Estonian Journal of Engineering, 2009, **15**, 1, 13–23 doi: 10.3176/eng.2009.1.02

Integrated knowledge-based model of innovative product and process development

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Received 28 July 2008, in revised form 28 November 2008

Abstract. An integrated knowledge-based model of innovative product and process development is dealt with at a business engineering stage of the order-handling manufacturing system. Mechanical products as solid design, also new kinds of products with plastics and sheet metal design have been considered. The developed model helps to systematize and acquire knowledge and experience for definition of customer requirements, configuration of innovative products, process alternatives and preliminary costs. It furnishes a possibility for the manufacturer to find and to estimate the product and process structure and the cost at an early stage of new business engineering. This integrated knowledge-based model has been tested and adopted in two Lithuanian manufacturing companies. The proposed model is being implemented both in industry and university education process.

Key words: innovative product, process, integrated development, cost forecasting, knowledge-based method.

1. INTRODUCTION

Since 1990s the manufacturing environment has undergone great changes; it has become modern and competitive in mastering new production methods, producing novel and innovative products. It turns into the Global Manufacturing (GM) environment which may be characterized by two main parameters: high level of competition and economy of labour [1]. The need for a new design of products and processes with minimum cost has considerably increased. A new manufacturing strategy with expanded agility and flexibility, high productivity, reduced design cycle and product delivery time to customer has sprung up. It demands effective new design methods, techniques and tools applying information and other high technologies. A new strategy to integrate product conceptualization and bid preparation, coordinating these two aspects, has been adopted [2]. The first is appointed for initial requirements acquisition and platform definition, and the second as a self organizing neural network is combined with a concurrent cost-schedule estimation strategy for the refinement of design options and bid evaluation. This procedure is related to a search of innovative products and processes, which have to show high performance and functionality, as well as to the economy of materials, power and other manufacturing resources. A cost forecasting model has also to be able to foresee different possibilities in discriminating the GM environment, finding the best developers of novel products and producers in the order-handling manufacturing system. It has to use the artificial new product development process starting with learning on the basis of an initial set of production and marketing data about possible products and their evaluation. Subsequently, in each step of the process, the agents search for a better product with the current model of the environment and, then, refine their representations based on additional prototypes generated [3].

Main objective of this research is to develop and generalize theoretical methods of innovative product and process modelling and cost forecasting at the business conception stage for production of a big variety of product types of low production volumes. Solid design, sheet metal design and new kinds of products with plastics have been also considered.

2. KNOWLEDGE-BASED METHODOLOGY OF INNOVATIVE PRODUCT AND PROCESS DESIGN

Integration of scientific principles and good practice for optimal new product and process development at an early business implementation stage is becoming inevitable. The role of winning orders and achieving high competitiveness in the GM environment belongs to computers and modelling of the product and process concurrent design [4]. The customer target cost of a product is often tendering close to materials cost. For this reason, order-winners have to develop an optimal product and process structure with minimum cost and appropriate tooling, facilities, material suppliers and logistics functions. When managing the aforementioned problem of new product development, a company needs to cooperate with or compete with its strategic partners in a network if it wants to survive in industry [5]. This research analyses how a company can operate efficiently, effectively and innovatively applying both suitable knowledge management and process development management.

2.1. Methodology and model structure

The methodology applied in this research is modelling of the information-based systems. It is based on the investigations carried out in the mechanical products and processes development area for 15–20 years. The investigations of different solid parts and parts produced from sheet metal, also new kinds of products with plastics, appropriate processes, manufacturing operations and costs and product delivery times have been motivated by the interaction of these elements. To achieve the objectives of this research, causal models have been used in the form of mathematical equations [6], because various factors are influencing the cost forecasting of product and process development at a business engineering stage.

The structure of a proposed model for a single run, small batch and medium batch order-handling manufacturing system is presented in Fig. 1. The model is based on a man-machine computing approach and it concurrently considers the early stage of new product and process development. The first step of its development is observation of market needs and proposals. There are two possibilities – to get a customer's order for producing a product or to try to develop an order by themselves. Creation of a new product requires high investments and is risky, therefore majority of the companies prefer the first possibility. Next steps are product and process development, applying the experience and traditions of customers, producers and competitors. Products classification approach, aiming at a decrease in uncertainty, is willingly used. It helps employing knowledge and good practice in products and processes that are set up in separate class levels. The forecasting of manufacturing cost for each alternative is arranged and checked with market requirements. If an alternative does not satisfy market requirements, then product or process is to be redesigned. In business the best product alternative is implemented.

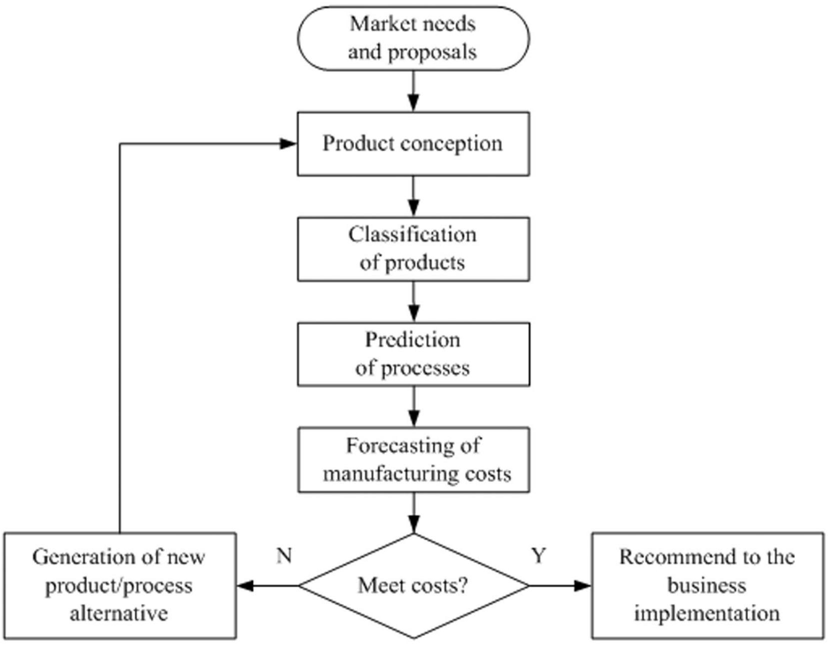

Fig. 1. Structure of a developed model.

2.2. Knowledge-based approach of innovative product and process structure development

A knowledge-based approach should support the decision maker in handling poorly structured decision problems. A poorly structured decision implies that the factors to be determined are unknown, they are either numerous or subject to impenetrable relationships. Poorly structured decisions in innovative product and process development arise in the following functional areas: definition of customer requirements, configuration of innovative products or customer orders, functions within product and process design and preliminary costs.

An integrated manner of innovative product and process development applying knowledge-based approach is illustrated in Fig. 2. It has created a tool for close cooperation among the customer, consumer, designer and manufacturer. This tool consists of four blocks:

- systematization of customer requirements;
- development of product alternatives at a separate class level;
- development of process alternatives;
- estimation of alternatives and selection of the optimum.

The block of systematization of customer requirements is presented in Fig. 3 as deployment of hierarchy distribution according to the product life cycle phases. In the following sections the rest of knowledge-based approach blocks are analysed.

2.3. Development of a new product conception

As a first step of a new product conception development an optimal version of a virtual prototype of the product (VP) is elaborated according to the customer requirements. Functionality of the product, its parameters and production costs have been used as the main criteria. Product analogues are frequently taken. In case of no analogues, design axioms and design for excellence (DFX) methodology [7] have been used. Necessary information for product design is systematized in Fig. 4.

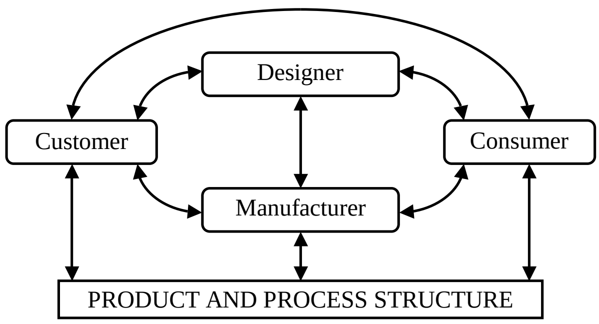

Fig. 2. Integrated development manner of innovative product and process.

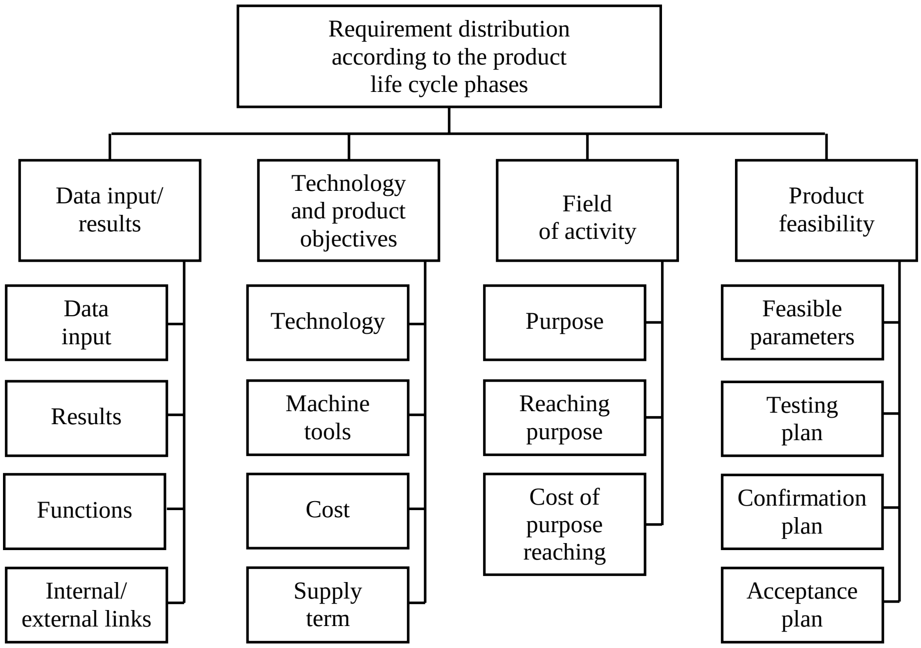

Fig. 3. Hierarchy of requirements distribution and product objectives.

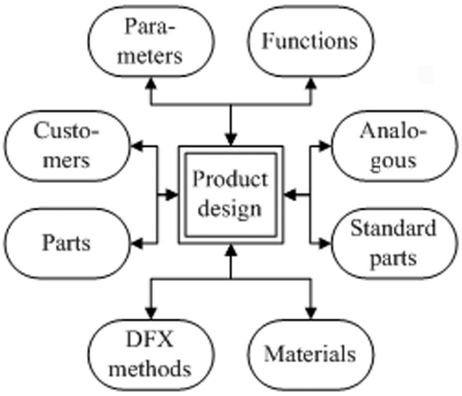

Fig. 4. Systematized information of product design.

The following step is creation of the product physical prototype (PP) applying rapid prototyping (RP) techniques to solid products and traditional technologies to sheet metal design products. Product PP is useful for:

- design visualization;
- finding design mistakes;
- marketing studies;
- consideration and improvement of product functionality and parameters;
- communication in simultaneous engineering.

Different RP methods for new product development are available. Web-based portal of RP customers and developers [8] is created for this aim. It supports cooperation among customers, suppliers and product developers in finding the best RP alternative based on costs estimation and delivery reliability. Sometimes, when product is very simple or its production volume is small, application of PP may be avoided. In this case all necessary data about the product may be presented in VP.

A classifier of mechanical and electronic products, produced in Lithuania, is presented in Table 1. Conditional values of investments m for a design infrastructure such as CAD licenses, RP facilities, models, etc and coefficient r of product design complexity have been jointly modelled by applying statistical data.

According to the developed classifier, available products G are classified into a number K of different class levels:

$$G = \{G_1, G_2, \ldots, G_i, \ldots, G_s\}. \tag{1}$$

The G_i, belonging to class K_i, could be expressed as

$$G_i = \{K_i : K_i \in A_i\}, \tag{2}$$

where A_i is the multitude of parameters of products of class K_i.

Any product G_i consists of a lot of R original parts and a lot of S standard components. Aiming at an optimal product and process design, the best combination of parameters R and S are to be searched as follows:

$$\begin{cases} 0 < R \le n,\ n \to \min, & (3) \\ 0 < S \le k,\ k \to \max, & (4) \end{cases}$$

where n is the number of original parts and k is the number of standard parts and components.

Table 1. Classifier of products

Product type	m Euro/h	r
CNC Machine tools	40	1
Precision machinery	36	2
Mechatronics products	32	3
Refrigerators	28	4
Agriculture machinery	24	5
TV components	16	6
Moulds and dies	13	7
Heating boilers	10	8
Sheet metal design	6	9
Solid parts	3	10

Each original part R and standard component S consists of design features D with various qualitative and quantitative parameters. The multitude of design features D is also divided into two classes – rotational and prismatic geometrical forms. Thus, the original part R of a product as a lot of D can be written as

$$R = \bigcup_{j=1}^{l} D_j = \{D_1, D_2, \ldots, D_j, \ldots, D_l\}. \quad (5)$$

The complexity of the design feature D_j is expressed by a lot of parameters like the geometrical form, dimensions, tolerance, surface roughness, etc. Therefore, each design feature D_j can be described by a set of parameters as follows:

$$D_j(f_j, a_j, b_j, c_j, d_j), \; D_j \in KEK \subset E, \quad (6)$$

where f_j denotes geometrical form, a_j – dimensions, b_j – qualitative and quantitative parameters, c_j – surface roughness, and d_j – tolerances. KEK denotes classifier of design features, and E the set of design features.

Costs of the product conception development are determined by investments N:

$$N = (m + s)/r \cdot p, \quad (7)$$

where m is the investment for design infrastructure (Euro/h, Table 1), s is engineer labour cost (6.2–9.3 Euro/h in Lithuania), r is the coefficient of the product complexity (Table 1) and p is probability of the requested target value and the actual designed value [9].

Figure 5 presents the real investment curve for cost definition of complex products at the conception stage and Fig. 6 presents the same data for simple products. Distribution of products into two groups is conditional and does not say that development of simple products is easier than that of the complex ones. Definition of customer requirements and market needs and also creation of an optimal process with minimal manufacturing cost is a labour consuming and hard job. Planning of resources for it requires great efforts.

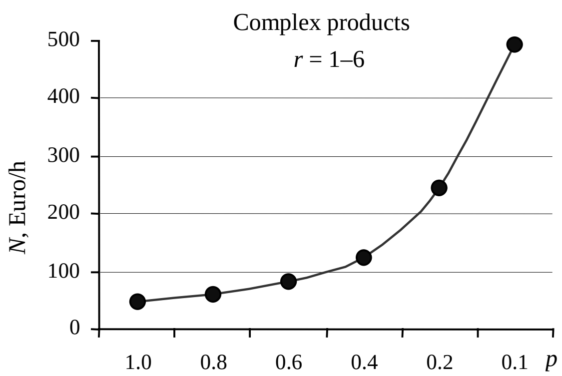

Fig. 5. Investment curve for the development of complex products.

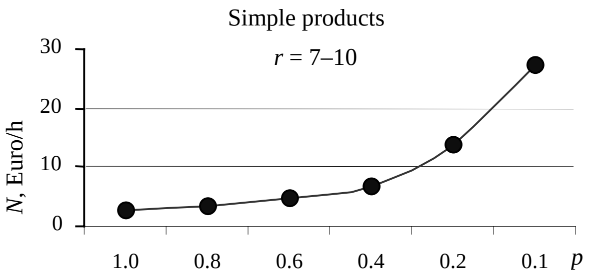

Fig. 6. Investment curve for the development of simple products.

2.4. Prediction of process engineering and production costs

A process prediction model has been developed considering the relationship of production volume (V), initial material of a part (M), material profile (P), variety of design features (D) and their qualitative and quantitative parameters (Q). In this way, any particular material and its initial profile type demand appropriate technological operations, e.g., if a part is made of thin sheet metal (thickness from 0.7 to 6 mm) then the operations will be as follows: preparatory, guillotining, cutting, punching, stamping, bending, welding, cleaning, painting, galvanizing, etc. Manufacturing process can be elaborated with different sequences of technological operations. When sheet thickness is increased, some of the mentioned operations are omitted, and instead additional operations (milling, heat treatment, grinding, etc.) are introduced and all of them may be included in one complete set or may have various combinations. Therefore, any material M and other above mentioned parameters correspond to function f of a definite set of technological operations O:

$$O = f(V, M, P, D, Q). \qquad (8)$$

The number of product parts, their size as well as the parameters mentioned in Eq. (8), predetermines the combination of technological operations not only for metal sheets, but also for any type and profile of the material (bars, moulds and forges). There are chances to achieve minimal costs by matching the number of product parts and their complexity.

When a production process plan of a part with its technological operations and appropriate machinery is predicted, the manufacturing cost can be forecast.

Manufacturing costs are divided into three fundamental categories [10]: fixed costs, labour costs and material costs. Thus, total costs C of a manufacturing process are calculated as

$$C = C_1 + C_2 + C_3, \qquad (9)$$

where C_1 denotes material costs, C_2 is fixed costs and C_3 is labour costs.

Material costs C_1 can be easily defined by the dimensions of the work pieces. There is sufficient software and methods for the definition of the material consumption applying a 3D CAD model of a part [11,12].

Fixed costs C_2 are related to the investments for machine tools, working space rental and overheads. It is to be spent before the parts are produced; therefore, it must be allocated to an individual component. The rate of machine maintenance costs, currently obtained from the machine supplier, has been also used. Average set-up time costs, statistically defined per month, are also included in the machine costs category.

Labour costs C_3 depend directly on total floor-to-floor time in a manufacturing shop. Methodology, described in references [10,13], has been employed for the definition of labour costs C_3. By applying the above-mentioned costs calculation peculiarities and the acquired statistical data, a broad-brush parametric function is developed, extending Eq. (9) for forecasting the manufacturing costs at an early business engineering stage:

$$C = \left(C_1 + \sum_{j=1}^{m} \left(AT \right) \right) F + \frac{J}{V}, \tag{10}$$

where C_1 is part of material costs (in Euros), A is cost of a technological operation (Euro/h), T is time of manufacturing a part in an hour of an operation, F is a coefficient estimating overheads ($F = 1.05$–1.20 in Lithuania), J denotes costs for special tooling (Euro) and V is the volume of production.

3. RESULTS

This new methodology has been tested developing an integrated innovative product and process. Analysis of the global network of customers, suppliers, producers and consumers has shown that Lithuania is a country of producers. It is historically conditioned because Lithuania has entered the market too late and at the current moment it is troublesome to develop competitive products to market. Local businessmen fear to invest in the development of new products because it bears high risks of getting positive results.

The model has been veryfied on the accuracy of investment forecast of conditionally simple products development. Principal data of the considered products are presented in Table 2. Product $G1$ consists of a table and 2 chairs and its purpose is to be used in a summer cottage. Product $G2$ is to be used in an office or a living room when working at a computer. Product $G3$ consists of 5 assembling units which can make a big variety of products in living rooms and offices. Powder painting and galvanized processes have been applied by finishing operations of parts. These products have been developed and produced by two separate SMEs.

Table 2. Principal data of products

Products	Number of components	Raw material
Set of furniture $G1$	3	Plastics, tubes, sheet metal
Chair $G2$	1	Leather, solid metal, tubes
Set of shelves $G3$	5	Sheet metal

Table 3. Cost of various product development stages in hours

G	Customers requirements	Design	Test
$G1$	80	120	50
$G2$	120	260	90
$G3$	50	100	60

The investment to product development, applying the statistics DB and experience of companies, is illustrated in Table 3. Main difficulties have appeared in defining customer requirements for all considered products. Requirements also include the product address, the needs and objectives of the stakeholders, expressed by the constraints and performance parameters; therefore, product engineers derive a consistent set of more detailed engineering statements of requirements. In fact, the data presented in Table 3 have proved to be true with a probability of 0.8–0.6. The last step of development is forecasting the product manufacturing costs, applying expression (10). The experimental investigations into the manufacturing costs of the developed forecasting model at an early product design stage have shown acceptable accuracy – the errors have been in the limits of 5 to 12 percent.

4. CONCLUSIONS

The created methodology and integrated knowledge-based model estimate the investment to the development of a new product and process with sufficient accuracy. The developed model has been tested in two Lithuanian manufacturing companies and test results have shown its correctness and possibilities for its further improvement extending the types of products and processes.

The model helps stakeholders in resolving uncertainties when starting a new business. The presented methodology can systematize and acquire the knowledge and experience for the definition of customer requirements, configuration of the innovative product, process alternatives and preliminary costs. It stimulates activity in search of new products and modern manufacturing methods.

ACKNOWLEDGEMENT

This research was partially supported by the Leonardo da Vinci Project Interstudy contract No. EE/06/B/F/PP – 169004.

REFERENCES

1. Ribbens, J. A. *Simultaneous Engineering for New Product Development*. John Wiley, New York, 2000.
2. Yan, W., Pritchard, M. C., Chen, C.-H. and Khoo, L. P. A strategy for integrating product conceptualization and bid preparation. *Int. J. Advanced Manufact. Technol.*, 2006, **29**, 616–628.
3. Mild, A. and Taudes, A. An agent-based investigation into the new product development capability. *Comput. Math. Organiz. Theory*, 2007, **13**, 315–331.
4. Ullman, D. G. Robust decision making for engineering design. *J. Eng. Design*, 2001, **12**, 3–13.
5. Hsing Hung Chen, He-Yau Kang, Xiaoqiang Xing, Lee, A. H. I. and Yunhuan Tong. Developing new products with knowledge management methods and process development management in a network. *Computers in Industry*, 2008, **59**, 242–253.
6. Ayyub, B. M. *Elicitation of Expert Opinions for Uncertainty and Risks*. CRC Press LLC, New York, 2001.
7. Huang, G. Q. and Mak, K. L. The DFX shell: a generic framework for applying design for X tools. *Int. J. Computer Integrated Manufact.*, 1998, **11**, 475–484.
8. Sackus, A., Bargelis, A. and Cesnulevicius, A. Web-integrated product modelling using rapid prototyping techniques. In *Proc. International Conference on Industrial Logistics ICIL'2003* (Barros, L. et al., eds.). Vaasa, 2003, 464–474.
9. Bargelis, A. Cost forecasting model of product and process development at the business conception stage. In *Proc. 6th International DAAAM Baltic Conference "INDUSTRIAL ENGINEERING"*. Tallinn, 2008, 303–308.
10. Bargelis, A. and Rimasauskas, M. Cost forecasting model for order-based sheet metalworking. *J. Mech. Eng. Sci.*, 2007, **221** C, 55–65.
11. Puisa, R. and Pauza, V. Adaptive design in CAD systems. *Mechanika*, 2001, **6**, 61–66.
12. Niemi, E. Part allocation to nesting layouts under variable demand. *Int. J. Production Res.*, 2003, **41**, 1549–1563.
13. Bargelis, A., Hoehne, G. and Cesnulevicius, A. Intelligent functional model for costs minimization in hybrid manufacturing systems. *Informatica*, 2004, **15**, 3–22.

Innovatiivse toote- ja protsessiarenduse integreeritud teadmuspõhine mudel

Algirdas Bargelis, Rasa Mankute ja Dalia Cikotiene

Innovatiivse toote- ja tootmisprotsessi arenduse integreeritud teadmuspõhine mudel kuulub tootmissüsteemis tellimuse käsitluse ossa. Uurimuses on vaadeldud masinaehituslikke tooteid ja uusi, nüüdisaegseid plastist ning lehtmetallist tooteliike. Väljatöötatud mudel aitab süstematiseerida ja talletada teadmust ning kogemusi kliendi vajaduste ja innovatiivse toote konfiguratsiooni määratlemiseks, võimaldab leida alternatiivseid tootmisprotsesse ning kujundada esialgse hinnaprognoosi. See annab tootjale võimaluse leida ja hinnata toote ning tootmisprotsessi struktuuri ja maksumust uue toote evitamisel. Antud integreeritud teadmuspõhist mudelit on katsetatud kahes Leedu tootmisettevõttes. Väljatöötatud mudel on leidnud rakendust nii tööstuses kui ülikooli õppeprotsessis.