 12 | 1.75 | 1.71 | 0.04 | 0.0001 |
| 4 | 6.40 | 6.36 | 0.04 | 0.0001 | 13 | 0.98 | 1.06 | −0.08 | 0.0164 |
| 5 | 5.73 | 5.76 | −0.03 | 0.0065 | 14 | 0.47 | 0.42 | 0.05 | 0.0000 |
| 6 | 5.15 | 4.96 | 0.20 | 0.0202 | 15 | 0.11 | 0.00 | 0.11 | 0.0033 |
| 7 | 5.06 | 5.28 | −0.22 | 0.0745 | | | | | |
| 8 | 4.40 | 4.36 | 0.04 | 0.0002 | | | Sum (Σ) : | | 0.4435 |

enable the observation of similar conflicts in the system, a condition that is useful to determine the solving sequence or the more relevant problem to solve. The second part consists of performing the SFM and the Forrester diagram in parallel. Both approaches produce complementary information and a broad perspective about the problems in the system and their conditions. The third stage launches the simulation model created in the previous phase. The sensitivity analysis plays an essential role because it allows the test of different scenarios and guides the user in the solving process. In the fourth step, it is necessary to ensure the compatibility between the two diagrams. Finally, the last phase involves a decision-making process where the user evaluates the best solution based on previous simulations. The SD added value when it is necessary to carry out simulations over time. The results obtained in the simulation allow the user to analyze the system's behavior in a period graphically. This analysis produces a valuable insight during the inventive problem-solving process because the user can compare the effect of modifying a specific variable in the system (Cosenz & Noto, 2018). According to the methodology presented in Table 3, the simulation model allows observing the causal relationships of the CLD and the SFA. The evaluation of different scenarios, which represent the potential solutions that take shape in the conceptual designs, enables the observation of their effects in the system and facilitates the decision-making process to select the solution that produces more value. Perhaps the main contribution of SD to SFA is to model a system and quantify it through equations, giving mathematical support for the modeling process in TRIZ. The synergy between SFA and SD is possible because both techniques have some common steps within their methodologies, particularly during the modeling stage, which involves representing the variables that produce at least one useful function in the system.

### *5.3. The ability to support the decision-making process*

The proposed methodology improves the decision-making process due to the SFA's capabilities and the System Dynamics, particularly the combined modeling approach and the simulation of conflicts and potential solutions. The modeling process allows the creation of a Causal Loop Diagram (CLD), which helps identify inventive conflicts in the system (Delgado-Maciel et al., 2018). Then, the information in the CLD allows the creation of the SFA diagrams. It is interesting to notice that this complementary modeling process is also useful as a verification mechanism in the formulation of inventive problems. Both diagrams address the same problems as Figs. 2 and 5 depict but from a different perspective. The synthesis of the CLD and the SFA diagrams also provide the user some potential strategies for problem-solving, which depend on the nature of the conflict represented in the SFA. These solving strategies are the 76 Standard Solutions, which are useful to create a solving scenario in the simulation stage.

Finally, the simulation stage in the methodology consents several advantages: it helps to find the limits of the system, allowing the identification of some relationships among variables to observe the effects of any modification in the system (Rendon-Sagardi, Sanchez-Ramirez, Cortes-Robles, Alor-Hernandez, & Cedillo-Campos, 2014). The graphical interface of the simulation facilitates this process because the user observes the system's behavior and the changes that take place according to a conceptual design.

Table 10 shows a comparative analysis between the advantages individuals of each technique (SFA and SD) and its comparison with the synergy SFA + SD. The advantages of Table 10 are focused on the decision-making process.

**Table 10**
Comparative analysis to advantages.

| Advantage | SFA | SD | SFA + SD |
|---|---|---|---|
| Graphical analysis through interface creation | – | X | X |
| Use of diagrams to analyze the relationship among variables | – | X | X |
| Use of diagrams to analyze the relationship among functions | X | – | X |
| Analysis of the system over time | – | X | X |
| Development of conceptual designs | X | – | X |
| Evaluation of multiple simultaneous scenarios | – | X | X |

## 6. Conclusion and future work

The synergy between SFA and SD generates a research opportunity for proposing new methods and unveil new resources for problem-solving. In this combination, TRIZ acquires the capacity of modeling conflicts mathematically, other analytical tools, and also the ability to analyze the behavior of a system over time. In turn, SD extends its application via the assimilation of some tools for inventive problem-solving.

The proposed methodology demonstrates the feasibility of combining SFA with SD. The main contribution of this work is the proposal of a framework with mutual benefit for both techniques: SFA is still a tool with significant limitations, perhaps the most important is its inability to analyze systems with continuous variables. In exchange, the System Dynamics approach gains the TRIZ toolbox or the ability to guide a user during the formulation and solving of inventive problems. This work underlines the opportunity to combine both techniques to get a more productive and more flexible modeling process. The intention of the article is not the proposal of a universal method of modeling, but to propose a function-oriented approach that is verified through simulation. This new approach creates the need to strengthen SFA with some tools capable of improving their performance.

The methodology proposed in this work has some characteristics that produce several benefits while solving inventive problems. The next point underlines the most relevant benefits.

(1) A versatile modeling process. The CLD allows the causal analysis among the system variables, and the SFA contributes to the functional analysis of the components. On the one hand, the CLD has a broad application domain as the state of the art underlines, particularly in the process domain. On the other hand, the SFA approach can deal with physical products, which is an atypical use of the system Dynamics technique.
(2) The (SFA + SD) methodology allows for solving inventive problems. Once there is enough information about the conflict in the system, the modeling process of the SFA creates a link with a set of problem-solving strategies and in this process, unveils new solving capacities that are useful to conceive a simulation scenario in SD, and in consequence, the evaluation of conceptual designs through simulation.
(3) The methodology involves mathematical concepts during the inventive problem-solving process. Furthermore, it uses the student's paired *t*-test to statistically validate the results.

Due to these characteristics, the SFA + SD methodology is a versatile tool and applicable to a large number of inventive problems. The adaptation of this new tool contributes to solving inventive conflicts and produces new resources that are useful in the decision-making process.

Future work suggests using the SFA + SD methodology to solve problems with a higher degree of complexity. The proposed case has a didactic purpose, and it includes only one object of daily use. The next evaluation of the methodology is to apply it to solve conflicts generated in the design of new products or the improvement of processes. These applications have a greater number of variables, and therefore there will be a higher number of interactions in a system. For the moment, the methodology only show the synergy between SFA and SD. However, both techniques are capable of including new approaches from other knowledge tools.

## CRediT authorship contribution statement

**Jesús Delgado-Maciel:** Conceptualization, Investigation, Software. **Guillermo Cortés-Robles:** Investigation, Methodology, Supervision. **Cuauhtémoc Sánchez-Ramírez:** Software, Investigation. **Jorge García-Alcaraz:** Validation. **Juan Manuel Méndez-Contreras:** Writing - review & editing.

## Acknowledgments

The National Council on Science and Technology (CONACyT) for the grant number 637564, FC-2433 and the Secretariat of Public Education (SEP) through the Tecnológico Nacional de México and PRODEP sponsored this work. Additionally, the ROPRIN working group (Industrial Process Optimization Network) supported this work.

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