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Cost Projections for the Product Life Cycle at the Early Stages of Product Development

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Abstract. The paper is concerned with predicting the total cost of a new product and searching for cost reduction at the early stages of product development. The costs of a new product development project, product promotion, production and after-sales service are predicted using parametric models. The identified relationships are also used to searching for possibilities to reduce the cost of faulty products and after-sales service through increasing prototype tests. As a result, the trade-off between the cost of a product development project and costs of production and after-sales service are sought. Company resources and product specification are formulated in terms of variables and constraints that constitute the systems approach for a problem related to cost optimization. This problem is described in the form of a constraint satisfaction problem and implemented using constraint programming techniques. An example shows the applicability of the proposed approach in the context of searching for the desirable level of the cost related to prototype tests, faulty products and after-sales service. This study develops previous research in the context of adding the cost of after-sales service to a model of total costs of a new product. Moreover, the proposed method of predicting cost has been developed towards using the similarity value to data selection.

Keywords: Product Data Management, New Product Development, Production Cost, Decision Support System, Constraint Programming.

1 Introduction

Cost management is one of the most important business activities, affecting the sales revenue, profits and competitiveness. The effective cost management maintains a company growth and survival. However, its effectiveness depends on a stage of the product life cycle. The earlier total product costs are predicted, the more chance to obtain benefits of predictions. These benefits refer to the timing of price changes, product withdrawal, impacting strategies of product lifecycle management. Generally, total product costs are related to new products development (NPD), product promotion,

manufacturing, and after-sales service. Manufacturing is usually the longest stage in the product life cycle. Consequently, production cost has the largest share in the total product costs. However, the costs related to production and after-sales service depend on the quality of product design created in the NPD process. This process is therefore one of the most important activities in today's companies, also taking into account shortening product life cycles and competitive markets. Moreover, shorter time for developing new products and the limited resources impel companies towards greater effort and attention in managing the NPD projects. Increasing competition and customers' requirements impose more often product launches on the market within the acceptable cost that is prerequisite for the product success. If predictions of the total product costs do not satisfy the company's top management team, then there are sought possibilities to reduce costs. This paper is concerned with developing an approach to cost projection and searching for the trade-off between costs at the early stages of the product life cycle (product design and prototype tests) and in the later stages (production and after-sales service).

The NPD costs are related to market research, generating concepts of a new product, its design and prototype tests. Specially, the latter cost is often a long-term process which absorbs the majority of the NPD budget. However, prototyping costs are usually low (if not negligible) in comparison to the overall cost of production [1]. Moreover, the number of prototype tests affects product reliability, and finally, the costs related to faulty products in manufacturing and the after-sales stage. The low product reliability can reduce customer satisfaction and increase the warranty cost. Companies usually tend to seek the trade-off between the prototyping cost and costs related to production and after-sales service. Cost projections can be based on relationships between variables that are identified by parametric models. These relationships can also be used to the search for possibilities to reduction of the number of faulty products and return of goods, and the trade-off between different type of costs.

The identification of possibilities for reducing the costs variants requires the specification of variables, their domains and constraints, including the mentioned relationships between variables. This specification can be formulated in terms of a constraint satisfaction problem (CSP). In the context of product development, the CSP paradigm has been mainly applied to product design [2]. Taking into account cost projections and simulations, the CSP paradigm has been used in the context of the NPD cost [3], and production and advertising cost [4]. The contribution of this study is the development of previous research in the context of using the CSP paradigm to find the trade-off between the mentioned costs. Moreover, a method of cost estimation is proposed using databases of project-oriented enterprises, in order to identify the possibility of cost reduction of the total product cost. The proposed method includes a step related to using the similarity value to data selection. Finally, this study presents the use of constraint programming (CP) techniques to identify possible variants of cost reduction. The paper is organised as follows: Section 2 presents problem formulation in terms of a CSP. A method of projecting cost and searching for possible variants of cost reduction is shown in Section 3. An illustrative example of the proposed approach is presented in Section 4. Finally, conclusion is shown in Section 5.

2 Problem formulation

The proposed approach allows the decision maker to identify prerequisites, by which an NPD project can obtain the trade-off between costs related to prototype tests, production and after-sales stage. The number of possible variants of cost reduction depends on constraints, domains related to variables, and their granularity. Relationships between variables can be identified using previous experiences related to the similar completed projects. The identified relationships are used to cost projections and verification of the existence of such changes, by which the target cost could be reached.

The application of the proposed approach requires the specification of variables, their domains, and constraints that can be described in terms of a CSP in the following form: *((V, D), C)*, where V is a finite set of n variables $\{v_1, v_2, \ldots, v_n\}$, D is finite and discrete domains $\{d_1, d_2, \ldots, d_n\}$ of variables V, and C is a finite set of constraints $\{c_1, c_2, \ldots, c_m\}$. Constraints can link variables and restrict their values. The solution of a CSP is a set related to the value of each variable that satisfies all constraints C.

Problem formulation in terms of a CSP includes the variables and constraints regarding an NPD project and company resources. The selection of variables is performed in an arbitrary way, taking into account the impact of a specific variable on the cost of NPD, production, and after-sales service. The specification of a cost model as a CSP enables the search for a set of values of decision variables, for which cost reduction is possible, if any. The problem solution is related to possible changes in NPD project performance that satisfy all specified constraints, including the desirable level of costs.

There are the following variables regarding cost estimation of a new product:

V_1 – the cost of an NPD project (product design and prototype tests),

V_2 – the cost of product promotion,

V_3 – the unit production cost,

V_4 – the cost of after-sales service,

V_5 – the number of employees involved in an NPD project,

V_6 – the number of prototype tests,

V_7 – the number of product components,

V_8 – the period of an advertising campaign (in weeks),

V_9 – the number of target clients in an advertising campaign (in thousands),

V_{10} – the amount of materials used to produce a unit of a new product (in kilograms),

V_{11} – the number of components in a product for assembling,

V_{12} – the number of components in a product for processing,

V_{13} – the number of faulty products in manufacturing (in each 1,000 final products).

The set of constraints is as follows:

C_1 – the budget of an NPD project,

C_2 – the budget of product promotion,

C_3 – the maximal unit production cost,

C_4 – the minimal number of product components,

C_5 – the minimal number of prototype tests,

C_6 – the total number of employees who may be involved in NPD,
C_7 – the maximal amount of materials needed to produce a unit of a new product,
C_8 – the maximal cost of faulty products in manufacturing.

The model specification in terms of a CSP integrates technical parameters of a new product, parameters regarding the NPD project performance, estimated costs of a new product, and available resources in a company. The solution of the above-described problem can be referred to the answers to the following questions:

- what is the cost related to an NPD project, product promotion, its production, and after-sales service?
- what values should have the variables related to prototype tests to reach the desirable level of total costs of a new product?

The answer to the second question refers especially to the problem formulation in terms of a CSP and its declarative programming paradigm. Using this paradigm all possible solutions are identified, if any. This often requires the verification of a large space of solutions, especially if there are many decision variables and highly differentiated domains. Consequently, there is a need to use the effective techniques of space search reduction, such as constraint programming.

3 A method of cost projections and searching for possible variants of cost reduction

The proposed method includes the following steps: collecting data from existing products that are similar to a new product, identifying relationships between input and output variables, predicting costs related to a new product, and searching for possible variants to obtain the desirable level of costs. A framework of the proposed method is presented in Fig. 1.

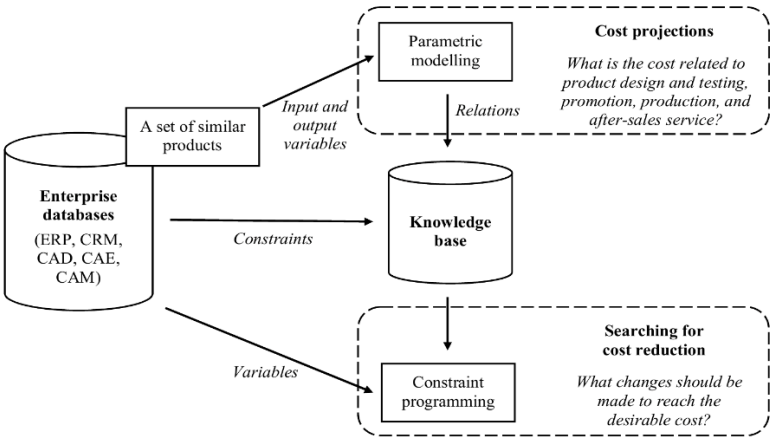

Fig. 1. A framework of the proposed method

The data is collected from enterprise databases stored in information systems that support product data management in a company. These information systems can include systems related to enterprise resource planning (ERP), customer relations management (CRM), computer-aided design (CAD), computer-aided engineering (CAE), or computer-aided manufacturing (CAM). The data stored in these systems is used in product lifecycle management.

Information of the product life cycle is acquired from specifications of past or existing products that are in the same product line as a new product. The most similar products to a new product are retrieved from the enterprise database using the similarity function (1) and similarity value – SV (2) that are calculated as follows:

$$sim(f_i^P, f_i^R) = 1 - \frac{|f_i^P - f_i^R|}{max(f_i)} \tag{1}$$

$$\mathrm{SV} = \frac{\sum_{i=1}^{n} w_i \times sim(f_i^P, f_i^R)}{\sum_{i=1}^{n} w_i} \tag{2}$$

where:

- $sim(f_i^P, f_i^R)$ – the similarity function of the *i*-th product features (e.g. weight, size) between the value of the new product f_i^P and the value of the retrieved product f_i^R; it ranges from 0 to 1.
- w_i – the weight of the *i*-th product features.

The costs of a new product can be estimated using analogical and parametric methods. Analogical methods estimate the cost using similarity to previous products. The comparison between the new and existing products can refer to cost reduction in different areas, for example, product design [5]. In turn, parametric methods estimate the cost from parameters that significantly affect the cost.

The proposed method uses cause-and-effect relationships to cost estimation within prototype tests of a new product, faulty products in manufacturing, and return of goods in the after-sales stage. Product reliability affects the number of faulty products and return of goods, increasing the total cost of production and after-sales service. Product reliability can be measured by the number of product usage to the first failure that directly depends on the number of prototype tests.

The variables to cost estimation are selected taking into account their impact on the specific cost and their controllability. For example, a company can manage the number of prototype tests, project team members, and product components. A set of variables, their domains, and constraints constitutes a CSP that is a framework for obtaining answers to the questions about the value of the cost, and if it is non-acceptable, about the values of variables that enable the desirable level of the specific cost.

The proposed method is based on parametric estimation models that include an analytical function of a set of variables. These variables are usually related to some features of a new product (e.g. the number of components, dimensions, materials used) and an NPD project (e.g. the number of prototype tests, project duration, project team members) that are supposed to have a significant impact on NPD project performance and the cost of a new product. Parametric estimation techniques often base on regression

analysis [6-7], artificial neural networks [8-9] or hybrid systems (e.g. neuro-fuzzy and genetic fuzzy systems). The identified relations are stored in a knowledge base and used to search for possible variants of designing and manufacturing a new product.

The last step of the proposed method refers to the search for possible solutions to reach the desirable cost of prototyping, promotion, production and after-sales service. The search space depends on the number of variables chosen to the analysis, their domains, and constraints that can link variables and limit possible solutions. An exhaustive search always find a solution if it exists but its performance is proportional to the number of admissible solutions. Therefore, an exhaustive search tends to grow very quickly as the size of the problem increases, what limits its usage in many practical problems. Consequently, there is a need to develop more effective methods for searching the space and finding possible solutions. As CP uses the specific search methods and constraint propagation algorithms, it enables a significant reduction of the search space. Consequently, CP is suitable to model and solve complex problems [10]. CP includes search strategies that are crucial for improving search efficiency of solving a wide range of problems, for instance, planning and scheduling [11-12], manufacturing [13-14], and resource allocation [15-16].

4 A case study

4.1 Calculating the similarity between new and past products

The first stage of the proposed method is related to data selection, namely selection of a set of the most similar existing products to a new product. The similarity between products is calculated for products belonging to the same product line. There are 22 products from the same product line as a new product. The following set of features has been chosen to evaluate the similarity between products: the number of parts, product size, product weight, and the amount of materials used. Table 1 presents the similarity function (*SF*) and similarity value (*SV*) for the most similar past product and new product.

Table 1. Similarity functions and similarity value.

Features	f^P	f^R	*SF*
Number of parts	42	45	93.3%
Product size	0.65	0.68	95.6%
Product weight	0.71	0.73	97.3%
Amount of materials used	0.77	0.81	95.1%
SV = (93.3% + 95.6% + 97.3% + 95.1%) / 4 = 95.3%			

There are 15 similar products with the similarity value above the assumed threshold of 85%, which are considered in the further analyses.

4.2 Predicting product development costs

The total cost of a new product mainly consists of costs related to product design, promotion, production, and after-sales service. These costs are further estimated using an arithmetic average that is calculated for a set of the most similar product to a new product, and a parametric approach, where the costs are identified using several independent variables. The relationships of the cost of product design and testing (3), promotion (4), production (5), and after-sales service (6) are as follows:

$$V_1 = f(V_5, V_6, V_7) \tag{3}$$

$$V_2 = f(V_8, V_9) \tag{4}$$

$$V_3 = f(V_7, V_{10}, V_{11}, V_{12}) \tag{5}$$

$$V_4 = f(V_6, V_7, V_{13}) \tag{6}$$

The relationships (1)-(4) have been identified using linear regression, and the results have been compared with the average of output variables to illustrate to what extent the parametric models outperform the arithmetic average. The dataset for analysis includes 15 cases that has been divided into training set (12 cases) and testing set (3 cases) to evaluate the quality of an estimation model. The experiments were performed using 5-fold cross validation, and the results were determined as the average of these folds. The identified relationships have the following form:

$$V_1 = 5.28V_5 + 0.64V_6 + 0.46V_7 + 64.04 \tag{7}$$

$$V_2 = 0.94V_8 + 3.70V_9 + 70.56 \tag{8}$$

$$V_3 = 0.50V_7 + 247.80V_{10} + 0.36V_{11} + 0.01V_{12} + 14.88 \tag{9}$$

$$V_4 = 0.41V_6 + 0.52V_7 + 15.73V_{13} - 17.69 \tag{10}$$

Table 2 presents the mean absolute percentage square error (MAPE) in the training set (TR_S) and testing set (TE_S) for the cost of an NPD project (V_1), the cost of product promotion (V_2), the unit production cost (V_3), and the cost of after-sales service (V_4). The results indicate that parametric models (PM) produce the less error than the arithmetic average, both in training and testing dataset.

Table 2. Comparison of MAPE for the parametric model and average.

Variable	Model	MAPE for TR_S in (%)	MAPE for TE_S in (%)
V_1	PM	1.00	1.56
	Average	6.05	10.16
V_2	PM	6.27	4.44
	Average	14.38	17.45
V_3	PM	2.62	5.48
	Average	23.69	17.73

V_4	PM	5.14	5.33
	Average	12.23	13.44

As the parametric models have been generated in the testing set smaller MAPE than the arithmetic average, they have been used to cost estimation. The cost of an NPD project (V_1) has been estimated at 310 thousand €, taking into account the following values of input variables: $V_5 = 5$, $V_6 = 300$, $V_7 = 60$. The cost of product promotion (V_2) has been predicted at 320.9 thousand € for the following input variables: $V_8 = 30$, $V_9 = 60$. The unit production cost (V_3) has been estimated at 218.7 €, taking into account the input variables such as: $V_7 = 60$, $V_{10} = 0.65$, $V_{11} = 35$, $V_{12} = 15$. In turn, the after-sales service cost (V_4) has been estimated at 183.7 € per 1,000 sold products, taking into account the input variables such as: $V_6 = 300$, $V_7 = 60$, $V_{13} = 3$. The values of input variables (V_5, …, V_{13}) are acquired from specification of a new product, including product design and testing, product promotion, production process, and after-sale stage. Specification of a new product is elaborated on the basis of experiences from the implementation of previous products.

The budget of an NPD project reaches 350 thousand €, so this constraint is fulfilled. In turn, the unit production cost, which is related to faulty products, and after-sales service is too high for senior managers, and they decided that these costs should be reduced to 210 € and 175 € for each 1,000 sold products, respectively. In the next step, the possibility of fulfilling these expectations is sought.

4.3 Searching for possibilities of cost reduction

The solution of the above-described problem is sought using constraint programming that requires the specification of decision variables, their domains, and constraints, including relationships between variables. Scenario analysis is carried out for three variables: the number of employees involved in an NPD project, the number of prototype tests, and the amount of materials used to produce a unit of a new product. Domains of these variables are as follows: $D_5 = \{4, 5, 6\}$, $D_6 = \{300, \ldots, 400\}$, $D_{10} = \{0.60, \ldots, 0.70\}$.

The criterion for selecting the best variant of cost reduction (SC) is as follows:

$$\min SC = V_3 + V_4 \tag{11}$$

Table 3 presents a few possible solutions for the specified variables, their domains, and constraints. The increment of prototype tests results in increasing the NPD cost but at the same time it reduces the costs of production and after-sales service.

Table 3. A set of possible solutions.

Values of variables	V_3	V_4	SC
$V_5 = 5$, $V_6 = 399$, $V_{10} = 0.65$	210.0	174.9	384.9
$V_5 = 5$, $V_6 = 400$, $V_{10} = 0.65$	209.8	174.9	384.7
$V_5 = 5$, $V_6 = 389$, $V_{10} = 0.60$	209.9	173.3	383.2
…	…	…	…

V_5 = 5, V_6 = 400, V_{10} = 0.60	207.2	172.3	379.5
V_5 = 6, V_6 = 375, V_{10} = 0.60	210.0	172.7	382.7
…	…	…	…
V_5 = 6, V_6 = 400, V_{10} = 0.60	208.8	173.8	382.6

Table 3 illustrates an example of changes in three variables. The increasing number of NPD project team members enlarges the cost of prototype tests but also can increase the quality of a new product, and consequently, reduce the cost of production and after-sales service. Moreover, this kind of analysis can be an advice for the decision maker about directions of changes that can lead to reach the trade-off between the cost of prototyping, production and after-sales service.

5 Conclusion

The presented approach supports the decision makers in cost projections for all costs related to the product life cycle, and in searching for possibilities of reaching the desirable level of the cost related to production and after-sales service at the early stage of product development. The approach is dedicated for project-oriented enterprises that register their product specification and develop NPD projects within the similar product line. This study presents the use of parametric modelling to identify the relationships for predicting the cost of a new product. Moreover, the identified relationships can be used to search variants of increasing the quality of a new product, and reduce the cost of faulty products and warranty. If these costs are unacceptable for the decision makers, then the identified variants can support them in identifying the impact of input variables on the specific cost within the assumed constraints. The proposed model encompasses the product specification and company's resources, and it is formulated in terms of a CSP. The application of CP techniques reduces computational time compared to an exhaustive search, what is especially useful in the case of a vast space of possible solutions. Constraint programming techniques enables the use of strategies related to constraint propagation and variable distribution, significantly reducing a set of admissible solutions and the average computational time, what improves interactive properties of a decision support system. Drawbacks of the proposed approach can be seen from the perspective of collecting enough amounts of data of the existing similar products. Future research directions include identification of the impact of the number of decision variables (including granularity of their domains) and constraints on the time needed to obtain solutions, and the effectiveness of using constraint programming techniques. Moreover, future research could specify the adjustment of weights related to the similarity value, and their impact on data selection, and finally, on cost projections.

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