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Storing and retrieving design solution in the physical domain based on DFX tools and morphological analysis

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Abstract

Today the design of a new product has become a very challenging process, due to the growing number of aspects that a product needs to deal with during his life cycle. Like: regulations from authorities, expectations from costumers, company's capabilities and more. To cope with this growing complexity, the field of design theories and methodologies is full of tools and methodologies that were developed to structure the design process. Axiomatic design is one those design methods that was built in the perspective of setting a rational framework where the design process must go through. The general idea of axiomatic design is to divide the design process into four domains: costumer, functional, physical and process domains. In this framework the designer needs to structure his design by mapping between those domains while in the same time respecting two fundamental axioms. (a) The independence axiom, (b) the information axiom. The zigzagging process for the transition between functional and physical domains starts by defining the functional requirement, from which the design parameters are driven and end up by selecting the physical solution. In this work a methodology for storing and retrieving physical solution for a given design parameters is proposed. The physical solutions are stored based on their level of attainment in regard to a number of predefined criteria. Most of those criteria can be derived from Design for X tools. Then using morphological analysis method, suitable physical solution is retrieved in regard to the level of attainment that we can reach in the predefined criteria. For illustrative purpose a program was designed to reflect the benefit of this method. This program was developed using Python programming language and his graphical user interface Tkinter.

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Keywords: Axiomatic Design; DFX; Morphological analysis.

1. Introduction

The key of success of any product relay heavily on the decisions made early in the design phase. the design phase is generally known to influence over 70% of the cost of the final product while the real cost of the design phase is approximately 5% of the final product [1]. Those values show that design phase plays a major role in the product life cycle. This importance is reflected by The big number of research and result that were developed and taught in industry and education in the field of design theory and methodologies [2]. One of those method for structuring the design process is the axiomatic design (AD) theory that was created and popularized by Suh [3]. In AD two axioms need to be applied in the zigzaging transition between functional and physical domain: the independence axiom and the information axiom, in regards to the relations between the functional requirements and the design parameters. At the end of this process physical solution need to be elaborated as response to the defined design parameters. Those physical solutions are generally derived whether from brainstorming session or handbook and sometimes from both. Then a selection process is elaborated to identify the right one. In the selection process the physical solutions need to overcome many criteria and guidelines like design for X (DFX) tools, Failure Mode Effects Analysis (FMEA)

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and more. While trying to apply all those guidelines a designer can find himself locked by the growing number of iteration that the design process may go through before reaching an optimal solution. In this work a methodology for storing and retrieving physical solution that fulfil a given design need is proposed. The physical solutions are stored based on their level of attainment in regard to a number of predefined criteria. Those criteria are defined based on the needed function and can be derived generally from DFX tools. Then by using the morphological analysis method, physical solution can be retrieve based on its level of attainment in each predefined criteria. For illustrative purpose a program was developed using Tkinter a graphical user interface under python programming language, to reflect the benefit of this method.

2. Axiomatic Design

Axiomatic design as developed by Suh [4,5] divides the design process into four domains (Fig. 1): the customer domain, functional domain, physical domain and process domain. The main activity in design process consists of mapping between the domains. During this mapping between the functional domain and physical domain there are two axioms that must be satisfied:

- The independence axiom :
  Maintain the independence of functional requirement.
- The information axiom :
  Minimize the information content.

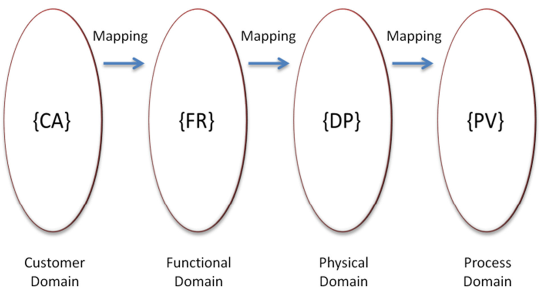


Fig. 1. Four domains of the design process. (Suh,2007)

3. The proposed method

Storing and retrieving technical solution is one of the hardest fields of research in mechanical engineering. Many research has attempted to make use of computer science technics like artificial intelligence and neural network [6,7,8] to store and retrieve the most suitable engineering solution for a given needs.

The proposed method is based on the use of DFX tools to classify and store technical solutions that fulfil design needs, then the use of morphological analysis to retrieve suitable one. This method goes throughout three steps. First a set of criteria are defined so they can classify properly the technical solution for a given design need. To set those criteria we use DFX tools and also other physical property of the solutions. Second each technical solution needs to be stored in the system based on its degree of achievement in regard to the predefined criteria. Finally the retrieving process is done using morphological analysis (MA). For every criteria in the MA matrix a set of values or ranges with equivalent significance are defined (Fig.2).

		Design need			
		Criteria 1	C.2	C.3	C.4
Physical Domain	Solution1	Value1$_{C1}$	Range 1$_{C2}$	V.1$_{C3}$	R.1$_{C4}$
	S.2	V.2$_{C1}$	R.2$_{C2}$	V.2$_{C3}$	R.2$_{C4}$
	S.3	V.3$_{C1}$	R.3$_{C2}$	V.3$_{C3}$	
	S.4	V.4$_{C1}$		V.4$_{C3}$	
	S.5	V.5$_{C1}$		V.5$_{C3}$	

Fig. 2. Retrieving suitable solution using morphological analysis.

3.1. Design for X tools

Design for X is a common word used to address for many other design method like Design for Assembly (DFA), design for Manufacturability (DFM) [9] and many others. The main advantage of using DFX tools is their abilities to enhance productivity while reducing cost of production and time to market [10] by defining guideline for maximum performance. The X is made up of two part [11] (Eq. (1)) :

$$X \; = x \; + \; bility. \tag{1}$$

Where "x" refer to life cycle business process and "bility" refer to performance measures.

In product design there are generally many physical solution candidate to perform a given design parameter. The use of DFX tools are one of the best classifying method that can help for finding the right one, based on their tools for performance measurement.

3.2. Morphological analysis

The general morphological analyses (GMA) which was first developed by Zwicky [12] to retrieve all possible solution for a multidimensional problem, where in every dimension one solution is possible, is one of the best technic of retrieving candidate solution for a multidimensional problem. Many work was inspired from this method like the work of Ritchey [13] who used software to develop the GMA method, to find all possible combination in a GMA problem.

4. Illustrative example

In this example the chosen design need is "mounting a spur gear in a shaft". Eight design solutions are proposed (Fig. 3) to fulfil this need. Where each design solution has different characteristics:

- S1: the spur gear is directly mounted in the shaft.

- S2, S4, S5, S6 and S7: A key is mounted between the shaft and the gear. The shaft and the spur gear hole have a cylindrical shape, with different blocking solutions.
- S3: An interference fit is used between the gear inner hole and the shaft.
- S8: A key is mounted between the shaft and the gear, the shaft and the spur gear hole have a tapered shape.

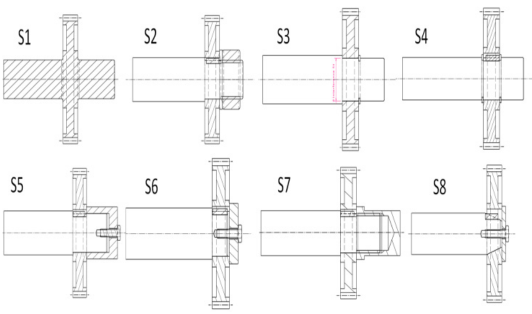


Fig. 3. Design solutions for mounting spur gear in a shaft

For this illustrative example the developed criteria are Manufacturability index (MI), Number of commercial part, Total number of part, manual assembly time and Reparation cost index. For each criterion the degree of achievement for each solution is calculated. The results of calculations are given in Table 1.

Table 1. Result for each solution

Solutions	MI	Commercial parts	N° of parts	$\frac{\alpha+\beta}{720}$	Reparation index
S1	0.31	0	1	0	1.00
S2	0.30	3	5	0.5	0.36
S3	0.49	1	3	0.25	0.41
S4	0.55	3	5	0.5	0.34
S5	0.28	2	5	0.5	0.35
S6	0.32	2	5	0.5	0.34
S7	0.30	1	4	0.5	0.41
S8	0.14	3	5	1	0.48

4.1. Manufacturability index

The manufacturability index represent how difficult a part to be manufactured, the lower the index represents the harder to machine it and the higher represent the ease to be machined. This index (Eq. (4)) was developed based on Ong work [14] (Eq. (2)) who developed a MI based on part feature for rotational part. In this illustrative example we will consider only the MI of the right side of the shaft since the left side and the machining of the spur gear are common to all solution.

$$MI = \sum_{i=1}^{n} \left(W_{Fi} \cdot MI_{Fi} \right) + MI_{Sup} + MI_{Clamp} \tag{2}$$

$$MI_{Fi} = MI_{OPi} + MI_{TOLi} + MI_{SFi} \tag{3}$$

Where:

- W_{Fi} : Weighting factor of feature i.
- MI_{Fi} :The manufacturability index of feature i.
- MI_{Sup} : MI of clamping method, or clamping index.
- MI_{Clamp} : MI of support method, or support index.
- MI_{OPi} : Operation index of feature i.
- MI_{TOLi} : Tolerance index of feature i.
- MI_{SFi} : Surface finish index of feature i.

The W_{Fi} is calculated using the analytic hierarchy process (AHP) which were developed by Saaty [15], to reflect the functional importance of each feature.

In this work the MI_{Sup} and MI_{Clamp} won't be considered since they depend from the size and the shape of the solution, and also MI_{SFi} and MI_{TOLi} will not be considered because in the solution we don't provide the tolerances and the surface roughness. So Eq. (2) and Eq. (3) will be transformed to Eq. (4) and Eq. (6) respectively. Eq.(5) represent the stock index which reflect the estimated removed material to manufacture a given part.

$$MI = \left[\sum_{i=1}^{n} \left(W_{Fi} \cdot MI_{Fi} \right) \right] \cdot S_{Index} \tag{4}$$

$$S_{Index} = \frac{V_{Part}}{V_{Stock}} \tag{5}$$

$$MI_{Fi} = MI_{OPi} = \frac{\left(M_{OP} \right)_{MIN}}{M_{OPi}} \cdot 0.9 \tag{6}$$

Where:

- S_{index} : Stock index
- V_{Part} : Estimated volume of the part
- V_{Stock} : Estimated volume of the needed stock
- MI_{OPi} : The operation index of feature i,
- $(M_{OP})_{MIN}$: The smallest relative operation cost factor of features on a part.
- M_{OPi} : The relative operation cost factors of feature i.

$$M_{OPi} = W_{opi} \cdot \mathrm{CF}_{opi} \tag{7}$$

Where:

- W_{opi} : The operation weight factor.
- CF_{opi} : Cost Factor of the operation.

The operation type can be classified as roughing, semi-finishing, and finishing. So the W_{opi} of 1.0, 1.5 and 2.0, are assigned to roughing, semi-finishing, and finishing operations, respectively. The operation cost factor of a feature is obtained by multiplying the cost factor of the operation (Table 2) and it's weighting factor (Eq.(7)). In Table 3 an example for calculating the MI_{Fi} for every feature in Solution 6 (S6), so by using a S_{Index} of 0.9 the MI for S6 will be 0.32 as shown in Table 3.

Table 2. Cost factors of turning operations

Operation		Cost factors
straight turning		1.0
Chamfering		1.0
Slots (keyways)		2.5
External threading		3.0
Internal threading		
	Through	3.5
	Blind	4.0
Boring		
	Through	2.0
	Blind	2.5
Facing		
	External	1.0
	Internal	1.5
Taper turning		
	External	3.0
	Internal	4.5

Table 3. Manufacturability index for the shaft of S6

Features	Slot	Straight turning	Int. boring	Int. threading	Facing	Chamfering
W_{Fi}	0.44	0.24	0.11	0.12	0.05	0.05
CF_{opi}	2.5	1	2.5	4	1	1
W_{opi}	2	1.5	1.5	1.5	1	1
MI_{OPi}	5	1.5	3.75	6	1	1
MI_{Fi}	0.18	0.6	0.24	0.15	0.9	0.9

4.2. Manual assembly time:

Based on the work of Yoosufani [16], it was shown experimentally that there are four categories of part angle of symmetry (Table 4), where a part require significant orientation time to be assembled. The angle of symmetry represents the angle of rotation for a part about an axis, to reinsert it properly, from an initial position where it was properly inserted. Those four categories were classified upon the sum of two angles of symmetry alpha and Beta:

- Alpha: axis perpendicular to direction of insertion
- Beta: axis in direction of insertion

Table 4. Classification of part symmetry

Group	α	β	$\theta = \frac{\alpha+\beta}{720}$
I	180	<180	< 0.5
II	180	180	$0.5 \leq \theta \leq 0.75$
	360	<180	
III	360	180	0.75
IV	360	360	1.00

To measure the alpha and beta symmetry angle, the shaft will be considered as the receptacle and the spur gear as the part to be inserted. The results of applying those criteria on the solutions are shown in Table 1.

4.3. The reparation index

For each solution a reparation cost will be calculated, to represent a relative cost of replacement for a probability of defect of one part in a solution. The reparation index will represent the relative cost of reparation for a solution compared to the first solution.

The reparation cost will be calculated for each solution as follow (Eq. (8)):

$$RC_{Si} = \sum_{i=1}^{n} (W_{Pi} \cdot C_{Pi}) \qquad (8)$$

The weight W_{Pi} will be calculated using AHP method to represent the probability of defect of part in each solution. The reparation index is given by dividing the costs of a solution by the cost of the first solution (Eq.(9)). The costs C_{Pi} were determined based on shop floor survey.

$$RI = RC_{Si} / RC_{S1} \qquad (9)$$

5. The designed program

The designed program was developed under python programing language using his graphical user interface (GUI) Tkinter. Fig. 4 show the stored Data relative to each solution and criteria, for the solution there are eight solutions and for the criteria we provide either a value or a range where the value of the criteria has an equivalent significance. Then the values corresponding to each solution for every criterion are set (Fig. 5). Finally the program provide a matrix where if we click to a chosen criteria it turn pink and it show us all the possible solution that are available with their corresponding criteria in sky blue. In Fig. 6 the chosen criteria was “symmetry in Group I” the program give us that only solutions S1 and S3 are the possible solution with their corresponding criteria. In Fig . 7 another criteria was added, which is “number of commercial part=0”. In this case only solution S1 was available that satisfies those two criteria.

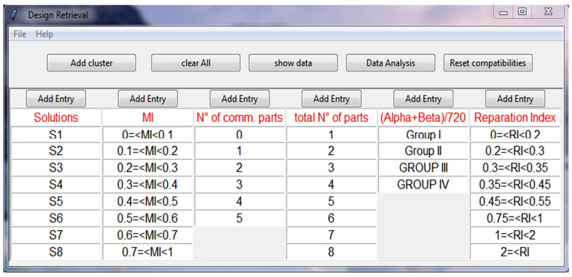


Fig. 4. Storing solution with relative criteria

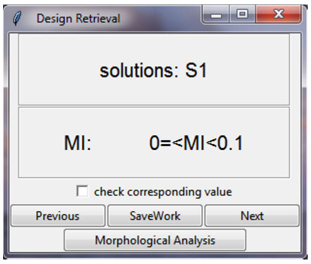
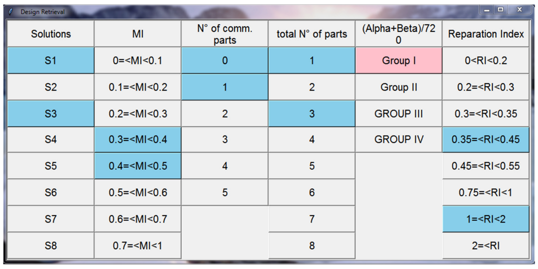
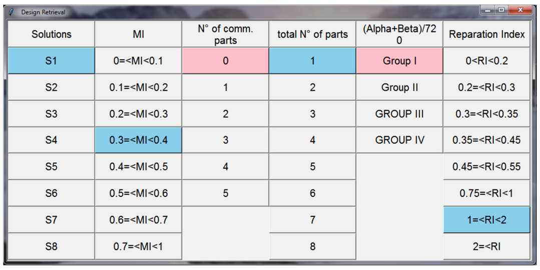


Fig. 5. Defining the corresponding value for each solution



Solutions	MI	N° of comm. parts	total N° of parts	(Alpha+Beta)/720	Reparation Index
S1	0=<MI<0.1	0	1	Group I	0<RI<0.2
S2	0.1=<MI<0.2	1	2	Group II	0.2=<RI<0.3
S3	0.2=<MI<0.3	2	3	GROUP III	0.3=<RI<0.35
S4	0.3=<MI<0.4	3	4	GROUP IV	0.35=<RI<0.45
S5	0.4=<MI<0.5	4	5		0.45=<RI<0.55
S6	0.5=<MI<0.6	5	6		0.75=<RI<1
S7	0.6=<MI<0.7		7		1=<RI<2
S8	0.7=<MI<1		8		2=<RI

Fig. 6. Looking for solutions with symmetry in Group I



Solutions	MI	N° of comm. parts	total N° of parts	(Alpha+Beta)/720	Reparation Index
S1	0=<MI<0.1	0	1	Group I	0<RI<0.2
S2	0.1=<MI<0.2	1	2	Group II	0.2=<RI<0.3
S3	0.2=<MI<0.3	2	3	GROUP III	0.3=<RI<0.35
S4	0.3=<MI<0.4	3	4	GROUP IV	0.35=<RI<0.45
S5	0.4=<MI<0.5	4	5		0.45=<RI<0.55
S6	0.5=<MI<0.6	5	6		0.75=<RI<1
S7	0.6=<MI<0.7		7		1=<RI<2
S8	0.7=<MI<1		8		2=<RI

Fig. 7. Looking for solutions with symmetry in Group I and number commercial part =0

6. Conclusion

The design is very challenging process, where the research for reducing its complexity and duration are gaining more and more importance, due to the huge benefice that can be extracted from it, in term of cost reduction and time to market. In this work a methodology for storing and retrieving physical solution based on predefined design needs was proposed. This method was specially developed for education purpose to help student to identify the benefit behind each different design solution that they may encounter in literature while they fulfill the same needed requirement.

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