Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 84 (2019) 143–148

www.elsevier.com/locate/procedia

29th CIRP Design 2019 (CIRP Design 2019)

Axiomatic design and solution variants applied to a modular 3D printing head based in material extrusion

Porpíglio I[a], Scalice, RK[b], Silveira ZC[a,*]

[a] Department of Mechanical Engineering, University of São Paulo, Av. Trabalhador São Carlense, 400, São Carlos 13566-590, Brazil.
[b] Federal University of Santa Catarina, Technological Center of Joinville, Rua Dona Francisca, 8330, Distrito Industial, Joinville 89219-600, SC, Brazil.

*Corresponding author: *E-mail address:* silveira@sc.usp.br

Abstract

This paper presents a design procedure based on integration of the solution variants method and axiomatic design as choice criteria during the conceptual design phase. In order to evaluate the design procedure was choice a real problem related to the transmission system of a vertical twin screw head applied to a desktop experimental 3D printer. The main technical and research opportunities of the case study (3D printer head) include the use of powder as raw material in small quantities (around 200 g) for exploration of 4D printing through formulating of compounds and polymer blends, as well filament generation. To be compact due small work envelope; provide to access to fast assembly, disassembly, and maintenance and generate a torque next to 15 N.m are the main technical characteristics required for driven system of 3D head. Considering the different gears geometry and configuration including flexible transmissions options, the solution variants method was choice as screening criteria to ranking the feasible solutions. Based on weighting order, method allowed establishing multifactorial criteria, organized in a hierarchical tree. According this method, the conceptual design option obtained higher value was a worm screw gear for use as power transmission in case study. The use of axiomatic design allowed exploring the relations between functional and technical domains of the driven system. In order to measure the robustness of the conceptual solution obtained through this design procedure was estimated the indices of reangularity and semangularity from axiom of the independence whose value were 0.838 and 0.500.

Keywords: Heuristics methods; Selection Criteria; Extrusion Additive Process; Robustness Design.

1. Introduction

Design activities has an important whole in the product life cycle in order to transform the conceptual solution into a robust product to fulfill the design requirements and to obtain degree of innovation when necessary. Park et al. (1996) point out that the design and manufacturing areas account for 70 to 80% of productivity in the product life cycle. Queiroz (2011) [1] points out that failures occurring throughout the product design cycle are due to mistaken decision-making in the initial project activities. They are in these design phases corresponding to the informational and conceptual design, in which there is greater opportunity of interaction with the users, helping in the identification of the requirements and the potential restrictions of the product. According to the Sheldon et al. (1992) *apud* [1], the errors in the early design activities can reach a rate of the 41% in the product design development. Robertson and Robertson (2006) *apud* [1] highlights these decision-making errors can reach 60% during informational phase. The main points are failure that occurs in the design team communication and during the knowledge transfer between stakeholders, and mainly end user and developer [2].

Additive manufacturing defined as one of the technological pillars of industry 4.0 [3] allows the materialization of a virtual model. The virtual model is the result of a chain of design and manufacturing activities, with strong interdisciplinary interaction of knowledge from its concept to the final product. The use of additive processes to the design activities allows the generation of progressive mock-ups until technical prototypes with possibility of customization or personalization of the product. The additive manufacturing allow the generation of

10.1016/j.procir.2019.04.319

complex geometries, design process time reducing and to optimize the material use. However, the manufacturing time is higher, there is need for post-processing, the price and the maintenance cost of the equipment for additive manufacturing are high [4]. The market segment of desktop 3D printers has gained much importance in recent years, with an average sales growth reaching 88.6% from 2012 to 2015. Desktop, low end or personal are the terms generally used to define additive manufacturing (AM) printers sold by less than $5000 [4].

According to Kumke et al. (2016) [5] despite significant technological advances in basic and technological researches in additive manufacturing, there are a set of challenges related to guarantee control dimensional and surface quality, as well of the mechanical properties of the final product.

In this context, this paper presents a design procedure based on integration of the solution variants evaluation and axiomatic design to guide the search of solution conceptual. The design procedure was applied to a problem related to the transmission system of an innovative vertical corrotational twin-screw head [11]; [12] applied to an experimental desktop 3D printer.

2. Background

2.1 Solution variants method

According to Pahl et al. (2007) [2] the use of the solution variants method is related with: "to formulate evaluation criteria, it is necessary to identify their relative importance, i.e. their weight, to the overall value of the solution, so that irrelevant criteria can be eliminated before starting the evaluation itself." This weighting factor is a positive number between 0 and 1 based on contribution of an evaluation criterion. It is important to emphasize that the sum of the factors of all the goals of the level of less complexity should be equal to 1, aiming a percentage analysis of the same ones. The parameters known are correlated with the evaluation criteria adopted in an evaluation table. Using a scale of the 0 to 10, values are assigned for each evaluation criterion within each different type of solution. Then, the weighted value of each evaluation criterion is determined within each variant, multiplying the values assigned to each variant by the weighting factor of the evaluation criterion.

In this way, the determination of the global value of a variant is the sum of the column of the values of each variant, to determine the global value.

2.2 Axiomatic design: concepts

Suh (1990) [8] proposed two axioms that define an appropriate engineering design. The first was called "Axiom of Independence," which states that the independence of functional requirements should always be maintained. The second called "Information Axiom" states that a good project has a minimal amount of information. Therefore, Suh (1990) defined that axiomatic design is based on these two axioms: Axiom 1 - Axiom of Independence, with the objective of maintaining the independence of functional requirements (FRs); Axiom 2 - The Information Axiom, which minimizes the information content of the engineering design.

Kulak et al [6] presented four approaches to axiomatic design: type of axiom, area of application, method and type of evaluation. In the research, the authors indicated the use of axiomatic design concepts in product areas (42%), software design (23%) and modular design of high complexity (19%).

Two axioms were identified by examining the common elements technical feasible design. The first is the Independence Axiom, which states that the independence of functional requirements must be maintained. The second is the Information Axiom and states that among the design to satisfy the Axiom of Independence, the design has the lowest information content will be more feasible design [7-8].

The Independence Axiom establish that there are a certain number of Design Parameters (DPs) that can be meet the Functional Requirements set (FRs) in order to maintain their independence [8-9]. According to Wang et al. (2017), the main concern of the Independence Axiom is the relationships between FRs and DPs. These relationships can be expressed by equation 1: the vector of the functional requirements {FR} are those that define the design objectives, whereas the vector {DP} of the design parameters are the elements that satisfy each functional requirement.

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

The relationships between {FR} and {DP} is the design matrix [A], which can be written as equation (2):

$$[A] = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ . & . & \cdots & . \\ A_{m1} & A_{m2} & \cdots & A_{mn} \end{bmatrix} \tag{2}$$

According to the characteristics of the design matrix [A], three design cases are shown in the Table 2.

Table 1 - Relationships between FRs and DPs. Adapted: [9].

Type	Ideal	Decoupled	Coupled
Design Matrix	$\begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix}$	$\begin{bmatrix} A_{11} & 0 \\ A_{21} & A_{22} \end{bmatrix}$	$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}$

There are three results: Ideal matrix (main diagonal are null); Decoupled and coupled. The functional independence calculation is associated with the relationship between the coordinates {FR} - {DP}, presented for the two-dimensional case in Figure 1.

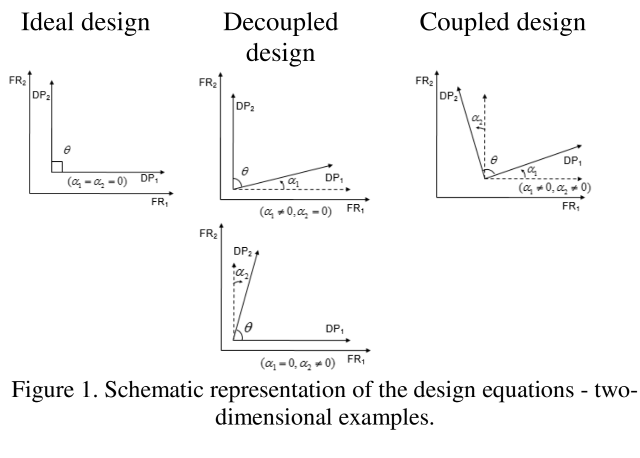

Figure 1. Schematic representation of the design equations - two-dimensional examples.

The Figure 1 demonstrates, according to [1], that FRs and

DPs must be orthogonal to do no disrespect the Independence Axiom. The DPs must be parallel to the respective axes of the FRs and the coefficients in the design equations are associated with the angles α_1, α_2 and θ. Based on it, were suggested two scales to measure the degree of functional independence: Reangularity (R) and Semangularity (S). The first metric (measure of Interdependence) that measures the degree of orthogonality between the design parameters is given by equation (3):

$$R = \prod_{\substack{i=1,n-1 \\ j=1+i,n}} \left(1 - \frac{\left(\sum_{k=1}^{n} A_{ki} \cdot A_{kj} \right)^2}{\left(\sum_{k=1}^{n} A_{ki}^{\,2} \right) \cdot \left(\sum_{k=1}^{n} A_{kj}^{\,2} \right)} \right)^{1/2} \quad (3)$$

According to Queiroz (2011), the measure R is not enough to fully represent the degree of functional independence. The measure of semangularity is an auxiliary criterion that measures the angular relationship between the corresponding axes of design parameters and functional requirements. It is defined by equation (4):

$$S = \prod_{j=1}^{n} \left(\frac{|A_{jj}|}{\left(\sum_{k=1}^{n} A_{kj}^{\,2} \right)^{1/2}} \right) \quad (4)$$

Therefore, the closer to 1 are the R and S measures, the greater the functional independence. The Information Axiom states that the design with the highest probability of success is the best. The content of information I_i for a given functional requirement (FR_i) is defined in terms of the probability P_i of satisfying FR_i explained by equation (5):

$$I_i = \log_2 \frac{1}{P_i} = -\log_2 P_i \quad (5)$$

The information is given in units of bits. The logarithmic function is chosen so that the information content is additive when there are many functional requirements that must be satisfied simultaneously. In the case of m functional requirements, the information content for the complete system I_{sys} is given by equation 6, being P_m the probability that all m functional requirements are satisfied by expression (6):

$$I_{sys} = -\log_2 P_m \quad (6)$$

When all the functional requirements are statistically independent, as is the case of a decoupled design, $P_{\{m\}}$ is given by the product operator of equation (7), and I_{sys} can be expressed by equation (8):

$$P_{\{m\}} = \prod_{i=1}^{m} P_i \quad (7)$$

$$I_{sys} = \sum_{i=1}^{m} I_i = -\sum_{i=1}^{m} \log_2 P_i \quad (8)$$

When no functional requirements are statistically independent, as is the case of a decoupled design, we have equation (9):

$$P_{\{m\}} = \prod_{i=1}^{m} P_{i|\{j\}}, \text{ considering, } \{j\} = \{1, \ldots, i-1\} \quad (9)$$

Being $P_{i|\{j\}}$ the conditional probability of satisfying the functional requirement FR_i since all the other relevant $\{FRj\}_{j=1,\ldots,i-1}$ are also satisfied. In this case, I_{sys} can be expressed by equation (10):

$$I_{sys} = -\sum_{i=1}^{m} \log_2 P_{i|\{j\}}, \text{ considering } \{j\} = \{1, \ldots, i-1\} \quad (10)$$

Summarizing, the Reangularity is the orthogonality between design parameters [8], but according to [1], it is not enough to present the degree of functional independence. The Semangularity is an auxiliary criterion that measures the angular relationship between the axes of design parameters and functional requirements. The Information Axiom states that the design with the highest probability of success is the best. The content of information I_i for a given functional requirement (FR_i) is defined in terms of the probability P_i of satisfying FR_i explained by equation (5).

3. Case study

The main technical and research opportunities of the case study 3D printer head based on twin-screw include the use of powder as raw material in small quantities (around 200 g) [9] for exploration of 4D printing through formulating of compounds and polymer blends, as well filament generation. To be compact due small work envelope (head volume is 33.2 x 35.4 x 156 mm, and the twin screws has a length of 111 mm); provide to access to fast assembly, disassembly, and maintenance (due to its modularity). The position of the center of mass is very important due to weight considering a support structure (Santos, 2017) [10]. Two kinds of material raw were considered for preliminary studies pure ABS and ABS + 5-wt% alumina [12]. From choice of the material raw, the torque was estimated by analytical method and fitted with data obtained by a torque rheometer. From these estimates, the requirement torque was next to 15 N.m [11-12].

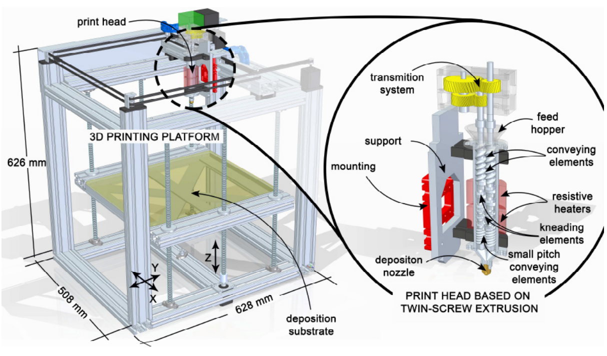

Figure 2. Support structure and interchangeable head 3D printer based on corrotational twin-screw [10-12].

In a pre-sizing carried out in showed by Figure 2, without application of a design conceptual method, the authors opted for helical-tooth cylindrical gears in two stages. From the required gear ratio (1:37.5) and motor power were made fitting and verifications related to mechanical strength of the gears: the pressure contact (1815.8 MPa) exceeded the allowable pinion value whose allowable material stress is 700 MPa [10].

4. Design procedure proposed

The main constraints are small gap between screws and screw-barrel where the theoretical value is 0.2 mm. In addition, the twin screws must not have relative speed between them [12]. The Figure 3 presents a technical drawing of the 3D printer head.

Material-Energy-Information diagram (MEI) was elaborated in order to obtain a semantic structure for study application of solution variants method and axiomatic design.

The choice of gears and configurations was guide by consulting technical literature related machine elements [13]; [14]; [15] in which there are some previous recommendations for the applications.

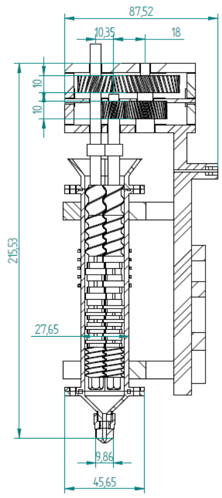

Figure 3. Technical drawing of 3D printer head (case study). Unit: millimeters. [11].

The Figure 4 shows the flowchart of the design procedure proposed.

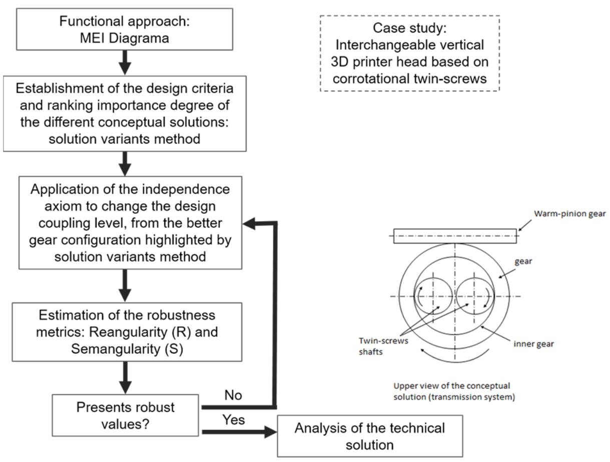

Figure 4. Flowchart for design procedure proposed.

This preliminary survey based on vantage and advantage was elaborated considering: gears with spur gears, helical-tooth cylindrical gears, bevel spur gears, bevel helical-tooth gears, crown and worm screw, planetary gearbox and harmonic drive gearbox. The same process was developed considering the mechanism to provide motion timing described by: belt connecting the two shafts, inner gear in worm gear, two motors and synchronizing gear connecting the two shafts.

In order to generate solution variants method weighting were listed the main technical characteristics (considering the design team composed by four engineers and graduate students): I - Compact configuration: the gear unit volume should be less than 106 mm^3; II - Low weight: the gear unit mass shall be between 2.0 kg and 2.8 kg; III - Ease of maintenance: it should be ease of assembly, disassembly and lubrication; IV - Low manufacturing cost; V - Be self-locking: the gear unit must prevent rotation in the direction opposite to that which is designed, as this movement is detrimental to the processing; VI - The speed the gear unit must deliver to the spindles must be between 8 and 16 rpm. Similarly, the requirements to the synchrony mechanism are I - Compact configuration; II - Low weight; III - The relative speed of rotation between both shafts must be zero; IV - The synchronization mechanism should be ease of assembly and disassembly; V - Low manufacturing cost. The table 1 presents the first level of solution variants.

Table 2 - Design objectives for power system (3D printer head).

Z_{1}	More adequate configuration of the gearbox system for vertical 3D printer based on corrotacional twin screw
Z_{11}	Most compact configuration
Z_{12}	Most functional performance configuration
Z_{13}	Interchangeable mechanical and electronic components configuration
Z_{111}	adequate size related to support structure and build
Z_{112}	have reduced weight
Z_{121}	to be self-locking
Z_{122}	structural stiffness during printing
Z_{131}	have low maintenance cost
Z_{132}	low manufacturing cost
Z_{133}	ease of assembly and disassembly

5. Results

The worm gear system was the configuration highlighted from all other solutions. Firstly, by allow, through a pair of crown and screw, a reduction of up to 1:100 (even with losses, the design torque has low value), also because worm shaft can be designed to be self-locking. The same procedure was used to choose the synchrony mechanism. From the selected evaluation criteria, the non-slip permission, the stability in the operation and the fact of sustaining the design gaps correspond to 60% of the weight of all the criteria. So, the solution with the synchronizing gear was selected with the sum of the weighted values of 7.55. Applying the solution variants method it was possible to select feasible transmission configuration for required torque of 15 N.m considering the user requirement and design constraints.

The results of the most appropriate design from the evaluation of the solution variants were verified according to the Axiomatic Design metrics. For this, the axioms foreseen in the methodology proposed by Suh (1990) [8] were applied to the best projects evaluated by the previous method. For this, it is necessary to map the functional requirements and translate them into design parameters. Thus, Figure 5 and Figure 6 respectively present the functional requirements and design parameters of the studied transmission system.

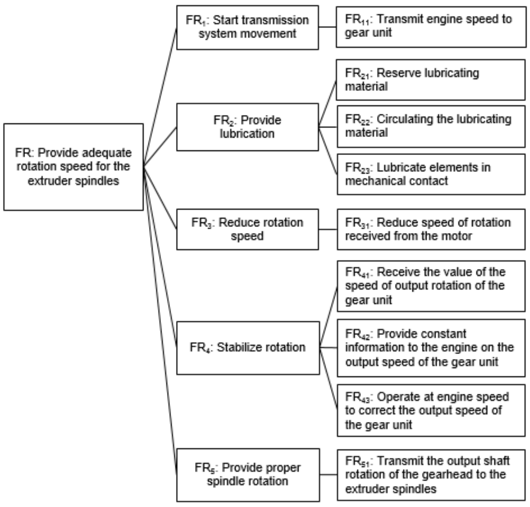

Figure 5. Functional requirements tree for power system.

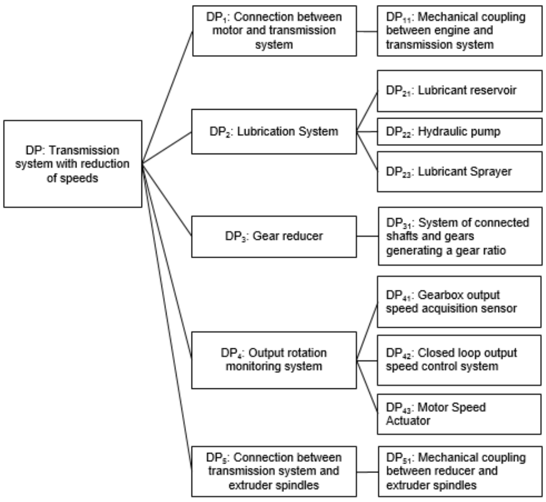

Figure 6. Design parameters tree for power system.

After mapping the FRs and DPs, it is possible to apply the independence axiom by assembling the design matrix. Figure 7 shows the design matrix for the transmission system of the 3D printer in question.

$$\begin{Bmatrix} FR11 \\ FR21 \\ FR22 \\ FR23 \\ FR31 \\ FR41 \\ FR42 \\ FR43 \\ FR51 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 & 0 & X & 0 \\ 0 & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & X & X & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & X & X & X & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & X & X & 0 & X \\ 0 & 0 & 0 & 0 & 0 & X & X & 0 & X \\ 0 & 0 & 0 & 0 & 0 & 0 & X & X & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X \end{bmatrix} \times \begin{Bmatrix} DP11 \\ DP21 \\ DP22 \\ DP23 \\ DP31 \\ DP41 \\ DP42 \\ DP43 \\ DP51 \end{Bmatrix}$$

Figure 7. Axiomatic matrix for 3D printer power system.

Through the design matrix represented by the Figure 8, it is possible to conclude that the adopted transmission system presents a feasible design option. From independence axiom, since there are only 7 elements different of zero above the main diagonal and only 2 elements different of zero below the main diagonal. Therefore, the matrix indicates proposed solutions for the conceptual design almost reaches the dissociation of the design parameters in relation to the functional requirements.

From the structuring shown in Figure 5 and Figure 6, FR3 has been studied in more detail regarding the axioms of the axiomatic design methodology because it is the functional requirement of the speed reducer itself.

Thus, the two best designs resulting from application of solution variants method were mapped into functional requirements and design parameters for the subsequent application of the independence axiom in the design matrix. The results are shown from Figure 8 to Figure 13.

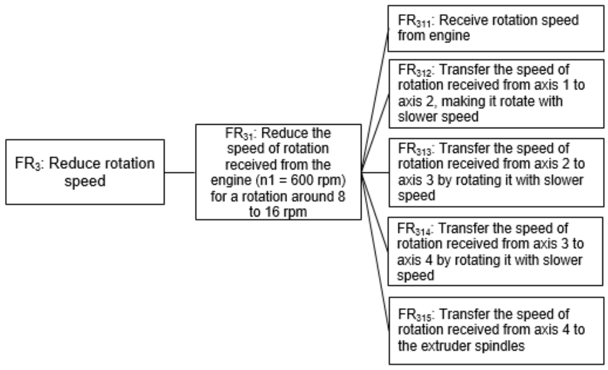

Figure 8. Functional requirements tree for helical-tooth option design.

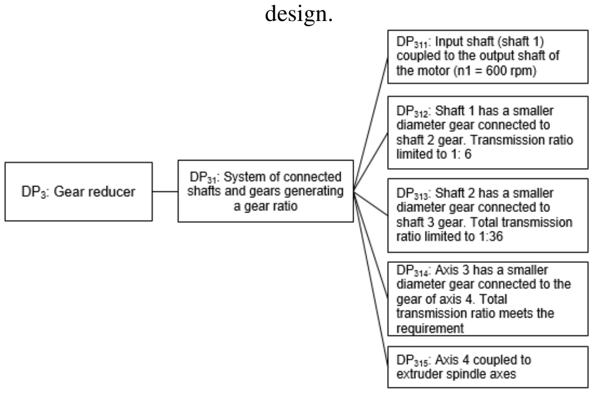

Figure 9. Design parameters tree for helical-tooth option design.

$$\begin{Bmatrix} FR311 \\ FR312 \\ FR313 \\ FR314 \\ FR315 \end{Bmatrix} = \begin{bmatrix} X & X & 0 & 0 & 0 \\ 0 & X & X & 0 & 0 \\ 0 & 0 & X & X & 0 \\ 0 & 0 & 0 & X & X \\ 0 & 0 & 0 & 0 & X \end{bmatrix} \times \begin{Bmatrix} DP111 \\ DP112 \\ DP113 \\ DP114 \\ DP115 \end{Bmatrix}$$

Figure 10. Axiomatic matrix for 3D printer power system helical tooth option.

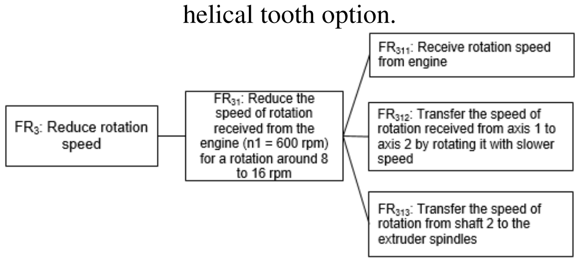

Figure 11. Functional requirements tree for worm gear option design.

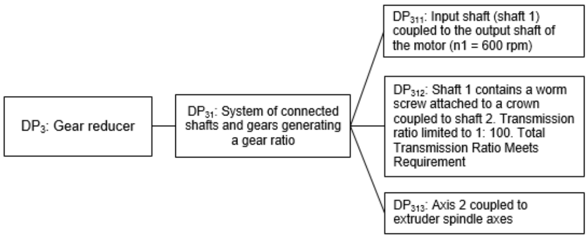

Figure 12.Design parameters for tree for worm gear option design.

$$\begin{Bmatrix} FR311 \\ FR312 \\ FR313 \end{Bmatrix} = \begin{bmatrix} X & X & 0 \\ 0 & X & X \\ 0 & 0 & X \end{bmatrix} \times \begin{Bmatrix} DP111 \\ DP112 \\ DP113 \end{Bmatrix}$$

Figure 13. Axiomatic matrix for 3D printer power system worm gear option.

Given the matrices assembled in Figure 11 and Figure 14, it is necessary to quantify the degree of independence of each solution studied, since the matrix format is very similar, disregarding its orders, since the first is 5x5 and the second 3x3. For this, the analysis of reangularity (R) and Semangularity (S) indicated the values 0.838 and 0.500, respectively, for the worm gear option, which indicates the robustness of the conceptual solution chosen for the case study, compared to previously proposed solution without application of systematic design method.

6. Conclusions

The systematic application of the two design techniques to refine and to guide conceptual solutions to a real technical problem that allowed learning to the design team.

In this work, the use of semantic/functional approach to support the application of variant solution method promoted the technical discussion by personal experiences but also search in technical literature. This design process applied to innovative 3D printer head promoted to think about optional configurations design from traditional gears and flexible transmissions. The use of systematic design methods promoted a design team synergy in order to find and study feasible solutions. By application of the solution variants, as screening method in design procedure proposed, was obtained the choice of worm gear pair to drive system (higher value obtained from evaluation solution variant) of the 7.58. Considering the synchronization mechanism to shafts (corrotational twin screws) it was select by evaluation solution variant a system which there is a synchronizing gear connecting the two extruders, which presented the sum of the weighted values equal to 7.55. The results were complemented by the indexes of reangularity and semangularity that provided the values 0.838 and 0.500, respectively, confirming the choice of worm gear pair as drive system with high degree of design independence.

These values indicated the robustness of the conceptual solution chosen for the case study, compared to previously proposed solution without application of design technique criteria [9]. After the conceptual selection of the worm screw system, a pre–dimensioning was carried out using a program based on Juvinall and Marshek (2006) [15] and the result indicates that the working stresses and the thermal verification present satisfactory margins of safety. The basic values found for the gear unit with worm screw design are crown with 75 teeth; angle of advance: 4.48 degrees; pressure angle: 30°; pitch: 3.18 mm (0.125 in).

Finally, the design procedure presented was important due to potential failure of the solution based on cylindrical gears, as option to driven system and the gap constraint between barrel-screw shafts and own shaft screws. It was required a detailed configuration study of the driven system and synchronization mechanism, since the 3D printer head can be defined as "on-demand" product.

Acknowledgments

This work was supported by grant #2016-4/442109, National Council for Scientific and Technological Development - Brazil (CNPq).

References

[1] Queiroz RAA. Processo de design baseado no projeto axiomático para domínios próximos: estudo de caso na análise e reconhecimento de textura. Thesis, Polytechnic School, University of São Paulo. 2011.
[2] Pahl G, Beitz W. Feldhusen J. Grote, K-H. Engineering Design: a systematic approach. 3rd. ed. London: Springer-Verlag; 2007.
[3] Wahlster W, Gallert H-J, Wess SFH, Widenka T. Towards the internet of services: The THESEUS Research Program. Springer. ISBN 978-3-319-06755. 2014.
[4] Wholers T, Campbell I, Diegel O, Kowen J, Caffrey C. Wholers Report 3D printing and Additive Manufacturing printing state of the industry, Annual Worldwide Progress Report. Wholers Associate. ISSN: 978-0-9913332-3-3. 2017.
[5] Kumke M, Watschke H, Vietor, T. A new methodological framework for design for additive manufacturing. Virtual and physical prototyping.11 (1):3-19. http://dx.doi.org/10.1080/17452759.2016.1139377. 2016.
[6] Kulak O, Cebi S, Kabraman C. Applications of axiomatic design principles: a literature review. Expert Syst. Appl. 37:6705-6717.2010.
[7] Vladu MR, Dobre G, Mirica RF. Application of the fuzzy logic in the evaluation of solution variants in the product development process. UPB Scientific Bulletin, Series C. (75)1: 207-222. 2013.
[8] Suh NP. The principles of design. Oxford University Press, New York. 1990.
[9] Wang H, Zhang X, Chengtong T, Thomson V. A semantic model for axiomatic systems design. Proc IMechE Part C, J Mechanical Engineering Science, p. 1-26. http://dx.doi.org/10.1177/0954406217718858. 2017
[10] Santos LFE. Numerical and experimental analysis to identify the dynamic parameters of an open platform for additive manufacturing. (In Portuguese). Dissertation, School of Engineering of São Carlos, University of São Paulo. 2017.
[11] Justino Netto JM, Silveira ZC. Vertical and modular corrotative twin-screw extruder device and extrusion process (*In Portuguese*). Deposited on 24 October 2017. BR 10 2017 022948 3. National Institute of Industrial Property (INPI), Brazil, 2017.
[12] Justino Netto J.M, Silveira ZC. Design of an innovative three-dimensional print head based on twin-screw extrusion. Journal of Mechanical Design. (140):125002-3. 2018.
[13] Niemann G. Elementos de máquinas. 3th. ed. Edgard Blucher, São Paulo. 1971.
[14] Shigley JE, Mischke, CR, Budynas RG. Mechanical engineering Design. Seventh ed. Higher Education, New York. 2004.
[15] Juvinall RC, Marshek KM. Projeto de componentes de máquinas. 4th. ed. LTC, 2006.