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Intelligent Interfacing Module of Process Capability among Product and Process Development Systems in Virtual Environment

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An intelligent interfacing module of process capability (IIMPC) between product and process design systems in virtual prototyping environment has been developed on the basis of the knowledge acquired at different organizations involved in new product development. The paper considers contradictions both, in product design procedure when seeking its best performance and in the principles of design for assembling (DFA) and design for manufacturability (DFM), whereas, when facilitating the product assembling process, the fabrication process of product parts becomes more complicated. This research can help to find the best decision of quality and lean manufacturing among available product and process alternatives. Mathematical formalization of a developed interfacing module is provided and appropriate software is created. The proposed interfacing module is being implemented for the integration of computer aided design (CAD) and computer aided process planning (CAPP) systems. IIMPC is used in industry and in study processes in universities.

Keywords: intelligent interfacing module, product and process development, integration, process capability, quality, virtual environment

0 INTRODUCTION

Manufacturing competitiveness of the 21st century is associated with computerization in the development of new products and processes and in employment of relevant information [1]. These procedures could not have been possible without integrating project management methods with concurrent engineering (CE) elements [2]. CE is oriented towards possibilities to minimize both, product and process development cost and delivery time in all stages of a product life cycle. A basic portion of the product development cycle is a conceptual design phase that greatly influences product's cost, quality, manufacturability and life cycle parameters [3] and [4]. During the product concept design phase over 5 to 10 versions are to be generated for the best solution of each product or its component. This generation concerns the design of product and process. The best solution means the lowest cost of product design and manufacturing maintaining required performance [5].

The inter-enterprise integration, when enterprises can co-operate together to develop, design, produce, and to distribute their common product, enables engineers to use the virtual prototyping environment more effectively. Engineering in virtual environment helps to save costs and time of the product and process development. The key point of engineering in virtual environment is virtual prototyping with 3D CAD systems for a new product design [6], and appropriate software for the production system design [7]. Virtual prototyping can carry out all the main functions of the new product development according to individual customer requirements in the virtual environment. The use of virtual prototyping in an organization has refocused product development philosophy incorporating the notion that products must demonstrate their value-added market capability prior to the approval of spending significant resources on product development and production. Virtual prototyping generates early product characteristics that can be compared with customer requirements and manufacturing capabilities. New intelligent support systems are necessary for a successful solution of the above–mentioned tasks.

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The research presented in this paper is intended for the development of a new intelligent support tool for making the best decision among available product and process alternatives. It considers how knowledge engineering of product and process development can help in creating the optimum of a production process. In this context, a developed intelligent interfacing module for product and process design raises the level of the enterprise integration, seeking minimization of new products delivery time to the market when its requirements have changed. This research is focused on the capability of various processes and suppliers located in different countries and companies to combine the product design, i.e. the number of original and standard parts, components as well as their manufacturing. An intelligent interfacing module of process capability (IIMPC) for product and process design in the virtual environment has been created on the basis of the knowledge acquired at different organizations involved in new product development. IIMPC considers contradictions both, in the product design procedure seeking the best performance and in the principles of design for assembling (DFA) and design for manufacturability (DFM). When facilitating the product assembling process, the fabrication process of product parts and components becomes more complicated and the problems related to the fabrication process capability can arise. Mathematical formalization of a developed interfacing module is provided and the appropriate software is created. The proposed IIMPC module is being implemented in the integration of computer aided design (CAD) and computer aided process planning (CAPP) systems.

1 PROBLEM DESCRIPTION

The problem considered in this paper can be formulated as follows. A designer using CAD can provide geometric modeling of a new product. There are some additional programming tools as FEM (finite element modeling), BOM (bill of materials), DFA, DFM, etc. coming in assistance to achieve the desired accuracy, performance, functionality and productivity of a product within the budget limits of its development. A production engineer using a CAPP system has to transform the designed parameters and characteristics of a product into a suitable process. CAPP is closely related to an appropriate software such as material resources planning (MRP), enterprise resources planning (ERP), group technology for operations and process development, etc., estimating the process costs. CAD and CAPP systems are developed to operate autonomously. Various external interfaces as the connection for hooking CAD to CAPP systems are used [8]. However, these interfaces can transfer the data (geometric form, dimensions, tolerances and specification) from one system to the other seeking the integrity of both systems only. Unfortunately, they can neither evaluate possible alternatives of a product and process nor upgrade them. A developed interfacing module can test and evaluate each product and process alternative to process capability when high dimension accuracy of parts and low production cost are needed. Process capability is strongly related to product quality and costs. When it is insufficient, then an IIMPC module can suggest generating a new process with sufficient capability for each product and process alternative (Figure 1) and with minimal production costs. Interfacing between CAD and CAPP systems using IIMPC is done in a virtual environment.

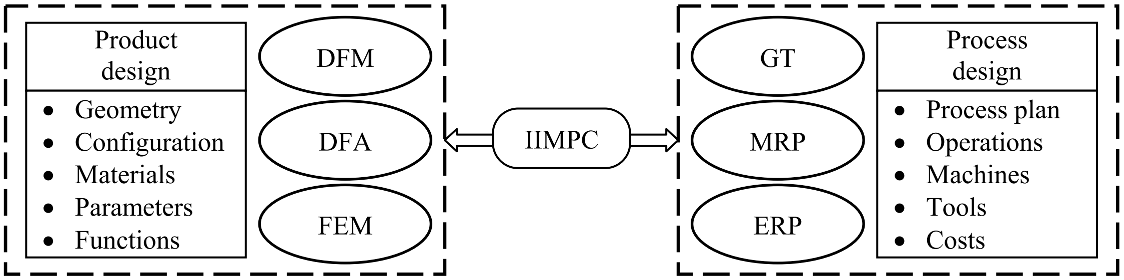


Fig. 1. *The framework of a product design for process capability*

The module architecture is presented in Figure 2. The starting point of an inference strategy is to place an overall functional requirement *F* into sub functions *F1, F2* and *F3*. Sub function *F1* is intended for the definition of material consumption. It formulates a work piece of the part as parameter *P11* and material cost as parameter *P12*. Sub function *F2* is intended for the analysis of part geometrical form, accuracy and tolerances. It examines the design feature types - *P21*, quantitative – qualitative parameters - *P22* and part overall dimensions - *P23*. Sub function *F3* considers the manufacturing process of a part as quality cost - *P31*, manufacturing cost - *P32* and machine tool and process capability indices - *P33*. The interrelationships among various design and process characteristics are elaborated and emphasized solving contradictions between process cost and capability. This consideration requires generating some alternatives of product and process seeking the best solution of product functionality, manufacturing cost and process capability.

In modern manufacturing it is important to extend the virtual prototyping principles from a conceptual product design phase to all the other phases of a product life cycle. The major phases of the product life cycle are: conceptual and preliminary design, detailed design and integration, production and use, retirement and disposal [9]. Manufacturability of a new product in this context plays a very important role. Modeling of product manufacturability and deliverability during the preliminary stages of design is critical in achieving the reduced time to market, high quality and low cost [4] and [10]. The integration of the product-process design in the development of a production system is emphasized in research [11] which had developed a virtual model for the production system design based on technical and temporal data such as work sequences, operations, components and products delivery time, and production resources. Assuming the existing advantages and drawbacks of the product and process development in virtual environment, the IIMPC module could help minimize the product and process development time and cost.

2 IIMPC DEVELOPMENT

New product design is a creative effort attempting to turn customer wishes into an economically producible product to be useful all over its life. In most design situations, compromises between product performance, cost, quality and delivery time cannot be avoided. Input data being different, variation enters into the product design. Production processes do not always make perfect products and, eventually, they introduce more variation and product defects. The capability of a process refers to its ability to meet the implementation needs of a product. Capability is not inherent to a process, but rather it depends on the designer's expectations [12]. In most cases, product implementation costs are directly related to process capability. Making the best choice of the available product and process alternatives is usually finding the trade-offs in each product life cycle stage between the product development cost, investment cost, and quality variables that are based on appropriate mathematical tools. The calculation of the product life cycle costs is a complex process [9], while production cost and process capability are just two of many factors. The research presented in this paper is devoted to a consideration of process capability aiming at minimization of both, product and process development costs and product delivery to customer time.

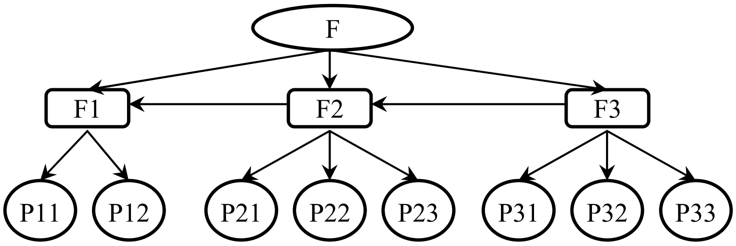


Fig. 2. *IIMPC module architecture*

Process capability is measured by its indices. A process capability index is a measure relating the actual performance of a process to its specified performance that depends on the traditions of enterprise and environment, peculiarities of equipment, operation, materials and people. The most popular process capability indices are C_p and C_{pk} [12]. Machine tool capability C_p and process capability C_{pk} are used to determine the work efficiency [13]. C_p is applied to determine the system's location within the tolerance limits. The size of deviations from the mean value of process dimensions will indicate how good the production is. If the system is not at the center of specification values, the trend of C_p is progressing faultily. C_{pk} is used to determine the average so that the system will work better within the specification limits. If the system is centralized on the target value, C_p and C_{pk} values will be equal. When the value of C_p and C_{pk} is 1, it is considered as a minimum requirement of the system for some companies. Alongside this, many companies accept greater C_p and C_{pk} values, for instance 2. C_p and C_{pk} are defined by the following equations [12]

$$C_p = \frac{USL - LSL}{6\sigma}, \tag{1}$$

and

$$C_{pk} = \min\left\{\frac{USL - \overline{X}}{3\sigma}, or \frac{\overline{X} - LSL}{3\sigma}\right\}, \tag{2}$$

where USL is the upper specification limit of a part, mm; LSL is the lower specification limit of a part, mm; σ is the process standard deviation or overall process variability, mm; $\overline{X}$ is the mean value of the whole process parameter, mm.

Process R of product P is expressed as a set of operations O

$$R = \bigcup_{i=1}^{r} O_i = \{O_1, O_2, ..., O_i\}. \tag{3}$$

The value of process capability indices is calculated for each operation O_i, and hereby a lot of C_p for the entire process R could be expressed as follows

$$C_p = \{C_p(1), C_p(2), ..., C_p(i)\}. \tag{4}$$

A critical operation in the set (4) is the minimum value of C_p index. On the other hand, the value of process capability indices with process costs is related to

$$\begin{cases} 0 < S \le S_{\max}, & S \to \min, \\ C_p^{\min} \le C_p \le C_p^{\max}, & C_p \to \max \end{cases}, \tag{5}$$

where S_{max} is the highest acceptable costs of an operation, Euro; $C_P^{\min} = 1$ and $C_p^{\max} = 2$ are the minimal and maximal values, respectively, of the acceptable capability indices seeking the minimal process costs.

In piece and serial production often $C_p = 1 \div 1.33$, because the companies apply a cost-of-poor-quality strategy that attempts to bring costs to everyone's attention as a basis for corrective action. In mass and high-run production it is accustomed to have $C_p = 2$, because investments to quality costs pay for production of big volumes of parts. The purpose is to minimize the manufacturing cost reducing the quality control cost. A parametric function is developed for determining quality control operation percentage to process capability index C_p (Figure 3). The parametric function is developed in accordance to the assumption when C_p = 1 or less, then it is necessary to arrange 100% quality control of parts, and when C_p = 2 or greater - 5% quality control of parts is sufficient. The percentage value of parts quality control Y is defined as follows:

$$Y = 100 \cdot C_p^{-4.35}. \tag{6}$$

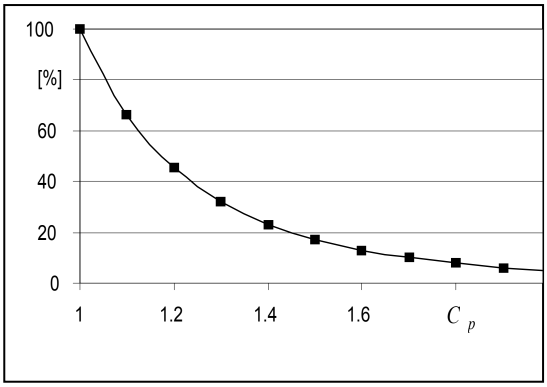


Fig. 3. *Parametric function for definition of quality control operation percentage to C_p*

The work is accomplished after the systematized theoretical and experimental research based on the methods of mathematical logic, the theory of sets and the theory of chances [14]. During the concurrent product and process development, DFA and DFM approaches [15] are aiming at reducing process manufacturing costs S, i.e. at achieving S_{min}. Unfortunately, when both methods DFA and DFM are used, they frequently cause conflict situations resulting in insufficient capability of a product manufacturing process, because when simplifying the assembling process, a designer reduces the number of product parts inducing the other parts to become more complicated. The solution of these conflict situations and search of the best version require engineers to generate a vital number of product and process alternatives checking their C_p and S. Manufacturing costs S of product P_j without material cost, set up time and overheads by production time consumption L are expressed as

$$S = e_j\left(\sum_{i=1}^{n} A_{ij} + \sum_{k=1}^{r} L_{kj} D_j\right) \tag{7}$$

where A_i is the assembling operation time of product P_j, h; e_j is the production volume of product P_j; L_{kj} is the predicted manufacturing time of product part k, h; D is the number of parts k in product P_j, n is the number of assembling operations; r is the number of different parts in product P_j.

Product assembling operation time can be expressed as an abstraction function

$$A = f_1\left(L_{kj}, P, r, q, e\right), \tag{8}$$

where P is the product type; r is the number of assembling parts; q is the product qualitative parameters; e is the high-run, serial or piece production.

$$L = L_h + L_m, \tag{9}$$

where L_h is the handling time in h of an operation, which is conditionally constant and depends on an operation, machine tool type, material profile and part dimensions; L_m is the machining time in h of an operation.

According to the research [5] and [10],

$$L_m = V^p \cdot C, \tag{10}$$

where V is the removed material volume in mm^3 from a work piece during part machining operation; p is the slope of a regression trend line; C is the intercept of a regression trend line.

The effect of material, manufacturing accuracy and production volume is estimated by correction coefficients [5] and [10].

IIMPC is constructed in the product and process development domain. The best available practice, experience and traditions of a simultaneous product and process design in different countries and companies have been used for this purpose. The knowledge was acquired and research was done on the integrated knowledge-based inter-discipline study program on the web site of geographically dispersed organizations [16]. Another approach of the process quality estimation by applying control charts has been used in research [17], regrettably, it evaluates neither the manufacturing cost nor quality cost. The framework of consideration dependence among process capability indices, standard deviation σ and manufacturing cost S as well as the product characteristics as class, part type, and design features with their quantitative – qualitative parameters has been developed (Figure 4). Statistical standard deviation σ of the data sets collected from factory processes was the starting point for predicting the process capability indices [18]. The considered parts might be minimum either of two different companies or of two different machine tools.

The IIMPC module has been developed on the software level and appropriate database (DB). The first version of software has been programmed applying Visual Basic 6.0 programming language and Structural Query Language (SQL).

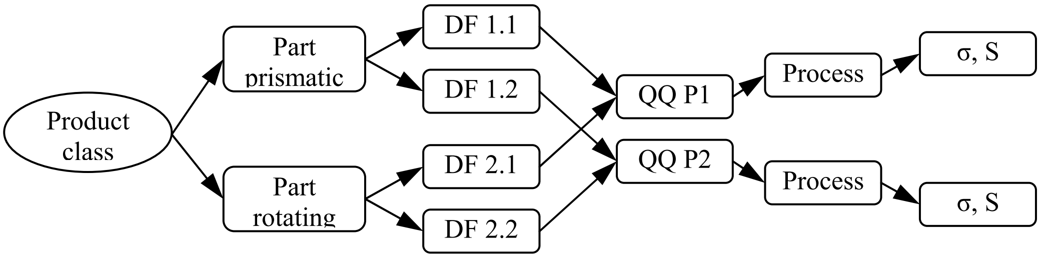


Fig. 4. *The structure of a frame for possessed σ and S in different manufacturing systems*

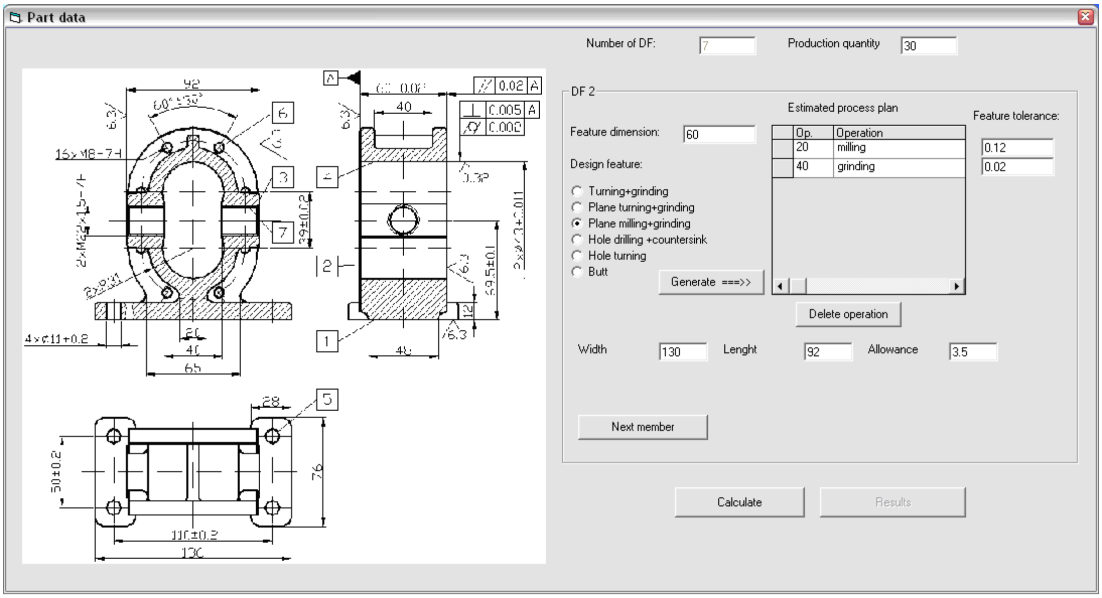
The developed software generates available process alternatives of a part with manufacturing cost *S* and capability indices. The software window for data input is presented in Figure 5; the results obtained when applying the developed software are illustrated in a case study.

The developed IIMPC module has been tested and validated in the laboratory of Integrated Manufacturing Engineering of Kaunas University of Technology (KTU) and in the department of Machine Design of Helsinki University of Technology (TKK). During the development procedure the IIMPC module was verified by a number of process plan alternatives with different C_p and *S* for various products and components.

3 CASE STUDY

A sequence of IIMPC module work has shown that it is aiming at the optimal C_p index and manufacturing cost *S* of a process in the early product design stage. A typical mechanical part – gear pump housing with seven various design features has been taken as a sample. The work piece of housing is made from cast iron. It was machined using various chip removing operations such as milling, turning, drilling and grinding. These operations for high-run and serial production have been investigated in two different medium-size manufacturing systems. The manufacturing system “A” runs its business on order handled piece and serial production with various NC and CNC machine tools, while the manufacturing system “B” has some special-purpose machines and production lines, and CNC machine tools. The manufacturing system “A” can survive without its own design department; however, it always experiences troubles related to the manufacturing processes when seeking less costs. The manufacturing system “B” develops new products itself, it can implement DFA and DFM approaches to a new product development procedure. Sometimes both companies co-operate in the production of mechanical parts and receiving mutual benefit.

Firstly, a 3D CAD model of a chosen mechanical part was created using the standard CAD system. The second step of IIMPC module work is the housing data extraction from the 3D CAD model. The extraction of the data is performed at the interactive regime applying the developed software data input window (Figure 5). The results of the second step module work are the process plan prediction of a housing and definition of statistical process standard deviation σ_a for each design feature, and then calculation of capability index C_p. The results of a second step module work are presented in Table 1 for both companies. Process standard deviation is obtained from the machine tool capability



Number of DF: 7

Production quantity 30

DF 2

Feature dimension: 60

Design feature: ● Plane milling+grinding

Estimated process plan

Op.	Operation
20	milling
40	grinding

Feature tolerance: 0.12, 0.02

Width 130

Lenght 92

Allowance 3.5

Fig. 5. *Software data input window*

study using the statistical data of previously produced parts and design features according to the methodology described in research [18]. The C_p index was defined applying the expression (1), upper and lower specification limits of each design feature and the statistical process standard deviation σ_a value.

The third step of an IIMPC module work is defining the material resources. The part manufacturing cost *S* and quality cost as the results of software third step processing are shown in Tables 2 and 3. The results have been analyzed by a designer and collected into the data base if they are suitable; conversely, the changes of the product or process design are to be made. Software programming mistakes are found and removed during the procedure of software development in the KTU laboratory of Integrated Manufacturing Engineering, while software validation in two Lithuanian manufacturing companies of production mechanical components has been performed.

The manufacturing cost *S* of each design feature and operation applying expressions (7), (9) and (10) and control percentage by applying expression (6) are predicted and presented in Tables 2 and 3. The manufacturing system "B" has higher C_p values and lower total manufacturing costs *S* compared to the manufacturing system "A" because of better tooling and quality management. The implementation of special-purpose machines, production lines and multiple drilling devices as well as investments to quality assurance helps in reaching the target values which are important to both, customers and producers. The data in Tables 1, 2 and 3, shows that increasing C_p value by one hundredth, it is possible to decrease the total manufacturing cost *S* by one percent.

4 CONCLUSIONS AND FURTHER WORK

Growing complexity of new products and stiff competition in marketplaces enhance the demand to minimize the product and process development costs and delivery time in all stages of a product life cycle. A proposed intelligent IIMPC module for the product and process design will raise the level of activity integration in the organization and will reduce the risk of implementing new processes and operations. It is shown that the analysis of capability and manufacturing cost helps determine the possibilities of manufacturing within the tolerance limits and engineering specifications. Capability and manufacturing cost analysis yields the information on the changes and tendencies of the system during production.

The improved intelligent support for modeling the concepts in the virtual environment of the manufacturing domain has been emphasized. Knowledge engineering is based on the research done on the integrated knowledge-based inter-discipline study program for geographically dispersed organizations. It has been shown that proper research can eliminate the shortage of appropriate engineering knowledge and experience. The appropriate software has been programmed for the confirmation of theoretical consumptions.

Regrettably, the suggested approach has some limitations, the main one being a relatively

Table 1. *Statistical standard deviation σ_a of serial and high-run production*

DF	Operation	Tolerance (mm)	Serial – MS "A"		High-run – MS "B"	
			σ_a	C_p	σ_a	C_p
1	Milling	0.200	0.0162	2.058	0.0152	2.193
2	Milling	0.120	0.0136	1.471	0.0125	1.600
	Grinding	0.020	0.0025	1.333	0.0022	1.515
3	Milling	0.220	0.0222	1.652	0.0183	2.004
4	Turning	0.080	0.0094	1.418	0.0089	1.498
	Grinding	0.025	0.0031	1.344	0.0029	1.437
	Precise grinding	0.011	0.0014	1.309	0.0013	1.410
5	Drilling	0.110	0.0092	1.993	0.0081	2.263
6	Drilling	0.090	0.0079	1.899	0.0075	2.000
	Tapping	-	-	-	-	-
7	Countersink	0.210	0.0206	1.699	0.0157	2.229
	Tapping	-	-	-	-	-

Table 2. *Manufacturing and quality control costs for serial production (Manufacturing system "A")*

DF	Operation	Serial production (quantity 30)						
		L_h (h)	V (mm^3)	L_m (h)	S (h)	Control percentage (%)	Control time (h)	Total costs (h)
1	Milling	0.083	$3.1 \cdot 10^4$	0.133	0.216	4.3	0.0013	0.2173
2	Milling	0.083	$7.5 \cdot 10^4$	0.203	0.786	18.7	0.0056	0.2916
	Grinding	0.083	$3.9 \cdot 10^3$	0.21	0.293	28.6	0.0086	0.3016
3	Milling	0.083	$6.9 \cdot 10^3$	0.083	0.166	11.3	0.0034	0.1694
4	Turning	0.102	$2.3 \cdot 10^3$	0.067	0.169	21.9	0.0110	0.1800
	Grinding	0.102	$2.01 \cdot 10^2$	0.121	0.223	27.6	0.0138	0.2368
	Precise grinding	-	$4 \cdot 10^1$	0.082	0.082	31.0	0.0155	0.0975
5	Drilling	0.07	$4.56 \cdot 10^3$	0.103	0.173	5.0	0.0008	0.1738
6	Drilling	0.07	$5.6 \cdot 10^3$	0.196	0.266	6.1	0.0010	0.2670
	Tapping	-	-	-	-	-	-	-
7	Countersink	0.075	$1.96 \cdot 10^3$	0.067	0.142	10	0.0025	0.1445
	Tapping	-	-	-	-	-	-	-
				$\sum$	2.516		0.0635	2.5795

Table 3. *Manufacturing and quality control costs for serial production (Manufacturing system "B")*

DF	Operation	Serial production (quantity 30)						
		L_h (h)	V (mm^3)	L_m (h)	S (h)	Control percentage, (%)	Control time (h)	Total costs (h)
1	Milling	0.075	$3.1 \cdot 10^4$	0.124	0.199	3.3	0.0010	0.2000
2	Milling	0.075	$7.5 \cdot 10^4$	0.105	0.180	12.9	0.0039	0.1839
	Grinding	0.075	$3.9 \cdot 10^3$	0.165	0.240	16.4	0.0069	0.2469
3	Milling	0.075	$6.9 \cdot 10^3$	0.071	0.146	4.9	0.0015	0.1475
4	Turning	0.092	$2.3 \cdot 10^3$	0.060	0.152	17.2	0.0086	0.1606
	Grinding	0.092	$2.01 \cdot 10^2$	0.116	0.208	20.7	0.0104	0.2184
	Precise grinding	-	$4 \cdot 10^1$	0.080	0.080	22.4	0.0112	0.0912
5	Drilling	0.063	$4.56 \cdot 10^3$	0.045	0.108	2.9	0.0005	0.1085
6	Drilling	0.063	$5.6 \cdot 10^3$	0.062	0.125	4.9	0.0008	0.1258
	Tapping	-	-	-	-	-	-	-
7	Countersink	0.067	$1.96 \cdot 10^3$	0.057	0.124	3.1	0.0008	0.1248
	Tapping	-	-	-	-	-	-	-
				$\sum$	1.562		0.0456	1.6076

narrow area of manufacturing systems, products and processes to be applied to.

Future work will focus on the expansion of the variety of data and features in the developed module, the number of product types, processes, operations, and in particular, at aiming to overcome the existing limitations of the proposed approach.

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