Structural identification of the bearing manufacturing process – Case-study

C Afteni1, G R Frumusanu1, M Afteni2 and V Paunoiu1
1 “Dunarea de Jos” University, Manufacturing Engineering Department, Domneasca Street 111, 800201 – Galati, Romania
2 Rulmenti S.A, Barlad, Republicii Street 320, 731108 – Barlad, Romania

E-mail: Cezarina.Afteni@ugal.ro

Abstract. In the manufacturing industry, globalization, shorter life cycles of products and changing customer needs, leads to high competitive pressure on companies. In addition to product quality and variety, flexibility, shorter processing times, and high-level compliance with delivery times have become essential factors for market success through efficient, efficacious and continually manufacturing processes optimization. To be successful in a highly competitive global production environment, a company must be able to deliver products that customers request at the requested time. In this paper is developed a novel method of structural identification of the bearing manufacturing process. This method allows the structuring of its activities, at all levels involved (order acceptance, production planning, product design, processes planning, and product processing), by elaborating the tree of the specific activities. The relations between the manufacturing process stages and related information circuit are revealed and the identification of the manufacturing process variants, at the level of each manufacturing activity is performed. Following the selection of the best alternatives from each level of the manufacturing activity, the optimal technological path is obtained for taking over an order for the bearing manufacture.

1. Introduction
In today’s unpredictable production environment, companies are faced with a multitude of challenges to meet ever-increasing customer’s desires and demands, to offer new and more customized products at the best price. Despite the benefits for consumers, global competition makes it difficult for manufacturers to select and configure their manufacturing processes.

In current manufacturing environment it is necessary to make diverse decisions, which mainly concern to all stages of the manufacturing activity: order acceptance, production planning, product design, processes planning, and product processing. Such a decision consists in selecting, at a given moment, the most suitable alternative among the potential ones. The selection can be made after a given criterion (e.g. cost, timespan, consumed energy etc.), or a combination of criteria [1]. The authors of this paper have already developed an original selection algorithm, based on comparative assessment [2]. Unlike the usual methods underpinning the comparative assessment, supposing the direct, separate evaluation of feature value for each alternative, before decision making, the developed algorithm of selection aims to establish a ranking of the potential alternatives set. The authors also suggest in [3], a new approach of optimizing the manufacturing process, based on both new concept (the holistic optimization), and method (“zoom & pick”) for its implementation. According to the new concept, the optimization problem gets a new structure, which includes not only the optimal solution
finding, but also the optimal formalization of the problem as well as the tooling for assessing the position of potential solutions relative to the optimal one. In paper [4], a methodology for preliminary process selection was created through its integration in a design process. Denno et. al presents in [5] a methodology, called production system identification, to produce a model of a manufacturing system from logs of the system’s operation. Production system identification is similar to machine-learning methods of process mining in that they both use logs of operations. The paper [6] describes an object-oriented manufacturing process information model which comprises classes on the necessary manufacturing information, such as manufacturing activities, work piece, manufacturing equipment, estimated cost and time, and manufacturing process sequences. The model includes the representation of concurrent activities, alternative activities, and parallel activities. This model is capable of describing the hierarchical structure of the information representing manufacturing processes of a product. Gecevska et al describe in [7] a model for manufacturing activities that allows integration, having considers three dimensions of planning. The product development cycle may be seen as a set of answers to a series of actually simple questions: Why to produce? What to produce? How to produce? Where to produce? Who to produce? When to produce? The answers to these questions will identify what functions are necessary for the cycle from developing an idea to the realization of the final product. In the paper [8], experimental investigation, modeling and optimization of the drilling are performed using Taguchi Design of Experiments (DOE) and artificial neural networks (ANN) methods. In [9] is proposed a method of production scheduling oriented to energy consumption optimization for process industry, a production scheduling model is established whose goal is to obtain the minimum of total process energy consumption. The simulation results show that the production scheduling method orientated to energy consumption optimization is superior to the production scheduling method oriented to process time optimization, and it can realize the goal of reducing energy consumption. The paper [10] presents a manufacturing process management (MPM) solution that enables a real-time assessment of component manufacturability and a parallelization of product design and manufacturing processes. This solution provides an interactive and effective bridge between the Product Data Management systems that support design activities, and the Enterprise Resource Planning and Manufacturing Execution systems that support production planning and execution activities of complex products.

Within this paper, a method for structural identification of the manufacturing process is developed. It allows the structuring of the activities, at all levels involved (order acceptance, production planning, product design, processes planning, and product processing), by elaborating the tree of the specific activities (the relations between the manufacturing process stages and the related information circuit are revealed). The identification of the manufacturing process alternatives, at the level of each manufacturing activity is also performed.

The method aims to enable the selection of the best alternatives at each level of the manufacturing activity, according to different optimization criteria (such as, for example, cost, timespan, energy consumption, and other critical consumption or combination combinations thereof); the selection itself does not make the object of presented research.

Following the section of the best alternatives from each level of the manufacturing activity, the optimal technological path is obtained for the manufacturing of a considered product.

This method has been sampled by a case study in the case of bearing manufacturing. The aim was to draw the manufacturing graph, including the structuring of its activities, at all involved levels, according with the new proposed method. There were also identified the manufacturing process alternatives, at the level of each manufacturing activity stage.

The paper is organized as follows: the second section presents the manufacturing process levels. The next section describes the activities identification from each level of the manufacturing process. The fourth section shows the alternatives for activities accomplishment at a manufacturing process level. Section five deals with the application of this method through a case study on bearing manufacturing. The last section presents the paper’s conclusion.
2. The manufacturing process levels
The manufacturing process will be further considered as composed of activities structured on five successive levels (order acceptance, production planning, product design, processes planning, and product processing, see table 1), [11].

Table 1. The manufacturing process levels [11].

| Level | A     | B         | C     | D                | E     |
|-------|-------|-----------|-------|------------------|-------|
|       | Order | Production | Product | Processes      | Product |
| Object of the activity | acceptance | planning | design | planning | processing |

The tree of specific activities that reflect the relationships between the activities at different levels of the manufacturing process, which will be subjected to optimization, as well as the related information circuit are sampled in figure 1.

![Figure 1. Levels for optimization of manufacturing process – block diagram – [11].](image)

In figure 1 at level A there are three potential activities A1, A2 and A3, according to the method, are selected two activities which lead congruent to previous experience to the best results (lower cost, highest profit, etc.), namely A1 and A3. For each of the selected activities, at level B there are four potential activities B1, B2 for A1 and B3, B4 in case of activity A3, of which only two are selected, namely B1 and B4. Next, at level C, there are four potential activities: C1, C2 for B1, C3, C4 for B4. From these four activities, after a new evaluation, only two are selected, namely C2 and C4. Furthermore, for the selected activities, at level D there are four potential activities D1, D2 for C2 and D3, D4 for C4. From the four activities, three are selected which lead, according to previous experience, to the best results, namely D1, D2 and D3. Finally, for each of the selected activities, at level E, two activities E1, E2 for D1 and E3, E4 for D2, respectively E5, E6 for D3. From the six activities, it is selected, only one that leads, according to previous experience to the best results, namely E4.

Thus, following the successive evaluations and selections of the activities from the different levels of the manufacturing process, an optimal technological path is obtained for the considered manufacturing process, which includes activities A1, B1, C2, D2, and E4 (marked in red in figure 1).
3. Activities identification at each process level
The generic manufacturing process can be described by means of the activity objects (these can be, at the different levels of the process: order, product, component, operation, and phase).

The result of the manufacturing process identification consists in the proposed method case from the manufacturing process activity chain. Such a chain is exemplified in detailed representation in figure 2-a or synthetic in figure 2-b.

![Activity Chain Diagram]

*Figure 2. The activity chain for a manufacturing process variant [11].*

In the example shown in figure 2 it was assumed that the manufacturing cost is 120 monetary units.
- At level A, activity 1 is carried out, having the cost of 10 monetary units, which will be divided into cost related to activities from level B.

- At level B, activity 2 is carried out, which is divided into three components 2.1, 2.2, and 2.3, having the following costs: 12 monetary units for 2.1, 6 monetary units for 2.2, 6 monetary units for 2.3. As mentioned above the cost of activity 1 is divided at this level so: 4 monetary units to 2.1, 2 monetary units to 2.2, 4 monetary units to 2.3. Both the cost of each activity and the cost assigned to itself are divided in turn to the next activities;
At level C, there are three activities: 5, 6, and 3.

Activity 2 with component 2.1 is continued by activity 5, which is divided into two components, 5.1, having the cost of 8 monetary units, and 5.2 having the cost of 9 monetary units. The cost of activity 2.1, of 12 monetary units, as well as the cost assigned to itself of 4 monetary units is divided in two: 5 monetary units respectively 2 monetary units belong to 5.1, and 7 monetary units respectively 2 monetary units to 5.2. At the end of this level for each of the two components are added 2 monetary units. The cost of component 5.1 results from 17 monetary units, and that of component 5.2 from 20 monetary units.

Activity 2 with component 2.2 is continued by activity 6, which continues with component 6.1, having the cost of 15 monetary units, to which is added the cost of units from activity 2.2 and 2 monetary units from the end of the level. The cost of activity 6.1 results from 25 monetary units. Activities 5 and 6 ends at level E.

Activity 2 with component 2.3 is continued at level C with activity 3, which is divided into two components, 3.1, having the cost of 13 monetary units respectively 3.2, having the cost of 9 monetary units. Activity 3 ends at level D.

At level D activity 3 is continued by two activities 7 and 4, which are each divided into two components, namely, 7.1, having the cost of 4 monetary units and 7.2, 4 monetary units, 4.1 – 8 monetary units and 4.2 – 6 monetary units. At the end of this level for each of the two activities is added 1 monetary unit.

At the last level – level E activity 8 takes place which completes the above activities, it is divided into eight components namely 8.1 and 8.2 completes activity 5, 8.3 completes activity 6, 8.4 and 8.5 completes activity 7, 8.6 and 8.7 completes activity 4.

In the tables in figure 2 is given a synthetic presentation of the impact on the final cost of each direction of action within the graph.

The chain of activities identified to satisfy a given order showed in figure 2-a it includes both manufacturing activities applicable to the whole product (marked with numbers simple 1…8), as well as activities related to components of the product (whose symbols include the separator ".", for example, 2.1, 2.2, …, where the numbers before and after the dot refer to activities and to component, respectively). These correspond to the 5 levels marked A…E identified in the figure 2-b. An arrow symbolizes each activity, the notations under each arrow represent an attribute (for example, cost, timespan, etc.) of the activities (components of activities) performed for the transition from one activity level to the next. A determined set of activities (hence a succession of arrows), starting from process beginning point, corresponds to each component, no matter of component level. This set means the activities chain of the considered component.

The accomplishment of each activity is characterized by a resulting effect (be it cost, timespan and consumed energy etc.). The cumulated effect of all activities corresponding to the ways composing a path (when all the effects of the activities are of the same types) means the process effect corresponding to this path. More types of effects can be measured for the same path, by values of the corresponding effect-variables.

The problem addressed in this paper can be formulated now as the selection, from the manufacturing graph, of the optimal manufacturing path, according to a flexible criterion/set of criteria.

As it can be easily observed, the manufacturing graph may be very complex. Frequently, the structure of activities needing to be performed in order to cover the manufacturing path is also complicated. Moreover, the evaluation of path effect by decomposing the typical activities in basic nominal activities, finding the effect for each of them, and, finally, cumulating these effects is also a difficult task. For these reasons, the application of the combinatorial optimization method is not feasible for solving the problem, neither the application of other methods selecting the optimal path on the base of path effects direct evaluation.
4. Alternatives for activities accomplishment

At a manufacturing process level, in general, there may be several variants of the process. For example, suppose that at level A there are variants A1 and A2, this situation being symbolically presented in figure 3.

![Figure 3. Variants of the manufacturing process at level A [11].](image)

Figure 3 shows a manufacturing process for which there are several variants at each level. It should be noticed that for actually accomplishing the process, it is enough to follow a single path only. The ensembles of all potential paths that can be used for obtaining the product form the manufacturing process graph (figure 4).

![Figure 4. Manufacturing process graph [11].](image)

The activities required to be carried out between two consecutive identification levels will be called paths. The paths are represented by thick arrows and marked with letters according to their level starting point (for example, the paths from level B to level C are B1, B2, B3 and B4). Because the object manufactured can be found in different forms, which can be found in different ways, each of these forms must be represented separately. The paths that come from different forms of the object belonging to the same level are also different. Despite that in practice there can be several ways to bring the object from one level to another, for simplicity was considered a maximum of two paths to do this. You can highlight a path between the state of the object, from a certain level, and the endpoint of the process. The path to the realization of the object is the path between the beginning of the process and any among its endpoints. To define a route, a certain level must be selected a certain path, passing through a decision point. The optimal manufacturing path can be chosen according to the values obtained; thus, three possible variants are exemplified: i) variant 1: after minimum value for cost, ii) variant 2: after minimum value for time, and iii) variant 3: after a combination of the two criteria, the variant marked with red in figure 4.
5. Case study

The case study was developed to exemplify the application of the structural identification method. To this end, the bearing manufacturing process was approached. The targeted optimization accuracy is set at 10%.

For the application of the structural identification method, the activities necessary for the manufacture of bearings and their components were identified, starting from the receipt of orders to the delivery of products to customers.

The bearing as a finished product consists of the following main elements: outer ring, inner ring, rolling elements (balls or rollers), and cage.

According to the proposed optimization method, the structural identification of the process of manufacturing was carried out along the optimal path. Thus identifying variants of manufacturing at each level was done only for the current point at the stage level (figure 5).

![Diagram](image-url)

**Figure 5.** The optimal manufacturing path for the case study considered.

In table 2 are sampled the hypothetical results of the stage "analysis of past activity", while the ones of the stage "assessment tooling" in table 3. Table 4 summarized the results of the stage "evaluation of the current processes".
Table 2. Analysis of previous activity.

| Identification level | Optimization object | Typical jobs |
|----------------------|----------------------|--------------|
| A                    | Order                | A1 – Thrust bearing; A2 – Spherical bearing; A3 – Radial bearing |
| B                    | Assembly             | B1 – Rolling element (ball); B2 – Rolling element (roller) |
| C                    | Subassembly          | C1 – Thrust bearing with steel cage; C2 – Thrust bearing with brass cage |
| D                    | Part                 | C1.1 – Outer ring; C1.2 – Inner ring; C1.3 – Roller |
| E                    | Operation            | D1 – Plan I outer ring; D2 – Plan II inner ring; D3 – Plan I rolls; D4 – Plan II rolls |

Table 3. Assessment tooling.

| Identification level | Optimization object | Typical features |
|----------------------|----------------------|------------------|
| P                    | Goal                 | P1- Efficiency; P2 - Productivity; |
| Q                    | Criterion            | Q1 - Cost/product; Q2 - Cost/quantity; |
| R                    | Function             | R1 - Cost [Euro/dm³]; R2 - Time [min/dm³]; |
| S                    | Arguments            | (S1.1, S1.2, S1.3); (S2.1, S2.2); … according to job causal model |

Table 4. Evaluation of the current process.

| Levels | Variables | Values | Goals | Criteria | Functions | Arguments | Results | Delta | Go to |
|--------|-----------|--------|-------|----------|-----------|-----------|--------|-------|-------|
| A      | x_A       | A1, A3 | P1    | Q1       | R1        | S1.2      | A1     | 35%   | B-level |
| B      | x_B       | B1, B2 | P2    | Q2       | R2        | S2.1      | B2     | 30%   | C-level |
| C      | x_C       | C1, C2 | P2    | Q3       | R3        | S1.2      | C1     | 25%   | C-level |
| D      | x_D       | D1, D2 | P2    | Q4       | R4        | S1.3      | D1     | 11%   | E-level |
| E      | x_E       | E1, E2 | P1    | Q1       | R1        | S1.2      | E1     | 9%    | Stop  |

Thus, at level A, is order acceptance, are three potential activities, namely: A1 – Manufacture of thrust bearings, A2 – Manufacture of spherical bearings, and A3 – Manufacture of radial bearings.

According to evaluation criterion Q1 – cost, activity A1 having the cost of 8 units/piece, activity A2 having the cost of 12 units/piece and activity A3 having the cost of 10 units/piece, two activities were analysed: A1 and A3. From these, the activity A1 was selected, which according to previous experience leads to best results (lowest cost), with the uncertainty of the evaluation of 35%. Consequently, the order for the manufacture of thrust bearings is accepted.

For this, at level B, corresponding to assembly design, these are two potential variants B1 – Thrust ball bearing, B2 – Thrust roller bearing. According to the evaluation criterion Q3 – timespan, in the case of thrust ball bearings, it is 10 units of time, while for thrust roller bearings it is 8 units of time. As a result, activity B2 is selected, the uncertainty of the evaluation being 30%, also higher that the accuracy level pursued.
Next, at level C, subassembly design, there are two potential activities C1 – Manufacture of a steel cage and C2 – Manufacture of a brass cage. According to criterion Q1, activity C1 (cost of 11 units/piece) and activity C2 (cost of 14 units/piece) were evaluated, being selected activity C1, with an evaluation uncertainty of 25%, also higher than the accuracy level pursued.

In terms of components at the same level, the following three have a significant impact on cost: C1.1 – Outer ring, C1.2 – Inner ring, C1.3 – Rollers. For these, the manufacturing cost is assessed C1.1 (cost of 2 units/piece) with an uncertainty of 17%, for component C1.2 (cost of 2 units/piece) with an uncertainty of 8% (in this case optimization stops) and for component C1.3 (cost of 3 units/piece) with an uncertainty of 12%. Furthermore, for the remaining components, at level D, process planning, there are four potential activities D1 – Plan I – Outer ring and D2 – Plan II – Outer ring for C1.1, respectively D3 – Plan I – Rollers and D4 – Plan II – Rollers for C1.3. Of the four activities, only two activities are selected, according to criterion Q1, for the manufacture of the bearing, namely D1 and D4, both activities having a cost of 4 units. In the case of activity D1 the evaluation uncertainty being 11%, the optimization is continued, while for the activity D4 evaluation uncertainty being 8%, the optimization stops.

Finally, for the selected operation plans, at level E, operation programming, two potential activities are identified E1 – Turning on CNC lathes and E2 – Turning on conventional lathes. These are evaluated according to the criterion Q2 – cost/quantity, the activity E1 having a cost of 4 units and the activity E2 a cost of 6 units. Activity E1 was selected as optimal. At this point, entire optimization process is stopped, because in all cases the resulting level of uncertainty drops below 10%.

Thus, following the successive evaluations and selections of activities at different levels of the manufacturing process, an optimal manufacturing path is obtained starting with an order for the bearings components manufacture, which includes activities A1, B2, C1 – C1.1, C1.2, C1.3, D1, D4 and E1 (marked in red in figure 5).

6. Conclusion
The method for structural identification of the manufacturing process allows the structuring of its activities, at all involved levels (order acceptance, production planning, product design, processes planning and product processing), by i) elaborating the tree of specific activities, the relations between the manufacturing process stages and the related informational circuit are highlighting, ii) identifying of the manufacturing process alternatives, at the level of each manufacturing activity, iii) selecting the best alternatives at each level of the manufacturing activity, according to different optimization criteria (such as, for example, cost, timespan, energy consumption, other critical consumption or combinations thereof). The exemplification regarding the application of the structural identification method in bearing manufacturing case, allowed the successive evaluation and selection of the optimal activities from different levels of the manufacturing process, thus obtaining the optimal manufacturing path starting with an order for the bearing manufacture.

7. References
[1] Frumușanu G, Afteni C and Paunoiu V 2020 Estimation of Roller Bearings Manufacturing Cost by Causal Identification and Comparative Assessment – Case Study Performed on Industrial Data Int. J. Model. Optim. 10(4) pp 114–120
[2] Afteni C, Frumușanu G and Epureanu A 2018 Instance-based comparative assessment with application in manufacturing IOP Conf. Ser. Mater. Sci. Eng. Pap. 400(042001) pp 0–8
[3] Afteni C, Frumușanu G and Epureanu A 2019 Method for Holistic Optimization of the Manufacturing Process Int. J. Model. Optim. 9(5) pp 265–270
[4] Martínez-Rivero M D, Hernández-Castellano P, Marrero-Alemán M D and Suárez-García L 2019 Manufacturing process selection integrated in the design process: Test and results Procedia Manuf. 41 pp 827–834
[5] Denno P, Dickerson C and Harding J A 2018 Dynamic production system identification for smart manufacturing systems J. Manuf. Syst. 48 pp 1–11
Acknowledgement

This work was supported by the Romanian Ministry of Research and Innovation, CCCDI – UEFISCDI, project number PN-III-P1-1.2-PCCDI-2017-0446 / Intelligent manufacturing technologies for advanced production of parts from automobiles and aeronautics industries (TFI PMAIAA) - 82 PCCDI/2018, within PNCDI III.