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IDEF0 modelling technique to estimate and increase the process capability at the early product design stage

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1. Introduction

Manufacturing competitiveness of the 21st century is associated with the computerization of the new products and processes development and employment of extensive information. These procedures could not have been possible without process tool like concurrent engineering (CE) in action [1]. CE is oriented on the possibilities to minimize the product and process development cost and delivery time in all stages of the product life cycle. The key part of a product development cycle is the conceptual design phase that greatly influences the resulting cost, quality, product manufacturability and its life cycle parameters [2, 3]. During the product concept design phase it is necessary to generate over 3 - 5 versions for each product or component for the best solution to be found. This generation deals with both the product and process design. The best solution means the lowest cost of the product design and manufacturing [4].

The inter-enterprise integration, where enterprises can be combined together to develop, design, produce, and distribute their common product, enables engineers to use a virtual prototyping environment more effectively. Engineering in virtual environment helps saving the costs and time of the product and process development. The key moment of engineering in virtual environment is virtual prototyping (VP) using the 3D CAD systems for the new product design [5] and appropriate software for the design of a production system [6]. VP can fully carry out all main functions of the new product development according to the individual customer requirements in virtual environment. The use of VP in an organization has refocused product development philosophy incorporating the notion that products must demonstrate their value-added market capability prior to obtaining approval to expend significant resources on product development and production. VP 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.

The research of this paper is devoted to the development of a new intelligent support tool for making the best decision among available product and process alternatives. It discusses how knowledge engineering of product and process development can help creating the optimum of a production process. This research is focused on the capability of various processes and suppliers located in different countries and companies to combine the product and process design, i.e. the number of original and standard parts, components and their manufacturing. An Integrated Definition of Function Modelling (IDEF0) technique [7] to estimate and increase the process capability at the early product and process design stage has been applied. It considers the contradictions both in product and process design procedure seeking best performance and also 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 gets more complicated and the problems related to the fabrication process capability can arise. Mathematical formalization aiming to keep a balance among the process capability and cost is provided and appropriate software is created. The proposed model is being implemented for the integration of computer aided design (CAD) and computer aided process planning (CAPP) systems.

2. Process capability estimation by IDEF0 modelling technique

The problem considered in this paper can be formulated as follows. A designer using computer-aided-design (CAD) can provide the geometric modelling of a new product. There are some additional programming tools as FEM (finite element modelling), 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 computer-aided-process-planning (CAPP) system has to transform the designed parameters and characteristics of the product into a suitable process. CAPP is closely related to appropriate software such as material resources planning (MRP), enterprise resources planning (ERP), group technology (GT) for operations and processes development on estimating the process costs. CAD and CAPP systems, in general, are created 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 only the integrity of both systems. Unfortunately, they can neither evaluate the possible alternatives of the product and process nor upgrade them.

Research applying IDEF0 modelling technique could test and evaluate each product and process alternative to the process capability when dimensions accuracy of a part is strongly related with low production cost. Process capability is strictly linked to the product quality and manufacturing cost. When these parameters are insufficient, then the developed model suggests generation of new process with sufficient capability for each product and process alternative and with minimal production costs. Interfacing among CAD and CAPP systems using IDEF0 technique is arranged in virtual environment.

An IDEF0 model has a purpose and viewpoint, and is comprised of two or more pages, each page being a syntactical element of the model. The A0 page is the context diagram, which defines the inputs, controls, outputs and mechanisms (ICOMs) for the single, top-level function, labelled A0. The context page establishes the boundaries of the system being modelled by defining the inputs and controls entering from external systems and the outputs being produced for external systems. Other pages in the IDEF0 model represent decomposition of a function on higher page, with the exception of the external system diagram page, which is described later. The number of subfunctions for any IDEF0 function is limited to six, or possibly seven, for the purposes of a readable display on a page.

Fig. 1 presents IDEF0 model of process cost and capability engineering. Diagram context defines product development by orders, stakeholders' needs and available partners. It has 4 sub-functions: process engineering and configuration, process cost and capability definition, and managing and implementation of a best alternative. This diagram has to comprise all necessary relations and interactions among engineering functions seeking minimum manufacturing cost and suitable process capability indices. The influence and help of product design and manufacturing partners and suppliers must be taken into account.

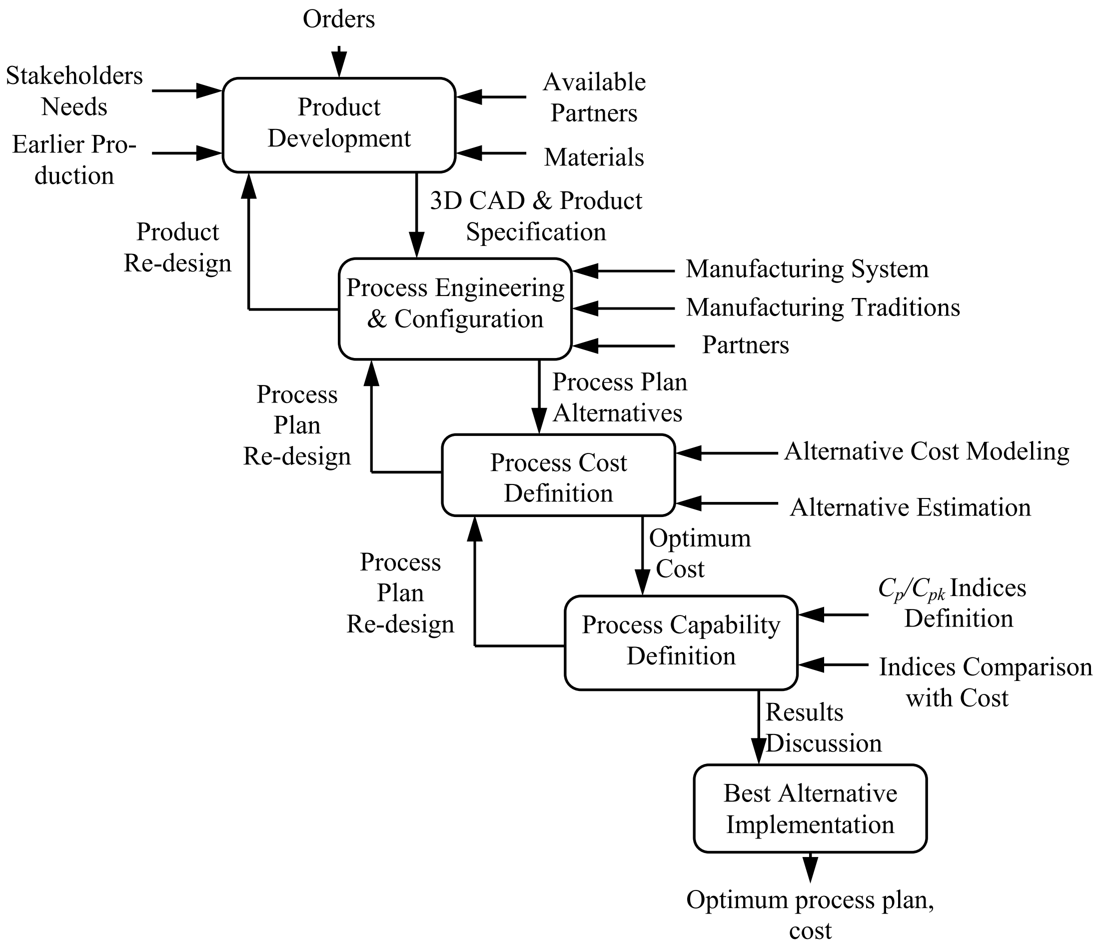

Fig. 1 IDEF0 modeling. Process cost and capability engineering

The decisive factor for process manufacturing cost and capability is product design feature (DF), in particular, geometrical form and qualitative-quantitative parameters (QQP). The developed DF classifier ranks design features according to manufacturing hardship applying various tools and facilities. Designer, therefore, can evaluate product manufacturing cost at the early design stage by developed IDEF0 model and can vary DF geometrical form and QQP if necessary. Process alternatives' capability also can be controlled. The best process alternative by two criterions – cost and capability at least can be implemented. Another approach of process quality estimation with the usage of control charts has been used in research [9]; unfortunately, it neither evaluates the manufacturing cost nor quality cost.

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 among product performance, cost, quality and delivery time cannot be avoided. Different input data is available, therefore, 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 the process, but rather it depends on the designer's expectations [10]. In most cases, product implementation costs are directly related to process capability. Making the best choice from the available product and process alternatives usually is the finding of trade-offs in each product life cycle stage among product development cost, investment cost, and quality variables that are based on appropriate mathematical tools.

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 which depends on the traditions of plant and environment, peculiarities of equipment, operation, materials and people. The main characteristic of machined parts in the product is dimensions' tolerance T

$$T = USL - LSL \tag{1}$$

where USL is the upper specification limit of a part, mm; LSL is the lower specification limit of a part, mm;

The most popular process capability indices are C_p and C_{pk} [10]. Machine tool capability C_p and process capability C_{pk} are used to determine the work efficiency [11]. C_p is applied to determine the system's location in tolerance limits. The size of deviations from the mean value of process dimensions will indicate how well the production is. If the system is not at the centre 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 in the specification limits. If the system 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, this is considered, as the minimum requirement of the system for some companies. Alongside this, larger C_p and C_{pk} values, for instance 2, are accepted by many companies. C_p and C_{pk} are defined by the following equations [10]

$$C_p = \frac{USL - LSL}{6\sigma}, \tag{2}$$

and

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

where σ is the process standard deviation or overall process variability, mm; $\overline{X}$ is the mean value of the whole process parameter, mm.

Manufacturing process G of product P is expressed as a set of various operations O

$$G = \left(O_1, O_2, ..., O_f, ..., O_i\right) \tag{4}$$

The value of process capability indices is calculated for each operation O_i, and hereby a lot of C_p and C_{pk} for the whole process G could be defined. The critical operation in a defined lot is that having the minimum value of C_p or C_{pk} index. $C_P^{min} = 1$ and $C_p^{max} = 2$ are the minimal and maximal values of the acceptable capability indices seeking the minimal process costs. On the other hand, the value of process capability indices with process costs K in this research is related also. If any machine tool has acceptable index C_p and any manufacturing process has acceptable index C_{pk}, but both have unacceptable cost K, it means they are not competitive for the considered part or component. In such a case, it is necessary to look for other more competitive process, machine tool or exchange component design, or at least to make outsourcing products and parts to developing countries. Lithuania is one of such countries and many SMEs that are keeping their business producing parts for Western customers are located here.

In piece and serial production often $C_p = 1 \div 1.33$, because companies are using 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 is used to keep $C_p = 2$, because investments to quality costs quit for big production volume of parts.

During the concurrent product and process development, DFA and DFM approaches are aiming at reducing process manufacturing costs K, i.e. at achieving K_{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 this conflict situations and search of the best version require generating a vital number of product and process alternatives checking their C_p and K acceptability. Manufacturing costs K forecasting method of product P_j applying research [4] to develop and implement IDEF0 model have been used.

Product's parts fabrication and assembly operation time forecasting is related with many statistical data. Data base (DB) of product fabricating and assembling time is applied for this reason. DB is specified by product type, size, functionality and accuracy with appropriate manufacturing processes, tooling, facility, and technological operations, which determine fabricating and assembling times. The fabricating and assembling operation time in developed DB is statistically defined by process charts and appropriate machines and tooling are fixed by considered company.

Next step is the definition of process capability for each product, process and machine tool alternative. Designer having process capability and manufacturing cost data is able to compare each product and process alternative and make a true decision. Decision making procedure involves sharing information among sub-functions of IDEF0 model (Fig. 1) including product and process redesigns procedures.

IDEF0 model is created on the software level with an appropriate DB. The first version of software has been programmed applying Visual Basic 6.0 programming language and Structural Query Language (SQL) query in one direction, and retrieving a set of answers in the other one. The developed software generates the available process alternatives of a product. On the other hand, some alternatives of the product with different tolerances and process capability indices are available.

The developed IDEF0 model has been tested and validated in Kaunas University of Technology (KTU), Laboratory of Integrated Manufacturing Engineering and Lithuanian medium size company X. IDEF0 model has been tested by a number of process plan alternatives with different C_p and K for various sheet metal design products and components. According to the testing results and remarks of company engineers in the process of model development, a vital number of IDEF0 model corrections have been made before sufficient results have been achieved.

5. Results and discussions

The sequence of IDEF0 model work aiming at the optimal process plan, manufacturing cost K and C_p index in the product manufacturing engineering stage of a batch production is shown. A typical situation of Global manufacturing (GM) environment is when product developers and customers are located in Denmark and producer in Lithuanian medium size company X. Ten similar products of low carbon sheet metal (thickness 1 - 2 mm) designs with various geometrical form, size, dimensions, parts tolerances and surface powder painting were considered. The fragment of principal data of considered product types are presented in Table 1. The products consist of various design features as rectangular and circular holes, slots, bended flats with dimensions from 3.5 to 500 mm. The production volume from 50 to 1000 units per year was fluctuated although some products had achieved 5000 and even 10000 units per year. In parallel with traditional stamping presses the modern CNC Laser cutting, punching and bending machines also powder painting line for parts fabrication have been used in this company. The products assembling applying riveting and welding operations in specialized manually and robotics operating work places have been arranged.

Table 2 illustrates the data of critical operations defined during research. CNC Laser cutting operation of slots and holes has bad C_p values (less than 1) for considered parts while the rest operations have suitable indices of machine tool capability. The reason of insufficient process capability indices is operators and engineers' low skill and random errors of cutting process. The necessity of the application of CNC Laser cutting operation in small volume production is defined by part geometrical form and design features peculiarities. These current research findings are confirmed by results published in paper [12]. Re-design of process or tooling also implementation other technical and organizational means are necessary avoiding considered errors.

Table 1

Principal data of considered products

No.	Product type	Part number	Product dimensions W x H x L, mm	Production volume per month	Lead time, days
1	Product A	5	417x375x202	500	20
2	Product B	10	430x1102x303	350	30
3	Product C	12	417x580x202	900	25

Table 2

Parts accuracy and CNC Laser cutting and CNC Punching operations capability C_p

No.	Part No.	Feature	Accuracy, mm	Operation	C_p
1	130	Holes and slots	±0.1	Laser cutting	0.92
				Punching	2.1
		Contour and positioning	±0.3	Laser cutting	1.3
				Punching	1.8
			±0.3	Bending	2.4
		All operations	±0.1	Stamping	2.3
2	120	Holes and slots	±0.1	Laser cutting	0.96
				Punching	2.2
		Contour and positioning	±0.3	Laser cutting	1.3
				Punching	2.4
		All operations	±0.1	Stamping	2.3
			±0.3	Bending	2.4
3	151	Holes and slots	±0.1	Laser cutting	0.97
		Contour and positioning	±0.25	Laser cutting	2.2
		All operations	±0.1	Stamping	2.3

Table 3 shows the manufacturing cost of considered parts produced by CNC Laser cutting, CNC Punching and CNC Bending machines. These machines when parts' production volume is up to 1500 - 2500 pieces per year. When production volume exceeds 2500 - 3000 pieces per year, it is better to use traditional technologies applying presses and dies. Table 4 presents the comparison of manufacturing cost of the two parts produced by traditional and modern CNC technologies. The critical points of manufacturing cost applying traditional and modern CNC technologies for sheet metal parts production are illustrated in Figs. 2 and 3. Both figures show that CNC machines can be used when production volume of parts are slightly increasing from critical points because they are rapid and no investment to dies with risky to use them in future.

6. Conclusions and further work

The growing complexity of new products and stiff competition in marketplaces enhance the demand to minimize product and process development costs and delivery time to customer in all stages of product life cycle.

Table 3

Manufacturing cost of considered parts produced by various CNC machines

No.	*T*, h	Perimeter, mm	Number of bends	Punching cost, €	Laser cutting cost, €	Bending cost, €	Total cost (punching & bending), €	Total cost (laser cutting & bending), €
Product A								
130	0.011	1038	5	0.450	-	0.712	1.162	-
105	0.01	955	4	0.409	-	0.570	0.979	-
900	0.061	3139	4	-	4.16	0.571	-	4.731
Product B								
120	0.027	1720	4	0.531	1.84	0.572	1.103	2.412
151	0.015	2192	8	0.613	2.34	1.139	1.752	-
105	0.008	806	7	0.327	0.57	0.996	1.323	1.566

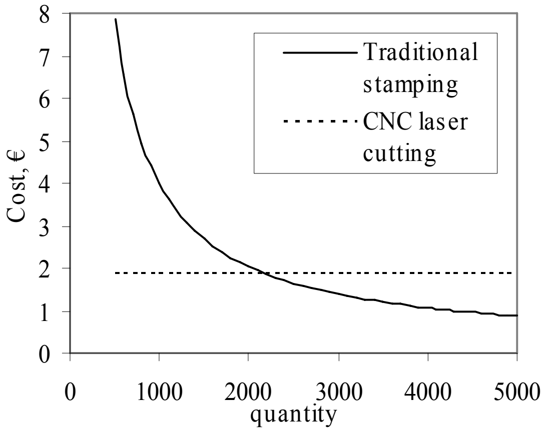

Fig. 2 Part no 120 manufacturing cost

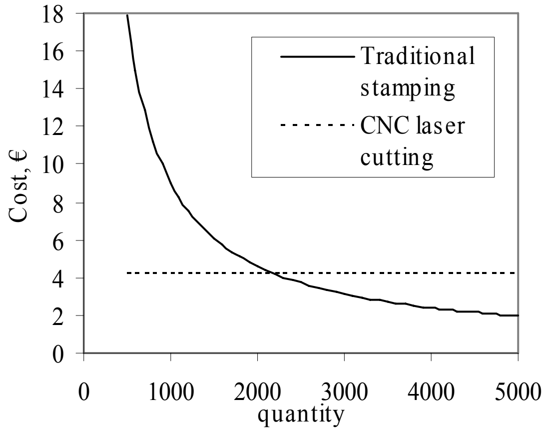

Fig. 3 Part no 900 manufacturing cost

Table 4

Comparison of manufacturing cost the different processes

Sort of cost	Part	
	No 120	No 900
Dies cost, €	3890	8852
Part stamping cost, €	0.09	0.18
Part CNC laser cutting cost, €	1.84	4.16

The proposed IDEF0 model for product and process design will increase the level of integrated activity in organization and will reduce the risk of implementing new products, processes and operations. It was shown that capability and manufacturing cost analysis helps to determine the ability for manufacturing between tolerance limits and engineering specifications. Process capability analysis can be applied not only to production process but also to machine tool. Capability and manufacturing cost analysis gives the information about changes and tendencies of the system during production.

The development of improved intelligent support for modelling concepts in virtual environment of manufacturing domain applying knowledge engineering has been emphasized. It is grounded on the research done in the integrated knowledge-based inter-discipline study program for geographically dispersed organizations. The appropriate software has been programmed, tested and validated for confirmation of the theoretical consumptions. Unfortunately, the developed approach has some limitations, the main of them being a relative narrow area of manufacturing systems, products and processes to which it could be applied.

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

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GAMYBOS PROCESO GALIMYBIŲ ĮVERTINIMAS IR GERINIMAS NAUDOJANT IDEF0 MODELIAVIMO METODIKĄ ANKSTYVOJOJE GAMINIO KONSTRAVIMO STADIJOJE

R e z i u m ė

Straipsnyje pateikta IDEF0 modeliavimo metodika, leidžianti įvertinti gamybos procesų galimybes ir sąnaudas ankstyvojoje gaminio kūrimo stadijoje. Nagrinėjama prieštara tarp gaminio kokybinių parametrų ir gamybos sąnaudų, naudojant konstravimo gamybai (DFM) bei rinkimui (DFA) palengvinti principus. Šis uždavinys tampa gerokai sudėtingesnis įvertinant gaminio rinkimo procesus. Atlikti tyrimai padeda atrasti geriausią kokybės ir sąnaudų santykį tarp galimų gaminio ir gamybos procesų alternatyvų. Pateiktas matematinis sukurto modelio formalizavimas bei programa kokybės sąnaudoms įvertinti. IDEF0 modelis integruoja kompiuterinio gaminio konstravimo (CAD) ir kompiuterinio gamybos technologijos projektavimo (CAPP) sistemas siekiant proceso pastovumo ir mažesnių gamybos sąnaudų ankstyvojo gaminio konstravimo metu. Šis integruotas projektavimo modelis naudojamas pramonėje ir techniškųjų universitetų studijų procese.

A. Bargelis, A. Stasiškis

IDEF0 MODELLING TECHNIQUE TO ESTIMATE AND INCREASE THE PROCESS CAPABILITY AT THE EARLY PRODUCT DESIGN STAGE

S u m m a r y

The paper deals with IDEF0 modeling technique to estimate the process capability and manufacturing cost at the early product design stage. It considers the contradictions that arise in product design procedure when seeking its best performance and minimal manufacturing cost. Applying the principles of design for assembling (DFA) and design for manufacturability (DFM), when facilitating the product assembling process, the fabrication process of product parts gets more complicated. The research done can help finding the best decision of quality and lean manufacturing among available product and process alternatives. Mathematical formalization of the developed interfacing model is provided and appropriate software is created. The proposed interfacing model is being implemented for the integration of computer aided design (CAD) and computer aided process planning (CAPP) systems. This integrated model is used in industry and in universities also for study process.

А. Баргялис, А. Стасишкис

IDEF0 ТЕХНИКА МОДЕЛИРОВАНИЯ ДЛЯ ОЦЕНКИ И УВЕЛИЧЕНИЯ СПОСОБНОСТИ ПРОИЗВОДИТЕЛЬНОГО ПРОЦЕССА В РАННЕЙ СТАДИИ ПРОЕКТИРОВАНИЯ ПРОДУКТА

Р е з ю м е

В публикации представлена о техника моделирования IDEF0, позволяющая оценку способности и стоимости производительного процесса в ранней стадии проектирования продукта. Рассматриваются противоречия в процедуре проектирования продукта при поиске его лучшей работоспособности и в принципах проектирования для легкой собираемости (DFA) и легкой изготовляемости (DFM). При облегчении процесса сборки, процесс изготовления деталей продукта становится более сложным. Произведенное исследование может помочь обнаружить лучшее соотношение качества и стоимости производства среди всех доступных альтернатив продукта и процесса изготовления. Предложена математическая формализация разработанного интерфейсного модуля и создана соответствующая программа. Предложенный модуль используется для интеграции систем автоматизированного проектирования (CAD) и автоматизированного планирования процессов (CAPP). Эта интегрированная модель используется в промышленности и в процессе преподавания в университетах.

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