Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 119 (2023) 357–362

www.elsevier.com/locate/procedia

33rd CIRP Design Conference

An approach to the selection of design parameters based on conflict with constraints

Filipe Sousa[a], António Gabriel-Santos[a,b,d], António Mourão[a,b,d], João Fradinho[a,b,d], Miguel Cavique[b,c,d,*]

[a] Department of Mechanical and Industrial Engineering—DEMI, NOVA School of Science and Technology, Campus de Caparica, 2829-516 Caparica, Portugal
[b] UNIDEMI, Department of Mechanical and Industrial Engineering, Faculty of Science and Technology, Universidade NOVA de Lisboa, Campus de Caparica, Caparica 2829-516, Portugal
[c] Naval Academy, Base Naval de Lisboa, Alfeite 2810-001 Almada, Portugal
[d] Laboratório Associado de Sistemas Inteligentes, LASI, 4800-058 Guimarães, Portugal
* Corresponding author's e-mail address: cavique.santos@escolanaval.pt

Abstract

The Axiomatic Design (AD) supports decision-making based on the axioms of independence and information. In the engineering design activity, the designer must make early decisions that impact the success of the project. These decisions are of paramount importance in the design of one-off products. In these products, one must make decisions in the early design phases, with scarce data about the product that will undeniably affect the solution. Applying the information axiom requires data from the alternative solutions under consideration that for one-off products are most often non-existent in the conceptual phase of the design.
Additionally, the design process is highly conditioned by existing constraints, which significantly influence the outcome. This work suggests selecting design parameters (DP) for one-off products from different sets of proposals that comply with the independence of functional requirements (FR). AD design follows a hierarchical decomposition process from a conceptual to a detailed design. The proposed method allows selecting the DPs among the set of alternatives by quantifying the degree of conflict each solution presents to the constraints. It shows the first step to define the DPs, at each level of decomposition of the AD process. It is the first step to establish a zig in AD or, otherwise, a way to find a solution in the conceptual phase. It applies to one-off products – any product with one chance to be right. The paper applies this method to the DP selection of a manipulation device.

Keywords: Constraints, Design Parameters, Axiomatic Design, one-off products

1. Introduction

One-off products are of crucial importance for a designer. In the conceptual stage, the designer needs to achieve a budget for an ill-specified product that anchors its price.

All one-off designs have no opportunity to fail. The methodologies to handle one-off products apply to all challenging humanity problems. Eco-design using the Axiomatic Design (AD) theory is a trend in this direction [1].

Many humankind problems, such as renewable energy, deforestation, water production, and control of weather patterns, have one-off solutions [2].

A first evaluation of the feasibility of a solution is of paramount importance. It is crucial for a first budget definition in any problem. Moreover, in some one-off industries, it also defines the budget and the solution. A design can be one-off due to budget or time frame commitments. The solution under evaluation must comply with the constraints (Cs).

10.1016/j.procir.2023.03.102

Nomenclature

A	Design matrix
AD	Axiomatic Design
AGV	Automated Guided Vehicle
Cs	Constraints
CN	Customer Needs
DP	Design Parameters
DM	Design Matrix according to Axiomatic Design theory
FR	Functional Requirements
PV	Process Variables

After defining the needs, the designer must identify the Cs. A limit in total weight, cost, or dimensions are examples of typical Cs. Cs restricts the hyperspace of solutions in the requirement, physical, and manufacturing domains. Therefore, successful one-off products are examples of concurrent engineering. Moreover, for some applications, a reverse process can be used [3]. Any coupling between Cs in the same or different domains is a further cut in the hyperspace of solutions. As an example, the inexistence of process manufacturing machines affects the physical solution domain.

There are input Cs and system Cs. Input Cs are defined in all mentioned fields at the conceptual phase of the design. Otherwise, system Cs arise during the development of the design. They emerge in the development of a physical solution. Moreover, the input Cs can interplay in more detailed design phases [4]. In this paper, conflicts are non-compliances between DPs and system Cs at a certain level of decomposition.

All system Cs are unpredictable until the design arises that specific level of decomposition. It is a cause for the oversize of some critical compounds in one-off products. Unlike mass-production products, oversizing one-off products is welcome. Cs can also measure the negative aspects of a design [5].

A design can be descriptive or prescriptive [6]. The prescription allows the designer to define the objects or processes to meet the customer's needs. Axiomatic Design (AD) theory is a well-known prescription theory. AD maps the design hierarchically in a zigzag between the domains of Customer Needs (CN), Functional Requirements (FR), Design Parameters (DP), and Process Variables (PV) [7] (Fig. 1). Moreover, AD grounds on two axioms: the first, maintain the independence of the FRs – the independence axiom; the second, minimize the information (maximize the probability of success) of the design – the information axiom [7].

The product design can be expressed by equation (1), where A is the design matrix, which relates FRs to DPs. If A is diagonal, the design is uncoupled; if A is triangular, the design is decoupled; and if A is neither diagonal nor triangular, the design is coupled. Regarding AD, the best design is uncoupled, and the worst is coupled. Uncoupled designs allow us to achieve all functions independently of each other. From two different independent solutions, the best solution has less information content (second axiom), which means that it has the best probability of success with actual knowledge.

As mentioned above, Cs may act as input or system Cs. All AD domains of Fig. 1 can be restricted by Cs [8].

AD is a solid theory to help define a design by mapping in sequence from CN to FRs, DPs, and, if necessary, PVs. However, AD lacks a fundamental approach to using Cs. Cs can interrelate [9] with variables of the design, creating a network of Cs and variables. Therefore, Cs may interact. A cross matrix of Cs well defines the interactions.

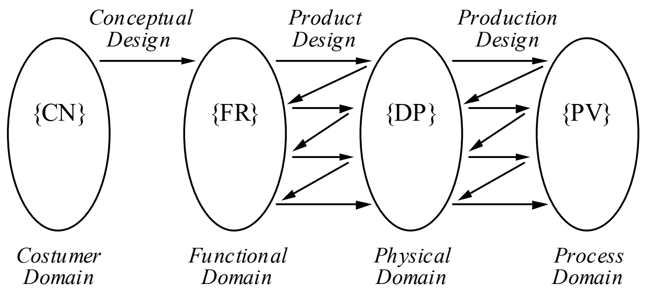

Fig. 1. The design process as mapping through the four design domains

$$\{FR\} = [A]\{DP\} \tag{1}$$

Many authors have discussed the interplay between AD and Cs. Ang Liu [8] introduced the internal and external Cs taxonomy. For an existing product, he defines and classifies the Cs. Then analyze the dependency of FRs on Cs and propose alternative DPs to synthesize in a solution. In Industry 4.0, human interference introduced extra Cs that need to be considered [10].

The region defined by Cs allows to "minimize functional coupling", minimize conceptual constraints, and maximize the system performance [11]. Cs reduce the hyperspace for available solutions. Other methods, like Analytical Hierarchical Process with multicriteria analysis, can also reduce the number of possible solutions [12]. Noise can enter the equation to increase the robustness of the solution [13]. System requirements and Cs may vary over time, making the problem more challenging. The solution is a programmed system reinitialization [14].

This work allows defining a conceptual physical artifact in the physical and process Cs regions. FRs should not conflict with Cs. The novelty of this approach is to identify the possible DPs that fulfill the FRs with a minor conflict with Cs. This work gives contributions regarding how to handle Cs in the AD theory. It applies to all levels of decomposition. However, at the high-level conceptual phase of the design, it allows a definition of the high-level DPs and, therefore, the cost range of a one-off product.

This work presents a methodology to reach the mentioned target in the next section. The methodology uses some fundamental theorems and corollaries of AD. Then section three shows an example. Finally, the interrelation between this method and AD and the conclusions are presented at the end of the work.

The authors intend to contribute to understanding the role of the Cs in the AD theory. An important conclusion regards incrementing the information content by minimizing the conflicts with the Cs.

Many one-off product malfunctions emerge from conflicts between design parameters and constraints, often detected at the implementation phase.

The manufacturing company contracts a product based on a budget defined in the conceptual design. It arises from the problem definition between the designer, the customer, and all stakeholders. The client's perception of the solution concepts is essential, a need that the designer must be able to explain. The Axiomatic Design is an excellent way to define and explain the design conceptually.

Specifications result primarily from a trade-off between the needs of the customer and the understanding and insight of the design team. One-off products are typically ill-specified. Consequently, the clients cannot identify the budget itself.

AD can help overcome the misunderstanding by defining a consensual conceptual solution. It begins with the definition of the independent high-level FRs. As previously declared, Cs arise from initial specifications and during the system design regarding interactions of proposed DPs. One critical issue is the establishment of DPs - it must be clear to the client that DPs fulfill a possible solution.

This approach also applies to any design at the first conceptual phase. Moreover, many projects have no second chance to redefine the design in more detailed phases. However, a budget is necessary without a detailed design. AD axiom of information can only be ambiguously evaluated. At the conceptual phase, the designer can perceive the information using their belief and plausibility about the solution [15]. Nevertheless, the less the DPs conflict with the Cs, the better they fulfill the FRs, which increases the belief and plausibility of the solution. Hence, reducing conflicts between DPs and Cs is a measure of the information content of the design.

2. Methodology

The methodology allows defining DPs at a certain level of decomposition in the AD process. At a high level of decomposition, it can be a single shoot to attain the solution. It can apply to a one-off product or other projects that make it impossible to come back and redesign. Due to contractual clauses, budget, or lack of time, coming back can be impossible. Otherwise, a new solution may be sought if the axioms of AD are not fulfilled. The methodology described below warrants fewer conflicts between the physical solution and Cs. Therefore, it improves the probability of success of the design. The proposed methodology has six stages in sequence [16], corresponding to six flow-charts as described below.

First stage – generation of alternative solutions to DPi – from a set N of FRs, FR_i (i=1, …, N) is created a set of M alternative solutions for DP_i (Fig. 2).

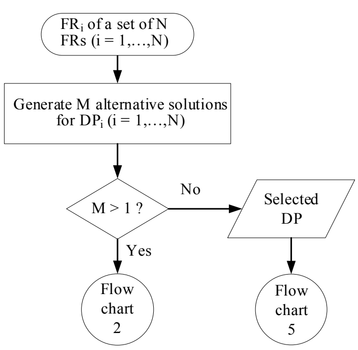

Fig.2. Flow-chart 1 - Generate alternative solutions to DPs

Second stage – selection of DPs that do not affect the remaining FRs – use the set of M alternative solutions and evaluate the $DP_{i(j)}$ ($i=1,...,N$; $j=1,...,M$), which do not affect the FR_k ($k=1,..., N$; $k\neq i$) (Fig. 3).

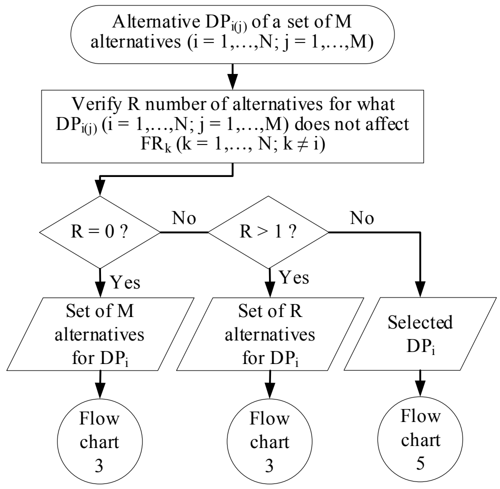

Fig. 3. Flow-chart 2 - Selection of DPs that do not affect the remaining FRs

Third stage – selection of DPs that include standardized components or previously successful solutions –reduces the uncertainty, therefore increasing the belief in the solution. Moreover, it counteracts data scarcity during the ill-detailed phase of the design. The same happens by using proven, successful solutions (Fig. 4).

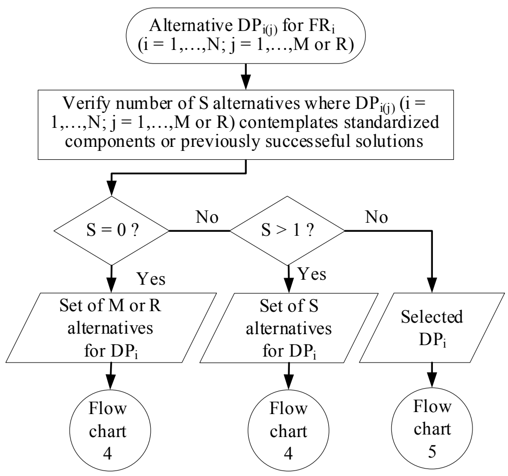

Fig. 4. Flow-Chart 3 - Selection of DPs that include standardized components or previously successful solutions

Fourth stage – selection of solutions with the least degree of conflict with the constraints – Cs create a region to define the solution. However, it may be impossible to maintain all DPs in the Cs region (Fig. 5). Try to find an alternative solution that is easy to develop and fulfills the FR under the Cs, by computing a conflicting value. The conflicting value of each conflict is computed for each DP_i assigned a degree of conflict for each constraint Cs_i. The Cs are weighted so that the computation regards the conflict and the Cs. The best DP_i solution is the one with the lowest sum of conflicting values. Solutions with similar low conflicting values are viable solutions. Other criteria, such as aesthetic, safety, or occupied space, can help choose between $DP_i s$. Selection criteria cannot be identified as FRs.

Fifth stage – validation of constraints between the set of selected DPs – the set of selected DPs may relate to each other.

Examples of relation are physical connections and relative movement of a DP_i to another DP_j. Display the DP relationships in a (DP_i x DP_j) matrix. A matrix element is "0" if DP_i does not constrain DP_j. Use "*C*" if there are constraints between DPs. Check if the DP relations cause any system Cs among the selected DPs. Case all off-diagonal of the matrix is zero, move to stage sixth. If some off-diagonals are "*C*" check the remaining alternatives using DPs of *StdSol*, and DPs that do not affect the remaining FRs. These DPs should be reassessed in the fourth stage (Fig. 6 and Fig. 7 – corresponding to the flow-charts 5 and 5.1).

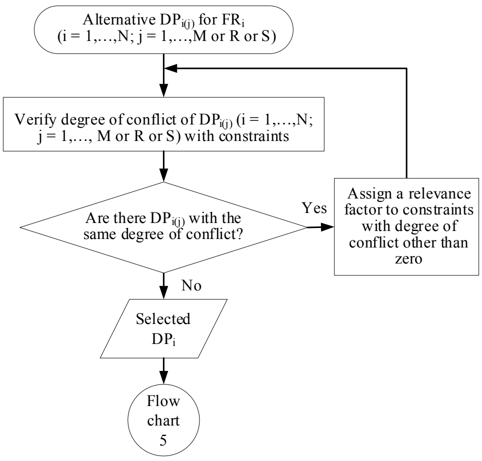

Fig. 5. Flow-chart 4 - Selection of solutions with the least degree of conflict with the Cs

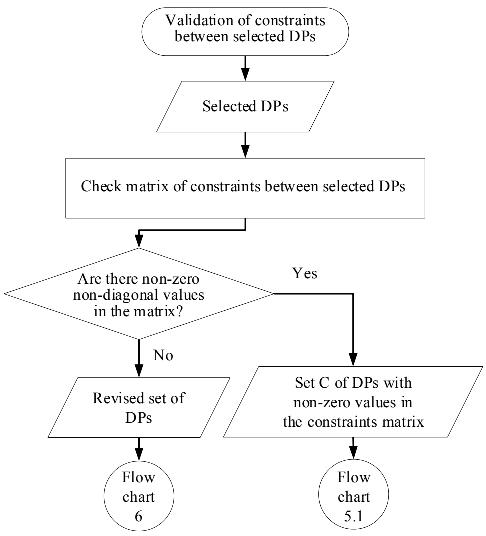

Fig. 6. Flow-chart 5 - Validation of Cs between the set of selected DPs

Sixth stage – validation of the independence of the global solution – defines the AD design matrix (DM) that expresses the relationship between FRs and DPs. This matrix is a consequence of decisions ending on a conceptual solution.

By analyzing the DM, the designer may identify couplings and try to select other DPs. Alternatively, a coupled solution can be accepted - if possible, join the couplings parts in a module. Eventually, the problem can be redefined by new FRs (Fig. 8 and Fig. 9 as per flow-charts 6 and 6.1).

3. Case study

This section illustrates the application of the methodology. Table 1 assesses the degree of conflict for the three alternative solutions for $FR_{1.2}$, showing the conflict with the Cs and $DP_{1.3}$. The first alternative solution will be the best, as described below.

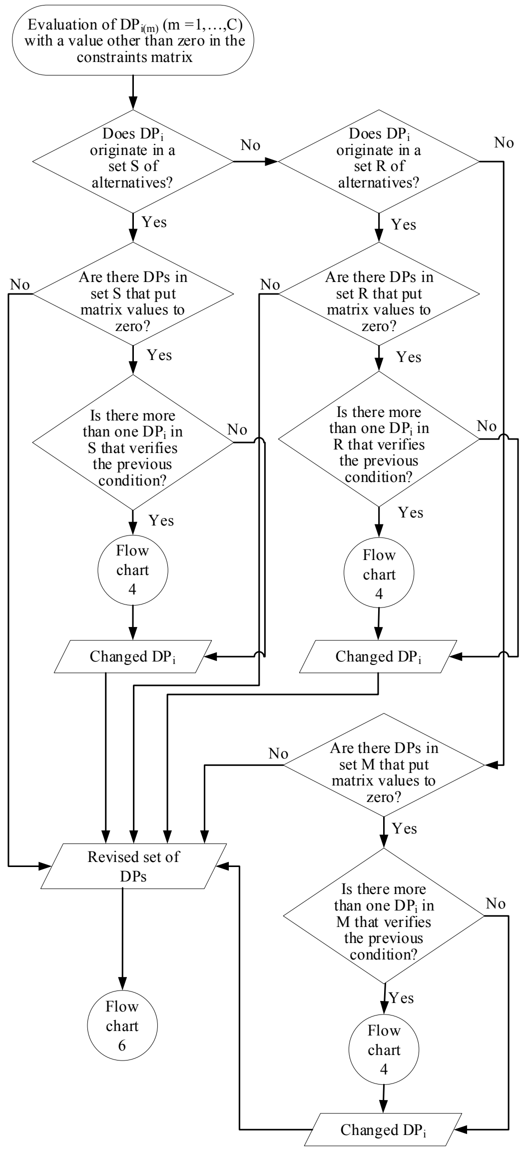

Fig. 7. Flow-Chart 5.1 - Verification of DPs with non-zero constraints on each other

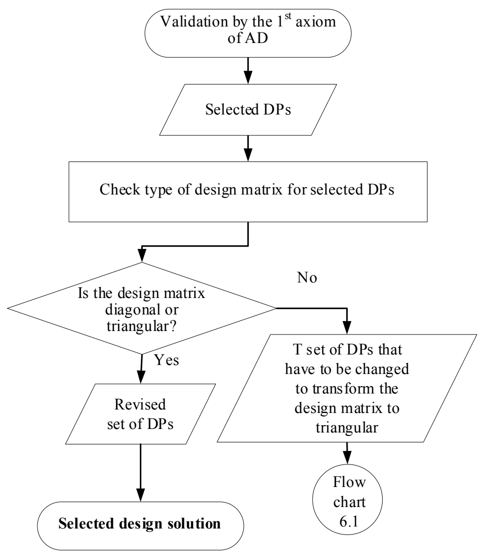

Fig. 8. Flow-chart 6 - Validation through the 1st axiom of AD

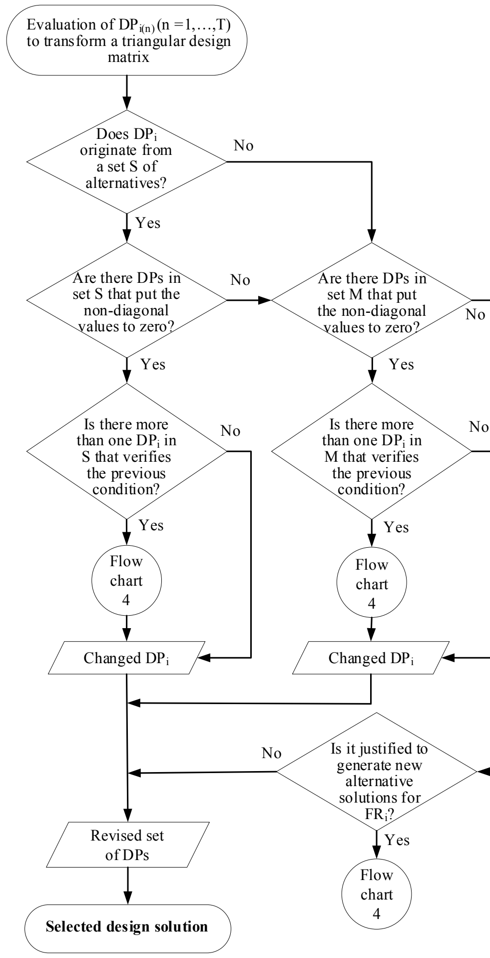

Fig. 9. Flow-chart 6.1 - DPs alternatives so that the DM is triangular

To avoid an uninteresting description of all details, this section deeply covers the selection of one of the DPs.

The complete application to an industrial design is described by Sousa [16]. The application covers step-by-step the definition of a one-off product for a manufacturing company. It concerns the transfer of loads in a warehouse from one position to another. The loads arrive on trailers moved by an automated guided vehicle (AGV) that follows a predefined path. The loads must be removed from the trailer and placed on an existing roller conveyor (Fig. 10).

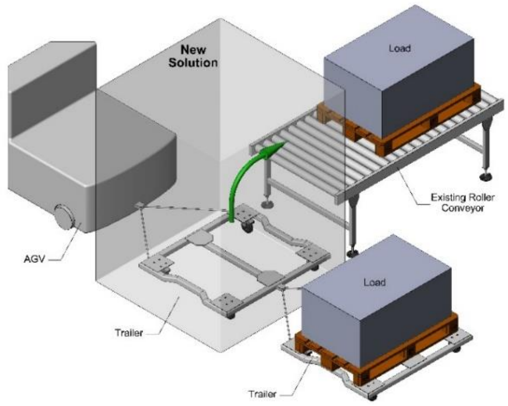

Fig. 10. Schema of the CN of this design

The high-level functional requirement FR_1 is "transfer loads automatically from the autonomous vehicle to the roller conveyor". An automatic load transfer system is the DP_1 that physically materializes FR_1. The system picks it up at the collection point, moves it, and drops the load at the delivery location. The transfer system should ensure each load is in the proper condition to be collected.

Thus, the following FRs are stated as a decomposition of FR_1 considering the selected DP_1: $FR_{1.1}$ Ensure the load is ready to be picked up; $FR_{1.2}$ Pick-up and drop the load; $FR_{1.3}$ Move the load; $FR_{1.4}$ Ensure safety during equipment operation.

From the warehouse working conditions, the following constraints were stated (Cs): C_1 Maximum load weight; C_2 Geometric configuration of the load; C_3 Maximum load dimensions; C_4 Distance between the vehicle and the load; C_5 Irregular distribution of the load; C_6 Predefined route of the automated vehicle; C_7 Maximum time for the vehicle to stay stopped; C_8 Maximum time for cargo transfer; C_9 Distance for detection the reaching of an automated vehicle; C_{10} Inability to communicate between vehicle and new systems; C_{11} Space available for implementing the solution; C_{12} Direction of movement of the existing roller conveyor.

This paper focuses on one component of the project. It aims to satisfy $FR_{1.2}$ regarding picking up and dropping the load. $DP_{1.2}$ materialize the solution. $DP_{1.2}$ is a system of lateral clamps running along the length of the load. Three alternatives illustrated in Fig. 11 are under evaluation: grippers with linear motion at the top, $DP_{1.2}(1)$; grippers with a rotary motion, $DP_{1.2}(2)$; and grippers with linear motion at the bottom $DP_{1.2}(3)$. Each DP at the second level of decomposition can have conflicts with Cs and other DPs.

The set of DPs obtained after using the methodology are as follows: $DP_{1.1}$ Validation system in the picking area; $DP_{1.2}$ Clamps with linear movement system on top; $DP_{1.3}$ Gantry for handling the suspended load; $DP_{1.4}$ Mechanical guards with optical barriers.

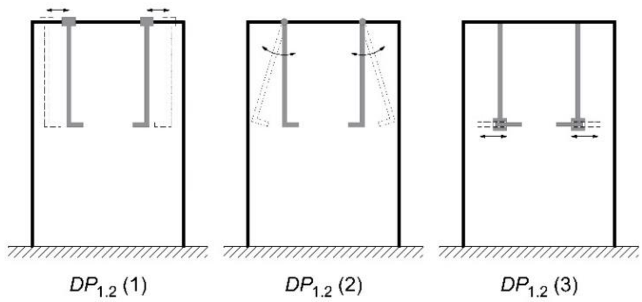

Fig. 11. Alternative solutions to materialize $FR_{1.2}$

There are constraints between $DP_{1.2}$, $DP_{1.3}$, and $DP_{1.4}$ (fifth stage). Table 1 shows the Cs between $DP_{1.2}$ and $DP_{1.3}$. At this stage, it was impossible to identify better DPs alternatives that would reduce the system Cs.

Solutions $DP_{1.2}(1)$ and $DP_{1.2}(2)$ have the same value for the degree of conflict for non-weighted conflicts evaluation. However, the geometric configuration of load (C_2) presents a greater degree of conflict for the $DP_{1.2}(2)$ solution than C_1 regarding $DP_{1.3}$. Due to the reduced space for inserting the grippers, it needs a small tolerance for rotary movement.

As shown in Table 2, $DP_{1.2}(1)$ is the solution, as it has the lowest degree of conflict with the constraints considering the relevant factors.

Table 1. Degree of conflict with Cs and DPs of the alternative solutions for $FR_{1.2}$

$FR_{1.2}$	Alternative Solutions		
Pick up and drop the load	$DP_{1.2}(1)$	$DP_{1.2}(2)$	$DP_{1.2}(3)$
Constraints	Degree of conflict (non-weighted)		
C_2	0	1	0
C_4	0	0	1
C_{11}	0	0	1
$DP_{1.3}$	1	0	0
Σ	1	1	2

$DP_{1.2}(1)$ - Grippers with linear movement system on top; $DP_{1.2}(2)$ - Grippers with rotary movement system; $DP_{1.2}(3)$ - Grippers with a linear movement system at the bottom

Table 2. Degree of conflict between alternative solutions for $FR_{1.2}$ considering relevance factors

$FR_{1.2}$	Alternative Solutions		
Pick up and drop the load		$DP_{1.2}$ (1)	$DP_{1.2}$ (2)
Constraints	Relevance factor	Deg. of conflict x Relevance factor	
C_2	2	0	2
$DP_{1.3}$	1	1	0
Σ		1	2

4. Discussion and Conclusions

The underlying approach to the budget for one-off products assumes decisive factors for its competitiveness: i) the customer's perception of the quality and functionality of the proposed solution; ii) the price; iii) the delivery time. It was assumed that for this purpose, to improve the functionality and the client´s perception and to allow right-first-time in project implementation, the conceptualization of the solution should follow the principles of AD theory.

This paper presents a methodology to select physical parameters (Design Parameters – DPs) among several alternatives. It aims to fulfill the Functional Requirements (FRs), avoiding interferences with the Constraints (Cs).

The methodology uses six stages. Stages one to four define each DP for each FR, by 1) selecting the possible DPs for an FR, 2) avoiding DPs that interfere with other FRs, 3) selecting standard or past well-performed solutions, 4) evaluating the possible sets for the DP under the Cs. Stage five checks the conflicts between DPs, and the last stage defines the Design Matrix. Stages two and four are AD procedures.

This work contributes to the DP definition under a set of Cs. It avoids optimization of DPs under a Cs space, which does not allow it to fulfill the independence axiom of AD. The methodology focuses on the physical domain, similar to a "constraint driven (re)design".

The methodology applies to one-off products. One-off products can be a machine, a process, a system, an organization, or any other product that has just one chance to be done. It happens due to a budget commitment or a time frame commitment. The methodology helps define the cost and budget of the product.

Moreover, it applies to the zig process at each decomposition level of AD, from the FR to the DP domains. If stage six shows a coupled design, then the design should be redesigned. New solutions should be envisaged if couplings cannot be removed from one-off products.

This work improves the belief in the solution due to the DPs compliance with Cs. Therefore, from the designer's point of view, the methodology helps increase the probability of success, or regarding AD, reduces the information content of the design. Therefore, the methodology helps to follow axioms one and two of AD at any zig from the FR to the DP domains.

Acknowledgments

The authors acknowledge Fundação para a Ciência e Tecnologia (FCT, I.P.) for its financial support through UNIDEMI, project UIDB/00667/2020.

References

[1] Giorgetti A, Girgenti A, Citti P, Delogu M. A Novel Approach for Axiomatic-Based Design for the Environment. In: Farid, A., Suh, N. (eds) Axiomatic Design in Large Systems. Springer, Cham.; 2016. https://doi.org/10.1007/978-3-319-32388-6_5

[2] Suh NP. Future Design Challenges. In Design Engineering and Science; Suh, NP, Cavique M, Foley J, Eds.; Springer Nature Switzerland AG: Cham, Switzerland; 2021. ISBN 978-3-030-49231-1.

[3] Vickery A, Rauch E, Brown C. Deriving Functional Requirements for Industry 4.0 from Industry's Assessment of Needs. in IOS Press, M. Peruzzini et al. (Eds.), Transdisciplinary Engineering Methods for Social Innovation of Industry 4.0. doi:10.3233/978-1-61499-898-3-23

[4] Zhang H, Han X, Li R, Qin S, Ding G,Yan K, A new conceptual design method to support rapid and effective mapping from product design specification to concept design, Int J Adv Manuf Technol, 2016, 87:2375–2389. doi: 10.1007/s00170-016-8576-6

[5] Brown C. Axiomatic design applied to a practical example of the integrity of shaft surfaces for rotating lip seals. Procedia Engineering 19 2011 53 – 59.

[6] Hubka V, Eder WE, Desing Science. Springer-Verlag London Ltd.; 1996. ISBN: 978-3-540-19997-7, doi:10.1007/978-1-4471-3091-8

[7] Suh NP. The Principles of Design. Oxford University Press: New York, USA, 1990. ISBN: 9780195043457

[8] Liu A, Wang Y, Teo I, Lu S. Constraint management for concept ideation in conceptual design. CIRP Journal of Manufacturing Science and Technology 2019, 24 35–48

[9] Hashemian M, Gu P. A Constraint-Based System for Product Design. Concurrent Engineering 1995; 3: 177 – 186. doi:10.1177/1063293X9500300303

[10] Ertay T, Satoğl SI. System parameter selection with information axiom for the new product introduction to the hybrid manufacturing systems under dual-resource constraint. Int J Prod Res 2012; 50:7, 1825-1839. doi: 10.1080/00207543.2011.560205

[11] Chen LC, Lin L. Optimization of product configuration design using functional requirements and constraints. Res Eng Des 2002; 13: 167–182. doi: 10.1007/s00163-002-0015-z

[12] Slătineanu L, Dodun O, Coteață M, Dulgheru V, Dușa P, Banciu F, Beșliu I. Selection of a Solution When Using Axiomatic Design. MATEC Web of Conferences 2017; 127, 01019. doi: 10.1051/matecconf/201712701019

[13] Wei W, Liang H, Wuest T, Liu A. A new module partition method based on the criterion and noise functions of robust design. Int J Adv Manuf Technol 2018; 94:3275–3285. doi: 10.1007/s00170-016-9797-4

[14] Matt D. Application of Axiomatic Design principles to control complexity dynamics in a mixed-model assembly system: a case analysis. Int J Prod Res 2012; 50:7, 1850-1861. doi: 10.1080/00207543.2011.565086

[15] Dodun O, Cavique M, Slătineanu L, Dușa P. Using the Axiomatic Design in Engineering, In: Advances in Product Design Engineering; Springer Nature Switzerland AG: Cham, Switzerland, 2022. ISBN 978-3-030-98123-5. https://doi.org/10.1007/978-3-030-98124-2.

[16] Sousa F. Uma Proposta Metodológica para Seleçao de Parâmetros de Projeto com base no Conflito com os Constrangimentos – Aplicação a produtos Únicos, Master Thesis, 2021, NOVA School of Science and Technology.