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Ideality in Axiomatic Design and beyond

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Abstract

AD helps to conceive controllable and manageable designs, beyond fulfilling initially posed requirements. According to authors' experience and understanding, this eases the evolution of designs towards their future versions. Thus, ideal solutions according to Suh's theory are characterized by a considerable capability of evolving and accelerating technological progress. Conversely, such an aspect is seldom considered in the most diffused definitions of ideality, although it can be easily regarded as a fundamental feature of good designs. In this context, the paper reviews the definitions of ideality dispersed in the literature. A particular attention is dedicated to TRIZ, since ideality represents a pillar of the former USSR-originating theory and many attempts have been performed to combine it with AD. The paper explores the compatibility of the surveyed definitions with AD objectives, revealing theoretical pitfalls, but also pointing out opportunities for increasing ideality in the design practice.

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Keywords: Ideality; Axiomatic Design; Design Theory; TRIZ; Modularity

1. Introduction, objectives and structure of the paper

The literatures documented a large number of theories, methods and tools to support engineering design and the development of new and better concepts in particular. By limiting his efforts to the most significant contributions, Horvàth [1] attempts to organize the plethora of existing methodologies and highlights their different objectives and roles in the design field. The way of thinking behind Axiomatic Design (AD) belongs to the most meaningful theoretical frameworks, although objections are not lacking. Previous authors' work [2] has been addressed at analyzing AD's affinities and incongruence with other design theories, by articulating and critically discussing insights from dispersed literature. A different result-oriented approach is employed in the present paper in order to define constraints of AD application and inherent strengths and weaknesses of design outcomes provided through strict adherence to AD principles.

In other words, the objective of the article is providing major understanding about the peculiarities of the designs AD intends to deliver and compare them with solutions addressed by other theories and methodologies. The paper analyzes first which are the circumstances in which AD displays maximum benefits. Subsequently, the manuscript attempts to point out the peculiar traits of designs developed by means of AD or that, at least, fulfil the axioms. These designs can be considered as ideal targets of AD application. An overview of ideal systems shaped by other theories and methodologies is illustrated in order to point out similarities and different scopes of conceptual design techniques with respect to AD.

The paper is structured as follows. Section 2 provides an overview of AD's domain of application and the kind of solutions that are generally achieved, meant as goals of AD employment. Section 3 describes the concept of ideality as it is interpreted in the Theory of Inventive Problem Solving (TRIZ) and in other contributions from design literature. While Section 4 attempts to draw a comparison between different meanings of ideality, Section 5 concludes the paper by introducing further discussion and outlining future authors' work.

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2. Outreach of Axiomatic Design: applications and solved problems

The articulation of AD foresees a cascade process, through which designers use the Independence Axiom and the Information Axiom sequentially. To this regard, it seems reasonable to assess that the diffusion of the former is widely greater. Many AD beginners are exposed to the one-to-one logic (mostly between Functional Requirements and Design Parameters) that urges to separate function carriers with the aim to avoid tangled interrelations. The classical faucet example is well tailored to demonstrate the applicability and the value of the first Axiom. However, AD's outreach cannot be restricted to the Independence Axiom and to its corresponding principles. Additional information about the impact of the whole AD corpus on design thinking can be achieved through literature sources.

According to authors' knowledge, [3] represents the most recent contribution in which the use of AD has been surveyed and analyzed. Indeed, while [4] just presents a general overview of the industries and application fields in which AD is adopted, [3] allows to understand which AD-oriented practices result the most successful and diffused. In principle, the mentioned study highlights the overwhelming majority of case studies in which just the Independence Axiom is used. More seldom, the Information Axiom is employed as a support for decision-making, but no manuscript actually documents the full procedure prescribed by AD theory.

By delving into product design examples presented in [3], it is possible to assess that the main drivers and targets of AD are constituted by the followings:

- Simplification and decomposition of complex systems;
- Optimization tasks conducted to maximize/minimize certain effects with the recurrent goal of enhancing operability and safety.

These kinds of design tasks are consistent with the scopes of AD theory largely.

The former mirrors the wide application of Independence Axiom and AD capabilities of decomposing problems and/or product architectures. The definition of complexity and its classification are actually undergoing fundamental research, also within AD community, e.g. [5]. A precise and formal definition of complexity falls outside the scopes of the present paper, which will use an intuitive meaning that involves e.g. the number of parameters and components and the existence of tangled interrelations. From this viewpoint, AD supports the creation of functional modules, as in [6]. Besides being quite logic, the link between modular design and AD is acknowledged in the literature [7-9], as independence is fulfilled through the introduction of different specialized sub-systems. It should be noted, however, how modularity and the consequent increase in the number of parts is not the only strategy that allows for the generation of systems that comply with the Independence Axiom. [10] remarks that the search for new Design Parameters that contribute to fulfil Functional Requirements can take place by exploiting features and characteristics of existing components.

With reference to the latter, the term "optimization" is widely employed in the design field, as the process of fine-tuning the functioning of a new product or system in the detailed design phase. The meaning to be intended here diverges from the above concept. Indeed, Axiomatic Design is classically employed in early design stages, mainly conceptual design [11, 12]. Hence, the term "optimization" has to be considered in this context as the process of devising the system in order to achieve functions with expected performances in an easy, controllable and repeatable way. Despite the use of Information Axiom is not widespread, these design objectives mirror its goal at least from a theoretical perspective. Indeed, the second Axiom takes into account the probability of fulfilling the intended functions that are associated with alternative independent systems. Besides, concepts such as "controllability" [13, 14] or "target value" [12, 15], i.e. optimal measures for a given parameter/function, are frequent in the literature that describes AD applications or design objectives.

As a result, it is possible to infer that designed ideal systems, according to AD principles:

- are suitable for achieving the desired target performances;
- are scarcely affected by sensitivity effects, as controllability ranges between the core objectives;
- replace existing ones by diminishing complexity through the separation of function carriers, by benefitting from the indications of the Independence Axiom.

In a graphical format, Fig. 1 describes the expected system transition. In the illustration, FR and DP stand for the overall set of Functional Requirements and Design Parameters, respectively. The recalled example of the faucet is paradigmatic in this sense, as both the target values of flow rate and temperature of water can be achieved in a stable and controllable way thanks to the mixer faucet.

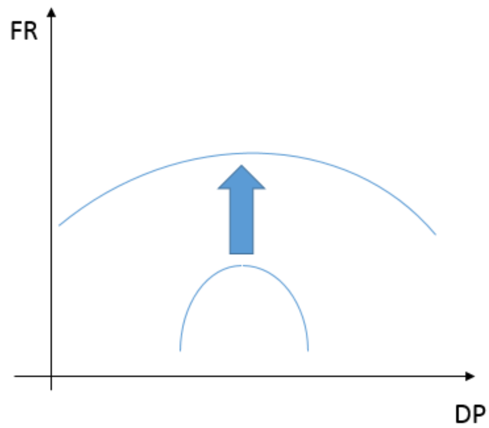

Fig. 1. How interdependences are expected to change when a system is modified based on Axiomatic Design principles.

As the above discussion has clarified the types of problems and solutions likely to be met in the AD domain, it would result useful to have an overview about its inherent limitations. Like any other discipline or design method, the literature about weaknesses is not abundant. On the one hand, scholars can achieve examples of AD limitations by observing the large variety of design methods and techniques that are juxtaposed to AD. On the other hand, AD displays limitations when it deals with dynamic systems and transitory effects [16].

3. Ideal systems for the scopes of other design methods

3.1. Ideality and product evolution in TRIZ

TRIZ includes numerous heuristics that support designers in the search for innovative concepts. Among them, ideality is introduced within TRIZ tools in order to urge designers to look for inventive solutions characterized by high performances and limited drawbacks.

Although the practical meaning of ideality is still questionable, its qualitative definition is agreed. TRIZ indicates ideality as the ratio between useful functions carried out by the system and the sum of its undesired effects and consumed resources. Thus, ideality is boosted by either the increment of useful functions and performances or the reduction of harm and required resources (space, time, information, materials or energy). The increase of ideality leads to design improvements and innovative concepts, as in [17, 18].

Thus, by considering the involved terms, the achievement of ideality is accomplished by new systems that perform the requested functions quickly, with no harm, no mass, no required energy, at no cost, etc. The growth of ideality can be therefore interpreted as a trend towards the birth of systems with a minor number of parts [10]. This circumstance fosters integral designs (as opposed to modularity issues of AD).

Besides, increasing ideality is considered as a natural process of systems' evolution according to TRIZ laws, which takes place by solving a contradiction (for the sake of understanding, examples of contradictions are available, e.g. in [19-21]). The contradiction paradigm, which involves connections and incompatibilities between more than a FR, is a key concept within TRIZ. Based on its definition, both affinities and inconsistencies between AD and TRIZ emerge [2, 22]. In a graphical form, the shift towards improved (and more ideal systems) in TRIZ can be represented as in Fig. 2, that shows that a contradiction is solved by changing/mitigating (Fig. 2a) or eliminating (Fig. 2b) the interplay between the FRs. With respect to Fig. 1, the difference in the axes is worth being highlighted.

Within the TRIZ branch that deals with forecasting and product evolution, the growth of ideality is characterized by an S-shaped trajectory or logistic curve. Some scholars, e.g. [23], agree that the increment of ideality happens:

- At a first instance, by performing expected functions better (the outputs are better in qualitative and/or quantitative form, e.g. a coffee machine is capable of delivering more coffees and/or coffees of a better quality);
- At a second instance, by limiting the amount of consumed resources and/or reducing harmful functions (less water or energy is required, less noise, etc.).

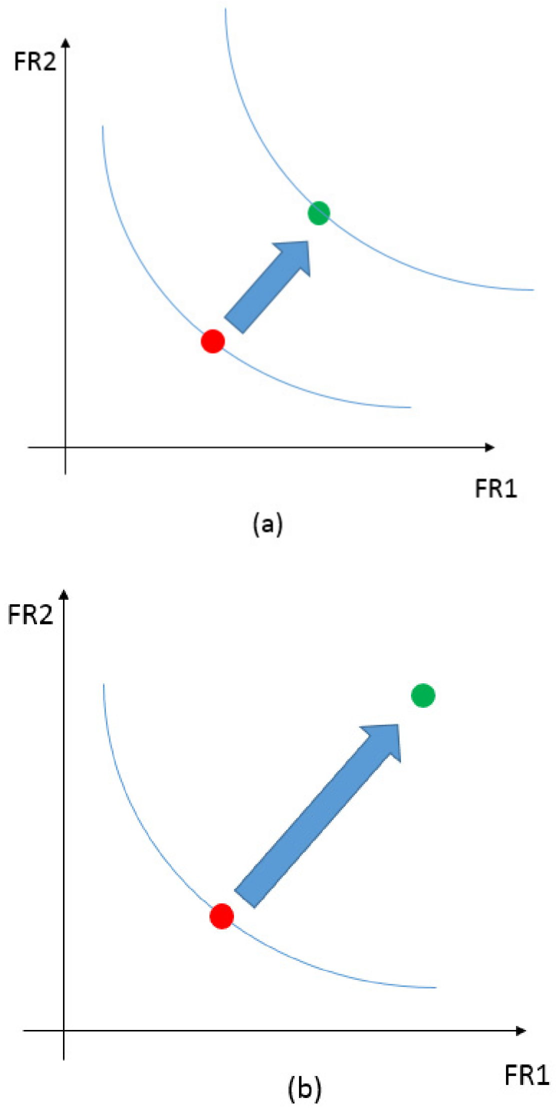

Fig. 2. How TRIZ contradictions are solved by modifying (a) or eliminating (b) the relationships between Functional Requirements.

In other terms, product development aims first at emphasizing those performances, functions and qualities that represent the reason of system's existence. Subsequently, side effects are taken into account. For example, the automotive industry, which can be considered as a mature one, currently focuses on safety, environmental-friendliness, comfort, noise to a considerable extent, rather than boosting the basic functions that vehicles fulfil. The tendence to increment the number of parts at the inception of the S-Curve (Fig. 3) and to diminish this quantity in the final part [24] can be seen as a different explanation of the same phenomenon.

However, neither ideality notion nor the use of S-curves are consistent throughout TRIZ community. To this regard, attempts are presented to build S-curves by using terms other than ideality in the diagram's ordinate, as well documented and discussed in [25] (this aspect is highlighted in Fig. 3). This is even not surprising, as the origins of interpretations of phenomena through S-shaped trajectories lies outside of the design domain.

Taheri et al. [26] deal with these different interpretations and applications: eventually, the study proposes new meanings for ideality and its evolution, in which:

- Ideality is used in a quantitative way, mirroring the initial definition given by the TRIZ founder Altshuller;
- It is shown that the objective of reaching ideality is a sort of chimera, but systems evolve by increasing ideality (an example is given);
- Formalisms are introduced to build the logistic curve mathematically;
- Greater ideality does not always mean greater value for customers; factors like perception of usefulness are not taken into account when assessing ideality of systems in a technological perspective.

Despite different interpretations, it is agreed that logistic curves contemplate a shift to a different kind of system when the existing technology has been pushed to its physical limit [27], as highlighted in Fig. 3. In these circumstances, no further functions can be implemented and/or undesired manifestations cannot be mitigated further. The recalled shift towards a new system, hence towards a new S-curve, is not particularly well supported by TRIZ instruments. Some issues suggest that new technology and knowledge are exploited to transform the basic physical principle underpinning the system functioning.

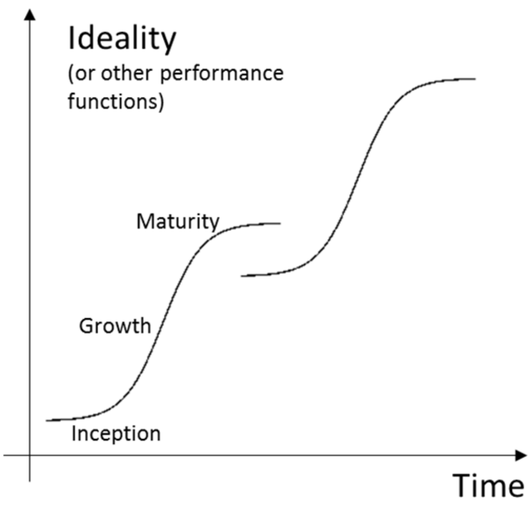

Fig. 3. S-Curves of ideality highlighting the transition to a new dominant system and the various evolution phases.

What is interesting for the scopes of the present paper is that the shift can imply a temporary drop of ideality, which is accompanied by not negligible changes in the system's structure. Otherwise said, the system that has undergone enhancements during the S-shaped evolution and got closer to ideality is unable to improve further. Besides, findings from [26] support the thought that external forces, e.g. customer wants, redirect systems' development to new trajectories, as increasing ideality could result in diminishing value. Consistently, it is possible to suppose that what to improve and when is often determined by external forces. For instance, if cost is the major competitive advantage at a given time, redesigns will focus on reducing cost. If the regulatory environment has changed, then efficiency will be likely the focus.

3.2. Other contribution to ideality concept in the design literature

Ideality concept is not formally defined by the large set of structured methodologies commonly designated as Design for X, where X stands for the objective to be achieved through the design activity, e.g. manufacturing, disassembly. However, it is possible to assume that a good accomplishment of the X represents the goal of these techniques and hence it can be considered the ideal target of design activities.

Within this branch, [28] introduces ideality features for Design for Changeability explicitly. This contribution highlights those peculiarities of designs that allow for a simple evolution of the system to new configurations, as new performances and benefits appear as new design goals. In this context, ideality belongs to the fundamental measures to attain changeability and mirrors diffused concepts of simplicity and (low) complexity. The given meaning, which is tightly correlated with the Information Axiom, originates from TRIZ background (a system with useful functions only, no harm and consumed resources). According to the provided explanations, simple systems are inherently characterized by little information content. Interestingly, [28] individuates a conflict between ideality, well achieved through the Information Axiom, and independence, as defined within AD. The supposed dichotomy stems from the consideration that the first axiom addresses modular designs, supposedly featured by a larger number of parts and greater complexity. Hence, the tendency of achieving integral designs by means of TRIZ ideality concept and modular systems by employing AD Independence Axiom is supported in [28]. Such an issue is introduced even more explicitly in [10].

Other contributions link ideality to the capability of systems to evolve and change. For instance, [29] introduces a trivial approach that foresees the increment of ideality (expressed in TRIZ terms) by replacing modules and parts with more advanced ones. In this sense, the growth of ideality is pushed by increasingly useful functions. In [30], the evolution of natural and technical systems, characterized by the three dimensions of TRIZ ideality, are compared in order to achieve design strategies for sustainability.

Eventually, [31] individuates different aspects of ideality that characterize different design domains and attempts to articulate them by benefitting from the principles of AD, TRIZ and Theory of Constraints.

4. Critical discussion about the different meanings of ideal designs

The presented investigation, which has taken into account various definitions and interpretations of ideality, has revealed some dimensions that characterize target design specifications. The following list includes some of the fundamental aspects that have emerged:

- Functionality
- Independence
- Complexity
- Number of parts and components
- Modularity vs. Integrality
- Capability to change and evolve
- Flexibility.

The above concepts are highly interconnected, thus it is difficult to determine for which dimensions priority should be assigned. For instance, the number of parts and components can be seen as a first approximation of complexity, as well as the latter comprises measures of independence in terms of limiting the quantity of mutual interrelations among parameters.

By comparing the design theories that have been discussed more largely, i.e. AD and TRIZ, the following conclusions can be inferred:

- The application of AD Independence Axiom, besides the most diffused tool from Suh’s theory, can lead to designs with many components; the undesired effects associated with the consumption of space and material resources are consequently overlooked;
- The concept of ideality introduced by TRIZ fails to include the evolution potential of systems, which is generally low for integral designs; this aspect mirrors the diminishment of the ideality content when jumping to a new S-curve; in a certain sense, designs characterized by high ideality risk to represent deadlocks in the product evolution.

These statements are intuitive in essence and partially supported by the literature contributions that have been illustrated and shortly discussed. Successful new designs likely overcome the contradiction between modular/independent and integral/ideal (in TRIZ terms) designs. A case in point is once again the faucet example, which presents aspects of both AD independence and TRIZ ideality, as the new system architecture is more compact. Rather than introducing new parts that fulfil a specific function, different DPs of a unique component (two distinct rotation angles of the mixer faucet) allow to attain independence. In another perspective, available resources have been exploited to create a product featured by the same degree of functionality of the previous reference structure, greater controllability and easier operability.

The faucet case can be seen as a win-win situation, but more studies should be carried out in order to establish whether akin outcomes could be accomplished in any circumstance and industrial field. If the answer will be positive, technical innovation theories should be updated in order to address the full spectrum of ideality nuances. Otherwise, as [10] suggests with regard to the evolution of jet engines, a certain degree of not-ideality should be accepted in the design practice, as multiple cases are shown, in which either TRIZ law of ideality increase or the first AD axiom fail to explain changes in successful designs. Besides, [32] contemplates the existence of certain degrees of non-ideality in terms of lacking coherence with AD principles.

5. Conclusions and future work

The paper has presented a discussion on the concept of ideality and ideal solutions within design, with a particular focus on systems engineering and new product development. Formal design theories, such as AD and TRIZ, as well as outstanding contributions dealing with ideality and systems evolution have been taken into consideration.

Among the findings, further insights have emerged into the affinities and incongruences between AD and TRIZ; therefore, further details in the scholar discussion about this topic are provided with respect to [2, 18, 33, 34]. Inconsistencies are not surprising, as the classical design situations in which the two methodologies are applied differ to a good extent (see Figs. 1 and 2).

In addition, a complex network of concepts that are relevant in design theory has emerged, as documented and summarized in Section 4. Contributions that do not focus specifically neither on AD nor on TRIZ (especially within systems design) highlight limitations in the usability of the understanding of ideality that underpins both theories. Consistently, a new definition of ideality that crosses the borders of different design doctrines should be developed and discussed. As an alternative, the adherence to a view on design evolution characterized by relentless laws should be put into discussion, at least partially.

In this sense, future research activities will be conducted to verify the existence and the acceptability of non-ideality in an empirical way. Such a work can result beneficial within design theory and aims at overcoming limitations presented by many methodologies, including AD.

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