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PROCESS OPTIMIZATION USING A NEW CONCEPT FOR PROCESS COUPLING

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ABSTRACT

This paper presents a new model for process optimization based on the evaluation of the process coupling using Axiomatic Design (AD). The model developed allows the evaluation of the efficiency of a process thanks to the use of a Process Design Matrix. This matrix links the basic process activities considering them as elements of an oriented graph. The result is the capability to evaluate the mean number of iterations needed to produce a product/service, the related cost and the overall efficiency of the process. Moreover, if the Process Design Matrix is merged with the information regarding the resources needed for each process phase, it could be used to simplify the definition of a Material Requirement Planning system for the process itself. This approach has been applied to an industrial case study and the ad-hoc MRP software has been developed starting from the input of this application.

Keywords: Axiomatic Design, Business Process Analysis, MRP, design coupling, ABC.

1 INTRODUCTION

Guided by the design axioms, Axiomatic Design [Suh, 1990] (AD) maps the functional requirements FRi to the Design Parameters DPi. This approach has been usually applied to the field of mechanical and system design because this application is the easiest to be implemented due to a clear definition of the FRs and the related performance measure of the product or system.

The proposed model wants to explore how AD could be applied to process design, with special regard to the evaluation and optimization of manufacturing process efficiency. A first model has been developed [Campatelli and Citti, 2009], where the AD representation has been adapted for process efficiency analysis implementing a new domain, the resource domain (that contains the Resource Needs - RNs), in order to evaluate the process costs. The RNs represent the amount of cost/resources needed to carry out a single phase of the process. The scheme of the 5 domains is presented in Figure 1 where the connection between the DPs and RNs is done thanks to a Resource Matrix [Campatelli and Citti, 2009].

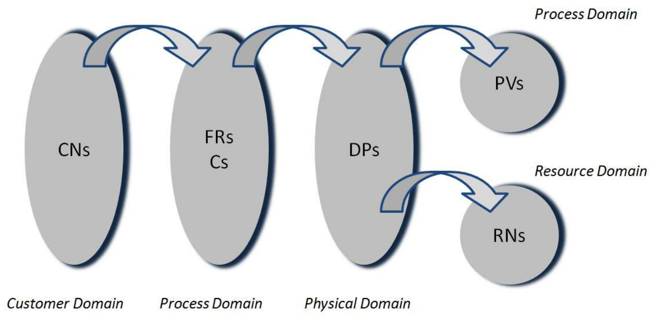


Figure 1. Five domains of the approach.

Another study regarding how to apply the AD approach to the process design has been carried out by many authors. Gonçalves-Coelho and Mourãoa focused their work on manufacturing processes [Gonçalves-Coelho and Mourãoa, 2007], developing an approach to select the best manufacturing process for a specific component. Manufacturing process redesign has been studied [Kulaka *et al.*, 2005] with special care on the implementation of optimized manufacturing cells instead of more traditional processes. Moreover Tang *et al.* [2009], as many others, worked to merge together AD with the Design Structured Matrix, an approach that has a longer experience in process design. The aim of this paper is to present an AD framework for the analysis of processes and a series of guidelines for process optimization, based on the evaluation of the design coupling for the process.

2 PROPOSED APPROACH

The implementation of the AD method to processes requires, while maintaining the basic structure, some specific definitions of the domains and variables. In case of a process, for example, it is trivial but really useful to remind oneself that the DPs must be phases or activities of the whole process.

Another relevant difference between product and process analysis is the definition of satisfaction. For a product the information content is the inverse of the probability of satisfying the FRs, providing a performance within its range of tolerances. It is possible to determine if a certain product complies or not with a functional requirement, for example, with the measurement of its properties (diameter, surface finish, length, etc.) and adopting a boolean gage. In case of processes, customer satisfaction is usually represented using a fuzzy variable [Tahera *et al.*, 2008] instead of a Boolean one. This application is not new for AD [Cebi and Kahraman, 2010] and this feature is always verified in the field of process design. This means that there is not a fixed threshold value for which the process output is fully unsatisfactory but its satisfaction assumes a different value ranging from 0 to 100% depending on the process output value. Often a satisfaction curve is used, as the one reported in Figure 2 that could represent, for example, the satisfaction associated to the delivery time of a requested service. Too low or high a delivery time could represent an issue for the production management of the customer but there are values for which the service is acceptable also if not fully satisfactory.

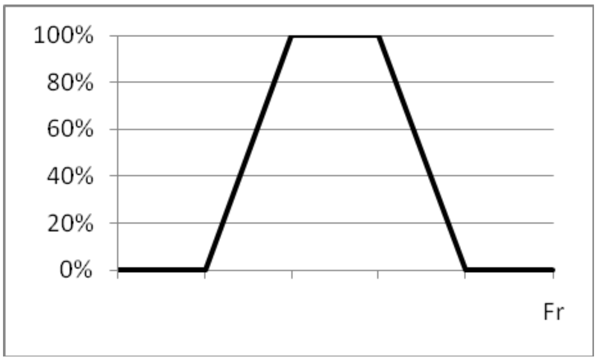


Figure 2. Satisfaction curve.

Due to this issue, the common range is no longer the simple intersection between the system and design ranges. For the evaluation of the "degree" of satisfaction in the case of processes is necessary to multiply the two functions of system and design range. An example of the resulting value is presented in Figure 3, where, calling *p* the probability of the system range and *s* the satisfaction value, the probability distribution will be *p *s,* and the probability of the common range is now the area under the light gray line.

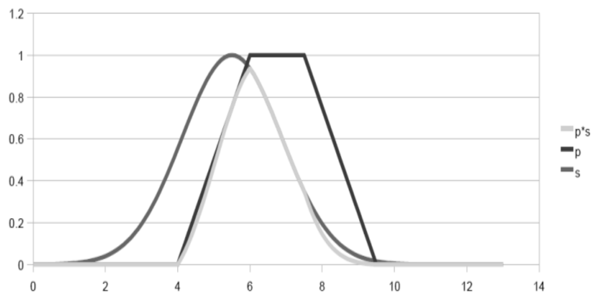
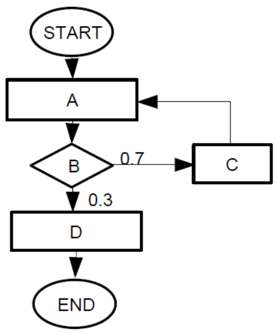


Figure 3. Process Common Range.

Regarding the evaluation of the degree of coupling for the process design is necessary to develop a mathematical representation more fit for process, where iterative loops are usually present. Our idea is to use a new concept of Design Matrix that could be better applied to evaluate the efficiency of the designed processes. The processes could be usually modeled as directed graphs, for which an efficient representation is a matrix where row and column elements are the steps of the process itself. The steps of the process must be DPs, because they are actions performed to satisfy a specific FR. If we consider in the oriented graph representation only the basic activities, all of these must be the DP leaves of the AD decomposition. The matrix that represents the oriented graph of the process has been called Process Design Matrix, later PDM, and it will be used to link together the terminal leaves of the DP tree. This matrix could not substitute the classical design matrix that links FRs to DPs, but it is an additional support to evaluate the process efficiency thanks to the analysis of its coupling.

In the application of AD to process design, the DP leaves could all be considered basic operations of the process. This definition implies that the resources consumed by these leaves could be computed easily because they are independent of other phases of the process. Using this representation each basic operation is associated with a row/column element of the matrix, and the arches indicate the logical junctions between basic activities; in the matrix, the a_{ij} elements represents the probability to start the *i* activity once the *j* activity is finished. If the *i* activity needs 2 or more other activities to start, it's necessary to use a decision node after each of them to ensure the continuation of the flow with a probability less than 1.

In Figure 4 a graphical and matrix representation is presented for a simple process.



	ST	A	B	C	D	END
ST	1	0	0	0	0	0
A	1	0	0	1	0	0
B	0	1	0	0	0	0
C	0	0	0.7	0	0	0
D	0	0	0.3	0	0	0
END	0	0	0	0	1	0

Figure 4. Graph and matrix representation.

In the matrix, the number of non zero values in each column are the total exits from the related node while the number of non zero values in a row are the total entrances in the node. An interesting property of the PDM is that this representation enables the designer to evaluate statistically how many basic operations will be performed to create a new product/service. This could be obtained by simply multiplying the matrix for itself until it "stabilizes" and only the two first rows assume values different from zero. This multiplying process is, mathematically, equal to the search of the eigenvectors of the matrix so also other numerical methods could be used to obtain such data. The multiplication is a simple approach to numerically extract this information from the matrix.

An example for the matrix in Figure 4 is reported in Figure 5 which computes the mean number of times that a basic operation is performed for every produced unit. In this case the number of multiplications used to obtain a stable matrix is 60.

$$\begin{bmatrix} 1 & 3.333 & 3.333 & 2.333 & 1 & 1 \\ 1 & 3.333 & 3.333 & 2.333 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Figure 5. Processed PDM.

Considering the first row of the processed PDM, it is possible to verify that the mean number of times that operation A will be performed is 3,33, the same as B, while the operation C accounts for 2,33, D for 1, and the supporting columns "start" and "end", obviously, 1 time each.

The main advantage of this representation is that, given the probability of a complex process in the PDM, it is possible in the design phase to obtain the mean number of times that an operation must be performed in order to produce a single unit. This could be used for the evaluation of the mean production cost if the matrix is multiplied for the vector of the manufacturing cost associated with each operation.

3 GENERAL APPROACH FOR PROCESS OPTIMIZATION

The idea of this paper is to evaluate if some general theorem could be developed to be included in the AD theory for the special field of process design. The first issue is the definition of the coupling of the PDM because, although this matrix is square by design, its diagonal is always zero. This implies that, differently from a classical DM, the PDM degree of coupling must be computed considering each single column and not for the whole matrix. It must be noted that the less coupled designs in AD are the ones where there is a single value in each column (diagonal matrix) and the coupling becomes greater increasing the number of non zero elements in each column (triangular and full matrix). This definition could be used to assess the coupling of the PDM. The coupling of the PDM could be analyzed also considering the study of Arcidiacono *et al.* [Arcidiacono *et al.*, 2001], where the coupling of the DM is computed considering not only the number of extradiagonal elements but also its numerical values and of Lee and Jeziorek [Lee and Jeziorek, 2006] where a model to compare the coupling of alternative solution/matrix includes also the FRs' and DPs' variation and introduce the concept of design equivalence.

Appling these concepts to the PDM it could be asserted that the least coupled solution is the one with only one element for each column. The PDM degree of coupling increases when the values of non zero elements increases. Physically this means that the process became iterative and the number of times that the iterations are performed increases. In this case, it could be useful, after creating the PDM, to perform a rearrangement of the matrix in order to graphically have the non-zero elements as near as possible to the diagonal. Differently from the DM, the diagonal would be zero, apart from the a_{11} element that is the starting condition of the process.

By simulating the PDM with different degrees of coupling it is possible to prove that the reduction of coupling brings also a reduction of cost for the production of a product/service. A simple example is reported in Figure 6 where the graph of cost with respect to the degree of coupling (descending) is plotted for the case of Figure 4. The degree of coupling has been reduced by considering an increasing a_{53} element. When this element is 1 the complimentary value a_{43} is zero and the matrix is fully decoupled. The resource vector considered has a cost of 1 for each basic operation.

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1-x & 0 & 0 & 0 \\ 0 & 0 & x & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

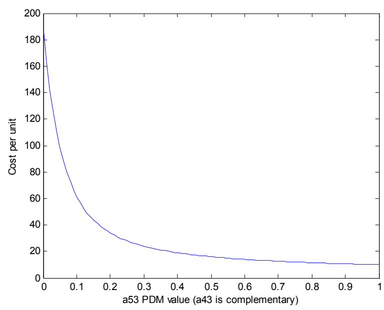


Figure 6. Graph of cost/decoupling.

Another example could be performed for a more coupled matrix, as the one reported in Figure 7. This is a parametric matrix in terms of x. Increasing the value of x, it is possible to reduce the coupling until the full decoupled matrix is obtained. The basic operation costs considered are still 1.

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1-x & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1-x & 0 & 0 & 0 \\ 0 & 0 & x & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & x & 0 \end{bmatrix}$$

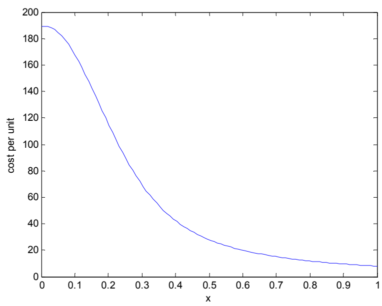


Figure 7. Matrix and cost analysis.

Also in this case the less coupled matrix, the more efficient the designed process is. In general the shape of the cost function depends on the PDM but the trend is always decreasing with respect to the decoupling.

From these simulated tests is possible to define the following theorem:

Process Efficiency Theorem: *A more coupled matrix, in the PDM sense, always produces a more resource expensive process on average.*

This means that the most efficient solution is the most decoupled in the PDM sense.

4 PDM MATRIX FOR MRP

The PDM representation could be also useful for the definition of the MRP (Material Requirement Planning) associated with the manufacturing process. In order to obtain the number of items/resources needed for the production of one unit, it is possible to use the RNs matrix that links the activities (DP leaves) to the resources needed. An example is reported in Figure 8.

	Resource 1	Resource 2	Resource 3
Activity 1	2	1	0.5
Activity 2		3	1
Activity 3			2
Activity 4		1.5	
Activity 5	0.3	0.7	
Activity 6	2		
Activity 7		2	

Figure 8. Example of Resource Matrix.

By multiplying the RNs matrix for the vector given by the first row of the processed PDM, it is possible to obtain not only the costs but also the quantity of an item/resources needed. This is the basis for the MRP. The analysis of resources/cost associated with the production of one unit of product/service does not consider that the cost of a rework could be different from the cost of the first time that the original operation is performed. Due to the nature of the operation this cost could be either lower or greater with respect to the initial one. The developed approach does not take into account such variation because it is supposed that the rework would happen a reduced number of times so some differences among costs would induce a small error on the average production. However this problem could be solved by adopting a solution similar to the DSM rework matrix [Yassine *et al.*, 2001], although this is not considered in the actual work.

5 CASE STUDY: MANUFACTUTING COMPANY

This approach has been applied to a mattresses manufacturer of the Tuscan area that works mainly for the large distribution and is a world leader. The main problem of this organization is the large number of customers and the high degree of customization of its products. There are more than 10.000 different product codes. The most used format of mattress are four: "normal" or "oversized" and both of them can be produced in two different ways, "closed" or "removable"; the last one is a mattress with a side zipper that allows it to be opened for an easy wash. "Normal" products are easier and their development is always the same. However, the "oversized" mattresses have an artisan component that makes the development in a production line difficult. The mattress is composed of an internal core, usually a PP or latex sheet (more than 30 type are possible), that is bought externally, and the cover, composed by a side band and two quilted towels. The final production step is the shipping that could be done in different way (i.e. with or without vacuum packaging). The purpose of the study has been to obtain and improve the process map and reduce the WIP and the not value added phases using the AD approach.

The first step for the optimization of the process has been the evaluation of the customer needs and their translation into FRs. Starting from them, a classical DM has been built and the process has been optimized using the classical approach. At the end, about 60 FRs and DPs of the lowest (the 5[th]) level have been found. The first level is presented in Figure 9 while the FR1x and DP1x are presented in Figure 10.

	DP1: Different combination of similar elements	DP2: High volumes, constant productive rhythm	DP3: Low production costs	DP5: Job - shop process	DP4: Fast shipping
FR1: 3 kind mattresses production mix	X	0	0	0	0
FR2: Satisfy high and constant customer demand	0	x	0	0	0
FR3: Keep down the selling price	0	x	x	0	0
FR4: Short lead time for the customer	0	x	0	x	0
FR5: Customization	0	0	0	x	x

Figure 9. First level DM matrix.

Thanks to this approach, the manufacturing process has been redesigned. One of the main results obtained has been the decoupling of the material flux from the information one. Another action has been the definition of two sub-processes to decoupled the flux of standard and oversize mattresses, that have different needs. For the first type, a more linear and flow tended process has been designed, while for the other a very flexible job shop cell has been preferred. According to the decreased coupling of the matrix we have obtained a more efficient process. The 3 months of process monitoring have proven that at least a 5% reduction in the manufacturing cost has been obtained. This is due mainly to the reduction of time needed to equip the machinery, to carry the materials and a little reduction of used semi-products due to greater process reliability.

After the optimization, to evaluate the production cost, a PDM between the 60 DP leaves has been implemented. The matrix relates DPs from different level. An example of a small part of the PDM is reported in Figure 11.

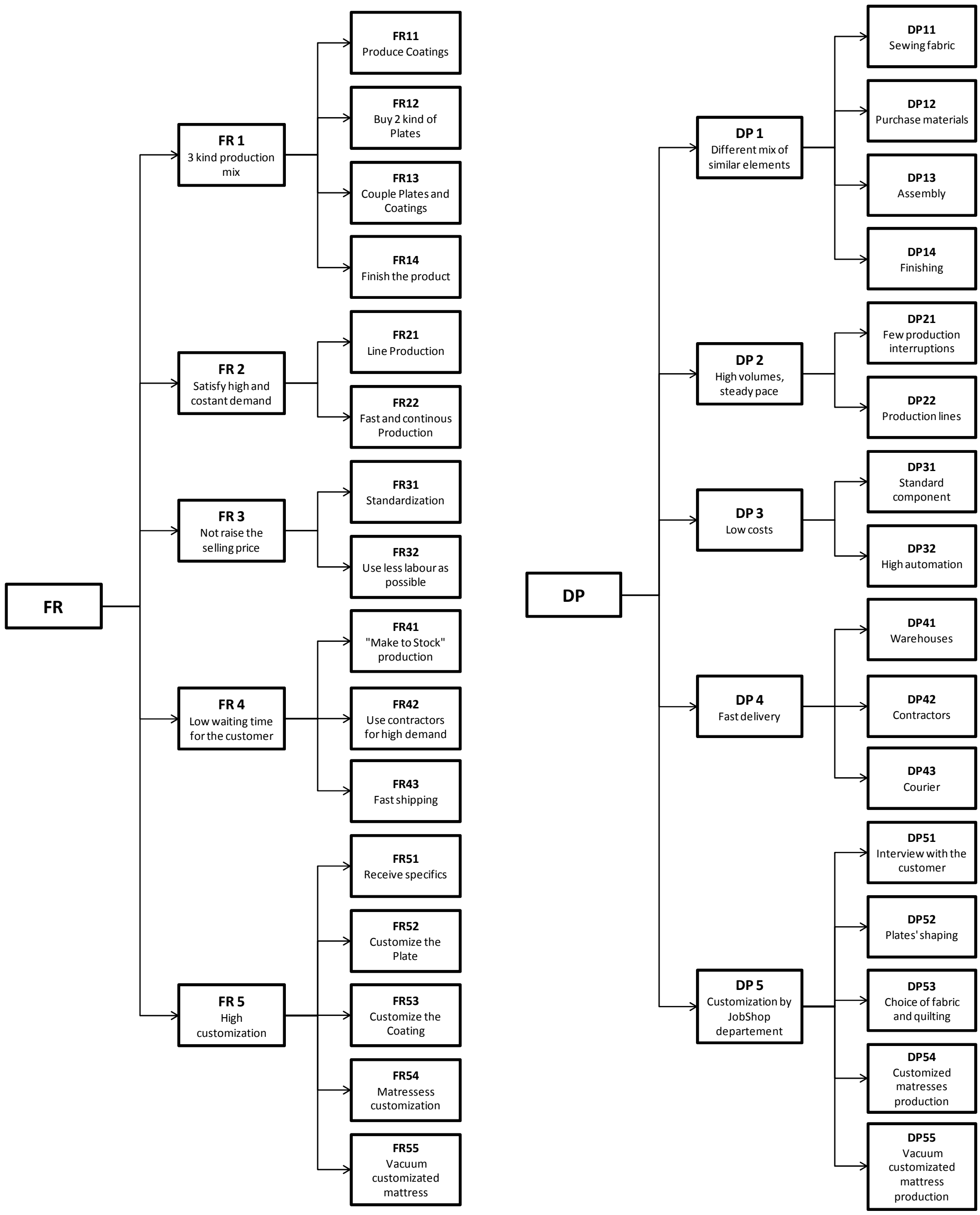


Figure 10. Part of PDM for case study.

To/Occours	DP1111: Fabric	DP1112: Material extracted	DP1113: Work unit	DP1114: Extraction from Warehouse	DP1115: Energy unit	DP1116: machine time to cut fabric	DP1117: Machine time to cut side bands
DP1111: Fabric	0	0	0	0	0	0	0
DP1112: Material extracted	1	0	1	0	0	0	0
DP1113: Work unit	0	0	0	0	0	0	0
DP1114: Extraction from Warehouse	0	0	0	0	0	0	0
DP1115: Energy unit	0	0	0	0	0	0	0
DP1116: machine time to cut fabric	0	0	0	0	0	0	0
DP1117: Machine time to cut side bands	0	0	0	0	0	0	0

Figure 11. Part of PDM for case study.

In order to evaluate the costs of the basic operations represented by the DPs, an ABC analysis [Homburg, 200] has been performed.

6 CONCLUSION

The developed approach has been tested and validated thanks to an application to a manufacturing company. In particular this approach has shown the following issues:

- it provides a definition of information content well suited for processes
- it allows an easy and fast identification of the coupling of the processes thanks to the study of PDM;
- it suggests which process step must be modified in order to improve the process;
- it allows a fast evaluation of the total manufacturing costs;
- the company MRP could be easily built starting from these data;
- a general Process Efficiency Theorem has been defined to evaluate the process efficiency.

7 REFERENCES

[1] Arcidiacono G., Campatelli G., Lipson H., "A measure for design coupling", *Proceedings of International Conference Engineering Design 2001 (ICED01) conference*, Glasgow (UK), August 21-23, 2001.

[2] Campatelli G., Citti P., "Business process analysis and reengineering of administrative processes using axiomatic design: theory and case study from the university of Firenze", *Proceedings of ICAD2009, The Fifth International Conference on Axiomatic Design*, Campus de Caparica – March 25-27, 2009.

[3] Cebi S., Kahraman C., "Extension of axiomatic design principles under fuzzy environment", *Expert Systems with Applications,* No.37, pp. 2682–2689, 2010.

[4] Gonçalves-Coelho A.M., Mourãoa A. J.F., "Axiomatic design as support for decision-making in a design for manufacturing context: A case study", *International Journal of Production Economics*, Volume 109, Issues 1-2, pp.81-89, 2007.

[5] Homburg C., "Improving activity-based costing heuristics by higher-level cost drivers", *European Journal of Operational Research*, Volume 157, Issue 2, pp. 332-343, 2004.

[6] Kulaka O., Durmusoglua M.B., Tufekcib S., "A complete cellular manufacturing system design methodology based on axiomatic design principles", *Computers & Industrial Engineering* , Volume 48, Issue 4, pp. 765-787, 2005.

[7] Lee T., Jeziorek P.N., "Understanding the value of eliminating an off-diagonal element in a design matrix" *Proc. of 4th int. conf. on axiomatic design,* 2006

[8] Tahera K., Ibrahim R.N., Lochert P.B., "A fuzzy logic approach for dealing with qualitative quality characteristics of a process", *Expert Systems with Applications*, Volume 34, Issue 4, pp. 2630-2638, 2008.

[9] Tang D., Zhang G., Daia S., "Design as integration of axiomatic design and design structure matrix" *Robotics and Computer-Integrated Manufacturing* , Volume 25, Issue 3, pp.610-619, 2009.

[10] Suh N.P., *The Principles of Design*, New York: Oxford University Press, 1990. ISBN 0-19-504345-6

[11] Yassine A. A., Whitney D. E., Zambito T., "Assessment of Rework Probabilities for Simulating Product Development Processes Using the Design Structure Matrix (DSM)", *ASME International Design Engineering Technical Conferences*, 2001