Domain Analysis with TRIZ to Define an Effective "Design for Excellence" Framework

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Abstract. Design for Excellence (DfEx) is the name given to an engineering process where a product is designed to meet a set of objective functions that cover its lifecycle. There are negative correlations between different objective functions in this set and issues related to technological complexity are added, since modern products typically fall into the category of smart connected mechatronic products. This context leads to complexity in terms of tackling the design process. Simultaneous engineering and PLM platforms can only partially handle such levels of complexity. To our knowledge, the subject of DfEx was treated in current researches from a limited perspective, which does not necessarily cover the complexity of the present-day context. In order to formulate a reliable DfEx framework, this research considers a strategy based on tools that manage in a systematic way the process of identifying the comprehensive set of barriers and conflicts that obstruct DfEx. This research highlights the level of complexity in setting up a reliable methodology to DfEx of modern, sophisticated mechatronic products. A set of guidelines to be placed at the foundation of an effective DfEx methodology is formulated with the support of TRIZ.

Keywords: Design for excellence · DfX · AFD · TRIZ · Systematic innovation · Open innovation · Design methodology

1 Introduction

Nowadays, most of the industrial sectors operate in a rapidly changing environment of demands, dictated by several factors such as the explosion of offers, the possibility for facile supply from any place in the world, easiness to inform, easiness for remote negotiation, an increasing number of educated consumers, facile access to competitive technologies for benchmarking, facile access to databases with inventions and innovations, plenty of data on the Internet in every business area, quite easy access to scientific publications, as well as fewer barriers to collaborate in open innovation value chain and supply chain networks.

In this global business landscape, customer expectations and requirements are significantly much higher than before. Markets become more and more volatile and technological progress forces producing companies to launch more sophisticated and customized

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product-service solutions [1]. The explosion of the Internet of Things (IoT) and controlling technologies with embedded software generate new streams of development and business models, such as product servitization [2], life-cycle approach in product design and development [3, 4] and smart connected products [5].

Having in mind the beforehand highlighted context, it is somehow obvious to think about how to handle such complex situations from an engineering perspective, especially for durable consumer products. In simple words, engineers are put in the position to design, in shorter and shorter periods of time, highly mature, novel, and sophisticated solutions to various market opportunities. Sophistication is dictated by a large pool of stakeholders, not only by end-users. Managers expect to launch products at high profits; thus, at low production costs and with many functionalities included. Marketing departments expect highly customized products for every market segment. Production engineers expect designs that are easy to manufacture and assemble, as well as to be robust to manufacturing tolerances. Product managers look for solutions that fall into lifecycle paradigms, including easy delivery, easy installation, easy servicing and easy withdraw, including efficient recycling and reuse. Customers expect solutions that operate at high efficiency, with low energy consumption, with low carbon emissions, with easy maintenance and high reliability, with high operational performances, with low operational costs, etc. Users want solutions that are ergonomic and intuitive, easy to set up (plug-and-play), with little effort involved to learn. Authorities ask for environmentally friendly products. And the list can continue.

The situation described in the previous paragraph invites engineers to look for new product design frameworks. Some 25+ years ago, when production was looking to automate manufacturing and assembly of products, the paradigm of design for an objective function (DfX) was born [6]. Since then, DfX has evolved only sectorial and horizontal, focusing on various areas of interest, such as eco-design, life-cycle cost, disassembly, quality, etc. [7]. Starting with the last decade, products have increased in sophistication and interdisciplinarity, embedding mechanics, software, hardware, control, and electronics.

Even if the complexity of the design settings has exponentially increased in the last years, engineering design approaches have remained weak in terms of comprehending all objective functions and tackling them in a concurrent (simultaneous) way. The popular design thinking models [8], collective creativity tools [9], agile design methodologies [10], and software platforms for product lifecycle management (PLM) [11] are still very far away from what it should be a truly concurrent design of lifecycle-driven mechatronic & IoT connected products. In other words, all the tools mentioned above act sectorial and in silos, not in an integrated manner. This does not mean they cannot be integrated, but integration is more than road-mapping sectorial tools; it is about aggregating them – and from this perspective, by our knowledge (based on online investigation of databases with scientific papers) the problem is still unsolved.

In this current situation, the present research paper investigates the way of profiling a more powerful and effective framework to tackle engineering design from a DfEx perspective. Power and effectiveness in this context are referring on one side to the capacity of simultaneously comprehending as many as possible objective-functions in the concurrent design process, and on the other side to the capacity to solve without compromises all conflicts that might occur between various objective functions (e.g., low cost versus high reliability, easy to disassembly versus functional sophistication).

The paper continues with a brief introduction to DfEx paradigm and the state-of-the-art in the development and use of this paradigm. Afterward, the methodological toolbox for investigating the problem is introduced. An important conclusion will be that the engineering design process falls into the concept of complex systems (meaning that small deviations of some inputs lead to significant transformations of the output - i.e., the designed solution). From this perspective, the conceptualization of the DfEx framework must be aligned with the principles that govern complex systems. The application of the methodology is included in the fourth section of the paper. Results are commented on in the fifth section of the paper. The paper ends with findings from this research, limitations with respect to this stage of the investigation, as well as with the introduction of some windows of opportunity for future researches.

2 Background

Design for Excellence (DfEx) is the name given to an engineering process where a product is designed considering a set of several objective functions [12]. In its simple form, it is called "*design for X*" when the focus is on a single or maximum of two objective functions (DfX) [13, 14].

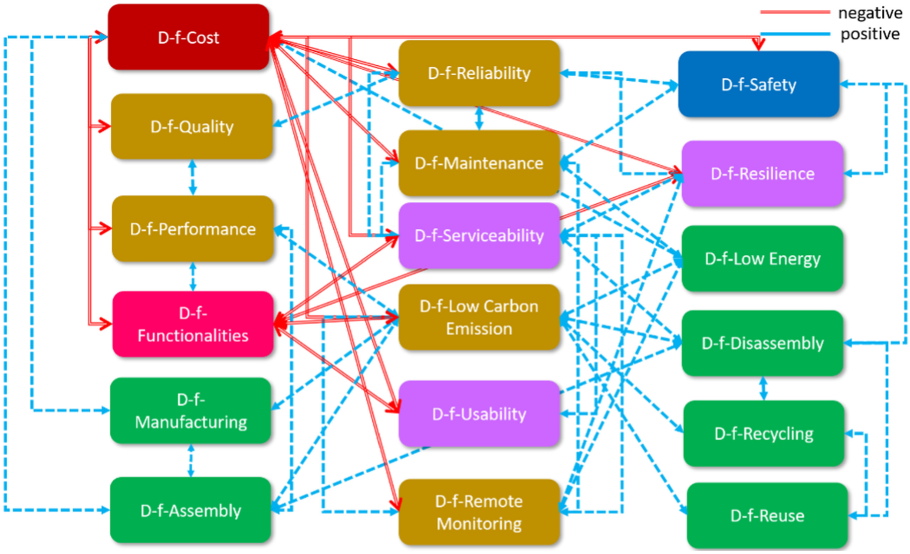


Fig. 1. Objective functions in DfEx and their relationships.

Due to the evolution of society and technologies, in the present times, the vision on DfEx is – or must be – significantly expanded in order to cover all phases of the product lifecycle and lifetime (e.g., cost, performance, functionalities, quality, manufacturing, assembly, serviceability, reliability, usability, safety, resilience, circularity; and granularity can be boosted). Some of the objective functions are negatively correlated, coupled, and complicated in terms of requirements (see Fig. 1). This leads to complicatedness and complexity issues in engineering design. The entropy of this process exponentially increases; thus, raising up challenges for mastering the design process.

In order to investigate the state-of-the-art on DfEx, several databases have been consulted: Web of Science, Scopus, Springer Link, IEEE Explorer, and Emerald. In addition, Google Scholar was consulted. The searching process included "*DfX*", "*DfEx*", "*design for excellence*", "*design for X*", "*framework*" AND "*design for excellence*", "*method*" AND "*DfX*", etc. After cleaning up the returned information, the relevant papers selected for deeper investigation are introduced in the section "References". DfX was, at its origin in 1990, an imperative for concurrent engineering [6]. At that time, "X" was treated as a single objective function, mostly in relation with manufacturing (DfM), assembly (DfA), or both (DfMA), quality (DfQ), modularity, inspectability, dimensional control or cost [15]. Later, it has been transformed into the design for product lifecycle management (DfPLM) and led to the raise of PLM software platforms [16].

From the analysis of papers along the time, an important conclusion is that DfX has evolved in close connection with the evolution of engineering challenges. For example, a very recent paper from 2019 [17], shows that DfX is now oriented towards smart products, and concludes that objective functions such as empowered users, product-in-use feedback, changeability, data analytics, cybersecurity, and emotional interaction are of a top priority nowadays. The same paper also highlights that lifecycle management, as well as changes in quality perception, shape the evolution of DfX.

The necessity for an integrated approach to mechatronic product engineering was highlighted first time in 1999 [18]. Evolution in this direction led in the last few years to a V-shape model of DfX in the case of mechatronic product design [19], with a lifecycle perspective included. The same is in the case of large-scale software systems or IT (hard-soft systems) [20]. One important conclusion from the literature review is that, for every specific "X", there are various methods and/or roadmaps to qualitatively and – in some cases – quantitatively optimize the results. Also, from the literature review, we cannot report the presence of a framework that concurrently approaches more objective functions, excepting the case of manufacturing and assembly (DfMA).

By screening the published papers on DfX, an important conclusion is that none of the existing researches is in the position to answer the following question "*Having a pool of objective functions that have to be included in the design of a new product, what principles and what framework should handle their integration into an aggregated design process?*".

It is the goal of this paper to introduce a more systematic analysis of this issue and to formulate a possible frame of action in this respect. The practical utility and, from here, the value of such contribution to knowledge creation stands in the capacity to visualize an effective and efficient path for concurrent integration of multiple objective functions into the design process and to maximize the utilization of state-of-the-art tools and practices in order to create, at least, close to optimal approaches of engineering design in the attempt to construct a highly mature solution to a complex problem. The subsequent section introduces the research methodology in relation to the question beforehand highlighted.

3 Foundation of the Research Methodology

The design of sophisticated products (e.g., social robots, hybrid cars, high-speed trains, airplanes) falls into the paradigm of complex systems from the perspective of the design process. Sophistication can be assimilated with complicatedness; meaning, the presence of many elements that are correlated (interdependent) and whose overall performance is strongly influenced by the value of various state parameters at the elemental level. In some cases, complicatedness leads to complexity, too; meaning that very slight variations in the value of some state parameters can generate dramatic changes in the overall system behaviors (e.g., see the situation in which a system enters into resonance if some parameters related to the dynamic behavior of the system are slightly modified).

In the design process of sophisticated products, complexity is generated by several factors: (a) incompleteness of information at the start of the design process, which generates a high entropy in the process; (b) the huge amount of interdependent and functionally correlated design parameters, which generates significant changes in the design patterns for small variations of the inputs (e.g., following idea A or idea B); (c) the multitude of possible combinations of sub-systems, which actually induce a high entropy in the design process. At every stage of the design process, results (R) are influenced by the creativity (K) and experience (E) of the person or the corpus of persons who indicate(s) the solution, the method-corpus (M) selected and applied to assist the team during solution formulation, and the technology-corpus (T) selected to indicate patterns for a solution. Thus, we can say that:

$$R = f(K, E, M, T). \tag{1}$$

In the decision-making process, in many situations, we operate with discrete values of the influence factors (inputs in the system), not with values that can be selected from a continuum. For example, when the manager decides to involve person X and not person Y to solve a certain problem, in the design process this situation is treated as a small variation of the inputs because the manager has a limited set of persons from which to indicate who is responsible for what. But this variation could bring a significant change in the output because of factor K, or factor E, or the combination of both. Selection of methods to be used for some design tasks (e.g., ideation) also falls into the category of complex behaviors, because even slight variations between the method M_1 and method M_2 lead to dramatic deviations of the results.

For example, choosing between brainstorming and TRIZ is not about a slight variation between M_1 and M_2, but the selection of practice P_1 or practice P_2 in the application of brainstorming session, or inclusion or omission of a certain person in the brainstorming session falls into the category or slight variations because we operate with limited instances in the space of possibilities. For example, the application of traditional brainstorming or circular brainstorming can lead to significant deviations of the results; or selecting between brainstorming with no special moderation rules, brainstorming ruled by the 6-Hats mechanism [21] or brainstorming ruled by the structured activation of vertex entropy (SAVE) mechanism [22] can lead to results that vary dramatically. These remarks are also based on experimental tests with focus groups of students in various semester projects.

An important aspect in relation to complex systems is the fact such systems do not have optimal solutions [23]. In other words, there is no unique combination of elements in the system that maximizes or minimizes a given objective function. Thus, in the case of complex systems, we can talk in the best scenarios about close to optimal solutions [23]. This aspect is very important because it indicates that the engineering design process can follow more reliable paths to achieve an intended goal.

4 Research Methodology

With the ascertainments from Sect. 3 in mind, we conclude that systematic analysis of the design domain could increase the chances to generate a mature DfEx framework. In this respect, it was formulated the research methodology from Fig. 2. The flow and the tools embedded in the flow were thought using a *reverse engineering process*. The reverse thinking starts from the set of key performance indicators (KPIs) associated with DfEx: (a) capacity to handle conflicts between several objective functions (see Fig. 1); (b) capacity to combine requirements of all objective functions in a concurrent way; (c) capacity to converge towards a mature solution from iteration to iteration; (d) capacity to operate with a limited number of items (in order to limit complexity and amount of work) without affecting dramatically the results.

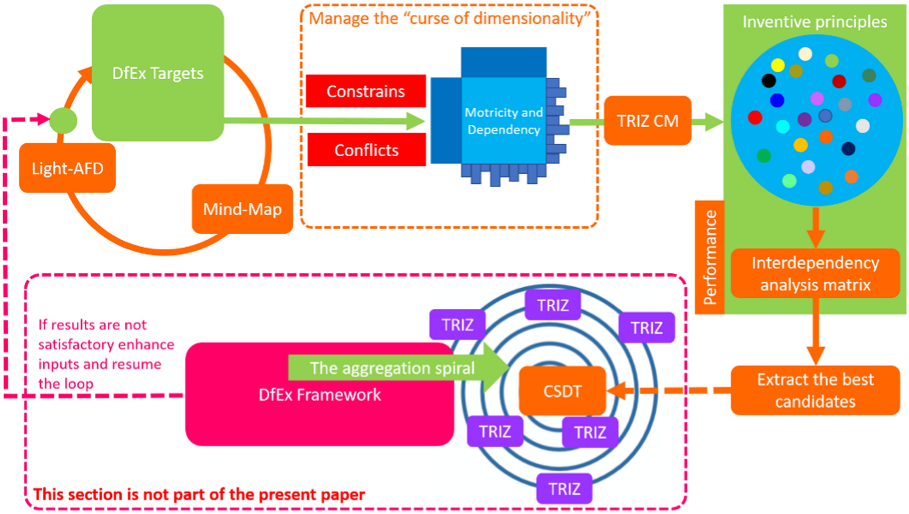


Fig. 2. Research methodology toolbox.

The research methodology (see Fig. 2) starts with a process of discovering the set of constraints and conflicts relative to the problem under consideration. A combination of Mind-Map [24] and light-AFD (anticipatory failure determination) [25] is used for this purpose. Mind-Mapping is a process through which the expertise of the team is directed to extract the significant set of elements that characterize the investigated space (in this case DfEx). Anticipatory failure determination (AFD) is used in this methodology in its most simplistic form (light-AFD); that is, by applying the principle "*break out the gained accessory to the proposed solution*" in order to identify weaknesses and omissions in the map generated with Mind-Map.

The combination "Mind-Map + Light-AFD" is applied in more cycles, until the generated map comprehends the critical mass of information (conflicts and constraints). An empirical recommendation is to follow 5 cycles, as in the case of 5-why root-cause analysis [26]. For the purpose of this research, it is sufficient to identify the conflicts that fall into the set defined by the 80–20 rule (the minority of the most influential conflicts). With the proposed approach, this target can be achieved. This was demonstrated along time by works in the field of information management [27].

A major challenge in the resolution of this research is the overpassing of the "*curse of dimensionality*". The number of conflicts and constraints is very large and leads to the problem called the "*wall of complicatedness and complexity*". It is important to highlight here the nuance between something complicated and something complex. A complicated problem is predictable and linear in nature, with a clear beginning and end, with both variation and repetitiveness involved. In a complicated problem, it is possible to model the relationships between the parts, which can be reduced to predictable interactions (e.g., building a nuclear reactor is complicated, but if done right, the inputs and outputs are highly predictable and repeatable). In opposition, a complex problem develops a behavior that cannot be predicted with linear relationships; such problems also have a high degree of self-organizing properties. This occurs in areas as ideation and conceptualization. There are three properties that determine the complexity of a system: the number of interacting elements, the interdependent connections among elements, and the level of diversity among elements. Thus, there is friction between the scope of analysis and the time necessary to analyze and solve a problem. In TRIZ language, we talk about "*reduction of complexity*" without damaging "*quantity and quality of relevant information*".

TRIZ suggests for this situation to increase the local quality and to dispose of some parts, comprising functions into other parts. In complex problem solving, omitting less relevant parts, and finding a frugal representation of the problem may enable and foster the search for a solution. The search for a solution based on a frugal model of the problem involves inductive and deductive reasoning, which are constitutive elements of "*intelligence*". In complex problem solving, operative intelligence calls for information reduction, building a model of the most relevant effects, calling for evaluation and setting priorities, involving systematically unveiling hidden information, and for dynamic decision making [28]. All these aspects influenced the foundation of the methodology from Fig. 2.

In this sense, the frugal model of the problem is the "*matrix of motricity and dependency*". In this matrix, constraints and conflicts are analyzed. Those at the top of the list with respect to the combination of motricity and dependency are of major concern for complex problem solving and shall be treated with priority. They are extracted and further used as entries in conceptualizing the DfEx framework. By means of TRIZ CM (contradiction matrix) [29], the related inventive vectors are identified, and by means of the "*interdependency analysis matrix*" [30] the most promising combination of inventive vectors is selected. They are reformulated into features of the DfEx framework. According to Fig. 2, for the foundation of the DfEx framework, a tool that handles aggregation is desirable. A good candidate for this purpose is CSDT (a tool for designing complex systems) [31]. Complex system design technique (CSDT) embeds TRIZ-related tools at various steps to accelerate convergence towards a robust solution. This last subject is not part of this paper.

5 Application

The result of Mind-Map and light-AFD application is illustrated in Fig. 3. It shows the constrains and challenges (conflicts) of the design landscape. Because the number of combinatorics for constrains and conflicts is very high, it generates a “wall of complexity” from a practical point of view.

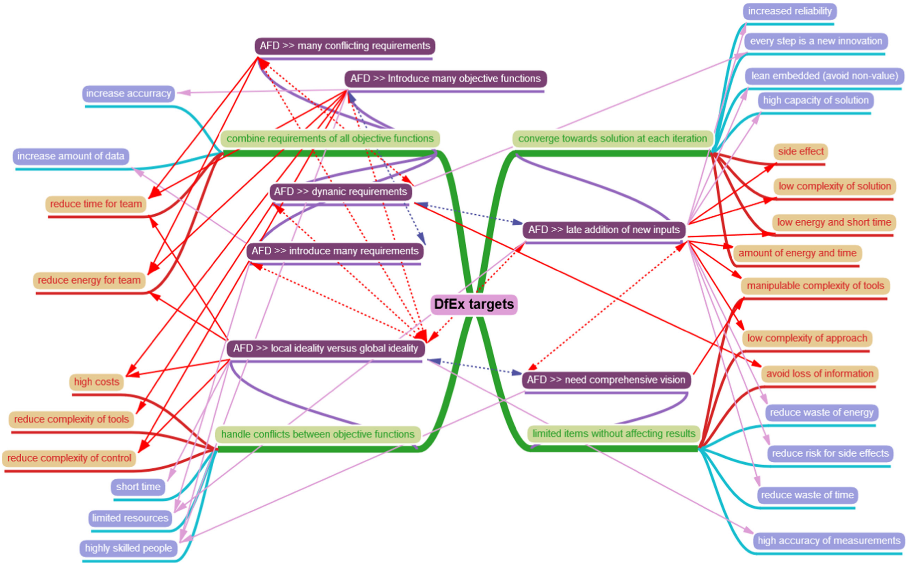
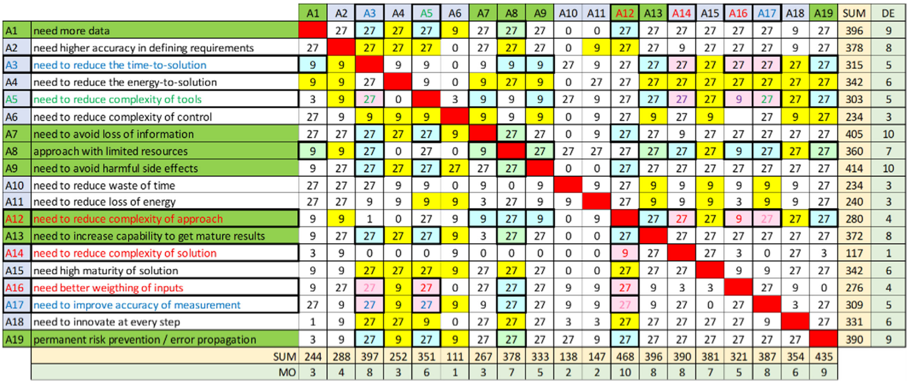


Fig. 3. The complex landscape of DfEx.

Data from Fig. 3 indicate about 130 + cases of conflicts ($\mathbb{C}_2^{17} = 136$). This perspective is not suitable from a practical perspective, as long as ideation is still the privilege of humans and less of machines. However, the collection of big data in the space of ideation might lead in the future to the possibility to put machines to assist engineers in ideation. There are software tools that assist people to map the conflicting functions (elements) and afterward generating long lists of vectors of innovation (e.g., Knowledge Wizard™, AIDA). However, automation must go beyond this stage. This requires engines that go beyond expert systems to extract the best candidates from the overall list of vectors. An automatic alternative could be deep learning GANN algorithms (generative adversarial neural network) [32] combined with SML (supervised machine learning) algorithms.

This strategy requires significant resources and time, but ultimately a database suitable for implementation might be realizable. This subject is not treated in the present paper.

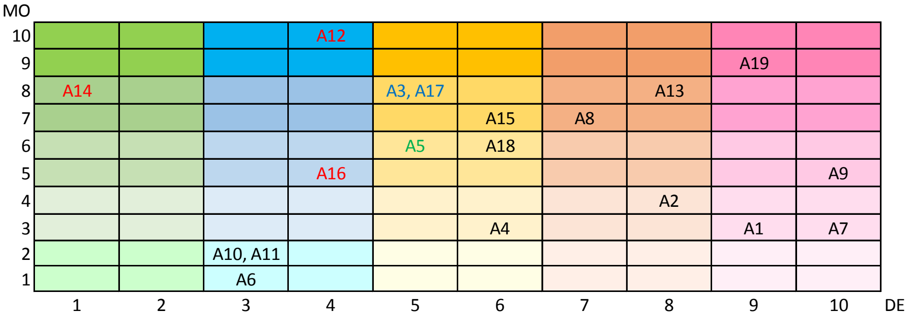
A novel alternative introduced in this paper is to reduce the number of inputs to those that are most relevant by measuring the motricity and dependency of these inputs and to analyze conflicts only in relation with the obtained subset of highly tractive inputs paired with highly dependent inputs. This approach makes sense only when 80–20 rule is present in the results of motricity and dependency. It happens that, for the case from Fig. 3, this approach is workable. Results are shown in Fig. 4.



		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	SUM	DE
A1	need more data		27	27	27	27	9	27	27	27	0	0	27	27	27	27	27	27	9	27	396	9
A2	need higher accuracy in defining requirements	27		27	27	27	0	27	27	27	0	9	27	27	9	27	27	27	9	27	378	8
A3	need to reduce the time-to-solution	9	9		9	9	0	9	9	9	27	9	27	27	27	27	27	27	27	27	315	5
A4	need to reduce the energy-to-solution	9	9	27		9	0	9	27	9	0	27	27	27	27	27	27	27	27	27	342	6
A5	need to reduce complexity of tools	3	9	27	0		3	9	9	9	27	9	27	27	27	27	9	27	27	27	303	5
A6	need to reduce complexity of control	27	9	9	9	9		9	9	9	0	9	27	9	27	9		27	9	27	234	3
A7	need to avoid loss of information	27	27	27	27	27	9		27	27	0	9	27	27	9	27	27	27	27	27	405	10
A8	approach with limited resources	9	9	27	0	27	0	9		27	27	27	27	27	27	27	9	27	27	27	360	7
A9	need to avoid harmful side effects	9	27	27	27	27	27	27	27		0	0	27	27	27	27	27	27	27	27	414	10
A10	need to reduce waste of time	27	27	27	9	9	0	9	0	9		9	27	9	9	9	9	9	9	27	234	3
A11	need to reduce loss of energy	27	27	9	9	9	9	3	27	9	9		27	9	9	9	3	9	9	27	240	3
A12	need to reduce complexity of approach	9	9	1	0	27	9	9	27	9	0	9		27	27	27	9	27	27	27	280	4
A13	need to increase capability to get mature results	9	27	27	27	27	9	3	27	27	0	0	27		27	27	27	27	27	27	372	8
A14	need to reduce complexity of solution	3	9	0	0	0	9	0	0	0	0	0	9	27		27	3	0	27	3	117	1
A15	need high maturity of solution	9	9	27	27	27	9	27	27	27	0	0	27	27	27		9	9	27	27	342	6
A16	need better weigthing of inputs	9	27	27	9	27	0	27	27	27	9	9	27	9	3	3		27	9	0	276	4
A17	need to improve accuracy of measurement	27	9	27	9	27	9	9	27	27	9	9	27	9	27	0	27		3	27	309	5
A18	need to innovate at every step	1	9	27	27	9	0	27	27	27	3	3	27	27	27	27	27	9		27	331	6
A19	permanent risk prevention / error propagation	3	9	27	9	27	9	27	27	27	27	9	27	27	27	27	27	27	27		390	9
	SUM	244	288	397	252	351	111	267	378	333	138	147	468	396	390	381	321	387	354	435		
	MO	3	4	8	3	6	1	3	7	5	2	2	10	8	8	7	5	8	6	9		

Fig. 4. Analysis of motricity (MO) and dependency (DE).

Figure 4 indicates with red, blue, and green colors the key inputs (A3, A5, A12, A14, A16, A17). They are selected from the table of “motricity and dependency”, which is shown in Fig. 5.



MO										
10				A12						
9									A19	
8	A14				A3, A17			A13		
7						A15	A8			
6					A5	A18				
5				A16						A9
4								A2		
3						A4			A1	A7
2			A10, A11							
1			A6							
	1	2	3	4	5	6	7	8	9	10	DE

Fig. 5. Selection of the key inputs.

Using a compounded index (CI), $CI = \sqrt{MO^2 + DE^2}$, for each input, we obtain the results from Table 1. With the 80–20 rule, it is possible to extract the most relevant inputs. They are highlighted with green background in Fig. 4 (A1, A7, A8, A9, A12, A13, A19). They represent 36.8% of the total inputs and the sum of their indexes is 47.2% from the sum of all indexes (Table 1).

Table 1. Position (P) of inputs relative to their compounded indexes *CI*.

P	Input	Index	P	Input	Index	P	Input	Index	P	Input	Index	P	Input	Index
7	A1	9.48	14	A5	7.81	3	A9	11.18	2	A13	11.31	9	A17	9.43
11	A2	8.94	19	A6	3.16	17	A10	3.60	13	A14	8.06	12	A18	8.48
8	A3	9.43	5	A7	10.44	18	A11	3.60	10	A15	9.21	1	A19	12.72
15	A4	6.70	6	A8	9.89	4	A12	10.77	16	A16	6.40			

This effort of analysis was necessary to achieve a tangible indicator on how to classify the conflicting spaces in setting up an effective DfEx framework. As Fig. 4 indicates, there are over 130 conflicting problems between inputs that shape the DfEx framework (see all boxes highlighted with colors – yellow, light red, light blue, and light green in Fig. 4).

The four categories of conflicting problems have the following priority: light red (priority 1), light blue (priority 2), light green (priority 3), and yellow (priority 4). Within the same category, we can organize priorities, as follows: priority 1 → pairs of inputs with boxes of higher value (e.g., 27 is higher than 9), etc. For the cases of boxes with the same value, priority is indicated by the sum of indexes of pair inputs (see Table 1) and in the case of equality, priority is given by the position of inputs in Fig. 5 (higher motricity and lower dependency are better than vice versa).

Figure 4 is very illustrative for indicating the complexity of engineering an effective DfEx framework. Usually, such situations discourage practitioners and urge them to adopt simplified approaches, rather than trying to set up a structured, more comprehensive, and systematic framework. The consequence is the generation of fragile solutions with respect to future situations over the lifecycle, rather than having robust solutions to future attractors and stimuli.

The ideal case is to tackle all conflicts. However, having prioritized the set of conflicts, we might consider an acceptable compromise and tackle only the subset that exhibits the 80–20 rule.

This thing can be done with accuracy by associating to each colored box from Fig. 4 a value, equal with the product of the strength of the link between the pair of inputs (1, 3, 9, 27) and indexes P of the pair of inputs associated with that box. A subset of 23 conflicting spaces has been formulated on this logic. They are further introduced in Table 2.

Table 2 also presents the TRIZ inventive principles that are associated with the critical conflicting spaces in DfEx. The code in the table indicates a combination of the decision area and the number allocated to the inventive principle in the traditional TRIZ list. For each problematic space, the goal is to select the best candidate from the list of proposed inventive principles. At this stage, we might say that the complexity of the DfEx framework can be reduced to 23 dimensions, and of each dimension, we

Table 2. Inventive principles for the key inputs.

Input 1	Input 2	Code	Inventive principle
Reduce complexity of process	Avoid harmful side effects	1.2	Extract, retrieve, remove
		1.21	Rushing through
Reduce complexity of process	Avoid loss of information	2.35	Transformation of system properties
		2.33	Homogeneity
		2.27	Dispose
		2.22	Convert harm into benefit
Reduce complexity of process	Need more data	3.3	Increase local quality
		3.27	Dispose
		3.29	Reconfigurable construction
		3.18	Exploit resonance (sensitivity)
Reduce complexity of process	Avoid error propagation	4.5	Combine and/or consolidate
		4.28	Replacement of traditional systems
		4.11	Moderation in advance
		4.29	Reconfigurable construction
Reduce complexity of process	Increase capability of results	5.35	Transformation of system properties
		5.18	Exploit resonance (sensitivity)
Reduce time-to-mature solution	Avoid harmful side effects	6.2	Extract, retrieve, remove
		6.24	Mediator
		6.35	Transformation of system properties
		6.21	Rushing through
Reduce time-to-mature solution	Avoid loss of information	7.13	Inversion or reversion
		7.26	Copying
Reduce time-to-mature solution	Need more data	8.10	Prior action
		8.19	Periodic action
		8.29	Reconfigurable construction
		8.38	Use strong “motivators”
Approach with limited resources	Avoid error propagation	9.29	Reconfigurable construction
		9.1	Deeper segmentation
		9.40	Composite structures
Approach with limited resources	Avoid harmful side effects	10.17	Translation into a new dimension
		10.2	Extract, retrieve, remove
		10.40	Composite structures
		10.1	Deeper segmentation
Reduce time-to-mature solution	Avoid error propagation	11.10	Prior action
		11.28	Replacement of traditional systems
		11.32	Changing transparency
		11.25	Self-service
Approach with limited resources	Avoid loss of information	12.2	Extract, retrieve, remove
		12.22	Convert harm into benefit
Approach with limited resources	Need more data	13.29	Reconfigurable construction
		13.30	Elastic construction
		13.6	Nesting system
Reduce time-to-mature solution	Increase capability of results	14.8	External support
		14.3	Increase local quality
		14.26	Copying
		14.14	Out-of-the-box (nonlinear)

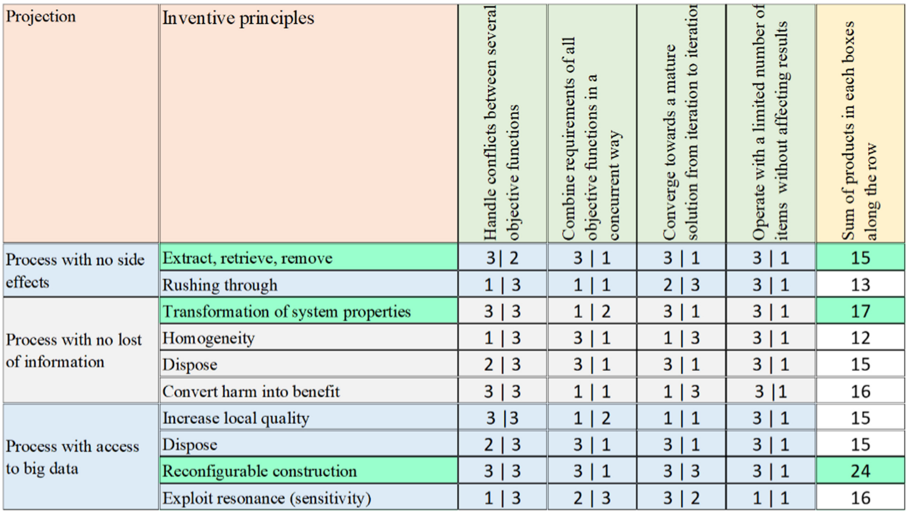
(*continued*)

Table 2. (*continued*)

Input 1	Input 2	Code	Inventive principle
Reduce complexity of tools	Avoid harmful side effects	15.19	Periodic action
		15.1	Deeper segmentation
Reduce complexity of process	Increase accuracy of measurement	16.26	Copying
		16.24	Mediator
		16.32	Changing transparency
		16.28	Replacement of traditional systems
Reduce time-to-mature solution	Approach with limited resources	17.8	External support
		17.15	Dynamicity
		17.35	Transformation of system properties
		17.38	Use strong "motivators"
Approach with limited resources	Increase capability of results	18.29	Reconfigurable construction
		18.1	Deeper segmentation
		18.40	Composite structures
Reduce complexity of tools	Avoid loss of information	-	No TRIZ principle
Reduce complexity of framework	Increase capability of results	20.27	Dispose
		20.26	Copying
		20.1	Deeper segmentation
		20.13	Inversion or reversion
Approach with limited resources	Increase accuracy of measurement	21.25	Self-service
		21.26	Copying
		21.28	Replacement of traditional systems
Reduce complexity of tools	Avoid error propagation	22.26	Copying
		22.24	Mediator
		22.32	Changing transparency
Better weights of inputs	Reduce complexity of process	23.28	Replacement of traditional systems
		23.29	Reconfigurable construction
		23.26	Copying
		23.32	Changing transparency

can define the projection of this framework by means of an inventive principle. This simplifies a lot the problem because we can look at each projection and define a solution aligned to the corresponding inventive principle. At the end, projections are aggregated into a functional, logical system. Aggregation might raise other challenges, but this issue could be treated with the second part of the methodology from Fig. 2 (which, as it was mentioned, is not detailed in this paper). Table 2 highlights a special case. Space "reduce the complexity of tools without losing information" has no TRIZ inventive principle. This is one of the cases met in TRIZ contradiction matrix [29]. The question is how to treat this case? The first conclusion is that we cannot reduce the complexity of tools without compromising the quantity and/or quality of information. Putting differently, the question is what tool is sufficiently simple for practitioners that is also robust in terms of the end result with no need for a big amount of information? This particular problem has a solution, but it will be treated separately in a new paper. To give an idea, we can comprise complex issues in a software tool that embeds an expert module.

To select the best candidates the “interdependency analysis matrix” is proposed. It analyzes the influence of each inventive principle on a set of KPIs and vice versa. The KPIs are already introduced in the first paragraph of the Sect. 4. “Research methodology”. The matrix has 72 rows, therefore only a selection from the matrix is presented in this paper for exemplification (see Fig. 6). The selected inventive principles are highlighted green in Table 2.



Projection	Inventive principles	Handle conflicts between several objective functions	Combine requirements of all objective functions in a concurrent way	Converge towards a mature solution from iteration to iteratio	Operate with a limited number of items without affecting results	Sum of products in each boxes along the row
Process with no side effects	Extract, retrieve, remove	3| 2	3 | 1	3 | 1	3 | 1	15
	Rushing through	1 | 3	1 | 1	2 | 3	3 | 1	13
Process with no lost of information	Transformation of system properties	3 | 3	1 | 2	3 | 1	3 | 1	17
	Homogeneity	1 | 3	3 | 1	1 | 3	3 | 1	12
	Dispose	2 | 3	3 | 1	3 | 1	3 | 1	15
	Convert harm into benefit	3 | 3	1 | 1	1 | 3	3 |1	16
Process with access to big data	Increase local quality	3 |3	1 | 2	1 | 1	3 | 1	15
	Dispose	2 | 3	3 | 1	3 | 1	3 | 1	15
	Reconfigurable construction	3 | 3	3 | 1	3 | 3	3 | 1	24
	Exploit resonance (sensitivity)	1 | 3	2 | 3	3 | 2	1 | 1	16

Fig. 6. Interdependency analysis matrix (exemplification for the first three decision areas).

It can be seen that “reconfigurable construction”, “transformation of system properties” and all the other selected inventive principles to represent the 23 decision areas fall in the category of nonlinearity. Even the decision area that has no TRIZ principle can be solved only with nonlinear transformations from the current space into a subspace of high variance.

6 Results and Discussions

As Table 2 highlights, nonlinearity and transfer to another dimension are the core characteristics of DfEx. This is one of the most important findings of this research because it proves that DfEx cannot follow the traditional patterns of engineering design. This thing might be intuitive for many of us, but with the support of TRIZ we have succeeded to pass from common sense to scientific demonstration of this matter. A revolution must happen in the PLM methodology and its associated tools to materialize DfEx. Todays’ PLM practices and tools pale in front of this challenge. Adoption of more specialized modules, in the spirit shown today by generative design, would be the right path of evolution for PLM systems. In terms of TRIZ system evolution theory, there is a strong unbalance between market needs and capabilities proposed by nowadays' PLM systems, which are still strongly "corseted" by old design models and mindsets, incapable to aggregate interdisciplinarity in design.

The second important finding is that DfEx cannot happen in ordinary organizational settings, because "reconfigurable construction" cannot be supported by such organizations. Most probable, excepting large organizations with financial potential, DfEx bet fits in polycentric open innovation schemes. Reconfigurability is not only about modularity. It embeds modularity, but as a secondary characteristic, together with scalability, convertibility, agility, flexibility, and others. DfEx is not only about methodologies and tools; it is also about the way we are organized to handle concurrent multi-objective function optimization design. And it is also about the qualification of the team. To implement the inventive principles highlighted with green in Table 2 it is necessary to operate with interdisciplinary concepts and skills, and with super-agile operational patterns. For the case of software design and development, such a framework is proposed by the author in [10]. The model called CALDET proved to be beneficial to win a project that develops a software system for "smart territory management", and it was inspirational for setting up the innovation pattern of a cybersecurity product-service solution dedicated to small businesses [33].

Results from this research are currently used within the H2020 project called GEIGER [33] to set up the frame for concurrent design of a cybersecurity tool, an educational network, and content, as well as the related environment for innovation, and finally for the increased potential to exploit project's results. DfEx is not applied to a product, but to a product-service system and the related business ecosystem. We are going to develop a multi-sided platform, therefore the focus is on design-for-usability (with a focus on the target beneficiaries), design-for-scalability (with a focus on solution providers over system lifecycle), design-for-robustness (with a focus on system performance against cyberattacks over lifetime), design-for-easy learning (with a focus on users in the setup phase), design-for-serviceability (with a focus on users in the usage phase), design-for-easy upgradability (with a focus on both users and providers), design-for-functionality (with a focus to a wider group of stakeholders, including multipliers, CERTs, etc.), design-for-resilience, design-for-redundancy, design-for-interoperability, and design-to-agile business model (with a focus on the forthcoming start-up that is going to take over the GEIGER results).

Even if we do not have yet elaborated the detailed DfEx with the second part of the methodology from Fig. 2, results we obtained after the application of the first part of the methodology from Fig. 2 were very useful to setup a lean agile framework for innovation in the GEIGER project (see Fig. 7). We passed through all 23 decision areas from Table 2 and formulated the framework to be adopted with respect to each area following the indication of the most representative inventive principle for each decision area. Because of the page limitation allocated to the paper, only few of these results can be further introduced.

The first example is "how to consider simple processes but with no loss of relevant information" using "transformation of system properties". We applied two actions "increase of flexibility" and "change the concentration of the state" (see TRIZ). They are

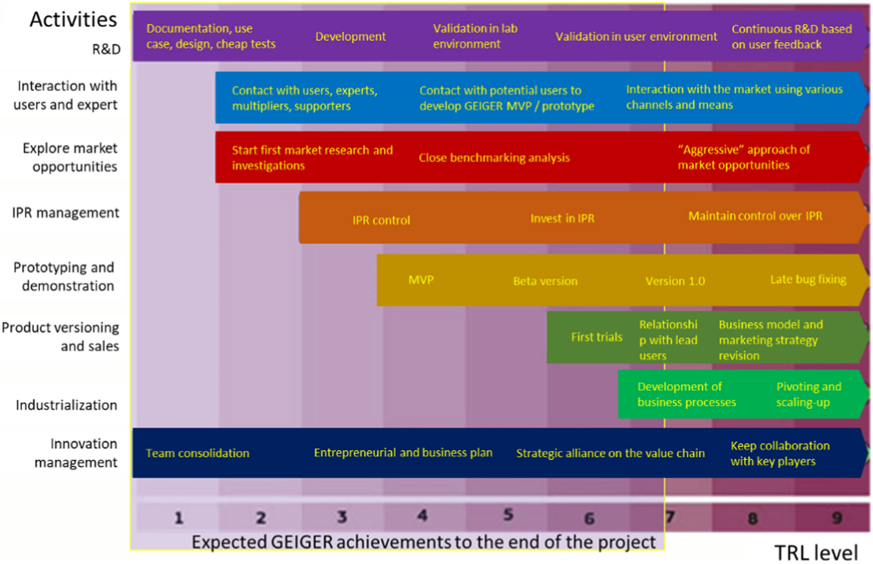


Fig. 7. Concurrent approach of innovation in the GEIGER H2020 project.

applied for all simultaneous processes (Fig. 7), and for each activity. There is an organizational dimension and a technical dimension. In terms of organization, we adopted the CALDET methodology, which is a lean agile approach that concentrates a lot of feedback from different angles (different stakeholders) in short sprints at every two weeks for each strip from Fig. 7. Various collaborative working platforms are used in this respect (e.g., MIRO, Google Drive, Next Cloud, GitHub, etc.). For example, IP is administrated in a cloud platform called DEIP, which uses blockchain technology and peer review with metrics to assess and protect intangible assets (all kind, not only patentable IP) that are generated by each partner in the project. Flexibility is put in practice by using simultaneously more than one strategy and related tools to solve various problems. For example, requirements identification, and analysis followed two parallel streams, with different philosophies and tools in order to unveil different sides of the user characteristics, needs, jobs, etc. The same is applied for the educational curricula associated to the education of the target market, as well as with the design of system's algorithms and architecture.

The second example is "simple processes but capable to generate and operate with big data" using "reconfigurable construction". Reconfigurable at organizational level consisted in rapid construction of various teams and best candidate persons for each task, using the pool of resources from 19 organizations. Reconfigurability on every task considered five characteristics: modularity, flexibility, convertibility, scalability, customizability. In continuation, this is exemplified on the process of requirements design and planning. Modularity was reflected in depicting the process in modules that can be approached in various combinations, not in a waterfall model. Scalability considered application of a module of a first focus group and afterwards, with the lessons learned is concurrently scaled up to more focused groups. Flexibility offered the space to select for tackling a certain task more than one roadmap. Thus, two or more roadmaps and specific tools have been concurrently applied to extract information, and some of them have been cross-multiplied. Convertibility was applied for aggregation of data in a single logical list of specifications. Customizability considered adaptation of various tools to better fit with the culture of interviewees.

7 Conclusions

This research highlights the level of complexity in setting up a reliable DfEx methodology to tackle modern, sophisticated mechatronic products or large-scale IT or software systems. It also displays a possible candidate pattern to solve this problem, as well as traps to be avoided. This research does not guaranty that all barriers and conflicts that populate the design scope in the case of DfEx is completely covered. Collective expertise might be useful to better comprehend analysis.

The research introduced in this paper is the first step to formulate a reliable and efficient DfEx framework; thus, viable from a practical perspective. In the paper the roadmap for continuing investigation is highlighted, which will be the subject of another research paper. However, even with the partial results presented in this paper it is possible to build a DfEx framework following guidance from the vectors and human experience and intuition.

Results of this research might inspire engineering offices to enhance their PLM practices with new tools because nowadays these systems operate very much in a breakdown structure to simplify the project management and act by dividing a complicated system (e.g., a car, an airplane, a train, a ship, an IT system, an energy system, etc.) into small pieces that can be tackled by different units, with very little interactions among contributors in critical sessions such as conceptualization, analysis, problem solving, and without an approach of aggregated design to embrace a holistic optimization vision.

In fact, we know that PLM systems do not integrate in their frameworks quality planning tools (e.g., QFD, FAST, FBD), or systematic innovation tools (e.g., TRIZ), or assessment tools (e.g., Combinex, FMEA), or ranking tools (e.g., AHP). Quantitative optimal design was limited in the past to FEA, and recently it was added generative design and topological design, as well as modules for electro-mechanical design and dynamic analysis.

Results from this research will be considered as inputs in the next phase of investigation (see Fig. 2), where it is expected to define the DfEx framework at high details, including steps and tools. Inclusion of artificial intelligence modules in PLM will be necessary to disrupt current design patterns. They must include evolutionary algorithms, generative adversarial neural networks based on large databases of solutions (note: patents represent a minority in the space of innovations generated by people and mostly by nature), and other deep learning models (e.g., Markov chains, Hopfield networks, Boltzmann machines, deep belief networks). It is an effort that cannot be done by a person, not even by a large organization with many resources. It calls for an open-source platform where collective, worldwide contribution to be brought for the benefit of all. This is about putting large-scale collaboration on top of priorities, which is somehow in contradiction to present mindsets and models of doing business. We have to imagine a toolbox of tools, clearly connected into a nonlinear flow, with APIs and plug-ins to ensure intercommunication between them and access to databases. Innovative start-ups work on these issues, which is encouraging.

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References

1. Rosa, M., Wang, W.M., Stark, R., Rozenfeld, H.: A concept map to support the planning and evaluation of artifacts in the initial phases of PSS design. Res. Eng. Design **32**(2), 189–223 (2021). https://doi.org/10.1007/s00163-021-00358-9
2. Gonzalez Chavez, C.A., Romero, D., Rossi, M., Luglietti, R., Johansson, B.: Circular lean product-service systems design: a literature review, framework proposal and case studies. Procedia CIRP **83**, 419–424 (2019)
3. Clermont, P., Kamsu-Foguem, B.: Experience feedback in product lifecycle management. Comput. Ind. **95**, 1–14 (2018)
4. Gebauer, H., Paiola, M., Saccani, N., Rappacini, M.: Digital servitization: crossing the perspectives of digitization and servitization. Ind. Mark. Manage. **93**, 382–388 (2021)
5. Fragal, A.C., Riberio, A.O., Baldo, C.R.: A cyber physical system approach to customer services of home appliances. Smart Innov. Syst. Technol. **198**, 34–43 (2021)
6. Boothroyd, G.: Design for excellence – Book review. J. Manuf. Syst. **15**(6), 443 (1996)
7. Sivaloganathan, S., Hills, P.: Design for excellence. J. Eng. Des. **12**(1), 1–2 (2001)
8. Irbite, A., Strode, A.: Design thinking models in design research and education. In: Proceedings of the International Scientific Conference of Society Integration Education, vol. 4, pp. 488–500, 27–28 May (2016)
9. Yu, L., Nickerson, J.V., Sakamoto, Y.: Collective creativity: where we are and where we might go. In: Proceedings of Collective Intelligence 2012 (CI2012), 10 January 2012. https://ssrn.com/abstract=2037908
10. Brad, S., Brad, E., Homorodean, D.: CALDET: a TRIZ-driven integrated software development methodology. In: Benmoussa, R., De Guio, R., Dubois, S., Koziołek, S. (eds.) TFC 2019. IAICT, vol. 572, pp. 400–416. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-32497-1_32
11. Halstenberg, F.A., Lindow, K., Stark, R.: Utilization of product lifecycle data from PLM systems in platforms for industrial symbiosis. Procedia Manuf. **8**, 369–376 (2017)
12. Barbosa, G.F., Carvalho, J.: Analytical model for aircraft design based on design for excellence (DFX) concepts and use of composite material oriented to automated processes. Int. J. Adv. Manuf. Technol. **69**(9–12), 2333–2342 (2013). https://doi.org/10.1007/s00170-013-5211-7
13. Manuel, J., Becker, J., Wits, W.W.: A template for design for eXcellence (DfX) methods. In: Abramovici M., Stark R. (eds.) Proceedings of the 23rd CIRP Design Conference, Bochum, Germany, 11–13 March, pp. 33–42. Springer, Heidelberg (2013).
14. Gatenby, D., Foo, G.: Design for *X* (DFX): key to competitive. Profitable Prod. AT&T Tech. J. **69**(3), 2–13 (1990)
15. Gatzen, M.M., Pemberton, R.W., Peters, V., Krueger, S.: A holistic design for excellence model based on life cycle costing and design scorecards. In: Proceedings of the 19th International Conference on Engineering Design (ICED13) Design For Harmonies, Design for X, Design to X, Seoul, Korea 19–22 August 2013, vol. 5, pp. 281–298. Baker Hughes Inc. (2013)

16. Aaramaa, S., Saukkonen, S., Hyysalo, J., Similä, J., Kuvaja, P., Oivo, M.: Design for excellence in the context of very large-scale requirements engineering. In: 2015 10th International Joint Conference on Software Technologies (ICSOFT), Colmar, 20–22 July 2015, pp. 1–12. IEEE (2015)
17. Benabdellah, A.C., Bouhaddou, I., Benghabrit, A., Benghabrit, O.: A systematic review of design for X techniques from 1980 to 2018: concepts, applications, and perspectives. Int. J. Adv. Manuf. Technol. **102**(9–12), 3473–3502 (2019). https://doi.org/10.1007/s00170-019-03418-6
18. Zheng, C., Bricogne, M., Le Duigo, J., Eynard, B.: Survey on mechatronic engineering: a focus on design methods and product models. Adv. Eng. Inf. **28**(3), 241–257 (2014)
19. Schoener, H.P.: Automotive mechatronics. Control. Eng. Pract. **12**(11), 1343–1351 (2004)
20. Lehto, J., Harkonen, J., Haapasalo, H., Belt, P., Mottonen, M., Kuvaja, P.: Benefits of DfX in requirements engineering. Technol. Invest. **2**(1), 11 (2011)
21. Gocmen, O., Coscun, H.: The effects of six thinking hats and speed of creativity in brainstorming. Thinking Skills Creativity **31**, 2840295 (2019)
22. Brad, S.: Structured activation of vertex entropy (SAVE): another way around creative problem solving for non-technical applications. Innov. J. Eur. TRIZ Assoc. **4180**(03), 76–81 (2017)
23. Liu, J., Chen, Y.W.: Towards understanding optimization of complex systems. Artif. Intell. Rev. **38**, 313–324 (2012)
24. Buzan, T.: Mind-Mapping. BBC Active, Harlow (2006)
25. Chen, J.L., Hung, C.: Eco-innovation by anticipatory failure determination (AFD) method. In: Proceedings of the Design Society: International Conference on Engineering Design, vol. 1, no. 1, pp. 3271-3280 (2019)
26. Murugaiah, U., Jebaraj Benjamin, S., Srikamaladevi Marathamuthu, M., Muthaiyah, S.: Scrap loss reduction using the 5-whys analysis. Int. J. Qual. Reliab. Manage. **27**(5), 527–540 (2010)
27. Mesbahi, M.R., Rahmani, A.M., Hosseinzadeh, M.: Highly reliable architecture using the 80/20 rule in cloud computing datacenters. Futur. Gener. Comput. Syst. **77**, 77–86 (2017)
28. Gonzales, C.: Decision support for real-time, dynamic decision-making tasks. Organ. Behav. Hum. Decis. Process. **96**(2), 142–154 (2005)
29. Altshuller, G.: The Innovation Algorithm TRIZ. Technical Innovation Center, Worcester (2000)
30. Brad, S.: Improving the use of AIDA method. Acta Tech. Napocensis Ser. Appl. Math. Mech. **50**(2), 4 (2007)
31. Brad, S.: Complex system design technique. Int. J. Prod. Res. **46**(21), 5979–6008 (2008)
32. Creswell, A., White, T., Dumoulin, V., Arulkurmaran, K., Sengupta, B., Bharath, A.A.: Generative adversarial networks: an overview. IEEE Sig. Process. Mag. **35**(1), 53–65 (2018)
33. GEIGER.: Solution for small businesses to protect themselves against cyber threats. H2020 project. https://project.cyber-geiger.eu/. Accessed 12 April 2021