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AXIOMATIC DESIGN PRINCIPLES IN TEACHING MANUFACTURING TECHNOLOGY DESIGN - PRELIMINARY APPROACH

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ABSTRACT

The future specialists in the field of manufacturing technologies of mechanical equipments must have adequate knowledge about the possibilities to design and materialize the manufacturing processes. In order to fulfill this requirement, the university curricula include activities in which the students learn to design manufacturing technologies for various parts. Since one is talking about a design problem, one can formulate the question of applying the principles of axiomatic design (AD) for approaching and developing the design of manufacturing processes. The analysis of the stages corresponding to designing manufacturing processes facilitated the definition of the functional requirements. Solutions for approaching these stages were considered as design parameters. The initial analysis showed that a coupled matrix corresponds to the current way of designing manufacturing processes. Some investigations were developed in order to remove the use of the same design parameters for many functional requirements. An uncoupled matrix was thus elaborated and some remarks were formulated in order to find better solutions for design of manufacturing process.

Keywords: axiomatic design, manufacturing process design, functional requirements, design parameters.

1 INTRODUCTION

Manufacturing refers to the process in which raw materials, components, or parts are converted into finished goods that correspond the to customer's expectations or specifications [Manufacturing, 2014, Kalpakjian and Schmid, 2008]. On the other hand, from a technological point of view, manufacturing consists of application of physical and chemical processes in order to change the geometry, properties, and/or appearance of a given workpiece, as a means to make parts or products [Groover, 2007].

A process is the succession of stages through which a product or a phenomenon passes consecutively. Thus, the manufacturing process can be considered as a succession of processing operations or assembling operations through which a certain product is obtained. Within *a processing operation*, a workpiece is transformed from one state of completion to a more advanced state, considered as being closer to the final desired product [Groover, 2007].

Because of the continuous increasing request for new and improved products, manufacturing engineering currently has a high developing dynamics. From the point of view of manufacturing engineering, one can consider two stages:

a) Design of manufacturing technologies and
b) applying manufacturing technologies.

Both activities could be coordinated by specialists in the field of manufacturing engineering.

Since there is a design problem, one could stress that the principles of axiomatic design could be applied for designing processing operations, as a part of the more general concept of *manufacturing technologies*. Another question concerns to the possibility of applying axiomatic design in the training of future engineers in the field of designing manufacturing processes. We do not propose an immediate solution to these problems, but, to begin with, just a more complete formulation of these problems, an analysis of the possibilities of using axiomatic design principles for solving some aspects specific to teaching how to design and optimize manufacturing technologies.

2 DESIGN ACTIVITIES STRUCTURE IN THE CASE OF COLD MANUFACTURING TECHNOLOGY

In the negotiation for manufacturing a certain product, a brief technology study is made, in order to establish/estimate the price of the product; only later the manufacturing technology is developed in detail. Usually, there is the interest of manufacturer to make the product at low cost, in order to maximize the profit and, if it possible, in a short time, so that the problem of manufacturing other products could be also addressed. This study is more detailed when the exigencies are higher or when the number of products to be manufactured is higher; for example, if in the case of low-quantity production, the main technological document is a master process sheet, but in the case of high production, an operation sheet (process plan) for machining is used.

In accordance with some accepted conventions, cold manufacturing technologies are usually executed in workshops where the workpieces are processed by cutting and by plastic deformation at temperatures not higher than 30% of their melting temperature. Yet, the temperature reached by the work zone could exceed the above-mentioned value in some cold processes. For example, in case of grinding processes or electrical discharge machining processes, the temperature in the work zone could reach 900 ^{o} C, or even more, but such processes are usually performed in workshops for cold manufacturing technologies.

There are various points of view concerning the stages of designing the manufacturing technology of a part. From a didactic point of view, when training students in the field of designing manufacturing technologies, one should take into account the following stages: *1)* Analysing the product technical drawings and verifying its manufacturability; *2)* Establishing the type of raw material to be used; *3)* Determining the machining allowances and intermediate dimensions; *4)* Determining the values of processing parameters (here, substages are addressed to select the machine tool, the tools and the devices for processing operations); *5)* Determining the operations time durations; *6)* Evaluating the selected technology from the technological and the economical points of view, or selecting the most appropriate one if two or more technologies were considered; *7)* Elaborating the relevant technical documents (master plan sheet or process plan, list of tools and fixtures, etc.).

In the manufacturing engineering practice, many of these stages are overlapped or more succinctly solved, but from didactical point of view, one considers that the student must know and apply fundamental knowledge about the above-mentioned stages.

Reynal and Cochran noticed that during the attempt to implement lean manufacturing, complementary or contradicting concepts are sometimes used in an ad-hoc basis; they proposed to apply the axiomatic design and developed a methodology in order to establish a sequence of implementation steps of lean changes [Reynal and Cochran, 1996].

Muñoz-Avila and Weberskirch considered that the main tasks that must be performed during the process planning of conventional machining could be: *1.* Identification of the processing areas; *2.* Selection of the machine tools; *3.* Sequencing of tool sets; *4.* Grouping of set-ups; *5.* Selection of machining operations and their sequence; *6.* Selection of the cutting tools; *7.* Selection of clamping devices and positions, and datum surfaces; *8.* Calculation of cutting conditions; *9.* Determining the path of the tools; *10.* Determination of cutting times, non-machining times and costs; *11.* Generation of the NC (numerical control) program to produce the part [Muñoz-Avila and Weberskirch, 1999].

Cochran *et al.* [2000] pondered that a possible solution for optimizing the design of production systems is the segmentation of the manufacturing enterprise in small, flexible and decentralized production units on the basis of an axiomatic design framework; in this way, they took into consideration the decentralization of production control functions to operators found in certain working areas.

N. P. Suh emphasized that manufacturing systems are complex and methods of reduction complexity should be applied. Such a reduction could be achieved by transformation of time–dependent combinatorial complexity into periodic complexity [Suh, 2005].

Amaitik considered that the steps in designing manufacturing technologies could be: Identification of part specifications; Selection of blanks or stock; Selection of machining operations; Selection of machine tools; Selection of cutting tools; Calculation of cutting parameters; Generation of setup plans; Selection of work holding devices (fixtures); Calculation of times and costs; Generation of process plans [Amaitik, 2005].

C. Brown showed that some difficulties specific to teaching traditional design could be avoided or diminished by applying axiomatic design [Brown, 2005]. When the axiomatic design is applied to the manufacturing engineering, he noticed that it is difficult to decouple the functional requirements concerning the cost from other functional requirements. He concluded that the main functional requirements applied to manufacturing processes could be maximizing the value added and minimizing the cost [Brown, 2011].

Gonçalves-Coelho and Mourão developed an AD-based procedure that could be applied to match a product with the most appropriate manufacturing process; they showed that there is a strong correspondence between the design of the products and the manufacturing technology that should be selected to achieve their cost-effective fabrication [Gonçalves-Coelho and Mourão, 2007].

Jeon et al. combined axiomatic design and Taguchi method, in order to solve a multi-response problem corresponding to the manufacturing of insulation for coaxial cables; they considered that the development of manufacturing processes and finding adequate responses for each process variable are possible [Jeon *et al.*, 2008].

Wisk appreciated that the stages for the case of computer-aided process planning are the following: *a)* raw material selection; *b)* process selection; *c)* tool selection; *d)* feed, speed selection; *e)* operation selection; *f)* setup planning; *g)* fixture planning; *h)* part programming [Wysk, 2009].

Housmand and Mokhtar used axiomatic design to create a universal manufacturing platform in an enterprise; they defined the functional requirements and developed design matrixes and equations that characterize the manufacturing platform [Housmand and Mokhtar, 2009].

Weng and Jenq formulated the problem of selecting an appropriate machine tool and related equipment on a basis of axiomatic design. They took also into consideration other aspects that are specific to the design of the manufacturing process (such as machining time, labor cost, machining cost, consumption cost, product quality, etc.); they proposed a hierarchical decision-making model for equipment selection in agile manufacturing units [Weng and Jenq, 2012].

M. K. Thompson highlighted the significance of axiomatic design for the stakeholders in the field of manufacturing processes (manufacturing teams), as stages that are placed just in the design process, inclusively by considering the lean production [Thompson, 2013b].

In addition, M. K. Thompson highlighted five classes of common procedural errors that can be made in the definition of the functional requirements. She appreciated that the investigation of experts' errors in this matter could generate new questions about the axiomatic design research and, in this way, could contribute to the improvement of design education methods [Thompson, 2013a].

3 TEACHING DESIGN OF MANUFACTURING TECHNOLOGIES ON THE BASIS OF AXIOMATIC DESIGN PRINCIPLES

The direct or close customer of the manufacturing technologies designers is the manufacturing workshop. The further customer could be considered the buyer of the product that results from the designed manufacturing technologies.

The main needs of the direct customer and, in fact, the request of the company leaders is the design of cost-effective technologies and, if possible, with high production rates (the last customer need could help the company to manufacture other products in the immediate future period).

There are yet other customer needs to be considered when the customer is the manufacturing workshop: for example, *a)* the designed technology must be adequate to the equipment existing in the workshop, in the manufacturing company or in external operators; *b)* In the first part of the manufacturing route, the operations aiming to prepare the technological bases could placed; *c)* If possible, a maximum number of machining steps could be performed at a single clamping of the workpiece; if this condition is met, a higher machining accuracy and a diminished time required per operation should be possible); *d)* If possible, a minimum number of workpiece fixings could be preferred, also in order to ensure higher machining accuracy and labor productivity; *e)* If possible, the operations should be grouped by considering the machine tools placement in the workshop; *f)* If possible, an optimized batch size should be used, etc.

The quality of the product will not be discussed here since technologies that do not allow obtaining the product in accordance with the quality requests is not taken into consideration.

The practice of designing manufacturing technologies proved that the problem is not simple and usually some simplifications are adopted.

Thus, in teaching designing manufacturing technology, just the first-level functional requirements that result from the customer needs are initially taken into consideration.

An equation for calculus of the production cost *C* of a single product (manufacturing cost) in the manufacturing workshop could be written by simplifying a more complex relation [Balakshin, 1971] as follows:

$$C = M + W + L \,, \qquad (1)$$

where *M* is the cost of materials required per unit of production, *W* is the sum of the wages expended per unit of production and *L* is the overhead expenses.

One can compute the sum of wages, *S*, by considering the sum of the products obtained by multiplying the standard times T_{pi} per piece at the *i*th machining operation by the salaries expressed per minute, $S_{min\,i}$, of the involved workers:

$$S = \sum T_{pi} S_{\min i} \,. \qquad (2)$$

In the first stage, the overhead expenses *L* can be estimated by means of the equation:

$$L = kS \,, \qquad (3)$$

where *k* is the fraction that results from distributing the overhead expenses.

In this way, the second-level functional requirements that goes after the first-level functional requirement concerning to the necessity to ensure a minimum cost *C* of the designed technology (FR1: Minimize the cost of designed technology) could be:

FR1.1: Minimize the row material cost;
FR1.2: Minimize the admissible machining allowances;
FR1.3: Minimize the number of processing operations;
FR1.4: Minimize the cost of using machine tools;
FR1.5: Minimize the tools costs;
FR1.6: Minimize the expenses of the necessary fixtures (in the education system applied in Romania and in other East European countries, there is the concept of *technological system* which is considered as including machine tool, fixture, jigs and workpiece);
FR1.7: Minimize the cost of the jigs;
FR1.8: Minimize the workers' salaries;
FR1.9: Minimize the overheads.

The labor productivity for the operation *i*th can be estimated by means of the standard output, Q_i, by taking into account the time T_{pi} required per operation [Balakshin, 1971]:

$$Q_i = \frac{1}{T_{pi}} \,. \qquad (4)$$

In turn, the time required per operation T_{pi} is considered [Balakshin, 1971] as being:

$$T_{pi} = \frac{T_{su}}{n} + \sum t_m + \sum t_a + t_s + t_f \,, \qquad (5)$$

where T_{su} is the setting-up time, *n* the number of pieces in a batch (batch size), t_m the basic processing time (machine time), t_h the handling time, t_s the time for servicing the workplace, t_f the time required for personal needs and for resting in case of strenuous work (fatigue allowance). The times for servicing the workplace, for personal needs and for resting are usually calculated as percentages of the machine time or of the sum including the machine times and handling times.

The machine time t_m can be determined [Balakshin, 1971] by taking into consideration the required length L (mm) of travel of the cutting tool at the working feed in reference to the workpiece (or the opposite, workpiece travel in reference to tool), rotation speed n, rpm (or the number of full strokes per minute, strokes/min) and the feed rate per min f of the tool or workpiece, mm/min:

$$t_m = \frac{L}{nf} i , \tag{6}$$

i being the number of passes or cuts necessary to remove the established machining allowance A_m. One can determine the number i of passes by means of the equation [Danilevsky, 1973]:

$$i = \frac{A_m}{a_p} , \tag{7}$$

where a_p is the depth of cut.

The first-level functional requirement concerning the *labour productivity Q of the manufacturing process under design (FR2:* Maximize the labor productivity)*)* leads to the following second-level functional requirements:

FR2.1: Establish the machine tools;

FR2.2: Establish the scheme for locating and clamping the workpiece;

FR2.3: Establish the fixtures;

FR2.4: Establish the tools;

FR2.5: Establish the jigs;

FR2.6: Maximize the depth of cut;

*F*R2.7: Maximize the feed rate;

*F*R2.8: Maximize the cutting speed;

*F*R2.9: Minimize the setting-up time;

*F*R2.10: Minimize the machine time;

*F*R2.11: Minimize the handling time;

The third first-level functional requirement concerning *the adequacy of the designed manufacturing technology to the available equipments and operators (FR3:* Use available equipment and operators*)* could be divided in the following second-level functional requirements:

*F*R3.1: If possible, use the available machine tools;

*F*R3.2: If possible, use the available fixtures;

*F*R3.3: If possible, use the available jigs;

*F*R3.4: If possible, use the available tools;

*F*R3.5. Use the available operators.

One does not divide the fourth first-level functional requirement (the requirement that the designed manufacturing technology should ensure, if possible*, a maximum number of processing operations achieved in the available workshop – FR*4).

According to the above mentioned structure for designing the manufacturing technology, the main steps in the design process in which the student/the engineer must make a decision consists in the selection of the design parameters of first or second level, which could be:

- Verifying the working drawings and the product manufacturability;
- Selecting the kind of blank (raw material);
- Planning the sequence of machining operations and operations elements;
- Determining the machining allowances;
- Determining the intermediate dimensions (these dimensions correspond to the blank/workpiece dimensions for the various machining operations that are applied to the same workpiece surface);
- Establishing the necessary dimensions of the blank and selecting, if possible, a blank having normalized dimensions;
- Selecting the machine tools;
- Selecting schemes for locating and clamping workpiece;
- Selecting fixtures;
- Selecting tools;
- Selecting jigs;
- Determining the depth of cut;
- Determining the rate of feed;
- Determining the cutting speed;
- Verifying the cutting forces, moments and effective powers;
- Determining the setting-up times;
- Determining the machine times;
- Determining the handling times;
- Determining the times for servicing the workplace, for personal needs and for resting;
- Determining the time required per operation;
- Determining the per-unit cost of the product;
- Comparing the per-unit cost of the product with the contract cost or with the expected one;
- Elaborating the final technological and economical documents.

If one takes into consideration the objectives proposed to be solved by the student in each of the stages, one can propose the appropriate design parameters for planning the manufacturing processes.

As design parameters corresponding to the functional requirement FR1 (minimize the cost of designed technology), one can consider DP1: Procedures for determining the elements of the cost:

DP1.1: Procedure for establishing the type of raw material;

DP1.2: Procedure for establishing the sequence of operations;

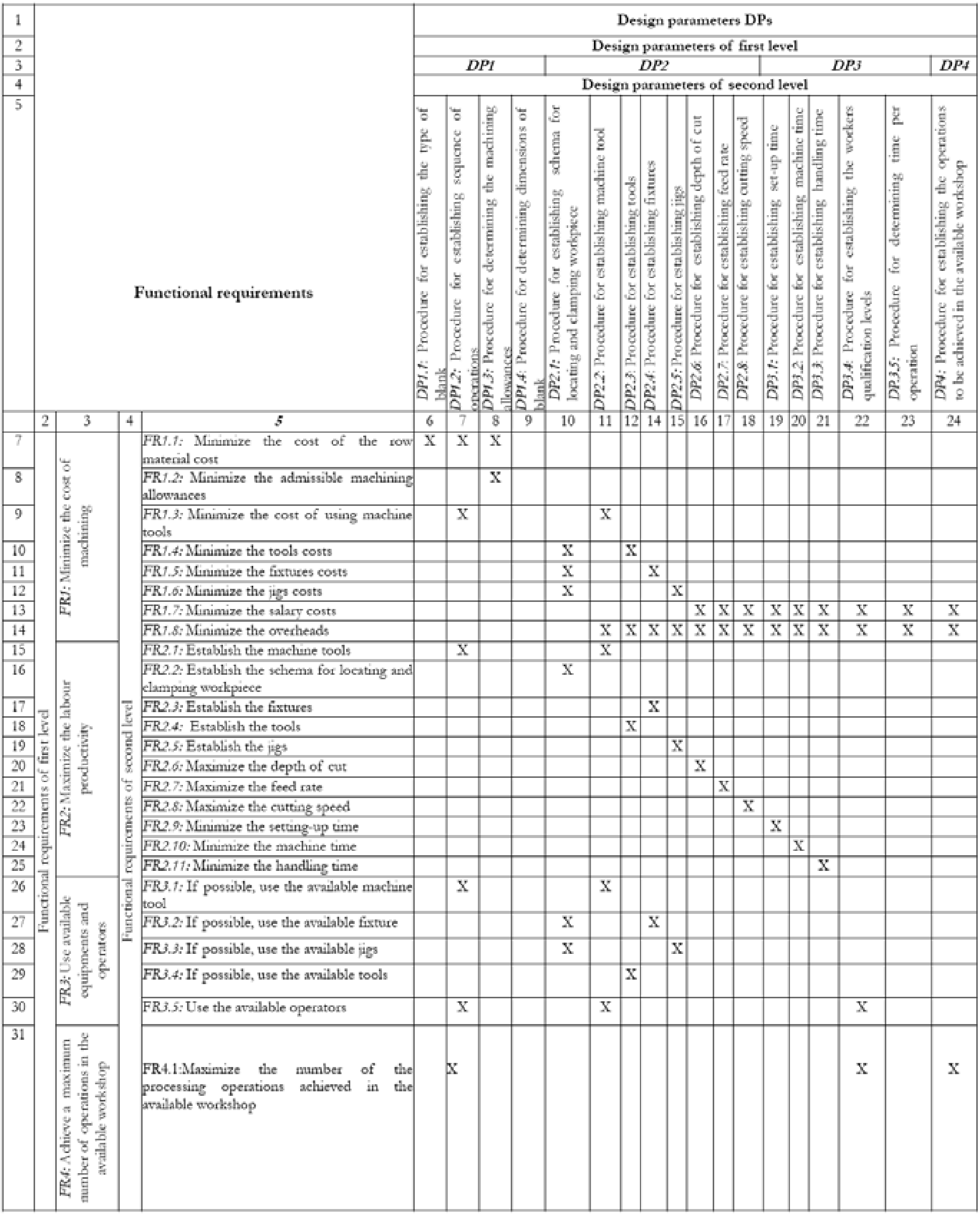
DP1.3: Procedure for determining the machining allowances;

DP1.4. Procedure for determining the dimensions of the blank .

The design parameter corresponding to the functional requirement FR2 (Maximize labor productivity) could be (DP2: Procedures for maximizing labor productivity), and:

DP2.1: Procedure for establishing the scheme for locating and clamping the workpiece;

DP2.2: Procedure for establishing the machine tool;



1					**Design parameters DPs**																	
2					**Design parameters of first level**																	
3					***DP1***				***DP2***									***DP3***				***DP4***
4					**Design parameters of second level**																	
5				**Functional requirements**	*DP1.1:* Procedure for establishing the type of blank	*DP1.2:* Procedure for establishing sequence of operations	*DP1.3:* Procedure for determining the machining allowances	*DP1.4:* Procedure for determining dimensions of blank	*DP2.1:* Procedure for establishing schema for locating and clamping workpiece	*DP2.2:* Procedure for establishing machine tool	*DP2.3:* Procedure for establishing tools	*DP2.4:* Procedure for establishing fixtures	*DP2.5:* Procedure for establishing jigs	*DP2.6:* Procedure for establishing depth of cut	*DP2.7:* Procedure for establishing feed rate	*DP2.8:* Procedure for establishing cutting speed	*DP3.1:* Procedure for establishing set-up time	*DP3.2:* Procedure for establishing machine time	*DP3.3:* Procedure for establishing handling time	*DP3.4:* Procedure for establishing the workers qualification levels	*DP3.5:* Procedure for determining time per operation	*DP4:* Procedure for establishing the operations to be achieved in the available workshop
	2	3	4	***5***	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24
7	Functional requirements of first level	*FR1:* Minimize the cost of machining	Functional requirements of second level	*FR1.1:* Minimize the cost of the row material cost	X	X	X															
8				*FR1.2:* Minimize the admissible machining allowances			X															
9				*FR1.3:* Minimize the cost of using machine tools		X				X												
10				*FR1.4:* Minimize the tools costs					X		X											
11				*FR1.5:* Minimize the fixtures costs					X			X										
12				*FR1.6:* Minimize the jigs costs					X				X									
13				*FR1.7:* Minimize the salary costs										X	X	X	X	X	X	X	X	X
14				*FR1.8:* Minimize the overheads						X	X	X	X	X	X	X	X	X	X	X	X	X
15		*FR2:* Maximize the labour productivity		*FR2.1:* Establish the machine tools		X				X												
16				*FR2.2:* Establish the schema for locating and clamping workpiece					X													
17				*FR2.3:* Establish the fixtures								X										
18				*FR2.4:* Establish the tools							X											
19				*FR2.5:* Establish the jigs									X									
20				*FR2.6:* Maximize the depth of cut										X								
21				*FR2.7:* Maximize the feed rate											X							
22				*FR2.8:* Maximize the cutting speed												X						
23				*FR2.9:* Minimize the setting-up time													X					
24				*FR2.10:* Minimize the machine time														X				
25				*FR2.11:* Minimize the handling time															X			
26		*FR3:* Use available equipments and operators		*FR3.1:* If possible, use the available machine tool		X				X												
27				*FR3.2:* If possible, use the available fixture					X			X										
28				*FR3.3:* If possible, use the available jigs					X				X									
29				*FR3.4:* If possible, use the available tools							X											
30				*FR3.5:* Use the available operators		X				X										X		
31		*FR4:* Achieve a maximum number of operations in the available workshop		FR4.1:Maximize the number of the processing operations achieved in the available workshop		X														X		X

Figure 1. Initial design matrix.

DP2.3: Procedure for establishing tools (standardized cutting tools, which must be purchased or tools which must be designed and achieved);

DP2.4: Procedure for establishing the fixtures; these fixtures could be the standardized/purchased ones or fixtures which must be designed and manufactured;

DP2.5: Procedure for establishing the jigs (the statements corresponding to fixtures are valid for jigs);

DP2.6: Procedure for establishing the depth of cut;

DP2.7: Procedure for establishing the feed rate;

DP2.8: Procedure for establishing the cutting speed.

In the case of FR3 (Use available equipments and operators), one can take into consideration as design parameters DP3 (Procedures for use the available equipments and operators), and:

DP3.1: Procedure for establishing the set-up time;

DP3.2: Procedure for establishing the machining time;

DP3.3: Procedure for establishing the handling time;

DP3.4: Procedure for establishing the workers qualification level;

DP3.5: Procedure for determining the time per operation

For the functional requirement FR4 (Achieve a maximum number of operations in the available workshop), one can take into consideration the design parameter:

DP4: Procedure for establishing the operations to be achieved in the available workshop. .

The design parameters *DP2.1- DP3.5* are valid for each processing operation.

The first version of the matrix corresponding to these functional requirements and design parameters is presented in figure 1; this version was elaborated by considering some requirements associated to the manufacturing technology design for a certain part by the student and the derived problems specific to solving each stage. One can see that there are many aspects that do not match the principles of axiomatic design. Firstly, one can notice that the matrix is not a square matrix, because there are 25 functional requirements and only 19 design parameters. In addition, there is many design parameters for some of the functional requirements. As a result, we have a *coupled design.*

During the process of the matrix elaboration, one noticed that there are dependencies between the considered functional requirements; for example, in order to diminish the raw material cost, one can act during selection of raw material type (laminated, cast, forged etc.), by diminishing the machining allowances and by establishing optimized dimensions of the blank. One can also notice that the salary costs are dependent on the cutting parameters, on the times affected to various components of time per piece, and on the level of qualification of workers; a similar statement could be formulated about the overheads, taking into account that these overheads can be estimated on the basis of salary costs. As the equation (3) shows, the overhead expenses depend on the salary expenses and on the service cost of machine tools, tools, fixture and jigs. There are also situations where the same design parameter is used to fulfill two or many functional requirements. For example, the selection of a certain machine tool must consider the necessity of diminishing the cost of the machine tool, which have to be considered in the final cost of the part; the possibility of using a machine tool already available at the workshop; and the necessity to ensure a certain distribution of the work tasks between several operators (workers) of the workshop (there is a match between the number of workers and their qualification levels, as well as the types and number of available machine tools). The above-mentioned contradictions to the axiomatic design principles determined us to reanalyse the problem through zigzagging as in order to find a better solution.

As a result, a second design matrix was elaborated (fig. 2). This is a 11x11 square matrix, and one can see that the number of functional requirements was diminished, by taking into account some specific aspects of the previous formulation.

For example, when the machine tool is selected, on can take into consideration the necessity of minimizing the cost of machine tool service, the technical possibilities to materialize the machining of a certain part on the selected machine tool, the existence of this machine tool in the workshop, etc.

The zigzag could be also completed by applying specific methods in order to optimize some design parameters. Thus, the method of dynamic programming could be applied in order to optimize the the sequence of operations. Other procedures can be used to find the optimal values for the cutting parameters (Monte Carlo method, linear mathematical programming, Taguchi method, etc.). Various methods could be also applied to find adequate solutions for multi-response problems (multi-criteria analysis, Grey analysis, etc.).

During the zigzagging, the diminishing of the time per piece T_{pi} at the *i*th operation could be taken into consideration; it is known that diminishing the value of a certain component of the time per piece could ensure conditions that, in a next step, makes it possible to diminish other components of the time per piece.

Additional problems appear in the case the design of technologies that use computer numerical controlled machine tools. In such a situation, establishing optimal tool path for each operation element could be a functional requirement needing adequate design parameters.

4 CONCLUSION

The design of manufacturing processes has a significant influence on the product price and on the time necessary for obtaining the product. Being considered as a design process, the problem of applying the axiomatic design principles was formulated. Various aspects specific to the use of the axiomatic principles in design of manufacturing or machining processes were investigated by the researchers interested in such problems. Taking into consideration the necessity of teaching the use of axiomatic design in didactic activities concerning the design of machining/manufacturing processes, the functional requirements and design parameters were investigated in correspondence with the stages solved by the students in their didactic projects. In this context, a first design matrix was elaborated. The analysis of this initial matrix highlighted that the principles of axiomatic design were not met. The functional requirements and design parameters were reanalyzed and a second uncoupled design matrix was elaborated. In the future, there is the intention to take into consideration a larger zigzagging path, in order to find ways to

Li-ne no. 1	Functional requirements				Design parameters *DPs*										
2					Design parameters of first level										
3					*DP1*		*DP2*					*DP3*			*DP4*
4					Design parameters of second level										
5					*DP1.1:* Procedure for establishing the type of raw material	*DP1.2:* Procedure for determining the machining allowances	*DP2.1:* Procedure for establishing the machining schema	*DP2.2:* Procedure for establishing the machine tool	*DP1.3:* Procedure for establishing tools	*DP1.4:* Procedure for establishing fixture	*DP2.5:* Procedure for establishing jigs	*DP3.1:* Procedure for establishing depth of cut	*DP3.2:* Procedure for establishing rate of feed	*DP3.3:* Procedure for establishing cutting speed	*DP4:* Procedure for establishing the workers qualification levels
6 Col. no. 1	2	3	4	5	6	7	8	9		10	11	12	13	14	15
7	Functional requirements of first level	*FR1*	Functional requirements of second level	*FR1.1:* Minimize the cost of raw material	X										
8				*FR1.2:* Minimize the admissible machining allowances		X									
9		*FR2*		*FR2.1:* Provide adequate machining schema			X								
10				*FR2.2*: Provide adequate machine tools				X							
11				*FR2.3:* Provide adequate tools					X						
12				*FR2.4:* Provide adequate fixtures						X					
13				*FR2.5:* Provide adequate jigs							X				
14		*FR3*		*FR3.1:* Maximize the depth of cut								X			
15				*FR3.2*: Maximize the rate of feed									X		
16				*FR3.3*: Maximize the cutting speed										X	
17		*FR*		*FR4:* Provide available operators having the necessary qualification level											X

Figure 2. Second design matrix.

optimize various stages of selecting the design parameters and process parameters that are specific to the activities of manufacturing process design.

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