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INTEGRATION OF PRODUCT DESIGN AND MANUFACTURING WITH THE USE OF ARTIFICIAL INTELLIGENT METHODS

Product and process design is time- and cost consuming [15]. To reduce the cost of product development, it is necessary to integrate product and process design. The proposed product planning approach integrates activities involved in product design and manufacturing process. The aim of this paper is to develop a method of knowledge integration about customer needs, product and process characteristics. The range of analyses is limited to mechanical product type manufacturing for institutional customers. Customer needs are focused on functional characteristics of the product and the trade characteristics include product price, timing and warranty.
Integration of functional requirements, product and process characteristics is needed to select the best product from a catalogue and adapt it to particular customer needs. From the given set of products, where a product is described by a set of attributes, the subset is chosen which roughly satisfies customer needs. Basing on artificial intelligent (AI) methods, data related to redesign and production processes is estimated.

1. DESIGN AND MANUFACTURING INTEGRATION

Design could be described as a process of satisfying functional requirements [4]. A designer has to transform functional requirements into physical product structures. Quality Function Deployment QFD is an approach to convert customer requirements into internal company requirements and integrate global product characteristics and parts that cause product functions to be performed.

In order to define design problems, the functional approach is a meaningful representation of knowledge about the existing products [4]. The functional approach to products and process design describe the relationship between inputs and outputs, which enable functional product configuration. In the case of adaptive design, general product structure and components are known, a functional configuration could be obtained by modifying subfunctions and creating product variants. The functional analysis of the existing products is useful in product configuration and helps to create modular structure of the product. The concept of the functional configuration is a tool of identifying proper product components and their parameters. During product functional configuration, the costs of product manufacturing are determined. Estimation of product costs needs

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knowledge associated with labour, material, and overheads. Manufacturing costs depend on static data like e.g.: labour consumption, and dynamic data like e.g.: load of machines, tools wearing. Labour consumption of product parts manufacturing depends, among others, on parts characteristics, processing parameters whereas overhead cost depends on e.g. load of machines.

Product functions depend on their parts and their characteristics described by attributes and their value.

Attributed product model integrates knowledge related to product functions and manufacturing data. The proposed approach may be regarded as development of work done by Dagli and Kusiak [4], who described a factory model of the manufacturing process.

2. ATTRIBUTED MODEL OF PRODUCT

The design and manufacturing integration could be based on attributed model of product [9]. The product functions could be characterised by a set of attributes:

$$F = \{f_1, f_2, \ldots, f_n\} \quad (1)$$

Based on toothed gear example, the set of attributes includes e.g.:
f_1 - reducer working arrangement
f_2 - kind of duty
….

Each attribute takes value from the set F_n^w.

$$F_n^w = \{f_{n1}^w, f_{n2}^w, \ldots, f_{nl}^w\} \quad (2)$$

An example of a set of attribute values F_n^w includes e.g.:
f_{11}^w - parallel axes
f_{12}^w - perpendicular axes
f_{21}^w - light duty
f_{22}^w - medium duty
f_{23}^w - heavy duty
…..
The set of product types was denoted P.

$$P = \{p_1, p_2, \ldots, p_m\} \quad (3)$$

An example of a set of products includes:
p_1 - helical gear
p_2 - bevel-helical gear
…
Each product type p_m includes products p_{m1}, p_{m2},…, p_{mk}., described by attributes p_{mkz} .

$$P_{mk}=\{p_{mk1,}\ p_{mk2},\ \ldots,\ p_{mkz}\} \tag{4}$$

An example of a set of products includes:
p_{11} - one stage helical geared reducer mouted on foots
p_{12} - one stage helical geared reducer hanged on the shaft
….
An example of a set of product attributes includes:
p_{111} - weight
p_{112} - dimensions
…
Each attribute p_{mkz} takes value from the $P_{mkz}{}^{w}$ set.

$$P_{mkz}{}^{w}=\{p_{mkz1}{}^{w},\ p_{mkz2}{}^{w},\ \ldots,\ p_{mkzt}{}^{w}\} \tag{5}$$

Product p_m consists of modules / elements belonging to the set M.

$$M=\{m_1,m_2,\ldots,m_k\} \tag{6}$$

Each element is described by attributes belonging to the set M_k.

$$M_k=\{m_{k1},\ m_{k2},\ldots,\ m_{kv}\} \tag{7}$$

Examples of attributes describing product parts are:
m_{k1} - weight
m_{k2} - type of material
…
Attribute values belong to the set $M_{kv}{}^{w}$.

$$M_{kv}{}^{w}=\{\ m_{kv1}{}^{w}\ ,\ m_{kv2}{}^{w}\ ,\ldots,\ m_{kvg}{}^{w}\} \tag{8}$$

$M_k{}^{*}$ set of variants of element m_k

$$M_k{}^{*}=\{m_{k1}{}^{*},m_{k2}{}^{*},\ldots,m_{kl}{}^{*}\} \tag{9}$$

$M_{kv}{}^{w}$ set of attribute values

$$M_{kv}{}^{w}=\{\ m_{kv1}{}^{w}\ ,\ m_{kv2}{}^{w}\ ,\ldots,\ m_{kvg}{}^{w}\} \tag{10}$$

Basing on the presented product attributed model, it is possible to analyse *customer product value*.

The vector of added value in case of industrial products includes [16]: product engineering characteristics (quality, safety, reliability, reparability, economical use, standards meeting), producer characteristics (punctuality, availability, service), pricing policy.

Among the methods which aid product development, the Quality Function Deployment QFD is a well known one. QFD helps in identifying spoken and unspoken customer needs and convert it into product characteristic.

3. INTELLIGENT METHODS IN DESIGN AND MANUFACTURING KNOWLEDGE INTEGRATION

QFD is one of the methods, which, basing on the functional approach to product structure, helps in design knowledge reuse and does so in a more fundamental way than CAD. Product components can be reused much more easily thanks to identifying the required functions, but there is still lack of standard methods to represent functions [1].

In the mechanical type of product in most cases individual parts cannot realise the function. The relationship between parts and functions must be taken into consideration in order to provide functioning [1] described a process based-knowledge reuse system applicable in case of organization has developed a similar products in the past. This knowledge is stored in organization databases and joins process, task and product knowledge. Literature [1] indicates needs of requirements management in engineering design.

Many authors [12],[6],[15] described intelligent systems designed to support product development. Those systems concern the process of design and manufacturing including conceptual and detailed design of new product. The design process includes concept generation and component design.

Among AI methods useful in product development knowledge based system (KBS) have been widely applied, which deals with knowledge processing and the decision making process. The KBS application areas have been in product and process design, project evaluation, conceptual design, QFD and decision making [13].

Rehman [14] used knowledge-based and case-based approaches to develop the cost modelling strategy. Cost estimation of a product is made during the design phase of product development and links design and manufacturing knowledge.

Another powerful AI method applied by researchers in the context of QFD is neural network (NN). Yan [18] applied NN to analyse and evaluate the relationship between the customers' and designers' knowledge. Other authors [10],[17],[3] use NN as a tool of estimation of missing product characteristics during the design phase.

4. ATTRIBUTED MODEL OF PRODUCT IN QUALITY FUNCTION DEPLOYMENT

To create product added value, it is necessary to use methods which give information related to product functions and their cost. Quality Function Deployment QFD aids product and process design. Identification of customer needs and product characteristics is made in QFD and the correlation between them is registered in a matrix. QFD includes a series of matrices. The first one represents the relation between customer needs and product characteristics. The second one describes the relation between product characteristics and product parts. The third QFD matrix gives information related to the production process. The fourth one provides information related to production process parameters. The proposed approach applies the second QFD matrix.

The proposed model joins internal human knowledge (tacit knowledge) with the articulated knowledge (explicit knowledge).

The QFD matrix could be used as a tool for cost assessment of product functions. The attributed model of product could be useful for that purpose (Table. 1).

Table 1. QFD matrix for product functions and part characteristics

What? \ How?			Design requirements			
Customer requirements	Functions / Attributes	Value	p_{mk1}	p_{mk2}	…	p_{mkz}
	f_1	f_{11}^{w}	c_{11}	c_{12}		c_{1k}
	f_2	f_{22}^{w}	c_{21}	c_{22}		c_{2k}
	f_n	f_{n2}^{w}	c_{z1}	c_{z2}		c_{zk}

What? \ How?			Parts requirements				Costs of functions
Design requirements	Functions / Attributes	Value	m_1	m_2	…	m_k	
	p_{mk1}	p_{mk1t}^{w}	c_{11}	c_{12}		c_{1k}	K_1
	p_{mk2}	p_{mk2t}^{w}	c_{21}	c_{22}		c_{2k}	K_2
	p_{mkz}	p_{mkzt}^{w}	c_{z1}	c_{z2}		c_{zk}	K_z
	Cost of parts		K_{m1}	K_{m2}		K_{mk}	K

In QFD matrix product functions are specified in the column on the left, whereas the product parts are listed in the row. In the upper part of the matrix relations between parts are pointed out. In the proposed approach costs of product functions are specified in the column on the right.

Correlation between product functions and parts is registered in the middle part of the matrix. The costs of the function could be calculated according to the following formula:

$$K_z = \sum_{k=1}^{K} \left(c_{zk} \cdot \frac{K_{mk}}{\sum_{z=1}^{Z} c_{zk}} \right) + K_d \qquad (11)$$

where:

K_z – costs of function *z*

c_{zk} – correlation between part *k* and function *z*

K_{mk} – manufacturing cost of part k
K_d – design costs
Costs of product parts could be calculated according to the formula:

$$K_{mk} = K_{rh} \cdot t + K_m, \tag{12}$$

where:
K_{rh} – processing costs per hour
t – labour consumption
K_m – material costs
K_{mk} – manufacturing costs

Labour consumption is one of the crucial data in production process which is a result of product characteristics, facilities, work methods and people's skills.

Methods of labour consumption estimation in production process included [11]:

a) direct methods:
- time study (standard time is calculated basing on the observed time of a task),
- activity sampling (the allowance time is calculated based on the number of successive observations made over a period of time).

b) indirect methods:
- synthetic timing (the time for new job is estimated by adding the previously assessed elemental times),
- analytical estimating (the time required per task is built up from synthetic data where possible and supplemented (estimated basing on the available knowledge), where such data is not available for particular elements),
- predetermined motion time system – method time measurement (MTM).

The new approach of time estimation applies an artificial intelligent method. The idea bases on NN application, where time consumption could be estimated basing on product and process attributes. That method provides time consumption in a fast and easy way. In this approach time assessment is performed using the attributed model of product, and time consumption could be estimated using chosen attributes and their value.

Among product characteristics analysed by customers, price is one of the most important. Product cost minimization could be done using product and process optimizing methods.

Time measurement methods are useful as a tool of process optimization. The idea of process optimization using MTM and Value Stream Mapping was described by Kuhlang, Minichmayr and Sihn [7].

Costs of product design for particular customer needs are high in many enterprises. Design cost could be calculated according to the following formula:

$$K_d = K_{dh} \cdot t_d \tag{13}$$

where:
K_{dh} – costs per hour
t_d – labour consumption of product and process design task
K_d – design costs

Time consumption of product and process design task could be calculated, among others, according to the following methods [5],[2]:

- Time estimation based on the previously elaborated project – the head of department estimates time consumption of development tasks.
- Activity sampling (the allowance time is calculated on the basis of the number of successive observations made over a period of time).
- Convert ratio method – based on product attributes, time consumption is calculated.
- Point method – based on complexity ratio, novelty ratio, similarity ratio, employee classification, and / or standardization ratio the number of points is fixed and time consumption is calculated.
- Synthetic timing – the time consumption is calculated basing on time standards fixed for a class of product parts.
- Method of representatives – time consumption is calculated basing on timing established for a representative product.
- Ratio method – time is calculated on the basis of labour consumption ratio

Neural network could also be used in this area as a tool for time estimation [17].

5. TOOTHED GEAR BOX EXAMPLE OF COST FUNCTION CALCULATION

The approach presented in previous points joins product functions and thier costs. An example of toothed gear box of cost calculation was presented in Table 2. Changes on product functions cause changes of their costs. Joint information related to product costs and product parts helps in product function selection.

Table 2. Toothed gear example of costs of product function calculation

			(7)			+	+				
			(6)			+					
			(5)			+				+	
			(4)								
			(3)	+	+		+	+	+	+	
			(2)	+		+		+		+	
			(1)			+					
What \ How				Product parts							
Engineering characteristic	Product			Toothed elements	Shafts	Housing	Packing	Bearings	Lubrication	Covers	Costs of functions
	Offered functions:	Attributes	Attributes value	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Allows installation	Reducer working arrangement	1a			9	9		9		372,5
	Transmits the torque	Power	30	9	9			9			847,5
		Rotational speed	100								
		Reducer ratio	15								
	Can work in explosive environment	ATEX norm fulfilling	I							9	60
	Cost of parts			400	300	200	50	40	30	10	

6. CONCLUSIONS

Customer needs identification and providing products tailored according to individual customer requirements is one of key points of success in many enterprises.

In order to create product added value, it is useful to apply AI methods to data analysis related to product design and manufacturing process. To make proper decisions related to product configuration, it is important to identify costs of product functions.

The idea of the paper is to develop methods useful in providing information related to the product function. The presented attributed model of product helps to create product functions characteristics. The model integrates information related to product design and manufacturing. AI methods could be useful in estimating the values of product attributes.

The proposed model is useful in the context of the QFD method. On the basis of correlation between product functions and its parts, the cost of product function was assigned. The integration of product design and manufacturing is focused on elaboration of product characteristics which provide information needed to predict costs of product function.

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