Proc. Estonian Acad. Sci. Eng., 2006, **12**, 3-1, 163–175
https://doi.org/10.3176/eng.2006.3.01

Coordination of complex tasks of engineering product and manufacturing process optimization

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Received 22 December 2005, in revised form 16 June 2006

Abstract. The objective of the study was to investigate how to optimize the family of products and their manufacturing processes, in particular, how to integrate computer-based product family planning, technology process planning and manufacturing resource planning activities. The main problem is to identify how to link different engineering decisions and to allow the individual design tasks to run separately in a concurrent manner. Models of the proposed subtasks are integrated so that they would support optimizing the life cycle of the product. For each considered subproblem, a multi-criteria optimization task is formulated together with the hierarchical coordination of the strategy.

Key words: complex engineering tasks, manufacturing, product family, technological process, planning, optimization.

1. INTRODUCTION

Current trends in manufacturing engineering lead from system-level to multiple-system-level design, for instance, from product-level optimality to optimality for the portfolio of products, from one enterprise to a network of cooperating enterprises, etc.

The challenge to design simultaneously multiple products has led to the investigation of collaborative optimization techniques in the engineering research community. There are several approaches to collaborative optimization [1–3]. The main problems are: to decompose initial complex design tasks and identify links between different engineering decisions, to reach coordination between different tasks and to allow individual design tasks to be conducted autonomously.

The objective of this study is to investigate how to optimize the family of products and their manufacturing processes, in particular, to integrate computer-based product family planning, technological process planning and multi-period manufacturing resource planning activities for an enterprise or network of cooperating enterprises, and to take full advantage of the computer-based optimal engineering decision process. The basic approach of the "evolutionary product and process development" has been accepted, which involves re-engineering and evolutionary improvement of products and processes.

The major concern in optimal planning is the overwhelming complexity of tasks. Simplification is based on the decomposition of the initial task. There are several reasons for the decomposition:

– the division of the initial task into smaller subtasks leads to a better understanding of the whole problem;
– dividing the tasks between the subsystems may lead to the realization of the design in different teams or functional units of the enterprise; there may be some already existing models that can provide useful information.

It is proposed that a complex engineering design task of a product family is decomposed into three design subtasks: product family design, manufacturing technology design and multiperiod manufacturing resource planning. Each of these subtasks can be represented in the form of a general goal-seeking system, based on the general optimization approach [4,5]. We represent each engineering design task $S:\hat{X}\to\hat{Y}$ explicitly with a planning component (goal-seeking component [4]) P and a (functional) design component D (Fig. 1).

In Fig. 1, P represents the planning component, with object $N=\{n\}$, denoting the domain of choices which P has. The task S is represented in terms of two mappings, P and D:

$$\begin{aligned} P&:\ \hat{X}\times\hat{Y}\to N,\\ D&:\ N\times\hat{X}\to\hat{Y}. \end{aligned} \tag{1.1}$$

N is an internal input, to be distinguished from $\hat{X}$ and $\hat{Y}$, which are the true input/output objects of S. Object $n\in N$ specifies a parameterized family of

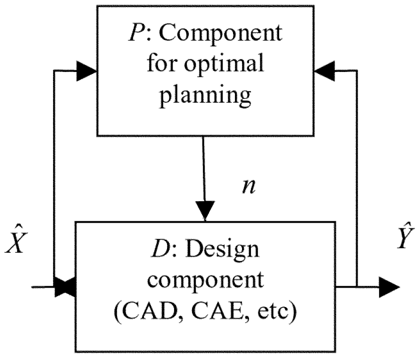

Fig. 1. Decomposition of a design task.

products (input/output data $\hat{X}$ and $\hat{Y}$ of design tasks for the product family) in the sense that to every $n \in N$ corresponds a subset $S_m \subset \hat{X} \times \hat{Y}$, such that

$$(\hat{x}, \hat{y}) \in S_m \leftrightarrow (n, \hat{x}, \hat{y}) \in D. \tag{1.2}$$

For specifying planning activities of P we must define an objective function $G : N \times \hat{X} \times \hat{Y} \to V$ and develop a decision strategy, which is used to select n. Here V is a vector-valued objective function of the corresponding design task.

Relations D and P must be consistent with the system S, i.e., they must satisfy the condition

$$(\hat{x}, \hat{y}) \in S \leftrightarrow (\exists n)[(n, \hat{x}, \hat{y}) \in P, (\hat{x}, \hat{y}, n) \in D]. \tag{1.3}$$

In the following we shall describe planning components for each of the defined design subtasks.

2. PLANNING OF THE PRODUCT FAMILY

Product specification and planning are the critical starting points in the development of any new product. The product plan helps to resolve the design issues related to the markets, the types of the products and the resources of the company. A product plan is generally prepared on an annual basis; it should be reviewed and updated at least quarterly. Market conditions will change, new opportunities will be identified, and a new product technology will emerge, all having a potential impact on the product plan. These opportunities need to be evaluated and the product plan changed, if needed.

Cost efficiency, technological leverage and market power can be achieved when companies redirect their thinking and resources from single products to families of products, built upon robust product platforms.

A product family is a set of products that share a common structure, function(s), and technology and address a related set of market applications. Derivative products are specific instantiations of a product family, which possess unique features and functions as compared to other members in the family.

The objective of product family planning is to create economically the desired variety of products. Parametrical models are used as instruments to link the planning tasks with the CAD and CAE systems. Each derivative product $p_i \in P$ is associated with a vector of design variables x_i^p and is composed of a series of modules and parts, corresponding to the set of features F_i, which are determined in the product family planning phase.

Next, a list of different variables is composed, which are used in the following models of planning tasks:

- i – index of a derivative product p_i, $i = 1, \ldots, m$, where m is the total number of product variants in a product family;
- a_i – time required to manufacture, assemble or purchase one unit (or a component) of the product p_i;

- a_{iw} – the same for workstation (or technology line) w, $w = 1, \dots, k$, where k denotes the number of workstations;
- c_w – capacity of the workstation (or technology line) w in units, consistent with those used to define a_{iw};
- η_{iu} – amount of the material (and purchased components) of type u, needed for the product p_i;
- r_i, s_i, h_i – net profit, selling price and cost to hold one unit of product p_i;
- C_i – unit production cost (excluding inventory costs) of the product p_i;
- M_u, μ_u – cost and resource of the material u;
- Inv_i – investment required for implementing product p_i (estimated costs related to the implementation of an appropriate product);
- X_i – quantity of products p_i, produced during the period analysed;
- $I_i - \begin{bmatrix} 1 & \text{if } X_i > 0 \\ 0 & \text{if } X_i = 0 \end{bmatrix}$ – indicator of using the product p_i in the family.

The combinations of products p_i and additional (specific) features F_j required by different customers of market segments are represented by integer indicators:

- $F_{ji} - \begin{bmatrix} 1 & \text{in the case of the use of feature } j \text{ in product } p_i \\ 0 & \text{in the case when feature } j \text{ is not used in product } p_i \end{bmatrix}$;
- cf_{ji} – cost of implementing additional feature j for product p_i.

Each market segment has its own customer preferences of additional product features, which are denoted by $d_{i\delta}^{\max}(F_{ji})$ and $d_{i\delta}^{\min}(F_{ji})$ – expressing maximum and minimum demand for p_i in the market segment δ (as a function of F_{ji}).

To determine optimal planning volumes of a product family and a module combination, we have developed a model that maximizes the net profit minus investment costs and is subject to upper and lower bounds of demand on the market and to the capacity constraints imposed on workstations and materials. The following optimal planning task can be formulated.

For the given a_{iw}, η_{iu}, r_i and cf_{ji} find the volumes of production X_i and use of additional features F_{ji} that maximize the profit C and minimize the manufacturing/purchasing lead time T for the total product family:

$$\mathbf{Max}\, C = \sum_{i=1}^{i=m} \sum_{j=1}^{j=k} (r_i \times X_i - I_i \times Inv_i - F_{ji} \times cf_{ji}), \tag{2.1}$$

$$\mathbf{Min}\, T = \sum_{i=1}^{m} a_i * X_i, \tag{2.2}$$

subject to conditions:

1) $d_{i\delta}^{\min}(F_{ji}) \le X_{i\delta} \le d_{i\delta}^{\max}(F_{ji})$ for all product variants i and market segments δ;

2) $\sum_{i=1}^{m} a_{iw} * X_i \le c_w$ for all workstations w;

3) $\sum_{i=1}^{m} \eta_{iu} \times X_i \le \mu_u$ for all materials u;

4) $X_i \ge 0, \quad F_{ji} \in \{0,1\}$ for all i, j.

Based on this planning model, a product concept for a family is selected.

3. PLANNING OF THE MANUFACTURING TECHNOLOGY

We define manufacturing planning as a process of identifying a manufacturing operation plan, which defines either a complete or partial order in which the manufacturing tasks can be performed. Generation and selection of manufacturing (operation) plans for a product family is a problem of great practical importance with many significant cost implications.

It is known that many feasible operation sequences exist, but some are more desirable than others, according to the utility criteria, such as quality, throughput, cost, need for special tools (incl. jigs or fixtures), etc. The planning problem encompasses generation of feasible manufacturing plans, evaluation of different feasible solutions and selection of optimal plans.

Modelling of the manufacturing process planning tasks is generating a set of correct and complete precedence graphs of operations rather than generating a fully specified sequence of operations. The word “complete” refers to the generation of a set of precedence graphs from which all possible manufacturing sequences can be derived. The word “correct” implies that all of these sequences are feasible, i.e., they satisfy all manufacturing constraints.

The technology planning model gives optimal selection of technology operation sequences for the manufacturing of the product family, based on the maximization of the total profit and minimization of the manufacturing time or other process performance criteria and is subject to all constraints of operation establishment (operation necessity and operation precedence), workstation time capacities, material availability, etc. The input data for manufacturing technology planning are derived from the product family planning and manufacturing resource planning tasks.

An example of a generalized structure of manufacturing plan for a product family is represented in Fig. 2.

We define an indicator of the use of the technological operation (workstation) j for product p_i as follows:

$$Op_{ji} = \begin{bmatrix} 1 & \text{operation } j \text{ is used for product version } i \\ 0 & \text{operation } j \text{ is not used for product version } i \end{bmatrix}. \tag{3.1}$$

Precedence conditions can be described by technological constraints (in the following the precedence conditions are specified implicitly by describing the system of constraints) in the form

$$(Op_{11} \vee Op_{12}) \to (Op_{21} \vee Op_{22} \vee Op_{23}) \to (Op_{31} \vee Op_{32}) \to Op_4 \to Op_5. \tag{3.2}$$

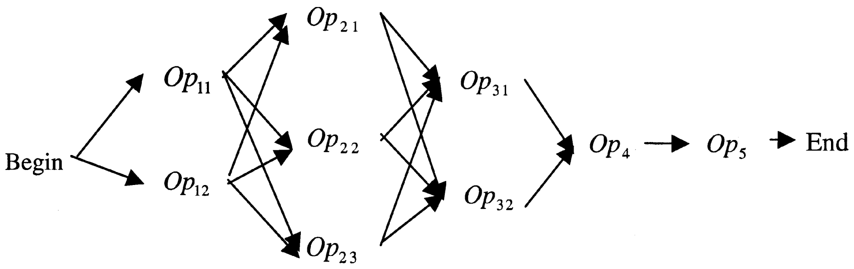

Fig. 2. Generalized structure of the manufacturing plan for a product family.

For each operation group, the condition of necessity of operations is given in the form $IF\ (Operation\ Op_{ji}$ is needed$)\ THEN\ Op_{ji}=1\ ELSE\ Op_{ji}=0$.

The necessity of an operation is defined by logical conditions of work pieces and features of work pieces (or features of products for assembly operations). The task is to find a sequence of operations that would give maximum profit and minimize the manufacturing time and is subject to capacity constraints for the use of technologies (workstations) and materials. We formulate the task as:

$$\mathbf{Max} \sum_{i=1}^{i=m} \sum_{u=1}^{n} X_i \times (r_i - C_i - m_{iu} \times M_u), \tag{3.3}$$

$$\mathbf{Min}\ T = \sum_{i=1}^{m} a_i * X_i, \tag{3.4}$$

subject to

1) $\sum_{i=1}^{m} a_{iw} * X_i \le c_w$ for all workstations w;
2) $\sum_{i=1}^{m} \eta_{iu} \times X_i \le \mu_u$ for all materials u;
3) $Op_{11} + Op_{12} = Op_{21} + Op_{22} + Op_{23} = Op_{31} + Op_{32} = Op_4 = Op_5 = 1$ (Fig. 2);
4) $X_i \ge 0$; Op_{ij} and $F_{ji} \in \{0,1\}$ for all i, j.

Based on the proposed model, technology planning is a combinatorial 0–1 integer programming problem.

4. OPTIMAL PLANNING OF MANUFACTURING RECOURCES

The objective of manufacturing resource planning is to plan the volumes of products produced X_{it}, sold S_{it} and hold as inventory I_{it} for given time periods $T_t (t=1,...,tl)$. The problem is called multiperiod aggregate planning (AP) [6]. Input for that task can be obtained from the technology planning and product family planning tasks.

The model of AP maximizes the overall profit and minimizes the manufacturing time, considering available resources and demand for multiple products subject to upper and lower bounds on the sales and capacity constraints. Formulation of the task is as follows:

$$\textbf{Max} \sum_{t=1}^{tl}\sum_{i=1}^{m} s_i * S_{it} - C_i * X_{it} - h_i * (I_{it} + X_{it}/2) \ \textit{net profit}, \qquad (4.1)$$

$$\textbf{Min}\ T = \sum_{i=1}^{m} a_i * X_i \ \textit{manufacturing time}, \qquad (4.2)$$

subject to

1) $d_{i\delta t}^{\min} \le S_{i\delta t} \le d_{i\delta t}^{\max}$ for all i, δ, t demand;

2) $\sum_{i=1}^{m} a_{iwt} * X_{it} \le c_{wt}$ for all w, t – capacity of the workstation w;

3) $I_{it} = I_{it-1} + X_{it} - S_{it}$ for all i, t – inventory balance;

4) $I_{it} \ge s_{it}$, for all $i = 1, m, t = 0, \ldots, tl$ requirements for safety stock;

5) $X_{it}, S_{i\delta t}, I_{it} \ge 0$ for all i, t – non-negativity.

The basic formulation contains capacity constraints for the workstations, but in some situations also other resources such as people, raw materials, transport device capacity, allowed maximum for inventory (capacity of warehouses), may be important factors [1].

5. COORDINATION OF SUBTASKS

We suppose that the initial task is to be decomposed because of its complexity. As the result of decomposition, for example in this study, three planning subsystems P_1, P_2 and P_3, corresponding to product family planning, technological process planning and multiperiod manufacturing resource planning, are introduced as shown in Fig 3.

We suppose that each planning task P_i is concerned with the decision problem related to its own planning task that has its own goal G_i. If there is no coordination among P_i, the overall optimum cannot be achieved because the component subsystems are pursuing their goals without paying attention to interactions. Consequently, a coordinator P_0 has to be introduced in order to coordinate the activities of the lower level decision subsystems P_1, P_2, P_3. The task of the coordinator is to choose suitable coordination variables $\gamma_i, i = 1, 2, 3$ such that the planning activities on the lower level subsystems would yield a result consistent with the requirements of optimality for the overall task.

The proposed optimal planning tasks are related to the analysis or design tasks (systems CAD, CAE, CAM, ERP, etc.). Those systems take the planning results,

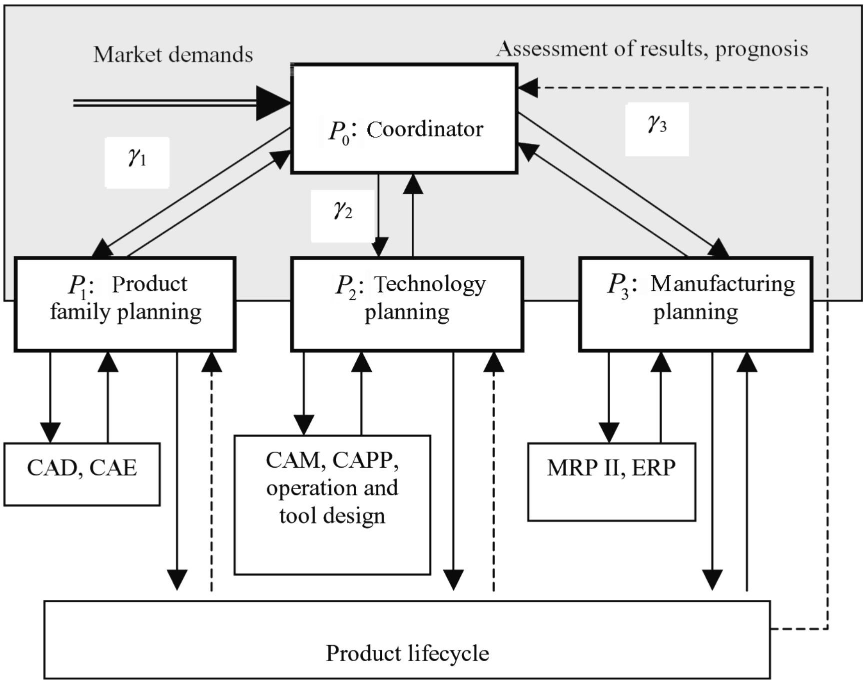

Fig. 3. Two-level scheme of product family production planning.

the variables and parameters as inputs and return the responses for upper level planning systems as outputs.

The main problem is the question of equivalence between the initial optimal design task and the tasks represented by the decomposition schemes. To coordinate and to eliminate possible discrepancies between the tasks step by step, the supervisory subsystem provides [4,5,7]:

- the prognosis of “auxiliary planning variables” representing the initial guesses of parameters for tasks, typical and recommendable solutions, etc.;
- additional constraints that represent the convergence restrictions on possible solutions;
- objective functions for the subtasks.

Consistent system design can then be accomplished with minimum communication, i.e., with maximum efficiency, avoiding costly iterations later in the process. The process for initial guesses for auxiliary planning variables aims at minimizing the gap between what higher-level elements “want” and what lower-level elements “can”.

The process of adding additional constraints, for instance, in the form of “Design for Manufacture”(DFM), “Design for Assembly” (DFA) is traditional for concurrent engineering design practice and is not described here.

To measure performance, to evaluate decisions and coordinate the objective functions of subtasks, optimization with multi-objectives is proposed as a general framework. For different tasks, different objective functions that represent some hierarchy of objectives can be used. Two methods for handling multiple criteria, (linear) physical optimization approach [8] and the goal programming approach [9], were investigated.

Goal programming [9] is a technique, primarily used to find a compromised solution, which simultaneously satisfies a number of design goals. In addition to initial planning tasks, the general goal programming model can be expressed as follows:

$$\mathbf{Min}\ Z = \sum_{i=1}^{m} (w_i^+ d_i^+ + w_i^- d_i^-), \tag{5.1}$$

subject to

$$\sum_{j=1}^{n} a_{ij} x_j + d_i^- - d_i^+ = b_i \quad \text{for all } i,$$

$$x_j, d_i^-, d_i^+ \geq 0 \quad \text{for all } i \text{ and } j.$$

In goal programming, the objective function minimizes the weighted sum of deviational variables d_i^+, d_i^-. The system of constraints represents (in addition to (2.1), (3.1) and (4.1)) the goal constraints, relating the decision variables x_j to the targets b_i. If the relative weights w_i^+ and w_i^- and targets b_i can be specified by the coordinating system, the model of linear programming can be used. Unfortunately, it is difficult to determine values of the weights in practice. In reality, goals are usually incompatible and an iteration process is needed.

A key characteristic of the physical optimization approach is the availability of information regarding the physical meaning of the objectives. The Linear Physical Programming (LPP) paradigm [8] is characterized by the following example, used in our study: assume that we wish to (i) maximize the profit r, and (ii) minimize the manufacturing time T. We assume that a coordinating subsystem knows significantly more than the fact that the coordinator wants to maximize the profit and minimize the manufacturing time. Instead of attempting to find correct weights, the coordinator, for example, expresses the following preference levels using the variables t_{iS}^+ and t_{iS}^-:

Ideal profit > 306 000 (EEK for the time period)	Ideal time <1295 hours
Desirable 306 000–305 000	Desirable 1295–1300
Tolerable 305 000–304 000	Tolerable 1300–1305
Undesirable 304 000–303 000	Undesirable 1305–1310
Unacceptable <303 000	Unacceptable >1310

The following linear programming problem is solved for each subtask:

$$\mathbf{Min}\ J = \sum_{i=1}^{n_{SC}} \sum_{s=2}^{4} (w_{is}^- d_{is}^- + w_{is}^+ d_{is}^+), \tag{5.2}$$

subject to

$$g_i - d_{is}^{+} \le t_{i(s-1)}^{+};\ d_{is}^{+} \ge 0;\ g_i \le t_{i4}^{+} \text{ for “profit criteria” } i=1,\ s=2,....,4,$$

$$g_i + d_{is}^{-} \ge t_{i(s-1)}^{-};\ d_{is}^{-} \ge 0;\ g_i \ge t_{i4}^{-} \text{ for “time criteria” } i=2,\ s=2,....,4.$$

The coordinator must give for each subtask the weights w_{is}^{-}, w_{is}^{+}, the preference levels t_{is}^{+}, t_{is}^{-} and the expected values of the criteria g_i.

6. EXAMPLE OF OPTIMAL DESIGN OF THE HYDRO-SPA EQUIPMENT FAMILY

As an example, the proposed approach is used to develop a family of products in Wellspa Inc. in Estonia. Simplified examples of basic functional features of the product family are shown in Table 1. The common basic structures of features (Table 2) represent the commonality and similarity pattern of features and design parameters for the corresponding derivative products.

Table 1. Use of basic functional features for four products P_1, P_2, P_3 and P_4

Features	P_1	P_2	P_3	P_4
Translucent shell	1	1	1	1
Far infrared heat	1	1	1	1
Vibratory massage bed	1	1	1	1
Touch-button control panel	1	1	1	1
5.6” LCD colour display	1	1	1	0
10 pre-set programs (+1 custom)	1	1	1	0
Steam (direct plumbing)	1	1	0	0
Steam (no plumbing)	0	0	1	1
Vichy shower	1	1	0	0
Underbody shower	0	1	0	0
Foot massage shower	1	1	0	0
Vitamin/mineral product diffusion system	1	1	0	0

Table 2. Optimization results

Parameters	p_1	p_2	p_3	p_4	
X_1, X_2, X_3, X_4	42	0	44	10	Production volumes
I_1, I_2, I_3, I_4	1	0	1	1	Indicators
F_{1i}	1	0	1	0	Additional function 1
F_{2i}	0	0	0	0	Additional function 2
F_{3i}	1	0	1	0	Additional function 3
F_{4i}	0	0	0	0	Additional function 4

Figure 4 shows simplified examples of the derivative products of a family of hydro-spa treatments for Wellspa Inc. with a reduced number of features.

To solve the given problem we used an integer-programming tool. An example of some results of optimal product family planning is represented in Table 2. In spite of different input parameters, we could see an effective set, the profit of which is maximal, when the first, third and fourth product are produced and optimal when an additional function to the first and third products are added.

Based on these results the company developed two additional functions and the present sale figures show that the decision was justified.

Thermoforming is the basic process in the manufacturing of a product family. Thermoforming uses heat, vacuum, and pressure to form the plastic sheet material into a shape that is determined by the mould. The sheet is heated to a temperature at which the plastic softens, but that is below its melting point. Using vacuum or pressure, the plastic is then stretched to cover and duplicate the form of the mould. Next, the plastics is cooled. By cooling it retains its shape. Finally, it is removed from the mould and trimmed as required to create a finished part [10]. Large plastic parts can be made using thermoforming without the capital cost of large moulds and expensive pressurizing machines. Thermoforming suits for low to moderate volumes of production. With the proposed model, the technology planning is a combinatorial 0–1 integer-programming problem. The results (in a simplified form) of the technology planning optimization task represent the list of operations used to manufacture the proposed family together with the data of the resource use (Table 3).

An example of the results of the manufacturing resource planning task, like the volume of production, sales and holding parts is shown in Table 4.

Fig. 4. CAD models of the derivative products.

Table 3. Technology planning optimization results

Op_{11}	Op_{12}	Op_{21}	Op_{22}	Op_{23}	Op_{31}	Op_{32}	Op_4	Op_5
0	1	0	0	1	1	0	1	1

Table 4. Manufacturing resource planning result

	Time period t = 1				Time period $t = i$				Time period $t = tl$			
	p_1	p_2	p_3	p_4	p_1	p_2	p_3	p_4	p_1	p_2	p_3	p_4
X_{it}	14	0	14	2	14	0	16	4	14	0	14	4
S_{it}	15	1	16	4	16	1	16	4	15	1	16	4
I_{it}	3	2	2	0	1	1	2	0	0	0	0	0
I_{i0}	4	3	4	2	–	–	–	–	–	–	–	–

7. CONCLUSION

The objective of this study was to investigate how to optimize a family of products and their manufacturing processes, in particular, to integrate computer-based product family planning, technological process planning and multi-period manufacturing resource planning activities for an enterprise or a network of cooperating enterprises. The accepted basic approach is the “evolutionary product and process development”. We suppose that the initial task is decomposed because of its complexity. For the assessment of the performance, evaluating decisions and coordinating the objective functions of subtasks, optimization with multiobjectives is proposed as a general framework. Two methods, the goal programming approach and (linear) physical optimization approach were used. The proposed approach is exemplified by the development of a family of products in Wellspa Inc. in Estonia.

ACKNOWLEDGEMENT

The study was supported by the Estonian Science Foundation (grants Nos. 5883 and 5620).

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Keerukate tehniliste süsteemide ja nende valmistamisprotsesside optimeerimisülesannete koordineerimine

Rein Küttner ja Kristo Karjust

On käsitletud tootepere, tootmistehnoloogia ja tootmise optimaalse planeerimise metoodikat. Optimaalse projekteerimise ülesanne on formuleeritud kahetasandilisena ja see sisaldab koordinaatorit ning madalamal tasemel erinevaid optimaalse planeerimise ülesandeid. Planeerimisülesanded on esitatud mitmekriteeriumilise optimaalse planeerimise ülesannetena. Koordinaator juhib erinevaid planeerimisülesandeid siduvate parameetrite väärtuste prognoosimise, täiendavate tõkete püstitamise ja sihifunktsioonide parameetrite täpsustamisega. Metoodika on realiseeritud MS Exceli keskkonnas ja selle kasutamist on kirjeldatud tervisekapslite tootepere projekteerimise näitel OÜ-s Wellspa, Eesti.