On Dynamic Axiomatic Design or projections of system control theory on Axiomatic Design

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Abstract. The Axiomatic Design (AD) instruments provide a valuable insight for qualitative design evaluation. After having defined the inputs and outputs for the designed system, one can quickly check if it is convenient for the user to address the outputs by the inputs. Thus, AD helps to evaluate the usability of the design or the user interface, although the user interface can be given much wider sense, evaluating the interactions of the design during manufacturing, installation and maintenance. At the same time Axiomatic Design has its restrictions of applicability, which we focus on here. First, AD only shows what design is good, but it provides less guidance on how to make a good/independent design from the existing structure. Second, AD covers the only case where the number of Design parameters is equal to the number of Function Requirements. Finally, AD assumes that the mapping from Design parameters (DPs) to Function Requirements (FRs) is static, whereas very often the influence of DPs on FRs is time-dependent and it also neglects possible valuable resource – the time. In the research these drawbacks have been addressed from Control/System Theory prospective. First of all, we reveal a formal procedure how to construct the independent design for a linear system when the number of DPs is equal to FRs; the idea is based on eigen-decomposition of a matrix. Then, we generalize AD with the time domain, thus making it possible to address dynamic systems and use all the operators of Control Theory. We show that a controller can be added for the system design to make it independent. Finally, we extend the definition of independence to the case where the number of FRs is not equal to the number of DPs.

Keywords: Axiomatic Design, Dynamic Systems, Control Theory, Dynamic Axiomatic Design.

1 Introduction

Axiomatic Design (AD) is a framework developed by Suh [1], which is based on two axioms, namely Independence and Information Axioms, which portray a relevant body of knowledge to support the definition of good designs. Recognition and application of AD principles in practice are known despite AD has been mostly developed at a theoretical level with limited quantitative evaluations of design results. Nevertheless, AD has gained a certain share of interest in the scientific community as a research topic. According to the SCOPUS database, the total number of papers with "Axiomatic design" in Title, Abstract of Keywords fields is about 1500 with the steady dynamics of around 100 publications per year. It is worth comparing this number with the most known alternative approach in the field of systematic inventive design: The Theory of Inventive Problem Solving, TRIZ, which has a similar number of publications but has more than doubled in volume dynamics of publication.

In the authors' best knowledge, Kulak et al. represents the most recent and cited attempt to survey and analyze the use of AD systematically [2]. It explains which AD-oriented practices are most successful and diffused, shedding light on the overwhelming majority of case studies in which just the Independence Axiom is used. More seldom, the classical version of the Information Axiom is exploited, but no article actually implements the full procedure prescribed by AD theory based on our literature exploration. By analyzing the illustrated product design examples insightfully, Borgianni and Matt summarize the emerging drivers and targets of AD into [3]:

- simplification and decomposition of complex systems;
- "optimization" tasks carried out in order to maximize/minimize certain effects with the recurrent goal of enhancing operability and safety.

In addition, the increasing integration of manufacturing and design areas might favor the attractiveness of AD, whose industrial focus might be seen at the border between the two disciplines [4].

Huge efforts are paid to merge the method and/or philosophy of AD with other approaches or principles. Robustness and uncertainty of AD is discussed in the light of possibly uncertain relationships between Design Parameters (DPs) and Functional Requirements (FRs) in the branch of literature concerning Fuzzy and Crisp AD [5, 6], which supports decision-making by managing imprecise and hardly predictable effects relevant for the application of the Information Axiom [7]. More articulated schemes for decision-making include considerations that pertain customer requirements to be fulfilled [8]. Complexity definition and AD is the focus of some literature contributions, e.g., [9]. Other instruments of quantitative analysis are used, from fuzzy logic to artificial intelligence [10].

The relation of AD with design theory represent another AD strength: for example, the link between modular design and AD is acknowledged [11], as independence is fulfilled through the introduction of different specialized sub-systems. This aspect represents a further element of compliance with the acknowledged design principles for Industry 4.0 [12].

The present paper and the literature overview that follows are by no means intended to deliver a comprehensive investigation of current efforts in AD. They rather highlight the research background and interesting trends to make AD (alone or along with other methods) more applicable to design problems.

2 Application issues in Axiomatic Design

The reduction of complexity appears to be supported by the axioms by both removing intertwined relationships within systems and attenuating the impact of uncertain events on design. If a recent review of complexity in manufacturing and design is considered, these two objectives can be seen as the attempt to limit complexity at the functional level and in information-related terms [13]. At the same time, still with reference with the design of systems that characterize the new industrial revolution wave, the increasing number of sensors, controls and interfaces embodied by products does not comply with the attempt to reduce complexity [14], as the quantity of components is an acknowledged dimension of complexity. Still with a focus on such a dimension, the reduction of complexity results conflicting also with the common strategy to ensure independence through AD, i.e. the introduction of new and specialized modules.

A similar paradigm emerges also when considering other fundamental dimensions of product and system design. Limited complexity is seen as a catalyst for changeability [15], which, in turn, represents another hallmark of Industry 4.0-oriented designs. In this respect, the principles of Design for Changeability have been introduced explicitly in [16], which indeed include simplicity and low complexity. Interestingly, this contribution identifies a conflict between the conditions achieved through the Information Axiom (little information content fostering change), and the independence concept defined within AD. Indeed, according to [16], the first axiom addresses modular designs, supposedly featured by a larger number of parts and greater complexity, while the second one favors the development of integral designs.

The same dichotomy complies with the discussion about the compatibility between the theoretical background of AD and TRIZ. It is worth emphasizing how often the latter is integrated with AD [17, 18, 19], in order to overcome the former's limitations in terms of identifying practical solutions to emerging design problems; a relatively recent contribution that combines the two design methodologies can be found in [20]. It is claimed that integral design is the "natural" outcome of the TRIZ ideality concept, in contrast with the first axiom. A possibility to overcome this contradiction is represented by leveraging independence without increasing the number of components. A case in point is the faucet example, which presents aspects of both AD independence and TRIZ ideality, as the new system architecture is more compact than its predecessor. Rather than introducing new parts that fulfill a specific function, different DPs of a single component (two distinct rotation angles of the mixer faucet) make it possible to pursue independence.

While the faucet case can be seen as a win-win situation, similar results could not be achieved in different circumstances, as the classical AD example includes just two FRs. A possible alternative is the partial infringement of some design fundamentals. As Frey et al. [21] suggest 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 ideality or the first axiom fail to explain changes in successful designs. Besides, Ibragimova et al. [22] admit and tolerate the existence of certain degrees of non-ideality in terms of lacking adherence to AD principles. More explicitly, Cebi and Kahraman [6] point out that some designs are to be considered satisfying, even if they do not comply with the Independence Axiom. Moreover, according to Tang et al. [23], the interactions (and independence) among DPs cannot be ensured in the initial design phases in which AD is commonly applied.

In addition to the above shortcomings, other inherent AD limitations concern dynamic systems and transitory effects. Time is never leveraged in AD, existing AD-based DPs vs. FRs matrices never include time-dependent factors [24], as well as Suh's design theory admittedly shows limitations with regard to time-dependent problems [25]. This is somehow reflected by the attempt of transforming time-dependent systems into designs with periodical functionality, whose predictable effects allow for comparing them with static systems in terms of stability [26]. However, different forms of time dependency associated to DPs are likely to emerge in engineering systems [27]. Moreover, the attempt of steering towards periodical functionality cannot be considered compliant with the objectives of Industry 4.0, where consumer-related information is massively introduced through big data [28]. It can be noted that customer preferences are hardly predictable and show markedly irregular patterns [29]. As a result, the need to adapt AD to dynamic models that include the social dimension is remarked in [30].

Overall, the applicability of AD seems to be limited to certain circumstances, which cannot be always met when designing, especially in the incumbent highly automated and digital technology-driven industrial framework, despite the supposed suitability of AD to face certain inherent design challenges. The ideal conditions for employing AD include absence of any time-dependent phenomena, full controllability of the DPs in play, existence of the possibility to decouple systems (despite good designs exist that do not fulfill independence) without increasing the number of components and modules. In this sense, the present research illustrates a way to include non-predictable time behaviors within the parameters that feature AD-based design processes and a procedure that favors the relaxation of the limiting one-to-one mapping between DPs and FRs.

3 Axiomatic Design extension for Dynamic Systems

We address here the limitation of required equality of functional requirements and design parameters.

We need to revisit the Control theory as it has already developed very useful analytic tools for system analysis. For those looking for foundations of Control Theory, which are taken here for granted, we recommend any classic control textbook, e.g. [31]. Thus, we first consider a general linear system that is seen as a transformation (called Transfer matrix) of the vector of inputs to the vector of outputs. The transformation is also called "multi input multi output (MIMO) transfer function". Let the MIMO system be described by a set of linear differential equations, so we can give it the operator form $y = G(s)u$. The variable s is Laplace operator and its simplified meaning is that the relationship between y and u is dynamic or the system has a memory or the inputs are transformed into outputs with a time delay.

For the MIMO system $G(s)$ is $m \times r$ matrix of transfer functions from the i-th element of the input vector u to the j-th element of the output vector y. The definition of output controllability from Control Theory is the following. Output controllability (OC) is the related notion for the output of the system (denoted y in the previous equations). The OC describes the ability of an external input u to move the output from any initial condition to any final condition in a finite time interval.

In other words, if the system has the property of OC, for any given output position $y(T)$ it can be found an input signal $u^{*}(t)$ that takes the output $y(t)$ to the desired position in the time interval T (from any initial state $y(0)$). In the case of static systems, the $G(s)$ degrades into a static gain matrix $G_{m\times r}$ and output controllability simply requires that G is to be square $m = r$ and invertible $det(G) \neq 0$. If we approach this "design" in an AD perspective, the system design would have been called "independent", because the number of inputs is equal to the number of outputs and each output is affected by its corresponding input.

But if we consider the general case where $G(s)$ represents a linear dynamic system, the latter requirements can be relaxed. First, the number of inputs can be less than number of outputs while the system is still under the conditions of OC. It is formulated in the following theorem [31]:

For a linear continuous-time system, described in time domain by a quadruple of state space matrices *A,B,C* and *D*, the matrix of the system operator *G*(*s*) can be directly found

$$G(s) = \mathrm{C}(sI - A)^{-1}B + D \quad . \tag{1}$$

We skip the derivation of the output controllability condition here that can be found again in [31]. Its simplified interpretation is the following: there is a specific algebraic matrix, the OC matrix, that can be found if we know system parameters (or, what is the same, *A,B,C*, *D* quadruple). This matrix has a full row rank if and only if the system follows OC.

Qualitatively projecting the statement above into AD evaluation principles, one can conclude that if the system is dynamic and "well designed", then any desired output position can be reached by manipulation with inputs, even in the case the input is scalar. In the design practice, this means that making the system dynamic may reduce the number of control inputs (i.e., making the control interface easier) while maintaining the full control of output.

The classical faucet example from AD is based on the statement that there are two DPs, (either hot and cold water valves or flow and temperature valves if the design is independent). If the faucet design is dynamic, we can reduce the number of valves (controls) to one. Indeed, the practical realization could for example mean the single valve that is first used to assign the flow and, after a period of time, is used to assign the temperature. Therefore, it may be seen that a DP controls both FRs when time is considered in such a model.

Then the interface concept of such a valve could have a look as in the Fig. 1. The first raw of numbers (black) can represent the required temperature while the second (blue) represents the flow intensity. It is assumed that the first move of the valve is used for temperature assignment and the second move (either immediately or after a short period of time) is used to assign the flow. The realization of such a mechanism does not seem to be a complicated problem, the same idea has been used for example for mechanical code locker in safes: the rotation of the same code wheel is used to input various number of the opening code.

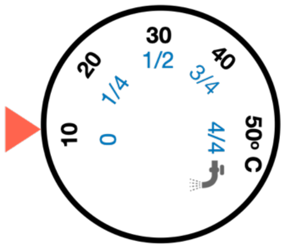

Fig. 1. A dynamic valve with time-sensitive scale.

It is worth mentioning that the variability of the transformation of DPs into FRs with time is already a point of discussion in the developments of AD [36]. Suh introduces the concepts of time-dependent combinatorial and periodic complexity. At the same time, it can be argued that these concepts and their definitions are used to illustrate complexity instead of seeing them as the source for design solutions.

4 Axiomatic Design extension for Dynamic Systems

The classical multivariable control theory affirms that a dynamic linear MIMO system with equal number of inputs and outputs, in which changes in each single input result in changes in all outputs can be decoupled and given an independent (according to AD) form by assigning proper feedback controllers. The idea is illustrated in the Fig. 2. A MIMO plant with the transfer matrix $G(s)$ is uncoupled. Under certain conditions, it can be given a feedback controller described by the transfer matrix $C(s)$, that the relationship between new inputs to the system w_{i} and outputs y_{j} is decoupled. So, the closed loop system, or the new system block (that is given the gray background in Fig. 3) has diagonal structure.

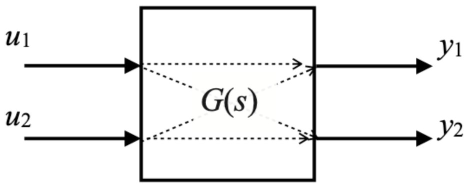

Fig. 2. Decoupling by feedback. Original plant.

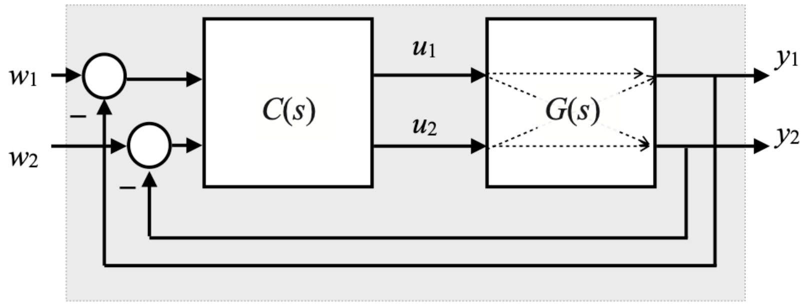

Fig. 3. Decoupling by feedback. Plant with feedback controller.

This theoretical result, most probably first delivered by Gilbert, can be seen as a hidden inversion of the plan $G(s)$ with the help of feedbacking [32].

A note about linearity is needed here: an obstacle for the applicability of the formal derivations above is the fact that input-output relationships are nonlinear in general. This means that the relationship between inputs and outputs has a more complicated form than $y = G(s)u$, so the matrix $G(s)$ cannot be extracted. Nevertheless, it should not be a conceptual deal breaker: first, linearization is always possible, so in the vicinity of a certain point (for example, near the basic operation point) we can approximate the reality by linear input-output relationships. Second, there are classes of nonlinear systems that can be decoupled [33].

To give this general fact an application example we choose the classical distillation column decoupling design [34] (see Fig. 4, 5). There are three inputs (valves' position u_i) and three outputs (distillate fraction concentration y_j) shown in Fig. 4. The relationship between the input and the output is dynamic and described by the linear transfer matrix $G(s)$. We take the valve position as DP and the concentration of the distillate as the FR for this system. The nature of the distillation process is such that changes in the position of any control valve affect all three concentrations of the output, which means that the matrix $G(s)$ is non-diagonal. The system design is coupled while we would like to be able to assign the concentration of any output independently. In other words, we would like to make the design independent. It is hardly possible to change the design of the operating device in most real industrial cases. But if the feedback control paradigm is admissible, the problem can still be solved. A new system architecture is illustrated in Fig. 5. It can be shown that, given the model of the process $G(s)$, the controllers $g_{ij}(s)$ can be tuned in such a way that the closed loop input-output behavior is autonomous. So, new input valve variations Y_{di} would affect the corresponding output concentration only.

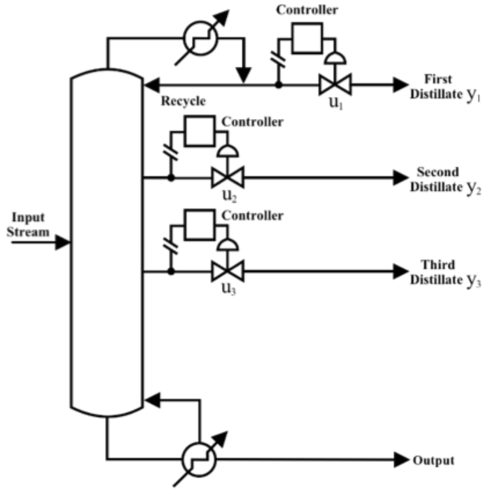

Fig. 4. Example of parameter-dependent design of a distillation column. u_i — input parameters (valves) and y_j — output parameters (distillate fractions).

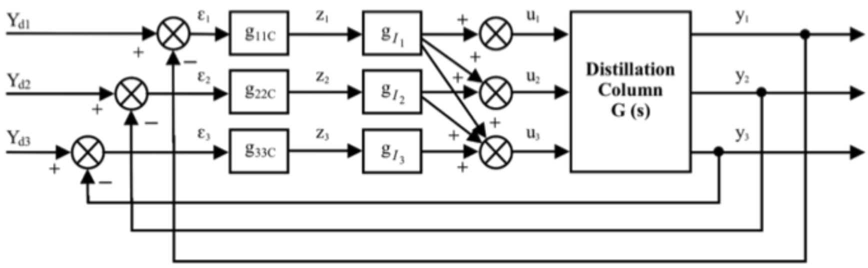

Fig. 5. Example of the structure of a decoupling feedback controller. u_i — input parameters (valves) and y_j — output parameters (distillate fractions), $G(s)$ — feedback control parameters.

5 Discussion, crosstalk of AD, TRIZ and Control Theory

It has been already mentioned in the introduction that the authors see TRIZ as one of the instruments closest to AD in inventive design. This section is not intended to extend the AD theory with TRIZ tools, but to point out how TRIZ is relevant to AD and also how TRIZ might be linked to the AD in the context of the Control Theory. More specifically, out of the basic concepts or formal tools of TRIZ, Contradiction analysis is directly addressing the uncoupled design situation with two important differences. First, TRIZ analysis is limited by the case of 2x2 design matrix. This is a serious drawback for the analysis of complex systems, as we need to reduce it to pair subsystems, which is not always possible. The second limitation is that, while in AD the FRs are mostly parameters or variables, the function requirements are always design criteria in TRIZ, so they are always fitness indexes that can be used to compare designs. In other words, TRIZ contradictions are correctly formulated when changes in one DP is good for one FR but bad for another. However, the advice from both AD and TRIZ is identical: change the design in such a way that the system is decoupled, that means the contradiction is resolved in such a way that each FR can be addressed (obviously, improved) independently by separate DPs.

However, the formal application of TRIZ can be extended even after the achievement of a decoupled design. The necessity to address two (or even several) FRs with only one DP can also be seen as a contradiction in TRIZ school of thought. Indeed, the situation when conflicting requirements are exposed to the same element of the system is called physical contradiction [35]. Coming back to the faucet example and the idea of Fig.1 solution: we have here a DP, ”a valve” and two requirements, namely, to use it for temperature assignment and for water flow regulation. TRIZ suggests separation principles as the systematic way to ideate a possible design improvement. Interestingly, separation means exactly finding a new design which is decoupled. In contrast to AD, TRIZ goes a bit beyond the recommendation and also suggests considering specific ideas for separation: separation in time and separation in space, among others. Using the time domain for decoupling, the design of faucet in Fig. 1 can be seen as a possible implementation of separation in time. One can also try to apply “separation in space”: a possible result could be embodied by a sector of the valve used for flow control and another sector for temperature assignment. Actually, this design is almost a standard for shower faucets in North America, where there is a single valve and a user is unable to get his/her warm shower without being exposed to a portion of cold water.

Finally, the ideality concept of TRIZ should force a designer to think of even simpler system interfaces. With this objective in mind, having ensured the possibility to address the FRs, the fewer DPs we have to deal with the better. Simply speaking, the fewer “valves” we have to control the better and the design with one valve is “more ideal” according to TRIZ. Moreover, the aggressive application of ideality concepts would model a controllable faucet without any valves at all (think of an AI-supported faucet that can predict what kind of flow/temperature combination will be needed). Again, these design ideas would definitely show how TRIZ-driven design differs from AD-driven design (and its possible combination with Control Theory), but for the practicing engineer the instrument is not as much important as the result.

A final comment needs to be added in regards to the quantitative system Control Theory. One can see a problem in the decoupled design that relates to system robustness. Having decomposed the system, we lose any possibility to influence a FR if the corresponding DP is not working well, the subsystem is broken. In other words, if the decoupled faucet has a problem with the water flow channel (e.g., it is clogged), changing the temperature valve does not yield anything, we are not able to get any “water”. While in the “old fashion” faucet, even having one of the valves broken, both FRs would still be partially delivered. This problem can also be tackled with the MIMO dynamic paradigm from Control Theory. In simple words, the theory says that input-output controllability can be achieved for the systems by introducing feedback controllers in which the number of inputs is less than the number of outputs.

6 Conclusion

AD instruments provide a valuable insight for qualitative design evaluation. Indeed, having defined the inputs and outputs for the designed system, one can quickly check whether it is convenient for the user to address the outputs by the inputs. Thus, AD helps to evaluate the usability of the design or the user interface, although the user interface can be given much wider sense, evaluating the interactions of the design during manufacturing, installation and maintenance.

At the same time, AD has its restrictions in terms of applicability. First of all, AD well identifies a good design, but it is more limited in terms of guiding the design process towards a good/independent design from the existing structure. Second, AD is particularly suitable just in those cases where the number of DPs is equal to the number of FRs. Another limitation is the fact that the mapping from DPs to FRs is static, whereas very often the influence of DPs on FRs is time-dependent; here, we have argued that AD also neglects possible valuable resource – time.

In current research these drawbacks have been addressed from Control/System Theory prospective, which is the original contribution of the present paper. We have speculated through some examples how Control Theory could help overcome some of the above limitations. More research is clearly needed to validate the benefit of juxtaposing AD and Control Theory, also in light of the possible difficulties in using the latter proficiently for designers. We have shown, yet through some examples, that some results could be similar if AD is integrated with TRIZ, where this combination is abundantly described in the literature. However, results can vary and the choice of the methodology might depend on design objectives and priorities.

It is in the authors' intention to develop a full integration of AD, TRIZ and Control Theory, which can possibly face the deficiencies of the used design methodologies.

However, already in the current integration of AD with Control Theory, it is possible to generalize AD with the time-domain, thus enabling tackling dynamic systems through the use all the operators of Control Theory. And even though the use of Control Theory causes the introduction of the time dimension with a consequent increasing complexity of AD, the new opportunities of such an approach make the applicability of the framework wider and more generalizable. Thus, we showed that a controller can be added for the system design to make it independent, which is one of the main challenges stated in AD. As an additional contribution, we extended the definition of independence to the case where the number of FRs does not correspond to the number of DPs.

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