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Computer-Aided Design
AND APPLICATIONS

Mapping Causal Relationships and Conflicts among Design Parameters and System Requirements

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ABSTRACT

This paper proposes a Computer-Aided tool aimed at increasing the efficiency of the Product Development Process by bridging the definition of system requirements to the preliminary assessment of the impacts of design choices on product characteristics. In details, it supports the designer in the definition of desired and undesired characteristics of a technical system throughout its entire lifecycle, according to a standardized set of criteria for eliciting and organizing knowledge from experts. The Computer-Aided tool also assist the user in managing the complex network between design variables and system requirements, characterizing their cause-and-effect relationships with the objective of determining critical parameters for product design. The paper also presents an exemplary application of the software prototype in the field of washing machines with the purpose of highlighting that a progressive integration of this kind of instruments into existing CAD/CAE tools also allows to promptly determine a connection between requirements and objectives of physically based simulations.

Keywords: system requirements, design variables, system parameters, PLM.
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1 INTRODUCTION AND RELEVANT SCIENTIFC CONTRIBUTIONS

Nowadays, Computer-Aided means supporting Product Development allow to manage the complexity of current technical systems by representing product data far beyond the geometrical features of the product itself. Plenty of commercial systems fulfill industrial requirements allowing to model system parts and to plan their manufacturing processes. Furthermore, the growing potential of multi-physics simulations allows also to analyze the product behavior upon different conditions and different environments. [1] Post processing software allow to interpret simulations with the objective of identifying which parts in system geometry needs to be redesigned according to the intended purposes. In other words, Computer-Aided systems allow to map the relationships between design variables and the expected behavior of the designed system, through the analysis of a virtual prototype. On the contrary, the early phases of the design process, namely conceptual and embodiment design, are still far from being assisted by computer applications [2]. However, several contributions [3,4] show that the early phases of the product development process may radically affect up to 70% of the whole lifecycle costs because of their significant impact on the manufacturing processes and product quality, respectively affecting industrial productivity and customer satisfaction. The same authors strengthen, in turn, the need of extending the computer-aided system domain towards the support of conceptual and embodiment design stages, with the purpose of determining robust design choices, leading to a more appropriate description of product shapes and materials. Wang et al. [3] remark that the causes of poor support for those design phases concern the fuzzy definition of design requirements and constraints characterizing a so-called **ò**soft**ó** concept model, showing, by its own nature, lacks in terms of electronic visualization and communication. Therefore, the management of the complex, interdisciplinary, informal and still uncertain data on which the whole product development is based, represents the most critical issue for a computer tool. In terms of system preliminary modeling, the architecture of a Computer-Aided system represents a key factor in order to both integrate it with the downstream Product Lifecycle Management applications and to increase the efficiency of the whole PDP, accomplishing the goal of reducing lead time at the maximum extent.

According to this perspective, great efforts have been made in this domain to improve the functionality of Product Data Management systems. They assist Product Lifecycle Management stakeholders in their own field of expertise, by collecting and managing the information and data flow with the objective of making them available also to other members of the design team, exactly when needed. In this regard, these kind of Computer-Aided instruments also aim at empowering concurrent engineering practice by creating a collaborative environment where members of the design team can share more easily knowledge elements [5]. Nevertheless, they partially achieve these goals and, moreover, they show some other deficiencies both in terms of performances and efficiency [6]. From the one hand, due to their broad scope, they constantly need to be updated in order to face the challenge of a quickly changing world of knowledge and, on the other hand, they lack in usability: teams or individual need a significant amount of time before mastering the software applications, while collaboration is improved just within a local, rather than global, perspective. Despite web-based systems partially compensate these lacks and widely diffused in the last decade, their use in supporting the early phases of product design is still limited.

Furthermore, enterprises can rely on tailored PDM systems, depending on the technical field of their products (e.g. Mechanics, Electronics, as well as Computer Science) [7], as it results by several efforts produced for determining what kind of modeling technique could provide the best benefits in each specific domain. Nevertheless, regardless the specific field of application, both those modeling domains converge towards the same objective: the definition of product/system requirements as the milestone for targeting the Product Development Process. According to this perspective, several similarities can be recognized between modeling techniques for software and physical products: systems, actors and use cases pertaining to the Unified Modeling Language well diffused for software, can be declined according to the exigencies of modeling artifacts, specifying, for example, what is their target of consumer, what purpose they have to fulfill and what characteristics should it have for satisfying both the objectives. Indeed, in [8] a recent and extensive contribution of PDM modeling based on UML is presented.

As said, current CAD systems focus on physical and geometrical modeling, resulting in an insufficient support for describing the abstract features that will drive the development of design choices. Indeed, such decisions are currently in charge of the designer: first, he/she must identify the main requirements to be fulfilled; then, what technical functions must be carried out and what principles should be used for such purposes; just finally, what are the geometrical characteristics of the embodiment capable to deliver the expected functionalities. In this context, the computer-aided analysis of requirements, their management and their elicitation represent a thriving field of research. The Computer-Aided Requirements Management (also presented as CARM) field partially addresses this issue. As a support for concurrent engineering, Fiksel and Hayes-Roth provided one of the first inputs within this domain [9]. They consider the chance of using dedicated ontologies for managing product requirements, even if their focus seems to be mainly on the definition of requirements for stakeholders within the Product Development Process. In [10] it is presented a method aiming at product definition by means of requirements satisfied by already existing artifacts and its potential evolution is taken into account by technological trends, product migration as well as competition. However, this approach cannot be considered completely systematic and, moreover, it narrows down the opportunity due to new demands that customers may express or recognize once a product has been launched in the market. With a different approach, Wang and Zeng present a prototype capable to propose questions to elicit product requirements from customersǐ answers [11]. It also organizes them in a graphical fashion for helping designers to elicit the customerǐs real intent and to collect complete product requirements. However, this system is just at a prototypal stage of development and, by authorsǐ admission, needs to be further tested and improved so that it is possible to proficiently use it in different contexts. Moreover, all these systems have never been integrated in the Computer-Aided perspective of Product Lifecycle management.

Recent demands for environmentally sustainable products become a pressing exigency for industries [12], thus new requirements appear as relevant within the design process. Most of the available techniques are aimed at evaluating the effect of geometrical modeling in terms of the environmental footprint of technical systems (e.g. according to their CO2 emission), in the framework of Life-Cycle Assessment [e.g.: 13]. However, the link between product model and the environmental requirements is just determined according to the Bill of Material, without providing any support to the design choices of conceptual and embodiment design stages that, in turn and as seen, dramatically affect product behavior through all its life-cycle.

For what concerns the conceptual and embodiment design stages, other authors proposed different product modeling techniques for easing the decision-making process in design, also trying to ingrate them into a broader context of PLM. Plenty of approaches are based on functional modeling: an exemplary application in this field is available in [14], where the modeling technique is aimed at linking together the functional (abstract) and geometrical (concrete) characteristics of a product as a means for managing product complexity at different level of description, thus focusing on design intent. Conversely, in [15] it is shown an opposite approach: functional modeling is integrated within a commercial CAD system with the objective of easing component trimming and the identification of existing conflict. This TRIZ-based approach represents an interesting example of integration of tools within the Product Lifecycle Management, but seems to be mostly tailored for already embodied systems and provides just small support for supporting the development of new concepts. Recent advancements in literature [16] present a software prototype whose architecture is based on System Modeling Language, a subset of the UML. The authors of this paper point out the importance of explicating the cause and effect models in product modeling as a means for managing their complexity and carrying out predictive analysis about product architecture. This kind of approach provides a viable direction of development towards the integration of Computer-Aided systems supporting the whole design process, since it allow to associate the impact of design variables on requirements, but the definition of product requirements is completely in charge of the designer and not supported at all.

Treasuring the relevant contributions in this field, this paper is aimed at showing some opportunities concerning the extension of CAD domain towards the preliminary phases of the Product Development Process. To this purpose, the next section presents the methodological framework that has been adopted as reference for the implementation of two different software prototypes aimed, respectively, at eliciting product requirements and mapping the cause and effect relationship between them and the design variables, with the purpose of driving the product feature definition in current CAD modelers. Section 3 briefly describes an exemplary application clarifying opportunities of integrations and finally the results of this research activity are discussed in order to highlight further development steps, shortcomings and expected potential.

2 DEVELOPMENT OF A COMPUTER-AIDED SYSTEM FOR EXTENDING THE DOMAIN OF CAD TOWARDS THE PRELIMINARY PHASES OF THE PRODUCT DEVELOPMENT PROCESS.

This section is subdivided into three parts. The first one depicts the profile of a new generation of CAD systems capable to fully support also the earliest stages of product development, according to the authorsÓ vision within the context described in the previous section. The combined use of two computer applications based on the proposed theoretical framework constitutes a preliminary support for designers, so that the CAD modeling task starts with an accurate description of the most relevant design parameters to cope with.

The following sub-section is dedicated to the definition of a standardized set of criteria for eliciting product requirements in terms of needed performance, capability to limit the emergence of harmful side effects and environmental impact (in terms of resources consumed by the system). It also presents opportunities of implementation in a computerized dialogue-based application assisting their definition. The last part introduces the theoretical framework for building a Computer Aided module for the management of system requirements and the definition of causal relationships with design parameters in a database-like structure. Such relationships are used as a basis for the construction of a complex network of conflicting requirements. The computer implementation of a decision-making algorithm for choosing the most relevant design problems within the network allow designer to prioritize strategies of intervention among conflicts for embodying a solution capable to satisfy as many requirements as possible, with the minimum number of conceptual iterations.

2.1 A Computer-Aided System for Supporting the Early Phases of the Product Development Process

The introduction of this paper has already highlighted that current CAD systems support the Product Development Process starting from the detailed modeling of system parts. However, several attempts tried to extend their capabilities so as to assist also the early phases of the design process. In this context, the definition of the profile of a comprehensive system aimed at filling the existing gaps in the computer domain is still missing, since the existing contributions just address specific stages of the whole activities that concur to the definition of detailed characteristics of products, being them shapes or materials.

A review of the state of the art of such systems highlights that a new generation of CAD tools with this objective must answer the following needs:

- Combine the competencies already available within an industry with knowledge acquired from different sources during the development of a product;
- Share information and knowledge among designers and design teams for

  - empowering concurrent engineering practices;
  - stimulating the extraction of tacit knowledge;
- Ease of updating the information retrieved during the whole process;
- Reduce the need of vocational activities for training potential users in the effective employment of software capabilities, increasing its ease of use with friendly interfaces;
- Allow the management of system complexity by
  - connecting different technical fields;
  - adopting a standardized modeling technique capable to fulfill multiple purposes and linking different layers of representation (from abstract to concrete);
- Have a systematic and holistic approach, so that it is possible to take into account all the demands emerging by different stakeholders involved in the design process, also introducing issues related to the smart and sustainable use of resources in order to reduce the environmental footprint of products;
- Establish a direct relationship between the goal of a product and, in detail, its requirements with system variables as a means for driving design choice, being them related to re-embodiment of existing products or to new projects from scratch.

On the one hand, modeling and simulations should continue relying on the increasing computational capabilities that are actually available just for powerful workstations or cluster computers. On the other hand, great emphasis needs to be placed on a more natural way the user currently manages and interprets information and data, also exploiting at the maximum extent both written and pictorial descriptions. Thus, it is possible to actually support the design process by exploiting individual0s cognitive potential, rather than strictly automatize the design process by constraining the reflections of designers. In other words, the expected CAD evolution should focus on the guidance and support of users along the design process by introducing new elements triggering the definition of creative solution concept, releasing the designer from time-consuming activities merely concerning computation.

The authors have developed two software prototypes to demonstrate that the theoretical advancement of knowledge in the field of inventive design allow to practically implement the above-described profile. In fact, they embed the theoretical frameworks that will be presented in the following sub-sections 2.2 and 2.3.

In detail, the introduction of a natural language questioning procedure for eliciting product requirements allow to query different designer sharing personal perspectives about the development of a same products. Thus, their tacit knowledge can be organized into a systematic and holistic set of measurable product requirements that ranges from performances to the prevention of undesired side effects, with a dedicated definition of needed resources potentially affecting both user acceptance and the environmental impact.

The introduction of a platform for managing such requirements together with system variables also allows to systematically determine causal relationships and potential design conflicts that can be easily updated after each conceptual or structural redefinition of product features. Moreover, the cause-and-effect modeling exploits at the maximum extent available knowledge and, on the other hand, points out existing gaps to be plugged. At last, the adoption of parameters as modeling technique allows to overcome the existing limits concerning traditional functional modeling (e.g. the already mentioned introduction of resources consumption in the same framework of performances and presence of side effects).

2.2 A Proposal for the Implementation of a Computer-Aided Requirement Elicitation System

As presented in the introduction, the early phases of the Product Development Process start with the analysis of system requirements. TRIZ [17], the Russian acronym for the Theory of Inventive Problem Solving, is based on the analysis of a huge amount of existing technical solution retrieved through patent databases. On this basis, the first of its postulates claims that technical systems evolve according to repeatable patterns, i.e. evolutionary laws according to TRIZ terminology. The fourth law of evolution is the so-called òLaw of the degree of ideality increaseó. It states that technical systems evolve towards the improvement of useful functions, the elimination of harmful undesired functions and the reduction of the resources it consumes, ideally tending towards a system that deliver the required function without physically existing. Thus, the adoption of an ideality-based classification system for system requirements represents a chance for introducing both the functional and the environment-oriented perspective within the same framework. According to a classification organized in Useful Functions, Harmful Functions and Resources Consumptions, the authors have already proposed a set of detailed criteria for a systematic and comprehensive description of system requirements. It is worth mentioning that an overall perspective on the product lifecycle can be obtained if different stakeholders take part in criteria examination for determining specific system requirements. Before describing them it is useful to share a common view on some involved concepts:

- a product/technical system, also called just òsystemó, is designed to satisfy one or more needs;
- the functions it carries out wholly or partially contribute to the satisfaction of that needs;
- each function can be modeled as an action aimed at modifying materials, energy or signals;
- what gets modified by the function is called òobjectó; moreover
- all these elements are part of an environment.

A brief description of the criteria follows; methodological details about their conceptual definition, together with results obtained through their use in industries, are available in [18]. The relative importance of the following requirements, while comparing different technical systems, can be weighted through target need characteristics:

- Popularity of the need: relates to the potential share interested in the fulfilling of the demand (e.g.: what part of the population express the demand of having clean clothes);
- Urgency of the need: more unavoidable is the request of fulfilling the demand, greater is the urgency level (e.g.: how essential is the need of wearing clean clothes);

Useful Functions related requirements (namely, performances) can be further classified according to 4 sub-categories (as depicted in Figure 1): Threshold achievement, Adaptability, Sensitivity to external environment, Controllability. The following list summarizes their overall abstract characteristics with brief examples, where relevant, in the field of clothes cleaning:

- Threshold achievement;
    - Quantity of the object: what is the load capability of the technical system (e.g.: how many clothes a washing machine can treat within a washing cycle);
    - Quality of the object: how well a technical system delivers its function (e.g.: how many residual stains, odors, pathogens are still present on clothes after a washing cycle);
- Adaptability;
    - Versatility: capability to carry out the function on different objects, producing outputs of standard quantity/quality (e.g.: capability to wash diverse kind of textiles);
    - Robustness: capability to carry out the function with input objects with varying characteristics, producing outputs of standard quantity/quality. (e.g.: capability to treat clothes with high variability of textiles characteristics, producing the same output in terms of cleanness);
- Sensitivity (to external condition);

  - Affecting object quantity: how much environment changes affect òquantity of the objectó (e.g.: not relevant in the field of cleaning clothes);
  - Affecting object quality: how much environment changes affect òquality of the objectó (e.g.: capability to keep the value of washing temperature regardless external conditions);
- Controllability;
  - Quantity: capability to regulate system characteristics to carry out the function on variable amount of objects (e.g.: capability to carry out a washing cycle with full or half load);
  - Quality: capability to regulate system characteristics in order to produce a particular result (e.g.: presence of variable spinning speed rate).

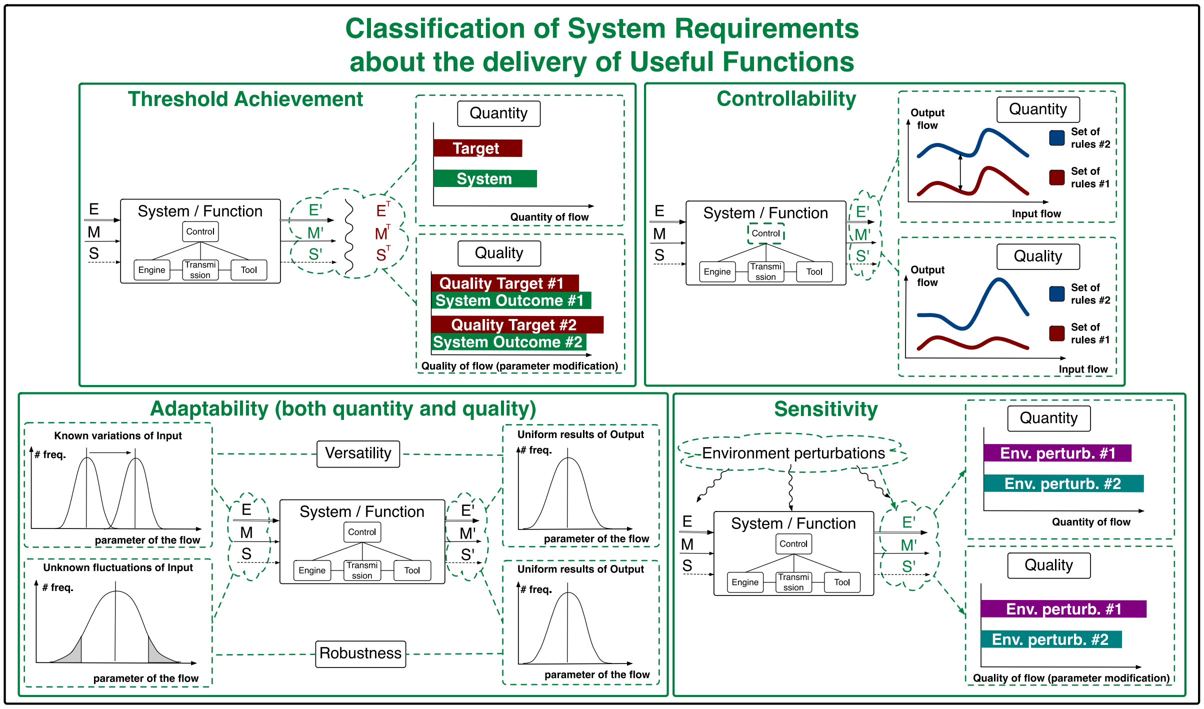


Fig. 1: Graphical representation of the requirements pertaining to system performances. The capability of carrying out Useful Functions is described by means of Pahl & Beitzõs EMS model [19] and by the Minimal Technical System model of TRIZ [17].

The Target Need Characteristics does not exactly represent a class of requirements. However, its definition and assessment allow to determine priorities between the different functions that the technical system performs. Moreover, the above-mentioned examples just represent a small set of requirements that can be elicited by means of the criteria. Their systematic use may lead to a wider definition of requirements: e.g. controllability in terms of quality in a washing machine may refer also to the capability of reducing the number of spinning sub-cycles as well as the possible selection of a prewash cycle.

Criteria pertaining the presence of Harmful Functions are aimed at determining system characteristics in terms of preventive requirements, designing the system in order to avoid the appearance of undesired harmful effects. Such criteria take into consideration, at an abstract level, all the potential interactions that may occur within the system and between the system and its surroundings, meaning the object of the function and the environment, as depicted in Figure 2.

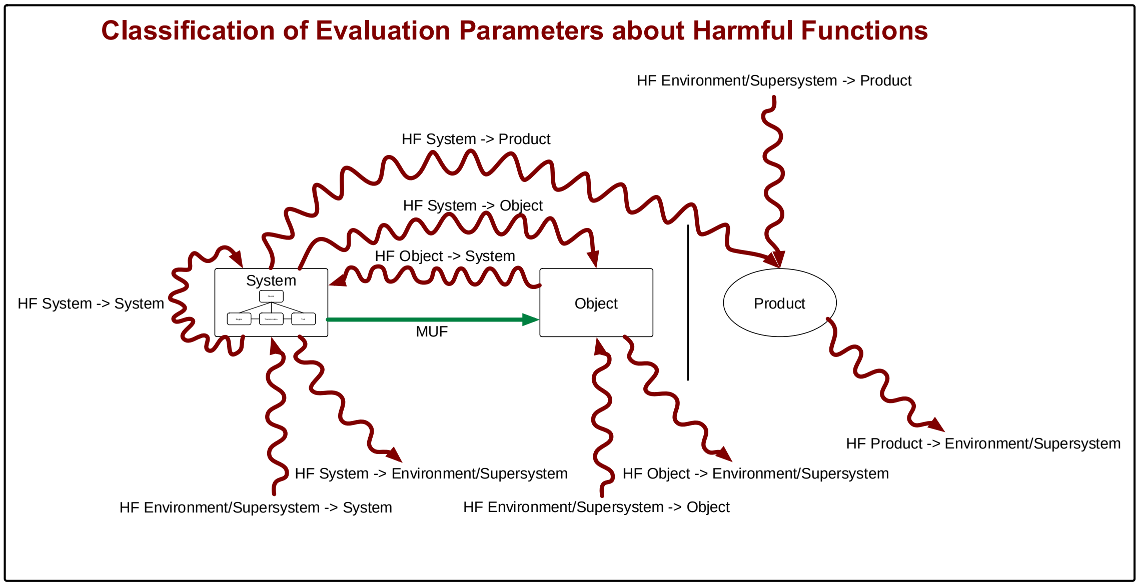

Classification of Evaluation Parameters about Harmful Functions
HF Environment/Supersystem -> Product
HF System -> Product
HF System -> Object
HF Object -> System
System
HF System -> System
Object
Product
MUF
HF Product -> Environment/Supersystem
HF System -> Environment/Supersystem
HF Object -> Environment/Supersystem
HF Environment/Supersystem -> System
HF Environment/Supersystem -> Object

Fig. 2: Graphical representation of the Harmful Functions which might jeopardize the ideality of a technical system and can be used as a reference to identify system requirements.

The following list summarizes a list of criteria that classify the most common undesired effects to be prevented; examples in the field of clothes cleaning are presented where relevant:

- Side effects the system causes on object;
  - Object integrity: effects compromising the object, fatally spoiling the results of working operations (e.g.: the drum spoiling clothes or color contamination between clothes);
  - Object wastes: effects causing an incomplete object modification into the desired result (not relevant for clothes, but common in metalworking operations: debris, wastes)
- Side effects the environment causes on the object;
  - Sensitivity to external conditions: side effects due to the environment, but concerning different characteristics than the ones modified by the useful function;
- Side effects the object causes on the system;
  - Mechanical resistance: side effects due to the poor capability of bearing loads due to counter-actions of the objects against system parts (e.g.: resistance of drum dumpers);
  - Wear resistance: side effects due to the physical contact between the system, or part of it, and the object: (e.g.: resistance of the drum bearings);
- Side effects the system causes on itself;
  - Reliability: side effects caused by failures of the system, but not to be intended as the amount of time to fix it (e.g.: the importance of a non-working detergent dispenser);
  - Expected life of the system: meaning the capability of the system to keep its integrity and working capabilities (e.g.: duration of the whole appliance);
- Side effects the environment causes on the system;
  - Corrosion resistance: side effects due to the presence of agents altering the chemical composition of the technical system parts;

    - Resistance to other critical external conditions: side effects pertaining to spoiling mechanisms not previously examined;
- Side effects the system causes on environment:
    - Noise production: side effects due to acoustic emission, with detailed focus on undesired frequencies (e.g. presence of noise during water removal by spinning);
    - Heat released: side effects contributing to the global warming phenomenon (e.g.: heat discharged with water drained by spinning);
    - Environment pollution: side effects due to each polluting agent of the system causing potential harm for the environment (e.g.: the effect of wastewaters on streamlines);
    - User safety: side effect the system may cause its user, if any (e.g.: potential harmfulness of the glass window in the washing machine door because of its temperature);
    - Comfort and ergonomics: effects resulting in pain for the body or long-term illnesses due to wrong postures (e.g.: comfort for loading, impose uncomfortable postures to users);
- Side effects the object causes on environment;
    - Pollution of object wastes: side effects due to object wastes causing potential harm for the environment (e.g.: presence in drained water of small plastic/metallic pieces torn away from clothes during spinning).

Finally, Resource Consumptions related criteria are aimed at eliciting requirements in different instants of the product lifecycle, starting from the manufacturing phase to product dismissal. Five classes detail these criteria: resources of Space, Time, Information, Material and Energy. The following list describes common, often self-explicative, examples of consumed resources; details in the field of clothes cleaning by washing machines are provided when significant.

- Space;
    - Accessibility: quantity of space the user needs for interacting with the systems (e.g.: space required for loading clothes in the washing machine);
    - Encumbrance/room required: the space occupied by the simple presence of the system (e.g.: room taken up by the appliance);
    - Storability: the amount of space necessary for stocking the product before their late use;
    - Space required for installation, dismantling, etc.: amount of space needed for carrying out specific lifecycle phases (e.g.: room for connecting/disconnecting the washing machine to/from power grid and water pipes);
- Time;
    - Quickness in carrying out the function: the amount of time the system needs for obtaining a desired functional result (e.g.: duration of a washing cycle);
    - Iterations for obtaining the desired result from the object: amount of processing phases the system need for obtaining a desired result (e.g.: number of rinsing cycles);
    - Time for assembly, dismantling, maintenance etc.: amount of time needed for carrying out specific lifecycle phases (e.g.: duration of connecting/disconnecting operations);
    - Availability: time to be waited before the system is ready to deliver its function (e.g.: time required to heat washing water to the desired level);
- Information;
    - User awareness: amount of information the user should posses for proficiently employing the system (e.g.: user awareness in choosing the right washing cycle);
    - Ease of use, installation, disassembly, upgradability, maintenance, etc.: information needed for carrying out specific lifecycle phases;
    - Complexity: intended as the variety of system parts and their mutual connection;
- Material;

    - Portability: capability, different from encumbrance, to easily move the technical system (e.g.: the weight of the appliance);
    - Required consumable/disposable material: amount of disposable material for carrying out the function (e.g.: amount of detergent required for washing);
    - Independence from other products: capability to work without additional materials to be treated by auxiliary functions (e.g.: need of using a detergent or a fabric conditioner);
    - Reusability of items: capability to work with already used items (e.g. capability to reuse cleaning agents, as with the Xeros ltd. washing machine);
    - Recyclability/Reusability of the whole system: capability to reuse or reprocess the whole system);
- Energy;
    - Energy required for working: overall amount of energy needed to carry out the function (e.g. energy needed for a washing cycle);
    - Dependency on a given energy type: different types of energy required for a washing cycle (e.g.: capability to use hot water through solar panels or boiler rather than ohmic heaters);
    - Number of energy transformation: determining the need of converting energy within the system;
    - Efficiency: ratio between used energy and obtained benefits;
    - Number of workers: the amount of manpower required within different phases of product lifecycles.

The elicitation of these requirements represents a time consuming activity: designers must correctly reflect upon a great number of potential system characteristics. It has been proved that a technical expert analyzes the main function of a product in the above-proposed terms, without considering the interactions between system components, in about 3 to 4 hours. Several improvements have been obtained by means of the introduction of Question and Answer (Q&A) techniques. Methodological facilitators obtain timesaving of more than 50% by asking questions about requirements [18], while software prototypes embedding these techniques allow an easier extraction and management [11]. Therefore, it is proposed to integrate this set of criteria within a Computer-Aided framework, using a dialectical Human-Computer Interaction capable to simplify the task and lighten the workload in charge of experts. Moreover, the authors have already experienced the use of dialogue-based framework within the early phase of the Product Development Process. The result they obtained so far [20], demonstrate that this is a promising research field to be extended to other domains of the Product Lifecycle Management, since the employment of Q&A techniques improve software usability and ease the definition of problem models especially in those who have not a dedicated background.

Nowadays, the implementation of the questioning procedure for eliciting product requirement is at a prototypal stage; however, the initial guidelines driving its development are quite clear and first tests on the field are necessary to prove the effectiveness of the questioning sequence. The software application aims at determining the main elements composing the abstract model of the technical system, identifying those elements presented before the description of criteria. Therefore, before the inspection of the criteria for eliciting system requirements, the user is supported in the identification of which features of the object should be changed in order to satisfy the original demands. An exemplary application of the software prototype is presented in Section 3, with the purpose of showing just how it could be integrated into a PLM system, since the number of tests conducted so far does not allow an extensive validation.

2.3 A Proposal for Mapping the Effect of Design Variables on System Requirements

The design of current products, as mentioned in the introduction, requires to fulfill a broad set of requirements at a time. Some authors claim that inventive problem solving methods are useful and efficient during the early phases of the design process, even if their limited capabilities to work on a greater number of requirements confine them to just an assisting role. Indeed, it is almost impossible to control all the contradictions, namely pairs of conflicting requirements, and constraints among them. Facing this kind of problems, the above approaches almost reach their limit [21]. Indeed, the traditional TRIZ instruments for non-routine design problems allow to work on a contradiction at a time, with the purpose of satisfying both the requirements by redesigning the product. In this regard, OTSM-TRIZ [22] brings significant advancements. By means of a more robust formalization of TRIZ concepts, it tries to enrich the TRIZ body of knowledge with new instruments and techniques capable to manage networks of problems, of conflicting requirements and of design variables, within the scope of the so-called Problem Flow Network (PFN) approach.

For what concern the purpose of this paper, Network of Contradictions (NoC) and Network of Parameters (NoPa) are the two key instruments capable to hierarchically and causally manage the relationship between their nodes: Evaluation Parameters (e.g.: system requirements) and Control Parameters (e.g.: design variables). Before describing them, it is worth to share a common vision on two models on which the two networks are grounded. The Element-Name-Value (ENV) model of OTSM-TRIZ enables to describe them by specifying the Name of the parameter, its Value and the Element it belongs to, thus creating a link from the abstract representation to the physical embodiment. According to this coding scheme, the OTSM-TRIZ model of contradiction, depicted in Figure 3, combines two different typical TRIZ concepts: Physical Contradiction (namely a conflict between the opposite values a design variable should assume, also expressed as PhC) and Technical Contradiction (the above mentioned two conflicting requirements, also expressed as TC). It also represent the cause and effect relationship between a design variable (the Control Parameter - CP) and two conflicting requirements (the Evaluation Parameters - EP) with the following pattern: *<Control Parameter> of <Element X> should assume <Value 1> in order to improve <Evaluation Parameter 1> of <Element Y>, but then <Evaluation Parameter 2> of <Element Z> worsens; <Control Parameter> of <Element X> should assume <Value 2> (with <Value 2> ≠ <Value 1>) in order to improve <Evaluation Parameter 2> of <Element Z>, but then <Evaluation Parameter 1> of <Element Y> worsens.*

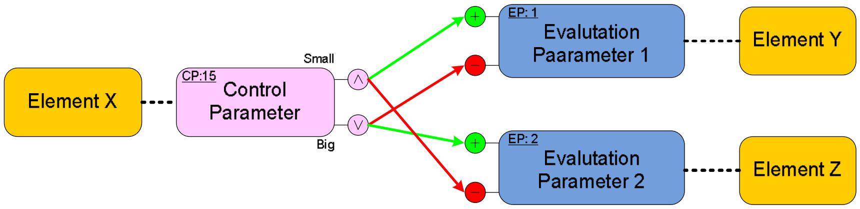


Fig. 3: A contradiction expressed by the ENV Model according to OTSM-TRIZ. The left side of the figure represents a Physical Contradiction, the right side represent the Technical Contradiction.

The systematic analysis of conflicting requirements is a tough task, and the definition of priorities during the conceptual and the embodiment design phase are completely in charge of designers that can just rely on few instruments supporting decision-making. In this regard, the Network of Contradictions and the Network of Parameters enable to consider with a comprehensive perspective how design choices may impact on system requirements. However, their construction and analysis are also hard activities. The authors elaborated a procedure suitable to carry out these tasks with the support of a Computer-Aided tool capable to map system requirements, design variables and their cause and effect relationship according to the above modeling schemes, thus building both kind of networks. Moreover, a specific metric for describing both Evaluation and Control Parameters supports the designer in network analysis, with the purpose of setting priorities in embodiment/re-embodiment design phases with the ultimate goal of increasing the efficiency of the whole Product Development Process, reducing onerous iterations and speeding up time-to-market. Extended details about the use of the software, including the embedded algorithm, are available in [23].

The introduction of design variables and system requirements, as well as the definition of their relationships, is assisted by a Graphical User Interface, presented in Section 3, that supports their organization according to a metrics based on both textual and numerical values:

- EP type: expresses a link to the classification in Useful Functions, Harmful Functions and Resources Consumptions as presented in paragraph 2.2;
- EP relevance (R_{EP}): describes the importance of the system requirement. The higher is the value of EP relevance (1÷3), the bigger is its relevance for the purposes of the design process;
- CP resource: specify what is the kind of resource (among Space, Time, Information, Material and Energy) that characterizes a design variable;
- CP cost: this value takes into account the economic expenses (e.g.: 3 relates to high costs, 1 to low costs) required to change a design variable with a new one having better capabilities to influence a system requirement;
- Impact (i_{CPvsEP}): assesses the impact, ranging from 0 (poor) to 2 (strong), a design variable has on a system requirement. Value are assigned just when a cause and effect relationship exists;
- Cause/Effect relationship (C/E_{typ}): a qualitative index considering direct (+1) or inverse (-1) cause and effect relationship between a design variable and a system requirement, as depicted in Figure 4.

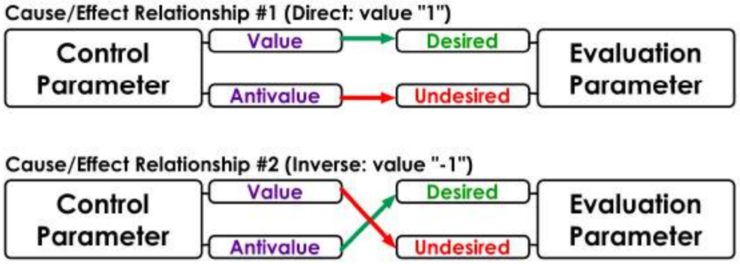


Fig. 4: Direct (above) and inverse (below) cause and effect relationship.

Once individuals or team of designers complete the definition of system requirements, design variables and their cause and effect relationship, the Computer-Aided system automatically builds the networks and calculate a set of specific values according to their structures, substantially weighing them. Table 1 presents the mentioned set of values:

Index	*Value/Meaning*	*Index*	*Value/Meaning*
TC relevance	$TC_{rel} = \sum_{i=1}^{2} R_{EP_i} = R_{EP_1} + R_{EP_2}$	CP overall impact	$CP_{k_{ov.imp}} = \sum_{j=1}^{CP_{k_{freqNoPa}}} i_{CP_k vsEP_j}$

TC overall Index	$TC_{ov.idx} = \sum_{k=1}^{2} R_{EP_k} \cdot i_{CPvsEP_k} =$ $= (R_{EP_1} \cdot i_{CPvsEP_1} + R_{EP_2} \cdot i_{CPvsEP_2})$	EP sensitivity	$EP_{j_{ov.imp}} = \sum_{k=1}^{EPj_{freqNoPa}} i_{CP_k vsEP_j}$
CP (EP) frequency in the NoC	$CP_{freq_{NoC}}$ or $EP_{freq_{NoC}}$ = Quantity of TCs of the NoC where the CP (or the EP) is involved.	ARIZ step 1.4	$ARIZ_{step-1.4}\left(CP_k\right) = \\ = \frac{\sum_{j=1}^{CP_{k_{freqNoPa}}} i_{CP_k vsEP_j} \cdot \left(C/E_{typ}\right)_{kj}}{CP_{k_{freqNoPa}}}$
CP (EP) frequency in the NoPa	$CP_{freq_{NoPa}}$ or $EP_{freq_{NoPa}}$ = Quantity of TCs of the NoPa where the CP (or the EP) is involved.		

Tab. 1: Resume of indexes and their meaning as calculated by the Computer-Aided system.

ARIZ, Russian acronym for the Algorithm of Inventive Problem Solving, is a step-by-step procedure that guides designers through the use of TRIZ instruments with the goal of satisfying two conflicting requirements. With reference to Figure 2 and the above reported definition of OTSM-TRIZ contradiction, its step 1.4 asks the designer to choose between one of the two qualitative or quantitative values of the Control Parameter, thus selecting the perspective for coping with the problem. This index, as explained in the followings, supports the decision of the step 1.4 between a wider set of parameters rather than the two usually considered in the problem solving process driven by ARIZ. Therefore, the index named òARIZ step 1.4ó, whose value ranges from -1 to 1, represents the main driver for decision-making during the embodiment design stage. The following description specifies how its value guides the designer for embodying a conceptual solution.

A dedicated algorithm eases their analysis and assists the user in selecting the most critical design parameters to focus on during the embodiment of a conceptual solution. The workflow of the algorithm is presented in Figure 5; its two branches are addressed, on the one hand, at the embodiment of concepts from scratch and, on the other hand, at the re-embodiment of existing systems. In details, the algorithm manages the complexity of both networks by considering them as a whole and, at the same time, as single pairs of design variables and system requirements as well as contradictions as depicted in Figure 2. The following steps details the content of Figure 4:

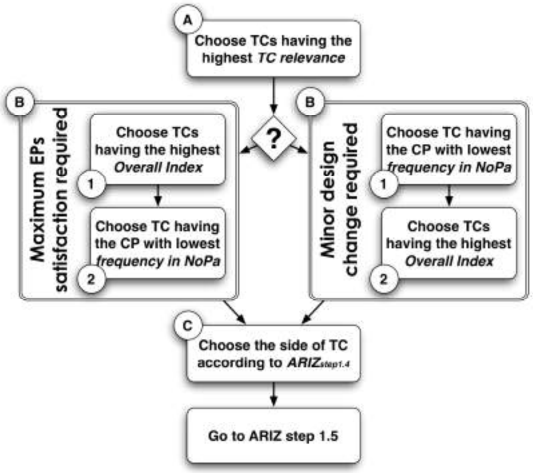

A
Choose TCs having the highest TC relevance
?
B
Maximum EPs satisfaction required
Choose TCs having the highest Overall Index
1
Choose TC having the CP with lowest frequency in NoPa
2
B
Minor design change required
Choose TC having the CP with lowest frequency in NoPa
1
Choose TCs having the highest Overall Index
2
C
Choose the side of TC according to ARIZstep1.4
Go to ARIZ step 1.5

Fig. 5: Algorithm for selecting the most critical design problems and the related design variables for the embodiment of a conceptual solution.

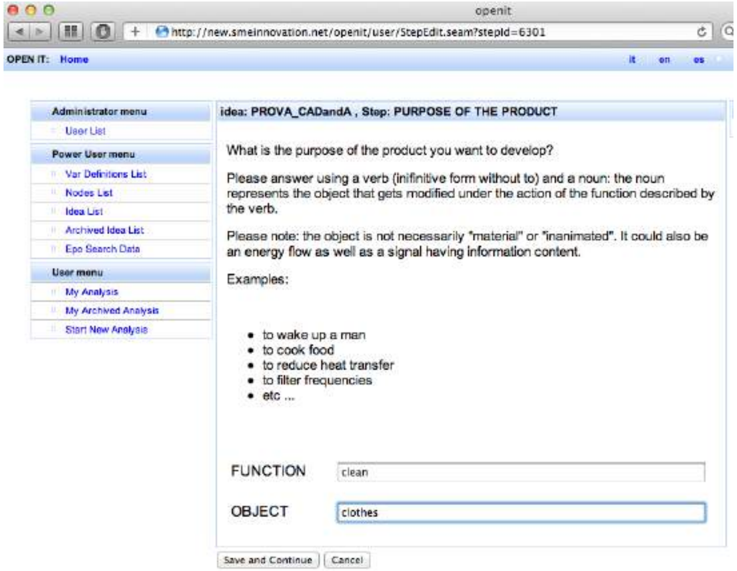
1. Choose, among the Network of Contradiction, a subset of nodes collecting the more critical system requirements for product development (Criterion A).
2. Examine the subset (Meta-criterion B).
    - In case of product embodiment from scratch, first it is necessary to keep just couples of conflicting requirements having the highest òTC overall indexó (Criterion B1) and, subsequently, choose the couple of system requirements characterized by the design variable (CP) less connected to other system requirements in the Network of Parameters (Criterion B2).
    - Whenever the Product Development Process should be carried out on an existing product and just minor modifications are necessary, the above-mentioned criteria must be taken into account in inverse order.
3. For the selected OTSM-TRIZ contradiction model, define the value of its design variable proving the best outcomes for the whole interested set of system requirements in the Network of Parameters and whose modification generates minimal side effects:
    - when òARIZ step 1.4 indexó approaches 1 the design variable must assume òValue 1ó;
    - when òARIZ step 1.4 indexó approaches -1 the design variable must assume òValue 2ó.

3 EXEMPLARY APPLICATION OF AN INTEGRATED COMPUTER-AIDED SYSTEM FOR SUPPORTING THE EARLY PHASES OF THE PRODUCT DEVELOPMENT PROCESS

The purpose of this section is to show how the combined use of the two prototypal versions of software applications can provide a valuable support within the early stages of the development process by driving the designer towards a robust definition of product characteristics to be modeled in a 3D environment. An exemplary and combined application in the field of domestic washing machines is presented.

Before approaching the design stages of the Product Development Process, system requirement should be systematically formulated, trying to be as exhaustive as possible. This stage is supported by a Computer-Aided module based on a web application. The prototype is structured in a dialogue-based algorithm that asks the user a set of questions. The web application enables different members of the design team to carry out, individually or in groups, this exploration. Thus, it is possible to retrieve elements of knowledge from an extended audience with the purpose of exploiting all the available information resources within an enterprise. As depicted in Figure 6, the questioning sequence starts with a question in natural language aimed at clarifying the purpose of the product to be designed. Each answer provided by the user is collected by the system in a repository of variables having a double goal: on the one hand, such variables can be reused along the analysis for contextualizing the Human-Computer Interaction during the questioning sequence; on the other hand, the repository can be neatly organized and easily accessed to obtain a list of requirements for a subsequent processing. Figure 7 and Figure 8 shows two examples of questions aimed at exploring the existence of requirements according to the criteria proposed in section 2.2.

Once the designer completes the analysis by means of the Computer-Aided Requirements Elicitation module, the set of recorded variables can be transferred to a second module aimed at determining their causal dependence on design variables. Such software application enables to organize the set of system requirements according to the metrics presented in Section 2.3. Figure 9 shows the Graphical User Interface of the software prototype supporting the input of the additional parameters related to System requirements.



idea: PROVA_CADandA , Step: PURPOSE OF THE PRODUCT

What is the purpose of the product you want to develop?

Please answer using a verb (inifinitive form without to) and a noun: the noun represents the object that gets modified under the action of the function described by the verb.

Please note: the object is not necessarily "material" or "inanimated". It could also be an energy flow as well as a signal having information content.

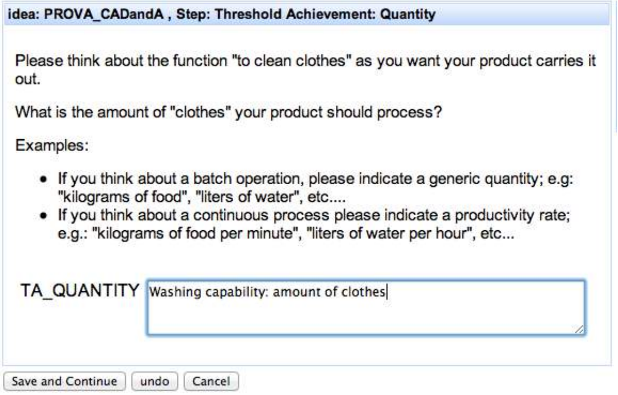
Examples:

- to wake up a man
- to cook food
- to reduce heat transfer
- to filter frequencies
- etc ...

FUNCTION clean

OBJECT clothes

Fig. 6: The initial question of the Computer-Aided system for eliciting system requirements from experts.



idea: PROVA_CADandA , Step: Threshold Achievement: Quantity

Please think about the function "to clean clothes" as you want your product carries it out.

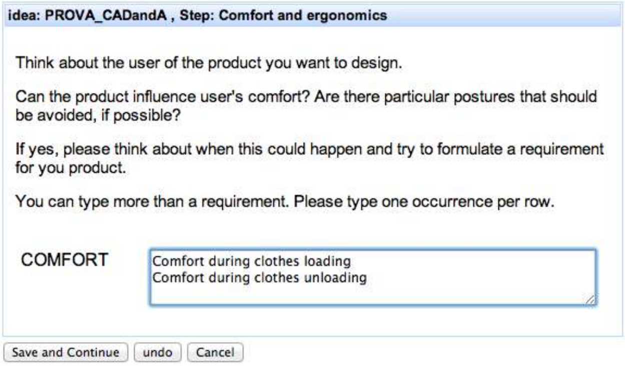
What is the amount of "clothes" your product should process?

Examples:

- If you think about a batch operation, please indicate a generic quantity; e.g: "kilograms of food", "liters of water", etc....
- If you think about a continuous process please indicate a productivity rate; e.g.: "kilograms of food per minute", "liters of water per hour", etc...

TA_QUANTITY Washing capability: amount of clothes

Fig. 7: Question aimed at determining what are the quantitative expected capabilities of the system in carrying out its function.



idea: PROVA_CADandA , Step: Comfort and ergonomics

Think about the user of the product you want to design.

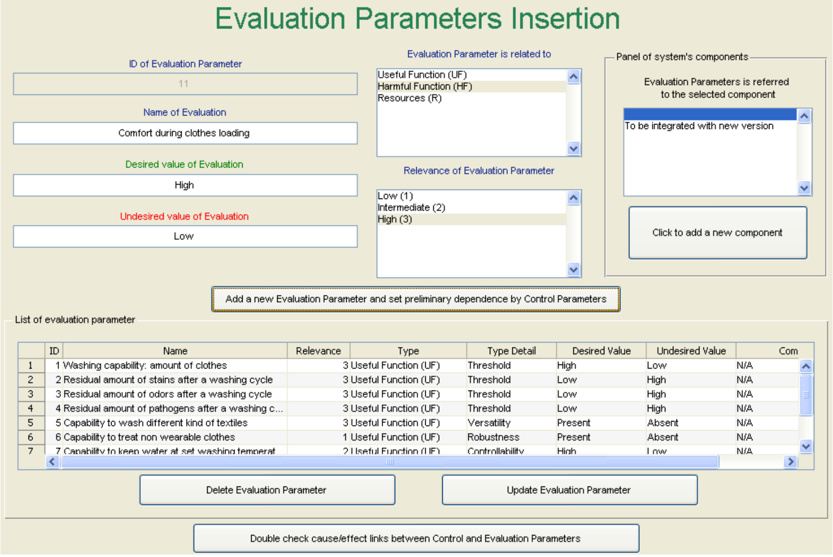
Can the product influence user's comfort? Are there particular postures that should be avoided, if possible?

If yes, please think about when this could happen and try to formulate a requirement for you product.

You can type more than a requirement. Please type one occurrence per row.

COMFORT Comfort during clothes loading
Comfort during clothes unloading

Fig. 8: Question examining potential requirements pertaining usersõ comfort, with the purpose of developing a system having good ergonomic capabilities.


Evaluation Parameters Insertion
Panel of system's components
Evaluation Parameters is referred to the selected component
Click to add a new component
Add a new Evaluation Parameter and set preliminary dependence by Control Parameters
Delete Evaluation Parameter
Update Evaluation Parameter
Double check cause/effect links between Control and Evaluation Parameters

ID of Evaluation Parameter: 11
Name of Evaluation: Comfort during clothes loading
Desired value of Evaluation: High
Undesired value of Evaluation: Low

Evaluation Parameter is related to:
Useful Function (UF)
Harmful Function (HF)
Resources (R)

Relevance of Evaluation Parameter:
Low (1)
Intermediate (2)
High (3)

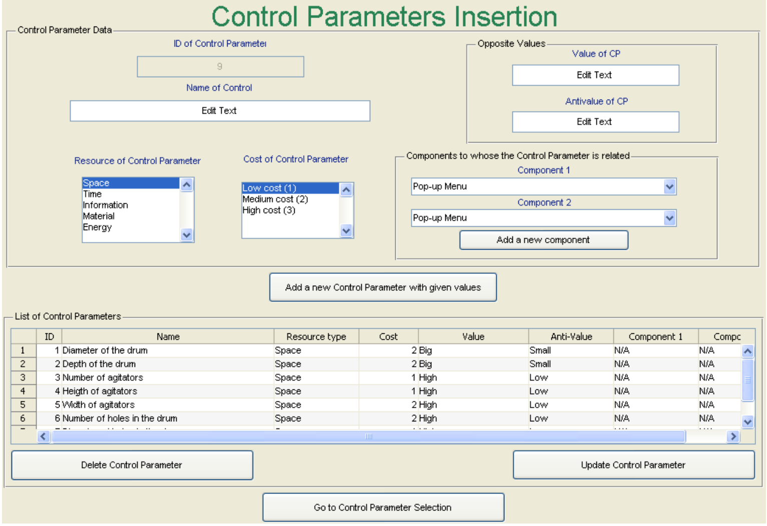
To be integrated with new version

List of evaluation parameter

	ID	Name	Relevance	Type	Type Detail	Desired Value	Undesired Value	Com
1	1	Washing capability: amount of clothes	3	Useful Function (UF)	Threshold	High	Low	N/A
2	2	Residual amount of stains after a washing cycle	3	Useful Function (UF)	Threshold	Low	High	N/A
3	3	Residual amount of odors after a washing cycle	3	Useful Function (UF)	Threshold	Low	High	N/A
4	4	Residual amount of pathogens after a washing c...	3	Useful Function (UF)	Threshold	Low	High	N/A
5	5	Capability to wash different kind of textiles	3	Useful Function (UF)	Versatility	Present	Absent	N/A
6	6	Capability to treat non wearable clothes	1	Useful Function (UF)	Robustness	Present	Absent	N/A
7	7	Capability to keep water at set washing temperat	2	Useful Function (UF)	Controllability	High	Low	N/A

Fig. 9: The GUI allows to set different characteristics pertaining to each system requirement.

After the insertion of each system requirement, the user has to clarify what design variables can fulfill it. A similar GUI enables their insertion and organization as in Figure 10:


Control Parameters Insertion
Control Parameter Data
Opposite Values
Components to whose the Control Parameter is related
Add a new component
Add a new Control Parameter with given values
Delete Control Parameter
Update Control Parameter
Go to Control Parameter Selection

ID of Control Parameter: 9
Name of Control: Edit Text
Value of CP: Edit Text
Antivalue of CP: Edit Text

Resource of Control Parameter:
Space
Time
Information
Material
Energy

Cost of Control Parameter:
Low cost (1)
Medium cost (2)
High cost (3)

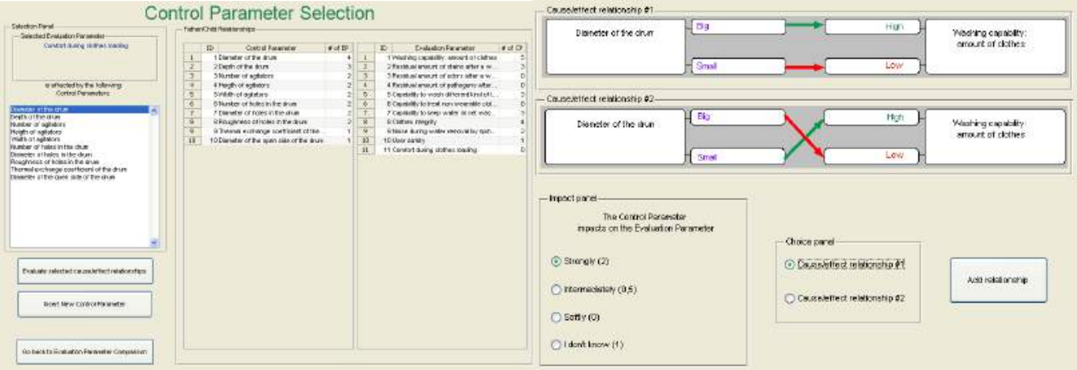
Component 1: Pop-up Menu
Component 2: Pop-up Menu

List of Control Parameters

	ID	Name	Resource type	Cost	Value	Anti-Value	Component 1	Compc
1	1	Diameter of the drum	Space	2	Big	Small	N/A	N/A
2	2	Depth of the drum	Space	2	Big	Small	N/A	N/A
3	3	Number of agitators	Space	1	High	Low	N/A	N/A
4	4	Heigth of agitators	Space	1	High	Low	N/A	N/A
5	5	Width of agitators	Space	2	High	Low	N/A	N/A
6	6	Number of holes in the drum	Space	2	High	Low	N/A	N/A

Fig. 10: The GUI for the insertion of design variables (above) and the spreadsheet summarizing their characteristics according to the metrics described in Section 2.3.

The cause and effect relationships between design variables and system parameters can be set downstream each insertion or at the end of the whole transcription of Evaluation Parameters and the identification of relevant Control Parameters. Figure 11 shows the GUI where the user can choose, among a list, the design variables affecting a system requirement.



Control Parameter Selection

Selection Panel

Selected Evaluation Parameter: Comfort during clothes loading

is affected by the following Control Parameters:

- Diameter of the drum
- Depth of the drum
- Number of agitators
- Heigth of agitators
- Width of agitators
- Number of holes in the drum
- Diameter of holes in the drum
- Roughness of holes in the drum
- Thermal exchange coefficient of the drum
- Diameter of the open side of the drum

Father/Child Relationships

	ID	Control Parameter	# of EP
1	1	Diameter of the drum	4
2	2	Depth of the drum	3
3	3	Number of agitators	2
4	4	Heigth of agitators	2
5	5	Width of agitators	2
6	6	Number of holes in the drum	2
7	7	Diameter of holes in the drum	2
8	8	Roughness of holes in the drum	2
9	9	Thermal exchange coefficient of the ...	1
10	10	Diameter of the open side of the drum	1

	ID	Evaluation Parameter	# of CP
1	1	Washing capability: amount of clothes	5
2	2	Residual amount of stains after a w...	3
3	3	Residual amount of odors after a w...	0
4	4	Residual amount of pathogens after...	0
5	5	Capability to wash different kind of t...	3
6	6	Capability to treat non wearable clot...	0
7	7	Capability to keep water at set valu...	3
8	8	Clothes integrity	4
9	9	Noise during water removal by spin...	2
10	10	User safety	1
11	11	Comfort during clothes loading	0

Cause/effect relationship #1: Diameter of the drum — Big → High; Small → Low — Washing capability: amount of clothes

Cause/effect relationship #2: Diameter of the drum — Big → Low; Small → High — Washing capability amount of clothes

Impact panel: The Control Parameter impacts on the Evaluation Parameter

● Strongly (2)
○ Intermediately (0,5)
○ Softly (0)
○ I don't know (1)

Choice panel:

● Cause/effect relationship #1
○ Cause/effect relationship #2

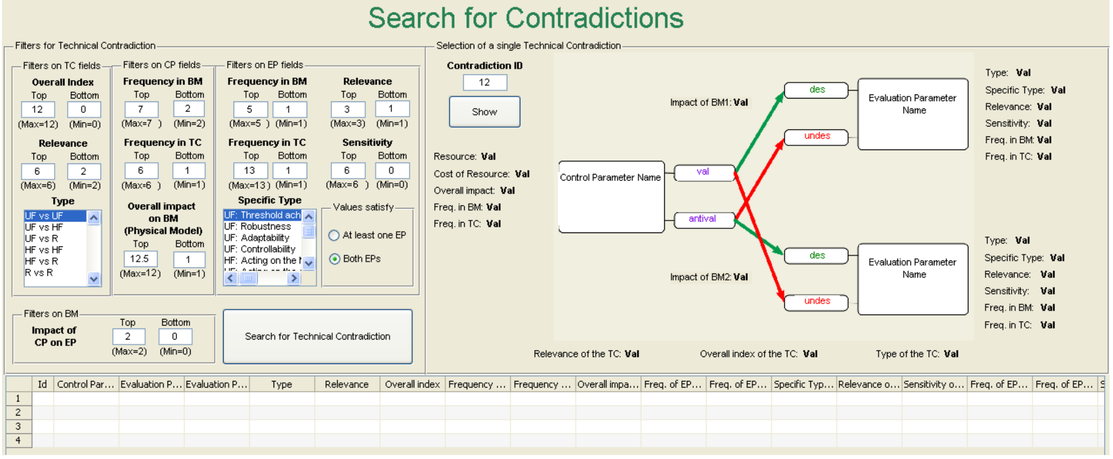
Evaluate selected cause/effect relationships
Insert New Control Parameter
Go back to Evaluation Parameter Comparison
Add relationship

Fig. 11: The GUI for the preliminary determination of cause and effect relationships (left).and for detailing the causal relationship between a design variable and a system requirement (right).

As soon as the designer completes the definition of cause and effect relationships, the Computer-Aided system can interpret data so that it is possible to automatically

- build a bipartite directed network whose nodes are Control and Evaluation Parameters constituting an equivalent representation of OTSM-TRIZ Network of Contradiction and of Network of Parameters; and
- weigh their links with the purpose of easing network analysis.

Figure 12 shows the GUI where OTSM-TRIZ contradictions can be filtered and examined with reference to the goal of the Product Development Process.



Search for Contradictions

Filters for Technical Contradiction

Filters on TC fields

- Overall Index: Top 12 (Max=12), Bottom 0 (Min=0)
- Relevance: Top 6 (Max=6), Bottom 2 (Min=2)
- Type: UF vs UF (selected), UF vs HF, UF vs R, HF vs HF, HF vs R, R vs R

Filters on CP fields

- Frequency in BM: Top 7 (Max=7), Bottom 2 (Min=2)
- Frequency in TC: Top 6 (Max=6), Bottom 1 (Min=1)
- Overall impact on BM (Physical Model): Top 12.5 (Max=12), Bottom 1 (Min=1)

Filters on EP fields

- Frequency in BM: Top 5 (Max=5), Bottom 1 (Min=1)
- Relevance: Top 3 (Max=3), Bottom 1 (Min=1)
- Frequency in TC: Top 13 (Max=13), Bottom 1 (Min=1)
- Sensitivity: Top 6 (Max=6), Bottom 0 (Min=0)
- Specific Type: UF: Threshold ach (selected), UF: Robustness, UF: Adaptability, UF: Controllability, HF: Acting on the I
- Values satisfy: ○ At least one EP ● Both EPs

Filters on BM

- Impact of CP on EP: Top 2 (Max=2), Bottom 0 (Min=0)

Selection of a single Technical Contradiction

Contradiction ID: 12

Resource: Val
Cost of Resource: Val
Overall impact: Val
Freq. in BM: Val
Freq. in TC: Val

Impact of BM1: Val
Impact of BM2: Val

Type: Val
Specific Type: Val
Relevance: Val
Sensitivity: Val
Freq. in BM: Val
Freq. in TC: Val

Type: Val
Specific Type: Val
Relevance: Val
Sensitivity: Val
Freq. in BM: Val
Freq. in TC: Val

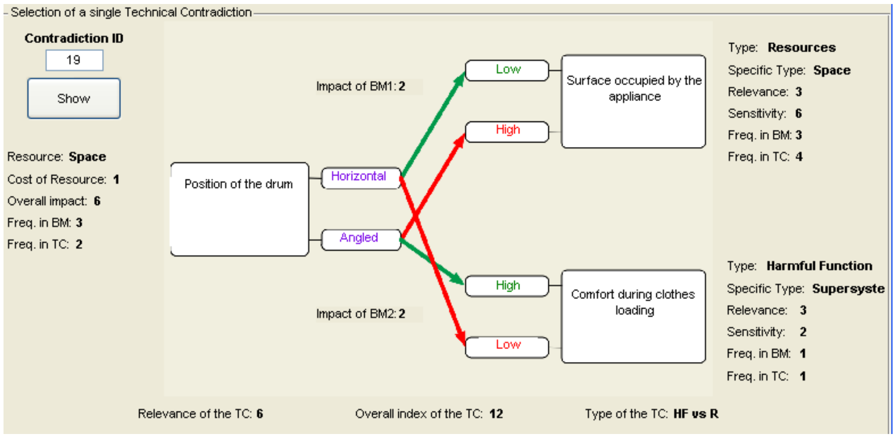
Relevance of the TC: Val
Overall index of the TC: Val
Type of the TC: Val

	Id	Control Par...	Evaluation P...	Evaluation P...	Type	Relevance	Overall index	Frequency ...	Frequency ...	Overall impa...	Freq. of EP...	Freq. of EP...	Specific Typ...	Relevance o...	Sensitivity o...	Freq. of EP...	Freq. of EP...	S
1																		
2																		
3																		
4																		

Show
Search for Technical Contradiction
Control Parameter Name
val
antival
des
undes
des
undes
Evaluation Parameter Name
Evaluation Parameter Name

Fig. 12: The GUI for the Network of Contradiction and the Network of Parameters analyses. On the top left side, the filters for selecting Elements according to the metrics described in Section 2.3. On the top right side, an interface for visualizing the characterizing element of an OTSM-TRIZ contradiction and, below, the spreadsheet collecting all the relevant data.

The application of the algorithm for selecting the most critical issues in the Product Development Process has been applied by inserting appropriate criteria in the related mask, highlighting main issues to be examined with priority. Figure 13 displays a contradiction as resulted from the analysis.



Selection of a single Technical Contradiction

Contradiction ID: 19

Show

Resource: **Space**
Cost of Resource: **1**
Overall impact: **6**
Freq. in BM: **3**
Freq. in TC: **2**

Impact of BM1: **2**
Impact of BM2: **2**

Type: **Resources**
Specific Type: **Space**
Relevance: **3**
Sensitivity: **6**
Freq. in BM: **3**
Freq. in TC: **4**

Type: **Harmful Function**
Specific Type: **Supersyste**
Relevance: **3**
Sensitivity: **2**
Freq. in BM: **1**
Freq. in TC: **1**

Relevance of the TC: **6** Overall index of the TC: **12** Type of the TC: **HF vs R**

Position of the drum
Horizontal
Angled
Low
High
Surface occupied by the appliance
High
Low
Comfort during clothes loading

Fig. 13: Excerpt of the GUI presented in Figure 11 showing the details of a critical contradiction among the network.

The selected OTSM-TRIZ contradiction shows that a horizontal position of the drum reduces room requirements, but worsens userõs comfort during loading/unloading. On the contrary an angled position of the drum axis improves userõs comfort, but the whole appliance occupies more room. The òARIZ step 1.4 indexó value for this contradiction is -0,6667, driving the user in an embodiment where the axis of the drum assumes the value òAngledó rather than òHorizontaló. Figure 14 shows the two alternatives within a 3D CAD modeling environment.

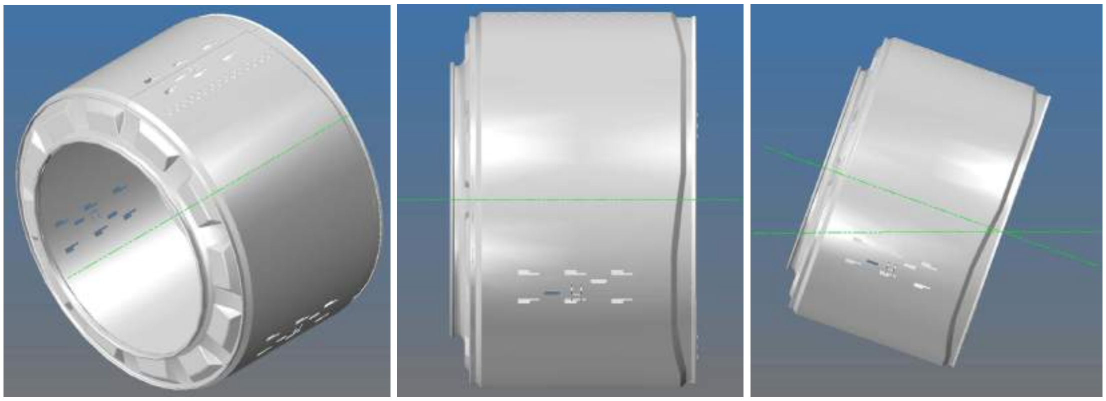


Fig. 14: From left to right. Views of the drum, axes in green: (a) ISO view; (b) side view, the symmetry axis is horizontal; (c) side view, the symmetry axis is angled upwards.

4 CONCLUSION

This article presents the preliminary results of a research aimed at bridging the CAD domain towards the early phases of the Product Development Process by managing product data. Two Computer-Aided modules have been integrated for such purposes. The first one is a dialogue-based system enabling the elicitation of system requirements from technical experts following a detailed set of standardized criteria. Its web-based implementation constitutes the basis for a potentially collaborative environment involving designers from the whole product lifecycle. The second software manages system requirements, design variables and their casual relationships with the purpose of building bipartite directed complex networks to be analyzed following the steps of an algorithm for improving the efficiency of the whole design process. The outcomes of such an analysis can guide the designers in the embodiment of a conceptual solution inside a 3D cad modeler.

Its promising results prelude to the integration of these two Computer-Aided modules in a unique software application to be embedded into a PLM system comprehending a 3D CAD Modeler and a CAE multiphysics simulator. Moreover, the introduction of backwards links from already existing results of smulation may enable to automatically carry out the definition of cause and effect relationships between design variables and system requirements, a task currently in charge of the designer.

Further test should be carried out on a wider number of test cases in order to measure the repeatability of the requirement elicitation questioning procedure and to assess the benefits of the proposed integrated system.

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