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OBJECT-ORIENTED PRODUCT MODELING FOR EARLY ASSEMBLY COST ESTIMATION

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1. Introduction

The orientation of the market to customer-tailored products in a fierce competition situation imposes enterprises to react promptly by improving their products as well as their production and organizational structures. As the product palette increases, the order size per bid decreases and the case of production of unique-manufactures or in small series increases, the reduction of both development time and production costs gains a central position. Although assembly costs can reach up to 70% of the total production costs [David et al. 2000] it is usually difficult to estimate them in the initial stages of product design especially for new of prototype products. This cannot only leave the assembly cost saving potentials unexploited but also lead to an increased product development time.
An object-oriented product-modeling framework for the early estimation of assembly costs for new or prototype products manufactured as a unique-manufacture or in small series by means of manually or hybrid assembly systems is presented. Therefore, based on the systematic engineering design theory critical product factors with assembly cost relevance will be classified in an object-oriented scheme. Then, based on the fundaments of the systems engineering theory an object-oriented class structure [Welp and Braun 1998] will be established in order to introduce the assembly cost estimation.

2. Current Situation and Requirements

Existent wide applied assembly cost evaluation methods can be roughly divided into two categories: assembly cost estimation methods like DFA, SEER-DFM, MTM, WorkFlow, MOMO, etc. as well as estimation models included in assembly process planning (i.e. [Zäh et al. 2003]) yield a cost value for assemblies; assembly cost evaluation methods like Hitachi-AEM, Lucas-DFA, etc. allow an index-based rating of design alternatives concerning their possible assembly costs, however without yielding a cost value. Common characteristic of these methods is that the more the product characteristics and the necessary assembly processes become concrete, the more the estimation accuracy increases. This implies that both embodies of a product must exist and the basic assembly processes and resources must be known precisely. In this case the development of a product has already reached a significant level of detail, which means that respectable development costs are already caused as well as that possible design changing costs will be high [Ehrlenspiel et al. 2003]. Therefore, it would be beneficial if assembly costs of product concepts could be early estimated. However, the lack of exact information on properties and shape of the product parts and their structure in the design concept phase practically hampers the application of methods like the above on early development stages.
In order to estimate the assembly costs in the concept phase an estimation framework must be built, which considers exactly the particular features of this development phase and link them with assembly cost generating processes. Furthermore, the calculation fundament should utilize principles of the activity based costing procedures, since so a transparent calculation can be achieved and indirect costs

can be fairly credited to the assembly processes causing them [Caplan and Cooper 1992]. This is a prerequisite for the localization and optimization of these construction zones, which affect decisively the assembly costs. Additionally, the product-modeling framework should be easy for a prompt implementation and have a transparent structure, which can be intuitively understand and handled from the user [Ehrlenspiel et al. 2003, Giannoulis and Welp 2003].

3. Method

The basic idea of the modeling procedure is that the product construction structure (*Baustruktur* [Pahl and Beitz 1996]) and the *connection types* between the *single parts or groups* described in the product constructional interrelationship (*Bauzusammenhang* [Pahl and Beitz 1996]) engage definitive elementary assembly process chains. These cause in the end the assembly costs (Figure 1). The kind of the process chains depends mainly on some key characteristics of the connection types of the components to be assembled. Therefore process chains can be common for similar assembly operations in similar production structures [Barton et al. 2001] for the construction of unique-manufactures or small series products. In such chains, both manual and automatized assembly operations can be involved. Each process chain necessary for the realization of the assembly between at least two single components engages some resources (Material, Personnel, Equipment and Operating Resources). The "consumption" of those resources causes assembly costs. The consumption rate or the "utilized quantity" of a process chain is defined from some key characteristics of the assembled parts. This cost generation procedure reflects an activity based cost calculation scheme with a deeper consideration of resources used [Giannoulis and Welp 2003].

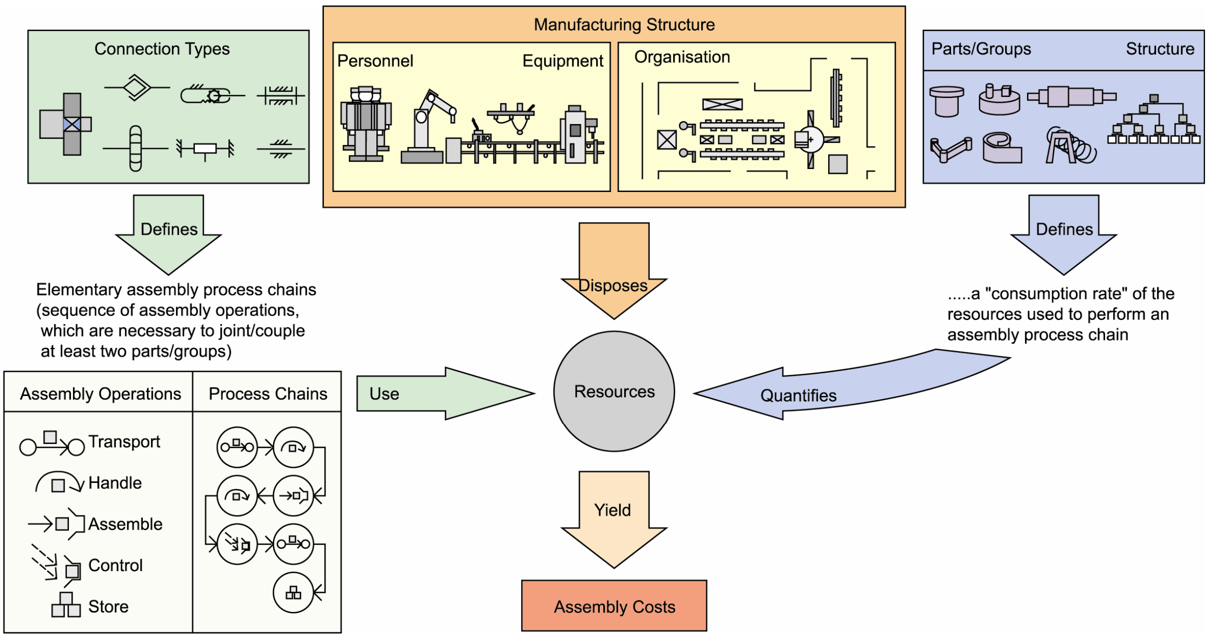

Figure 1. Concept fundament of the method

Thus, in a first step it is important for the assembly cost calculation method to "classify" assembly process chains in elementary patterns. Afterwards, these must be linked with key characteristics of connection types and single parts or groups as well as their structure in a product. These patterns can be then quantified by applying a costing method, thus yielding an assembly cost estimation value.

However, in order to conduct a cost estimation in the early design phases, product information on higher abstraction levels must be evolved, namely those contained in product concepts (described by the working interrelationship - *Wirkzusammenhang* [Pahl and Beitz 1996]). The goal here is to create a direct link between product information with assembly relevance comprised in a product concept (working structure [Pahl and Beitz 1996]) and elementary assembly patterns (assembly process chains). Therefore, based on the object-oriented analysis [Rumbaugh 1995] - and in this case based on the property of inheritance - a generalization hierarchy (ElementClass) is created (Figure 2). This contains in its upper level, classes having as objects, types of working elements. These objects (types of working elements) are used in the working structure for the product concept modeling. In it its lower lever this hierarchy contains classes with construction elements [Giannoulis and Welp 2003] with objects being similar to real parts. The attributes of the objects contain data appropriate to the corresponding working level. Concerning the working element classes, these attribute data involve physical effects, working region, working geometry, working motion and working material. The attributes of the construction element classes concern form or layout (dimensions, arrangement, number and shape) and material (kind, treatment, specifications, properties). In order to ensure the assembly cost relevance, the attributes of the classes are so chosen that they can yield information concerning the "assembly behaviour" [Lotter 1992] of an element. By this it is meant the behaviour of a hypothetical object when it is subjected to several activities for the assembly [Giannoulis and Welp 2003]: transport (i.e. stable by default or stable under conditions like the support of additional devices, etc.), handling (i.e. ease of orientation and positioning, fixing etc.), control (i.e. ease of the positioning for inspection or for the measurement of important connection parameters, etc.) and connecting (i.e. features accommodating insertion, adjustment, connections, etc). Therefore, special attributes of manual as well as hybrid assembly systems concerning their organization, the equipment and the procedures are examined and interrelated with attributes of the construction elements.

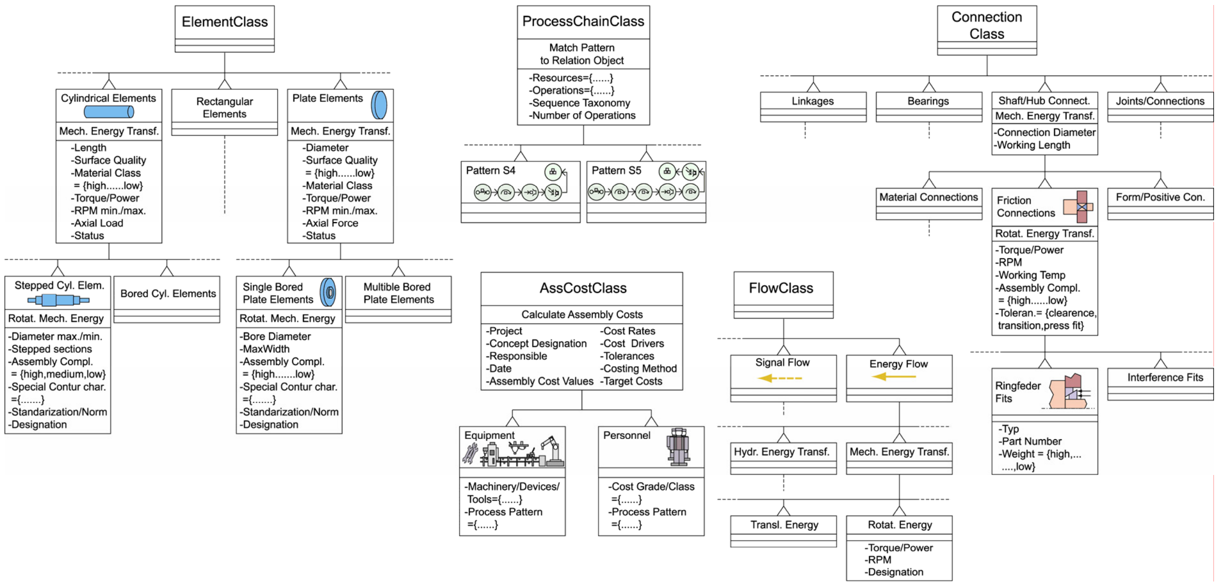

Figure 2. Generalization hierarchies for the working elements modeling, the CT's, the assembly process patterns and the cost

Besides, a generalization hierarchy for the element connection types (CT) is introduced (Figure 2). This contains classes (ConnectionClass) having in the upper levels as objects the abstract definition of CT's (form-, force- or material couplings, shaft-hub connections, bearings, linkages) and in the lower the most concrete type of them (i.e. bolted or welded joint, threaded fastener, roller of plain bearing, etc.). The operations that the objects of the classes can perform or allow are defined through the kind of flow (Energy, Material, Signal [Pahl and Beitz 1996]) that the objects can "transfer" to each other when linked in a system structure. For instance, a Stock-Key connection can be used to transfer a torsional moment between a shaft and a hub; that is an "Energy Flow". In order to sustain the framework's integrating character, the flows are also represented in a single class structure (FlowClass). Alike the elements generalization hierarchy, as attributes of the CT classes are these key characteristics chosen, which feature a significant assembly cost relevance.
Moreover, a hierarchy of elementary assembly process chains (ProcessChainClass) consisting of assembly operations is also created (Figure 2). These chains are groups of common elementary sequences of assembly operations, which are necessary to carry out an assembly process between two

construction elements. The chains are classified in "common" patterns containing similar operations (transport, handle, assemble, control, store [Giannoulis and Welp 2003]) ordered in a similar sequence (i.e. convey→clump→ orientate→fix→fit→check→place→convey→magazinise). The patterns are then structured in the generalization hierarchy. Such common patterns can be gained through the analysis of the *existing* manufacturing environment, which is beneficial for the cost determination [Barton et al. 2001]. The patterns contain assembly cost driving attributes of the resources they involve. The connection of these patterns with the CT's and the construction elements gives the "consumption" rate of the resources and thus it has a direct cost relevance.

The last generalization hierarchy necessary for the framework is that of the assembly cost (AssCostClass - Figure 2). Based on a chosen costing method, the (AssCostClass) contains classes with attributes concerning cost rates, prices, cost functions or other cost data needed for the "transformation" of the process-resource data to an estimation of an assembly cost value. In order to model the structure of a product on a concept level, principles of the systems engineering theory will be used and namely this of the black-box representation of concept solution elements for cost estimation [Giannoulis and Welp 2003]. Generally, depending on the abstraction level the "Black-Box" has *Relations* with its environment, which is enterprise or external influences as well as other black-boxes through its connections with them; its *Inputs* are product and assembly process parameters as well as a kind of "flow" transmitting them to the black box; the black-box itself can be a system, a subsystem, a group or a part of a product, which is described by certain characteristics-*Attributes*. The application of a *Function* (assembly process defined through the black-box's relations) leads to the *Output*, which contains assembly costs.

This model introduced from a system engineering sight can be converted to a model applicable in the practice for the assembly cost calculation of product concepts using the above-described classes. Therefore, using the principles of aggregation and association of the object-oriented analysis [Rumbaugh 1995] an appropriate object-oriented class structure for the representation of product concepts and processes [Welp and Braun 1998] is composed (Figure 3). Thereby a black-box is a concept solution element of the generalization hierarchy (ElementClass) described above.

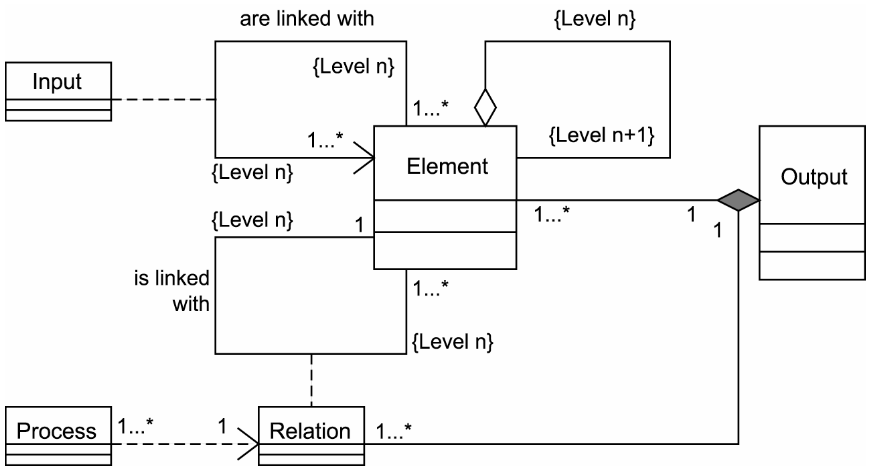

Figure 3. Class structure (Composition) for product concept modeling and assembly cost estimation

Depending on a certain abstraction level, each concept solution element corresponds to an object of the element class containing the working/construction *elements* (ElementClass), which has as attributes the attributes of his class. The *relation* between the solution elements themselves is realized through an attributed association with an object of the CT class (ConnectioneClass). Thereby, assembly process patterns of the (ProcessChainClass) are assigned to the (ConnectionClass) depending on the CT. For the solution element's link, flow types from the (FlowClass) are used. The *inputs* of those classes are certain "values" for their attributes-key characteristics transmitted through a flow. Specially, the placing of a value on each attribute "instantiates" an object, that is, it makes it concrete concerning the product and process being modeled. A "compositional association" of the connected groups of (ElementClass) via (ConnectionClass) with the (AssCostClass) assigns cost data to the instantiated object attributes, yielding so a cost value for their assembly process (*output*). The affiliation of a solution element to a super ordinate level is modelled by a recursive aggregation.

The framework is being implemented for the assembly cost estimation of different series of pasteurizing aggregates in cooperation with an enterprise for packing and handling of beverages, pharmaceuticals and chemicals. Therefore, after the analysis of the structure of the aggregates and the assembly processes as well as the assignment of cost factors (obtained from the controlling department), the above classes are built. Then, in order to estimate the assembly costs (for example these of the convey belt driving unit) of such an aggregate, concepts are generatated (Figure 4). Objects from the (ElementClass) are chosen to represent the working elements in the concept modeling (i.e. a shaft, by cylinder with sections, a chain wheel by a bore-dish), then the CT's are chosen (i.e. Ringfeder shaft-hub connection) and the flows as well (i.e. the transferred moment from the shaft to the chain wheels is a mechanical energy flow). Concurrently, a process pattern is "attached" to each CT object. The instantiated objects with the values of their key characteristics yield an assembly cost value after linked to the (AssCostClass) and processed according to the costing method defined there.

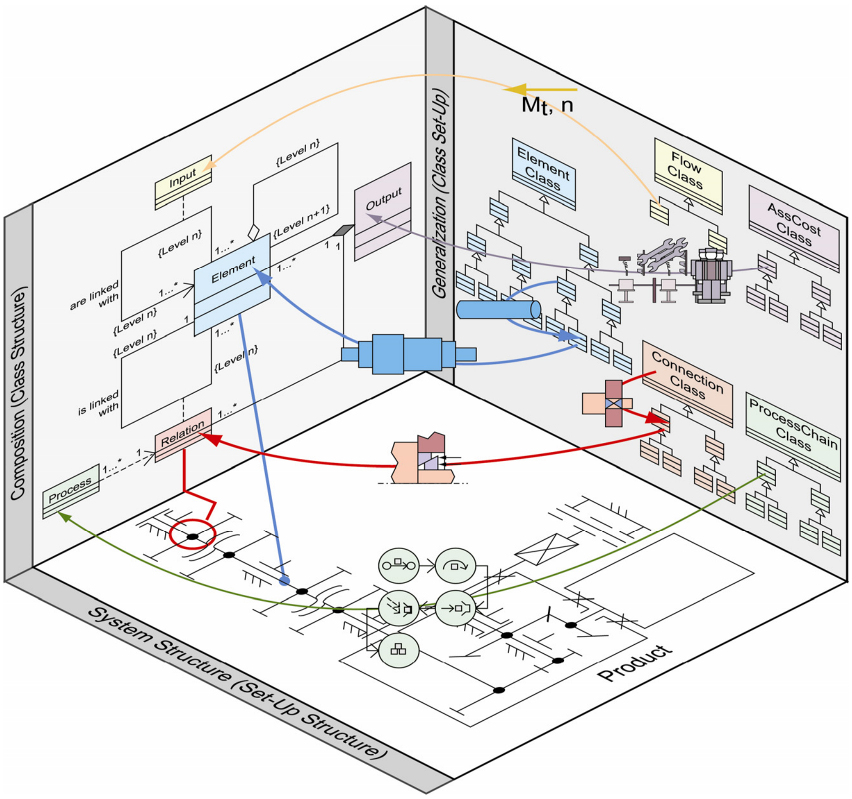

Figure 4. Example of the implementation of the framework for the assembly cost estimation of a concept for a convey belt driving unit of a pasteurizing aggregate

4. Results and Key Conclusions

The object-oriented product concept modeling framework for new or prototype products which has been presented, enables the early estimation of their assembly costs in an existing manufacturing environment. The framework is case-independent since the object classes created as well as class structure and content is case-neutral, which ensures its applicability on a wide palette of unique-manufactures or small series products. The utilization of the object-oriented properties of inheritance, association, aggregation and polymorphism contributes to the transparent and structured linking of elements, which sustain their physical meaning in all modeling levels, although their properties are reduced to those having assembly cost relevance. This allows the synthesis of "assembly-oriented" working structures representing product concepts. Moreover, the introduction of assembly process patterns and their crediting to each assembly procedure between the construction elements, allows a transparent and fair cost-allocation. This realizes the requirements of Active Based Costing and reveals optimization potentials of the cost intensive zones of a product concept as well. The transparency of its structure, its cost-focused attributes, the consideration of assembly cost generating procedures through process chains instead of individual assembly operations as well as the fair cost allocation are critical for the acceptance of the framework. The application of the model in an object-oriented database in connection with a cost calculation module allows the prompt estimation of the assembly costs of product concepts. Because of the form of the class structure target costs can be embedded and so establish it as a central element for proactive cost management.

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