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STUDY REGARDING THE SELECTION OF THE OPTIMUM PROCESS FLOW AT BEARING RINGS MANUFACTURING

Cezarina CHIVU, Mitica AFTENI, Gabriel-Radu FRUMUSANU, Florin SUSAC

Abstract: *In the actual economical and technical environments, selecting the optimum manufacturing process from a several alternatives becomes the most important task for process designers, process planners and for process engineers also. The first selection step is encountered in quotation phase. In this paper a study concerning the structural identification of the process flow, based on the combinatorial optimization approach is proposed. The structural identification of the process flow, for each main process indicated as part of the flow diagram, becomes more and more complicated when more alternatives are available. A decision related to structural identification of the alternative process flow is requested in order to solve the problem occurred in the case when unpredicted events happen during the process. The proposed approach could be integrated and used also in the phases as: quotation, design, product development and related manufacturing processes ongoing. The database was built using data collected from industrial environment.*

Key words: *combinatorial optimization, structural identification, bearings manufacturing, process flow diagram, design, quotation.*

1. INTRODUCTION

The changes of the business environment registered during the last years could be approached using different strategies in the cases of developing the business through rapid quotation process and then, developing and implementing the manufacturing processes in the workshops in a manner that ensures both the lead time improvement and the maintaining the quality of the products, also, considering the rapid decisions needed. The promoting in the industrial companies of the approaches that the risks mitigation actions addressed to the potential occurrence of unpredicted events should be implemented by the engineers through the selection of the most suitable alternative for a given process step has become one of the most important and hard tasks. Considering that more alternatives for a given manufacturing process are available, the risk to select one which will not give the expected results after its usage occurs when the decision should be taken by the engineer based on his experience. A great waste of production resources of the factory may result then [1]. The implementation in the manufacturing workshop of the process flow used in the quotation phase and process design becomes a difficult job due to the unexpected events, which occur in the manufacturing workshops. In these situations, which are currently met in industrial activities, it is useful for process implementation to analyze the combinations of the potential alternatives and to take the decision of the running the most economical alternative considering the lead time in the first step and then the total cost of the manufacturing process.

In the actual context, the manufacturing plants managers start to define and implement different strategies to dispose of flexible production systems that can respond quickly to demand changes and to the processing of a variety of products [2] and also to invest resources in different applications or support decisions systems. To achieve the goal of the manufacturing process itself to produce good products using a homologated process flow sometimes is not an easy task, due to different problems which occurs in the implementation phase of the processes. In order to help the process planers and process engineers to decide from a couple of alternatives which one could be used in a sustainable way, considering as input the set-up and cutting time, the present study is focused on a combinatorial optimization analysis of the different alternatives of the process flow in the case of bearing rings manufacturing process, by using the structural identification of the activities. In this purpose, they were selected three pairs of rings, inner and outer ring, from the category of spherical bearings. The input data of the proposed analysis are: set-up time, cutting time and the process alternatives.

In each studied case, the alternatives were studied using the structural approach of the activities of the manufacturing process. For example, one alternative is to use in turning process a classic turning machine in the place of a CNC machine, with the associated set-up, the cutting times in both cases being homologated. The rest of the process flow it is maintained identical with the homologated one.

In each product, manufacturing step decision should be taken regarding different process activities. These decisions are token based on the analyses type: “what happens if?”, [3]. This analysis requests models, which are able to provide the relation between the decision parameters and the results of the analyzed step from the manufacturing process, considering that for each step could exist different alternatives, both from technological point of view and from the side of the machine-tools availability. In the current approaches, the identification of the existence of the alternatives which are qualified or could be qualified from quality point of view on the first instance and then from the manufacturability point of view considering that this parameter could involve some supplementary costs becomes one important job of the process designers and process planners.

Quick decisions are requested to be taken in case of some unpredicted events occur such as:

- Accidental defects of the machine tool identified in the base process flow,
- Unavailability of the qualified human resources both for set-up and running of the machine-tools in case that some supplementary qualifications or skills are requested, and
- Overlapping of two or more production orders which are using some machine tool for a process step.

In most of the cases, one has to analyze through the combination of different potential solutions and, at the end, to select the optimum one in order to process the goods at the requested levels: quality, time and quantity.

Even though different researchers have studied the optimization of production routing problem during the last decades, research and works on integration of optimization of the production routing in phase of production scheduling and then in phase of production running is limited, [4], [5].

In the decision-making process, many real-life situations, in addition to the objective assessments, multi-objective combinatorial optimization problems have expert preferences and assessments that are often formulated in terms of natural language, like “second alternative is better than third alternative with respect to an attribute” or “x is too large”. The conventional methods, both deterministic and random processes, tend to be less effective in conveying such imprecision and vagueness characteristics. It is therefore necessary to extend classical multiple attribute decision making techniques to the case where subjective assessments come from experts, [6].

In the case of a small range of products and available machine-tools the selection process of the most appropriate alternative, considering the homologated one as the best one, could be performed by the process engineers using only the registered data for timespan, set-up time in correlation with the machine-tool availability.

In real manufacturing environment the implementation of a defined process flow sometimes becomes a hard job due to the independent factors, which can affect the results such as lead time, quality and finally the production costs.

In the present paper, the case study was developed based on a small data base to identify the optimum flow diagram using the approach of the combinatorial optimization. A characteristic to solving a combinatorial optimization problem is that it becomes more difficult to obtain an exact solution when the number of parameters increases. The paper is organized as follows: the second section presents the structural identification of the flow diagram for the bearing components manufacturing process. The next section describes the combinatorial optimization. The fourth section approaches the structural identification of the manufacturing activities through combinatorial optimization in the case of the manufacturing flows for the inner and outer rings of spherical roller bearings. The last section presents the paper's conclusion.

2. STRUCTURAL IDENTIFICATION OF THE FLOW DIAGRAM AT BEARING COMPONENTS MANUFACTURING

The structural identification of the process flow for each main process indicated as part of the flow diagram becomes more and more complicated when different alternatives are available on one side and on another side when the basic alternative it is not available due to an unpredicted event such as an accidental defect of one machine-tool. In these cases, there should exist a possibility to identify in precise manner the alternative which should be used in the workshop. The selected alternative should assure quality of the produced good, appropriate production cost and lead time and also the sustainable usage of resources and protection of the environment as a mandatory request. In order to achieve the goals, the database with alternatives should be available and interrogated in the phase of process development. In order to identify the optimum process flow some analysis should be performed. The next step is to describe with the needed details the process flow in the: Work instructions, Verification plans, Control Plans and Operation Plans. To develop a system which can help process engineers to identify the most suitable alternative the combinatorics optimization principle is used in the present paper considering a data base for 3 pairs of bearing components (inner and outer rings) in case of spherical bearings.

The bearing components manufacturing processes are identified generally in flow diagrams, see Figure 1.

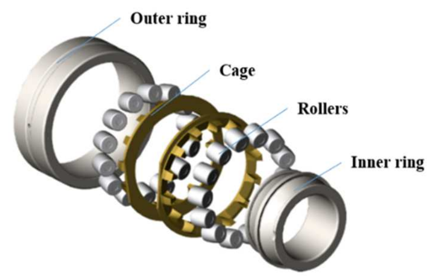

Fig. 1. Components of the spherical roller bearings.

The identification of the most feasible process flow to be developed for manufacturing and then assembly the bearing components in the final product it is a complicated task for process engineers in order to satisfy market demands, improve the quality of the products [7] and manufacturing process performance.

The structural identification method of the activities of a manufacturing process, [8] at each phase of the technological processes (rough process, semi finishing, finishing and superfinishing) involves in the first step the identification of the general flow diagram. This flow diagram it is designed during the process development phases by the process designer in order to identify very clear all necessary manufacturing steps and related control and inspection methods. In the flow diagram are depicted the relations between the operations of the manufacturing process and the information flows. In the phase of the process development the implementation in production of the processes described in the flow diagram it can be predicted through the analysis of the potential manufacturing alternatives. In these cases, the reaction plan it is described in case that an unpredicted event occurs and the alternative manufacturing flow it should be used.

Another situation is that during the manufacturing activities the events occur and at that moment the decision should be taken as quickly as possible. In this case, the advantages of the using of the structural method could: make shorter the analysis and decision time; improve the accuracy of the results and increase the machine-tool efficiency. The proposed method, for the structural identification of the activities of one or more manufacturing steps, supposes the selection of the most suitable alternative at the operation level considering different optimization criteria such as: cost, time, set-up time or different combinations of these parameters. After the selection of the most suitable alternatives, at the level of manufacturing operation level, it is obtained an optimum process flow. Using this optimum process flow assure the manufacture of the ordered product at the request levels of quality, time and quantity.

The application of the structural identification method was sampled in the bearing manufacturing case, in paper [9]. After the successive evaluation and selection of the optimal activities from different levels of the manufacturing process, the authors of this paper obtained the optimal manufacturing path starting with an order for the bearings manufacture.

3. COMBINATORIAL OPTIMIZATION

Combinatorial optimization is a subset of mathematical optimization, which is related to operations research, algorithm theory and computational complexity theory. It has important applications in several fields, including artificial intelligence, machine learning, mathematics and software engineering, [10]. Combinatorial optimization is a very important field of computer science and applied mathematics, combining techniques from operational research, combinatorics, mathematical optimization and algorithm theory, to solve optimization problems defined on discrete structures. Combinatorial optimization has many applications, [11]:

- In engineering (planning of energy resources, highways, bridges, telecommunications);
- In the field of economic sciences (production, planning, management, finance, marketing);
- In road, rail, air transport issues.

In the combinatorial problems, priority are the questions of existence and counting:

- Is there a particular type of arrangement?
- How many such arrangements can be formed?

An optimization problem is combinatorial if each variable can independently take several known numerical values, for example: integer, non-negative values below a given threshold, or only 0 or 1 values. The main characteristic of a combinatorial problem is that the number of possible combinations of values is finite. These combinations are called solutions of the problem. Combinations that, in addition, satisfy the restrictions of the problem, also in finite number, will be called admissible solutions.

Combinatorial optimization has found wide applicability in ranging from industrial, academic, logistic to manufacturing applications, etc. In paper [12] are presented the merits and demerits of combinatorial optimization models, also the authors proposed the development of more efficient and user-friendly combinatorial optimization methods.

In paper [13], the authors propose a new graph convolutional neural network model for learning branch-and-bound variable selection policies, which leverages the natural variable-constraint bipartite graph representation of mixed-integer linear programs.

In practice, most combinatorial optimization problems can be formulated as mixed-integer linear programs (MILPs), in which case branch-and-bound (B&B) [14], [15] is the exact method of choice. Branch-and-bound recursively partitions the solution space into a search tree, and computes relaxation bounds along the way to prune subtrees that probably cannot contain an optimal solution. This iterative process requires sequential decision-making, such as node selection: selecting the next node to evaluate, and variable selection: selecting the variable by which to partition the node's search space, [16].

The combinatorial optimization could become a tool which can be used also to manage the processes and to analyses which alternative it is the most suitable to be implemented. In these cases, considering that an event could occur in the company's activities to mitigate the risk to delay the deliveries the process engineers could decide to switch on the suitable alternative and decide accordingly only through a database interrogation.

4. CASE STUDY

In this chapter, the proposed approach of the structural identification of the manufacturing activities through the combinatorial optimization was studied in case of the manufacturing flows for inner and outer rings of spherical roller bearings (see Figure 1). The optimum processing time was identified and used in the present study as a decision parameter for each analyzed manufacturing step.

The mentioned bearings are for some industrial applications, as wind turbine main shafts, continuous casters, vibratory applications and high-speed applications.

The structural identification of the activities involved in manufacturing process of bearings components, inner and outer rings, was studied in case of grinding process phases.

In order to obtain the final products at the requested deadline within the imposed parameters according to product design in terms of: surface quality – profile and roughness, dimensions and deviations as: ovality, radial run-out, axial run-out and conicity decisions are needed in case of different process phases performed on dedicated machine-tools.

In Figure 2 a generic flow diagram is presented in case of a bearing manufacturing process that involves different manufacturing operations phases to achieve the requested final parameters for the product. In case of a manufacturing process at different levels, there are different phases, which can be implemented on a machine-tool. From production order at level A through the phase of superfinishing machine-tool alternative at last level. Through the identification of the correlation between activities of a manufacturing process it is obtained the chain of activities from production order to last technological operation phase. In the case of bearings components, the last operation phase it is superfinishing of the raceway. In case that the basic process flow it is not available due to an unpredicted event such as an accidental defect of one machine-tool there should exist a possibility to identify in a precise manner the structure of the alternative process flow which should be used in the workshop. Using a dedicated software or application based one a database with information collected from past jobs or determined from measurements with data regarding set-up time and cutting time for each process step, help the designers to select in a rapid way the most suitable alternative.

The levels of orders for 5 products in the last 5 years have been identified and the forecast for 2023 is included in Table 1. It was selected for the case study of proposed approach the product named P1 which was produced and delivered close to the minimum ordered quantity and the forecast for current year is under the minimum order quantity.

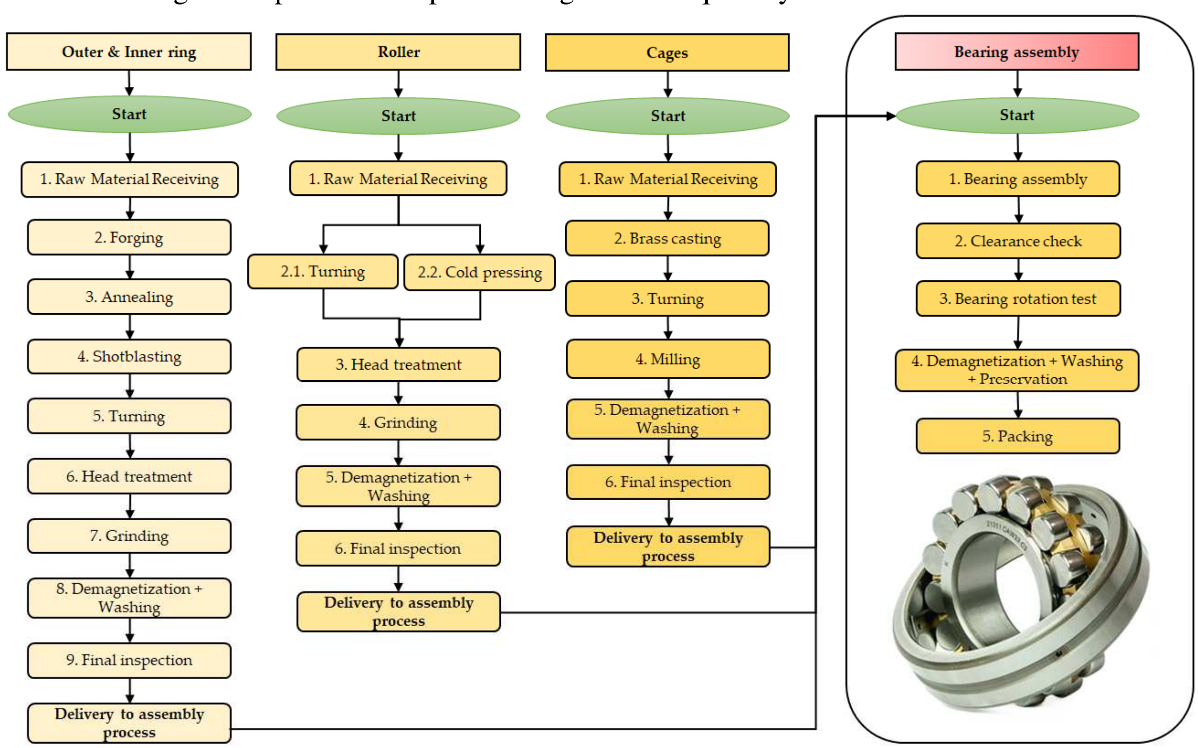

Fig. 2. The flow diagram for manufacturing of bearings components.

Table 1

Reference data used in the case study.

No.	Products	Ordered and delivered quantity / Reference year					Total ordered and delivered quantity	Forecast 2023	Minimum order quantity
		2018	2019	2020	2021	2022			
1	P1	73	29	18	25	7	152	68	200
2	P2	10	17	31	30	0	88	22	200
3	P3	4	6	10	9	0	29	-	200
4	P4	17	27	34	11	0	89	-	200
5	P5	2	6	2	28	4	42	-	200

In Tables 2 and 3, the list of activities in cases of outer and inner ring manufacturing is presented. According to the proposed approach, the structural identification of the manufacturing processes and phases using to the combinatorial optimization method it was identified the optimum graph of activities in case of outer and inner ring of spherical bearings manufacturing processes. The mentioned graphs are shown in Figures 3 and 4.

In the representation of the graphs in Figures 3 and 4, the symbols presented in Table 4 were used.

The optimal paths for the manufacturing of the bearing components (inner and outer ring) were identified through the interrogation of the database with data collected from the industrial environment.

A resume of the data used for the comparative assessment and selection of the optimal paths can be observed in Tables 5 and 6.

Table 2

List of activities in the case of outer ring manufacturing process.

Activity	Alternatives codes
Production order	A_1, A_2, A_3
Forging process (including shout blasting and primary heat treatment)	B_1, B_2
Turning + Secondary Heat treatment	C_1, C_2
Grinding process (process phases)	$D_{1.1}$, $D_{1.2}$, $D_{2.1}$, $D_{2.2}$, $D_{3.1}$, $D_{3.2}$, $D_{4.1}$, $D_{4.2}$, $D_{5.1}$, $D_{5.2}$, $D_{6.1}$, $D_{6.2}$, $D_{7.1}$, $D_{7.2}$, $D_{8.1}$, $D_{8.2}$

Table 3

List of activities in the case of inner ring manufacturing process.

Activity	Activity code	Alternatives codes
Production order	A	A_1, A_2, A_3
Forging process (including shout blasting and primary heat treatment)	B	B_1, B_2
Turning + Secondary Heat treatment	C	C_1, C_2, C_3
Grinding process (process phases)	D	$D_{1.1}$, $D_{1.2}$, $D_{2.1}$, $D_{2.2}$, $D_{3.1}$, $D_{3.2}$, $D_{4.1}$, $D_{4.2}$, $D_{5.1}$, $D_{5.2}$, $D_{5.3}$, $D_{6.1}$, $D_{6.2}$, $D_{7.1}$, $D_{7.2}$, $D_{8.1}$, $D_{8.2}$, $D_{8.3}$, $D_{9.1}$, $D_{9.2}$, $D_{9.3}$

Table 4

The symbols used in manufacturing graphs.

△	- Levels of manufacturing activities;
▭	- Levels of the manufacturing phases associated to the manufacturing activities;
→	- Transition from one level to another.

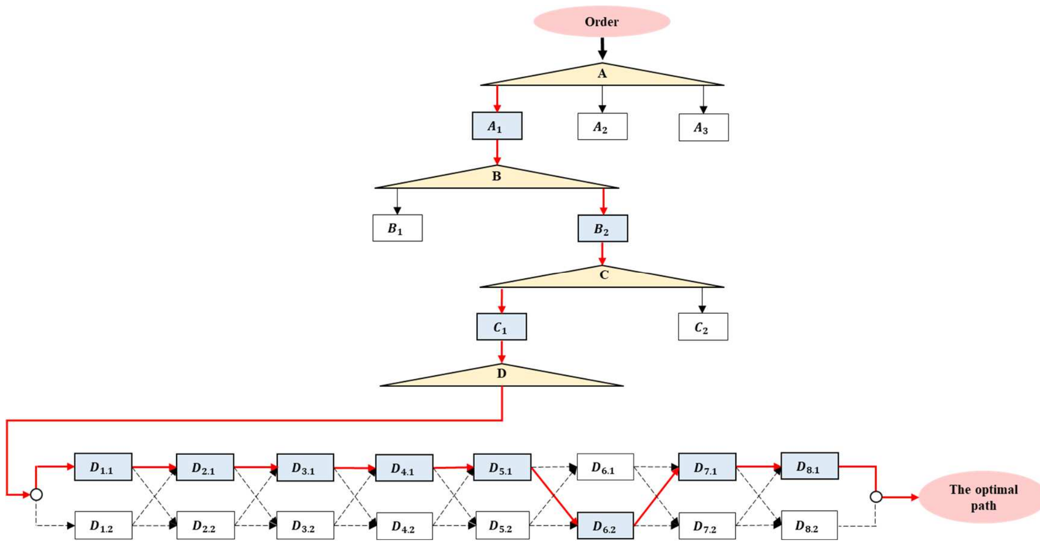

Fig. 3. The graph of activities in the case of outer ring manufacturing process.

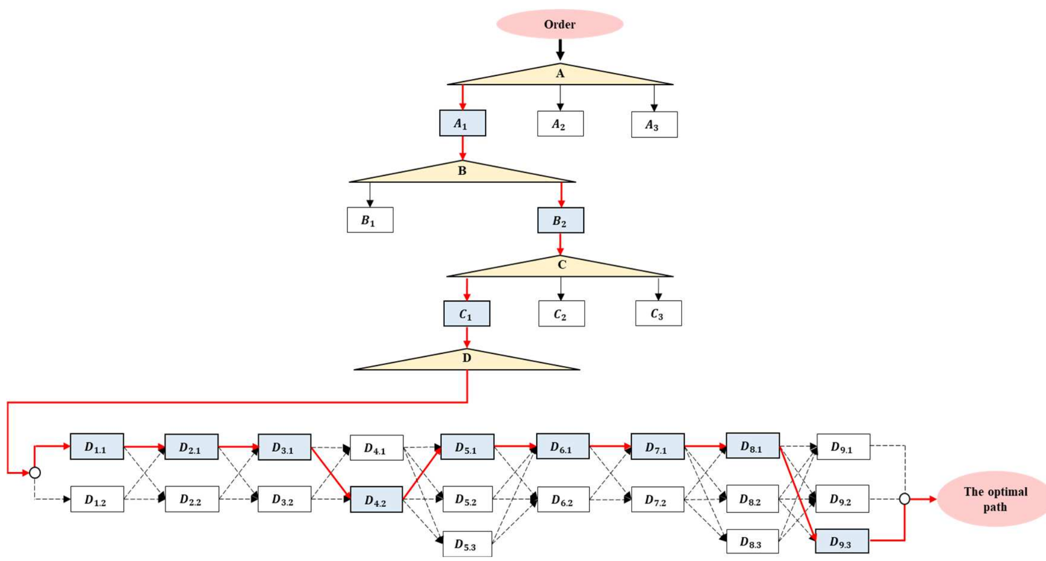

Fig. 4. The graph of activities in the case of inner ring manufacturing process.

Table 5

Comparative assessment of the potential alternatives for outer ring process flow.

Activities level	Outer ring processing alternatives	Process time	Optimum process time
Level B	Total B_1	8,057	-
	Total B_2	7,877	7,877
Level C	Total C_1	14,56	14,56
	Total C_2	28,041	-
Level D	Total $D_{1.1} \div D_{8.1}$	9,39	-
	Total $D_{1.1} \div D_{5.1} + D_{6.2} + D_{7.1} \div D_{8.1}$	9,005	9,005
Selected alternative: $A_1 + B_2 + C_1 + D_{1.1} \div D_{5.1} + D_{6.2} + D_{7.1} \div D_{8.1}$		-	31,442

Table 6

Comparative assessment of the potential alternatives for inner ring process flow.

Activities level	Inner ring processing alternatives	Process time	Optimum process time
Level B	Total B_1	6,917	-
	Total B_2	5,029	5,029
Level C	Total C_1	18,279	18,279
	Total C_2	25,413	-
	Total C_3	18,559	-
Level D	Total $D_{1.1} \div D_{9.3}$	15,743	-
	Total $D_{1.1} \div D_{3.1} + D_{4.2} + D5_{.1} \div D_{9.3}$	15,366	15,366
Selected alternative: $A_1 + B_2 + C_1 + D_{1.1} \div D_{3.1} + D_{4.2} + D_{5.1} \div D_{9.3}$		-	38,674

The manufacturing processes of bearing rings are complex and require a succession of stages (production route) that take place in different sectors of a factory. The manufacturing process is also inflexible, involving many adjustments of machine tools, usually specialized, when changing between different types of manufacturing batches [17]. Manufacture of bearing rings in small batches requires long adjustment times of the high productivity equipment, [18]. The most sophisticated bearings for the most demanding applications are very precise devices; their manufacture requires some of the highest standards of current technology, [19], [20]. In the case of a manufacturing process successively performed at different levels, there are different phases, which can be implemented on a given machine-tool, from production order at level A through the phase of superfinishing machine-tool alternative at last level. Through the identification of the correlation between activities of a manufacturing process, the chain of activities from production order to last technological operation phase is obtained. In case of bearings components, the last operation phase it is superfinishing of the raceway.

At a level of the activities of a manufacturing process there could exist more potential alternatives. Figure 3 concerns a manufacturing process for which at each activity level are more potential alternatives which can be used to complete the activity at the requested targets (time, quality and quantity). The activities developed between two levels are named *ways*.

The ways are marked with bold arrows and are identified with letters according to the starting level. For example, the ways identified from level B to level C are B_1 and B_2. At a certain level, it should be selected a way, passing through a decision point. The manufacturing graph can be selected based on three different variables: minimum cost, minimum lead time or combination of the mentioned two parameters.

In Figures 3 and 4 the specific operations graph is designed in the case of bearings components (inner and outer ring) manufacturing process, in which:

- Level A (customer order selection) consists by 3 activities named A_1, A_2 and A_3. According to the proposed method, only one activity from the 3 potential alternatives is selected. Considering the historical data related to ordered and delivered quantities in the last 5 years (see table 1), the forecast for the current year and the minimum order quantity as important factors for first selection at level A it was selected activity A_1. The selected activity based on the mentioned factors leads to good results acceptable cost and profit. At level A the selection is valid for both bearings components. From level B to D for each bearing component, inner and outer ring, different selections are performed according to the designed flow diagrams and process time.
- Level B – case of outer ring process flow– at this level for the selected alternative at level A exists 2 potential alternatives (B_1 and B_2). According to the proposed method from the 2 alternatives is selected the most suitable one which is: B_2.

Considering the same algorithm at level C it is selected as a suitable alternative the activity C_1. At the last level named level D there are several potential alternatives. To obtain the optimum case, in the case of the outer ring manufacturing process, a combinatorial analysis was performed considering the following hypothesis: level D is the level of grinding process phases for each phase was identified minimum one alternative. The basic phase it is marked as: $D_{1.1}$….$D_{8.1}$ and the alternative phases are marked as: $D_{1.2}$….$D_{8.2}$. The alternatives were identified based on grinding machine process time and also based on alternative machine-tool available to be used to manufacture the product at the designed quality. From these alternatives after the comparison in terms of process time only one it is selected.

The selected alternative at this level is $D_{1.1} \div D_{5.1} + D_{6.2} + D_{7.1} \div D_{8.1}$ and it is the alternative which gives the good results. After the successive evaluation of the activities at different levels an optimum technological flow named the optimal path is identified for the manufacturing process of the product considered at the beginning. In the presented case the flow of the activities includes $A_1 + B_2 + C_1 + D_{1.1} \div D_{5.1} + D_{6.2} + D_{7.1} \div D_{8.1}$. In Figure 3 the identified optimal path is marked in red. In case of the inner ring, by following the same algorithm, the identified flow of activities includes $A_1 + B_2 + C_1 + D_{1.1} \div D_{3.1} + D_{4.2} + D_{5.1} \div D_{9.3}$. In Figure 4 the identified optimal path is marked in red.

5. CONCLUSION

The present study was developed using data collected from the industrial environment based on the quantities produced in the last 5 years for 5 products. All quantities were under the minimum order quantity and considering this hypothesis as reference was identified in both cases for inner and outer ring of a spherical bearing the optimum process flow through the combination of several alternatives. Optimization of the manufacturing processes based on the integration of the comb-database optimization method in the structural identification could be applied to entire data base of a dedicated step from a manufacturing process or in case of the entire process flow.

The case study developed in the present paper shows that the flexibility of the process flow could be used before the unpredicted events happens (lack of tools for a specific machine-tool, lack of a qualified operator to operate a specific machine-tool, planned or unplanned stoppage of one or more machine-tools, accidental defects of the machine-tools, devices or tools). Using the proposed approach both in quotation phase and then in real time during the process running could lead to reduction of the decision time on one side and on another side to have a tool for manufacturing phase's comparison. The proposed approach could be used also in case different alternatives are available for the machine-tools intended to be used considering the maintenance plan and also the interruption time for maintenance. The proposed approach could also be used in the case of different production orders with quantities under the minimum order quantity. In this case the homologated manufacturing process it is in some situation no efficient and a quick decision it is needed to manufacture a product in the targeted efficiency using an existent or potential alternative for one or more process phases and machine-tools. The optimum flow identified after the analysis of the data considering the process time in case of:

- *Outer ring process flow:* $A_1 + B_2 + C_1 + D_{1.1} \div D_{5.1} + D_{6.2} + D_{7.1} \div D_{8.1}$.
- *Inner ring process flow:* $A_1 + B_2 + C_1 + D_{1.1} \div D_{3.1} + D_{4.2} + D_{5.1} \div D_{9.3}$.

Considering the above presented approach and the conclusions of this paper, in a future study the subject will be extended and the downtime of the machine-tools will also be considered as input parameter.

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Studiu referitor la selecția fluxului tehnologic optim pentru procesarea unor elemente de rulmenți

În mediul economic și tehnic actual, selectarea variantei optime pentru un proces tehnologic dintr-o sumă de alternative disponibile a devenit o sarcină importantă pentru proiectanții de procese, planificatorii proceselor și, de asemenea, pentru inginerii de proces. O primă selecție trebuie să fie disponibilă și utilizată în faza de ofertare a produsului. În această lucrare este propus un studiu referitor la identificarea structurală a unui flux tehnologic bazat pe abordarea optimizării combinatoriale. Identificarea structurală a fluxului tehnologic, pentru fiecare proces inclus în diagrama de proces proiectată, devine o sarcină din ce în ce mai dificilă atunci când mai multe alternative sunt disponibile. O decizie referitoare la identificarea structurală a alternativelor tehnologice este necesară pentru a rezolva problemele legate de apariția unui eveniment neprevăzut în timpul rulării procesului de producție. Abordarea propusă poate fi integrată și utilizată în fazele de ofertare, proiectare și dezvoltare produse și tehnologii și implementarea proceselor tehnologice. Baza de date utilizată a fost concepută cu date colectate din mediul industrial.

Cezarina AFTENI, PhD. Eng., Assistant, “Dunarea de Jos” University of Galati, Manufacturing Engineering Department, cezarina.afteni@ugal.ro, +40 754 636 731, 111 Domneasca Street, Galati, Romania.

Mitica AFTENI, PhD. Eng., Assistant Professor, “Dunarea de Jos” University of Galati, Manufacturing Engineering Department, mitica.afteni@ugal.ro, +40 740 018 750, 111 Domneasca Street, Galati, Romania.

Gabriel-Radu FRUMUSANU, PhD. Eng., Professor, “Dunarea de Jos” University of Galati, Manufacturing Engineering Department, gabriel.frumusanu@ugal.ro, +40 740 663 686, 111 Domneasca Street, Galati, Romania.

Florin SUSAC, PhD. Eng., Associate Professor, “Dunarea de Jos” University of Galati, Manufacturing Engineering Department, florin.susac@ugal.ro, +40 745 709 102, 111 Domneasca Street, Galati, Romania.