

A generic framework for cost estimation and cost control in product design

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Abstract

Traditionally, cost estimation was performed after the design process, though most opportunities of cost reduction have already passed. Therefore, it is advantageous to be able to estimate the product costs early in the product development cycle. By changing the way cost estimation is dealt with, it is possible to utilise all opportunities of cost reduction. To be able to control the product costs, it is necessary to estimate the costs adequately and to store the cost data in a generic way. A generic framework is developed to establish these requirements. The framework, which is the basis for the control of the production costs, takes into account design, process planning and production planning aspects. © 2000 Elsevier Science S.A. All rights reserved.

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1. Introduction

A need exists for adequate cost estimation and cost control during the planning phases of the product development cycle. Market demands have changed towards higher quality, shorter delivery times and lower product costs. To be competitive, it is necessary to keep the production costs as low as possible, in order to keep the selling price low. This can lead to an increasing amount of products sold. The larger part (75%) of the product costs is committed during the product design process. Consequently, after the design process has been completed, most opportunities of cost reduction have passed. Therefore, it is necessary to have knowledge about the cost consequences of decisions during the planning phases of the product development cycle. In these planning phases many decisions have to be made. Cost estimates in the product design process can be used to choose between design alternatives in order to make cost effective decisions.

2. Cost estimation

Cost estimation is concerned with the prediction of the costs related to a set of activities before they have actually

been executed. Within the existing cost estimating methods, two main approaches can be recognised (e.g. [5]): variant based and generative cost estimating. *Variant based cost estimating* depends on the similarity between the product under consideration and previously manufactured products. The cost record of the previously manufactured products can be used as a template in the cost estimation process of the new products. This method is useful in small and medium batch manufacturing of relatively standard products. *Generative cost estimating* is based on the fact that the costs of manufacturing a product depend on the required production operations. By determining the required operations it is therefore possible to estimate the production costs. This method is closely related to process planning and will usually be applied for new product elements for which no variants exist. Generally, a product consists of relatively standard elements and product elements that are completely new. Therefore, these two main approaches are almost always applied at the same time to the same product.

3. Decision making processes in product design

The product design process consists of a large number of decision making processes. These decision making processes finally lead to a complete product model, representing

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a physical object that has to be made. During the subsequent decision making processes the freedom for each decision is restricted by the constraints imposed by preceding decisions. In the embodiment design phase, these decisions are concerned with the material selection, surface roughness, tolerances, shape, dimensions, selection of production methods, etc. All these decisions are mutually dependent. For instance, a decision about the type of material leads to a reduction of the solution space concerning the production methods and vice versa. From a cost point of view this means that selecting a cheap material can lead to high production costs, whereas selecting an expensive material can lead to lower fabrication costs. The consequences of all such decisions have to be taken into account.

4. Reference model

In order to be able to deal with different views of a manufacturing system, the system is introduced by means of a reference model. A reference model represents a system as an organisation in terms of its structure of relatively independent, interacting components, and in terms of the globally defined tasks of these components [1]. The manufacturing engineering reference model (shown in Fig. 1), introduced by Lutters et al. [6] emphasises the equivalent importance of products, orders and resources in the entire manufacturing cycle. Product engineering is concerned with the design and development of a product and its variants, starting from the functional requirements up to final recycling/disposal.

4.1. Information management

The kernel of the reference model described above is information management. The management of information, concerning orders, resources and products, is organised in information management which becomes the pivot of the design, engineering and planning activities. Three information structures can be identified (Fig. 2): a product information structure comprising product information generated in

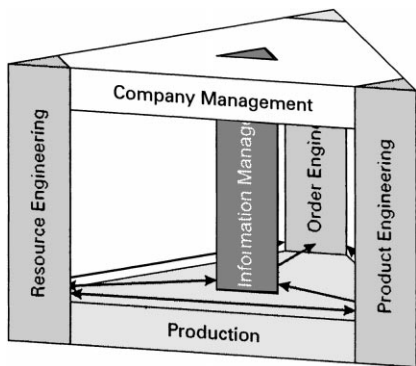


Fig. 1. The manufacturing engineering reference model [6].

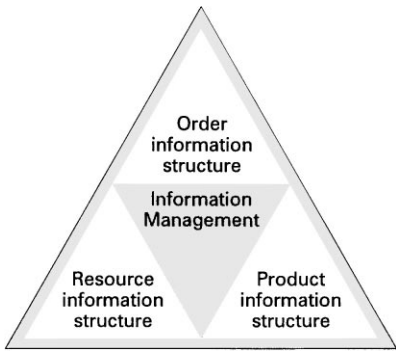


Fig. 2. The three co-operating information structures as part of information management [6].

the engineering and planning processes, a resource information structure comprising the information about the capability, capacity and life cycle aspects of the resources, and finally an order information structure concerned with the planning of the production activities, resulting in the in-time execution of given production orders, regarding the capacity of the resources.

5. Cost driving product characteristics

The existing cost estimating methods are able to estimate the product costs during the design process, but they are not capable to analyse and control the product costs. These methods are only applied to choose between design alternatives or to evaluate the product costs. The least requirements for cost control are knowledge of the costs, based on cost estimations, and a generic storage of these costs. Therefore, it is convenient to split up the costs into more constituents. Obviously, it is advantageous to have a highly differentiated view of the production costs [9].

From an analysis of the product design process and its decision making processes, based on the design models of Pahl and Beitz [7] and Ullman [8], it can be concluded that the committed product costs (the costs that are fixed during the product design process) are caused by the following cost driving product characteristics.

5.1. Geometry

The geometry determines the material quantity and the production processes that are required. The geometry includes the shape, dimensions, accuracy, etc. The influence of the geometry on the product costs is obvious. For instance, a higher level of accuracy requires more accurate resources (e.g. machine tools, equipment) which results in higher production costs. The shape can also cause increasing production costs; a pocket with straight corners requires generally a more expensive process (e.g. electrical discharge machining) than a pocket with rounded corners (made by, e.g. milling).

5.2. Material

Material is one of the most obvious cost driving product characteristics, because material costs constitute about 50% of the total product costs [2–4].

5.3. Production process(es)

Production processes are required to transform raw material into a component or to assemble components and/or assemblies into higher level assemblies. Resources (e.g. operators, machine tools, tool sets, fixtures) are needed to perform the required production operations. The resources have a certain capability, which means that resources have technical restrictions, concerning the power of the machine tool, accuracy, maximum dimensions of the workpiece, etc. The limited capability of resources restricts the execution of certain operations. This has to be taken into account in the planning phases of the product development cycle. The type of production method has a significant influence on the production costs.

5.4. Production planning

Besides the technical restrictions of resources, resources have also logistic restrictions, which means that a resource will not always be available. With the knowledge of these restrictions, operations can be allocated to resources that are available. It is necessary to ensure the due date, because otherwise a fine could be incurred. These time, and therefore, cost consequences must be regarded in the planning phases.

As mentioned before, the four cost driving product characteristics are interrelated. Material is influenced by the geometry (e.g. strength, stiffness) and the type of production process. The production process is influenced by the geometry (e.g. shape, accuracy) and the type of material. Besides, the geometry is influenced by the type of material and the production process (possible dimensions, shape, accuracy). The selection of one of these aspects imposes restrictions on the other aspects. The selection process depends on the type of production environment. In mass production, e.g. the emphasis is usually on the appropriate combination of process and material. Moreover, in this type of environment more time is available to make a good selection. In small batch manufacturing, material often is selected first, due to the general purpose machine tools that constrain the available production processes.

6. The generic framework

If a product structure is available, it is obviously advantageous to relate the cost information of a product to the same structure.

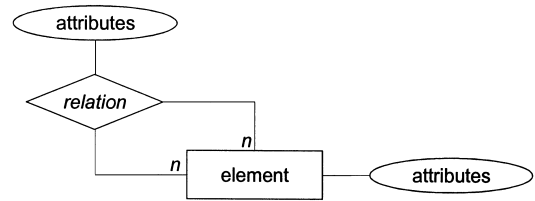


Fig. 3. The fundamental structure.

6.1. Product structure

In the product design process the product structure is determined. A product can be represented by means of elements and relationships between those elements. Both elements and relations have attributes, for instance dimensions, material type, colour, fitting, etc. The fundamental structure is given in Fig. 3. An element does not merely refer to geometric entities; it can also be a (sub)function, concept, requirement, etc. No explicit hierarchy exists in this model. Usually, this hierarchy is assumed in part-of relations. However, the part-of relation has the same status as any other relation between the elements.

The generic framework is based on the four cost driving product characteristics and the fundamental structure. It is only useful to allocate costs to physical product elements. This is obvious, in recognising that due to, e.g. function integration, standardisation and modularisation it is hardly possible to allocate manufacturing costs to non-geometrical elements. The four cost driving product characteristics are attributes of an element and can be labelled as the *cost attributes* of a physical element. The generic framework is presented in Fig. 4. The cost attributes are only related to the physical product *elements* and not to the *relations* between the elements. If a relation between elements (e.g. a tolerance) has certain cost consequences, these costs are related to a higher aggregation level.

The physical product elements are: assemblies, components, modules, faces and features (design/manufacturing features). In Fig. 5, the structure of these product elements is given. A distinction exists between the objective and the subjective view.

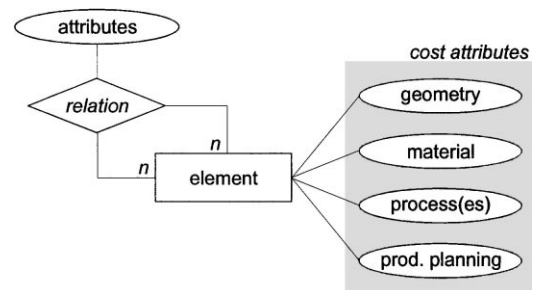


Fig. 4. The generic framework.

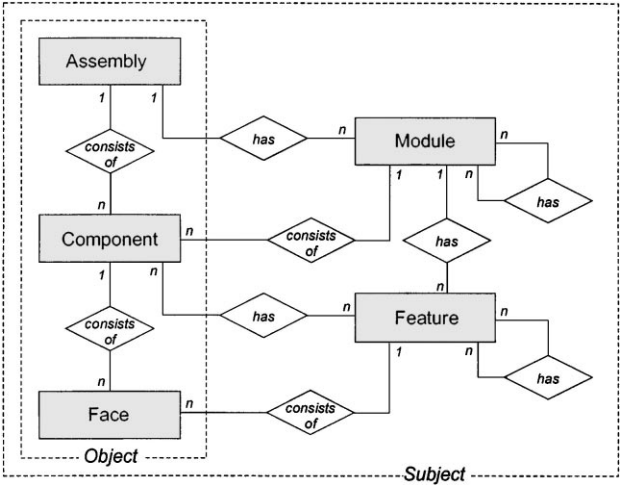


Fig. 5. Structure of the physical elements, with the distinction between the objective and the subjective view.

6.2. Relation of the framework with the information structures

The cost attributes are related to information management (the three information structures, see Fig. 2). The three information structures deal with the information concerning products, resources and orders. All cost attributes are related to the product information structure. The value of the cost attribute ‘process’ is influenced by the resource information structure, because this structure deals amongst others with the information concerning the capability of the resources. Moreover, the cost attribute ‘production planning’ is influenced by the order information structure, because this information structure deals amongst others with the capacity of the resources in a certain period of time. Due to the interrelations between the three information structures, the information about the resources, orders and the product can easily be used during the design decisions. For instance, information about the capability, capacity and costs of the resources is easily available and can be used in the decision making processes of the product design process.

7. Levels of aggregation

It is not useful to allocate costs to the product elements modules and faces. A face, which has to undergo any manufacturing operations due to tolerances on that surface becomes a manufacturing feature. From a cost point of view, a face is a surface that does not undergo any production operations. A module is a group of components, which is — for reasons of convenience — considered to be a distinct section of a product (a subjective view). Using this definition, a module is seen as an assembly with a specific name and can be different in different views. In other words, a module can be a different group of components in the design view than in the manufacturing view. When costs are related to the product elements, the manufacturing view is taken

into consideration. In the manufacturing view, the module is equal to a (sub)assembly. Therefore, it is ambiguous to relate costs simultaneously to (sub)assemblies and modules.

A short explanation about the cost attributes on the different product element levels is given below.

7.1. Feature level

The geometry is concerned with the feature’s shape, dimensions and tolerances and influences the possible production methods. The cost attribute ‘material’ on feature level can impose demands on the cost attribute material on component level, because features can impose restrictions to the type of material used. These restrictions have to be taken into account and can lead to higher material costs. Production processes are required to manufacture a feature. These processes are influenced or restricted by the other cost attributes. The relations between the different features are not part of this level. They belong to the attribute geometry on component level. In other words, when two features are related to each other, the relations (e.g. tolerances) are indicated at component level.

7.2. Component level

The geometry on component level consists of the global shape, dimensions and accuracy of the component. Also the dimensions and tolerances between the features are part of the geometry. The type of material is selected taking into account the requirements set on assembly and feature level. The material costs are determined by the geometry (weight, dimensions) and the type of production process (milling, casting). The processes on this level are for instance casting, injection moulding or extrusion. The type of process can influence the costs considerably. The processes are also concerned with changing tools and resources, transportation, etc. The amount of tool and resource change depends amongst others on the different production methods used to manufacture the features. These processes are amongst others influenced by the geometry on this level and the geometry and processes on feature level.

7.3. Assembly level

On this level, the cost attribute ‘geometry’ consists of the global dimensions and the relations and tolerances between the components and features. The cost attribute ‘material’ consists of the material requirements for the components. The processes on assembly level are obvious; assembly processes are required to assemble components and/or (sub)assemblies. It is also possible that fabrication processes are applied.

At all levels, the cost attribute ‘production planning’ is concerned with the in-time availability of the required resources. In general, the in-time delivery is very important, so expensive resources might be applied in order to deliver

on time. This is more likely than to produce with cheaper resources and exceeding the delivery date.

It is obvious that the cost attributes ‘material’ (on component level) and ‘process(es)’ (on all aggregation levels) determine the production costs. The other two cost attributes ‘geometry’ and ‘production planning’ have restrictions to the attributes ‘material’ and ‘process(es)’. These attributes have to be taken into account, because they influence the cost attributes material and processes significantly. By taking into account the geometry and production planning as well, the origin of the product costs can be determined easily.

8. Calculating product costs

After estimating the costs of the different elements, the total costs of the product can easily be determined. The total production costs can be determined by adding up the costs of every product element. The costs of a product element are a summation of the values of the cost attributes. Thus, the total product costs can be determined by adding up all values of the cost attributes of all elements. For instance, the costs of a component are a summation of the costs of material (on component level), costs of processes on component level and the costs of producing the features. An advantage of this method is that the costs can be related to the desired aggregation level. The costs of buy or semi-manufactured parts can easily be integrated in the generic framework. The costs of standard bolts and nuts are ascribed to the cost attribute material on component level. The lower aggregation level does not have to be taken into account. If a standard assembly is supplied from others, the costs are ascribed to the cost attribute material on assembly level.

9. Analysis and control of the product costs

With the use of the generic framework, the costs can be evaluated. In this way, it is possible to determine the origin of the possibly high product costs. The framework enables the control of the product costs. A systematic method, based on the values of the cost attributes of the generic framework, is applied during the design process to control the costs. Extensive cost driving elements are recognised and subsequently, the exceptional cost attributes of those elements are identified. In the example of Fig. 6, the most cost extensive element is specified in more detail. The costs of this element can be divided in material costs and production costs of one specific feature.

The high value of the cost attribute material on component level can be caused by the material requirements on feature and assembly level, but also by the selected processes. The value of the cost attribute processes on feature level is influenced by the geometry of the feature or the material of the component. These causes can be traced using the generic framework. With this cost information, the product costs can be controlled and the product design can be adjusted effectively.

9.1. Design alternatives

Using the generic framework, alternative designs can easily be compared. It is merely necessary to record the structures of the different alternatives in the framework. This can be accomplished by using option points in the structure (see Fig. 7). At the option point a decision has to be made about the element that will be used. The costs of the different design alternatives can easily be compared.

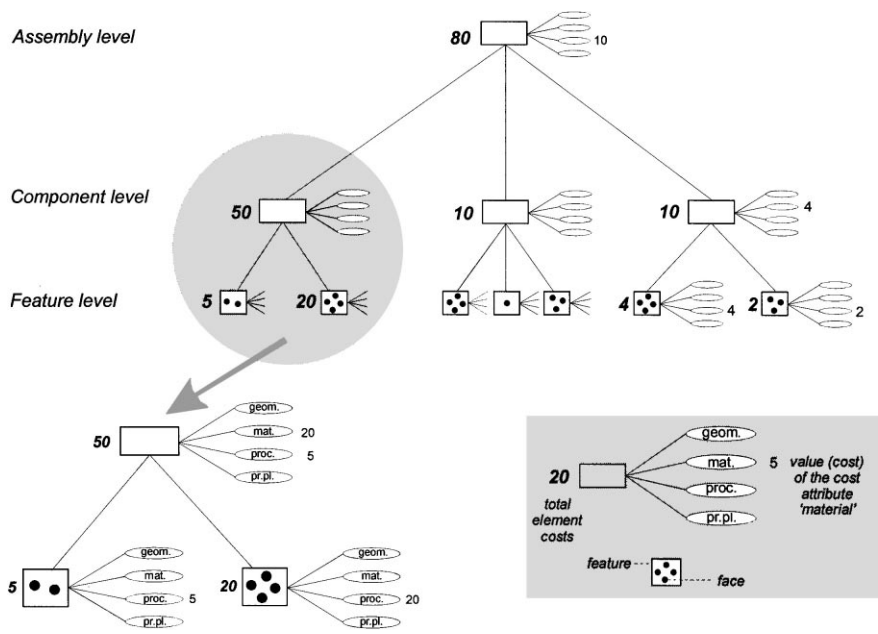


Fig. 6. Application of the generic framework to a fictive product.

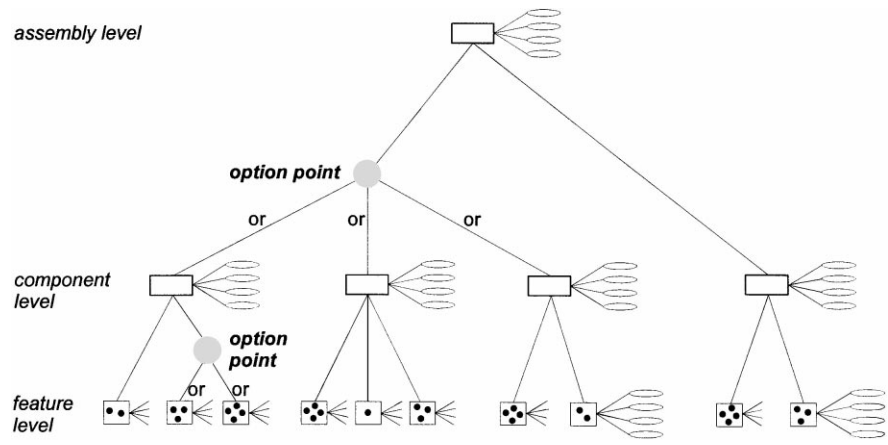


Fig. 7. Using option points in order to choose between design alternatives.

The decisions about producing in-house or buying standard or semi-manufactured products can be made more easily using the values of the cost attributes. The costs of standard buy parts or semi-manufactured parts are ascribed to the cost attribute material. This value must be evaluated against the sum of the cost attribute values if the part is produced in-house.

9.2. Product configuration

The generic framework is also applicable regarding product configuration. Using option points in the product structure (see Fig. 7), all possible product variants of a product family can be represented. The costs of these product variants are known. During product configuration, negotiations with the customer result in the establishment of one specific product variant. The costs of this product variant can easily be determined by adding up all the element costs of the selected variants.

10. Example

The generic framework will be illustrated by the example of a computer power unit as shown in Fig. 8. The product

will not be treated entirely; only a number of aspects will be elaborated upon. The power unit assembly consists of a base component, consisting of a lot of holes and slots, a small strip, consisting of two holes and a form feature, and a cap to seal up the electrical components inside. The base and the cap possess a lot of holes, which are necessary for cooling. The number of holes depends upon the amount of heat produced inside the unit.

The global structure of the power unit assembly is given in Fig. 9. As shown, the cost attributes are allocated to assembly, component and feature level. For reasons of readability, the cost attributes are not filled in. The costs of the features are determined by the value of the cost attribute process(es). By adding the values of the cost attributes material and process(es) of component level, the costs of the component are obtained. Finally, by adding the costs of all components and the values of the cost attributes on assembly level, the costs of the complete assembly are obtained.

The structure of the upper face of the cap component is given in Fig. 10. The grey regions around one or more white rectangles represent the features of the upper face. The cost attributes are allocated to these features and to the component itself. The mutual relations between the faces are not represented in this figure. Two bending lines are shown in this figure. In case the radii of these bends are not equal, a

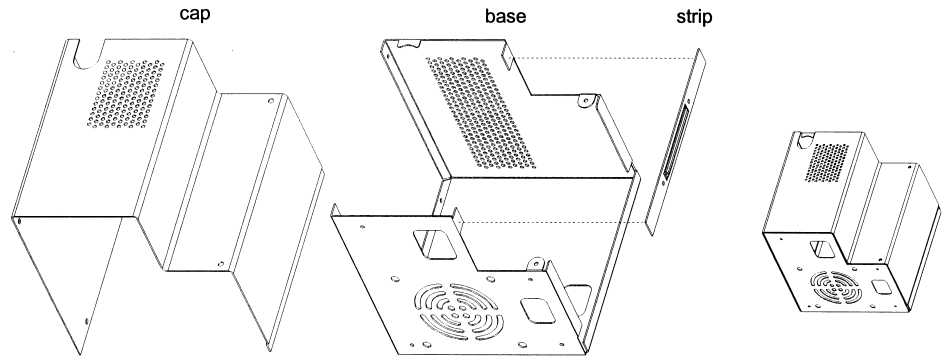


Fig. 8. The computer power unit.

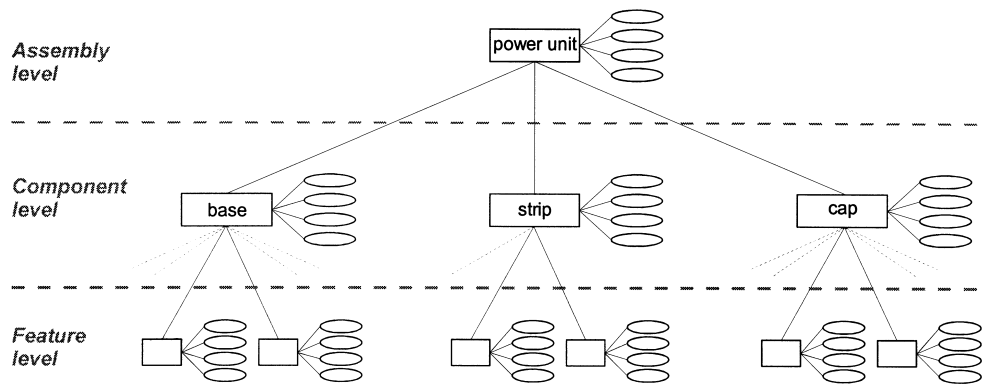


Fig. 9. The cost attributes related to the different aggregation levels of the power unit.

tool change has to take place. The costs of this tool change are allocated to a higher level, i.e. component level. The slot (represented by three faces) can be produced using a nibble or laser cutting process. The choice depends on the available resources and the costs of the operations. The material type

and the accompanying costs are specified on component level.

On this same level, the bending sequence determines the feasible tolerances. Furthermore, collisions can be avoided using certain bending sequences. For example, in the base

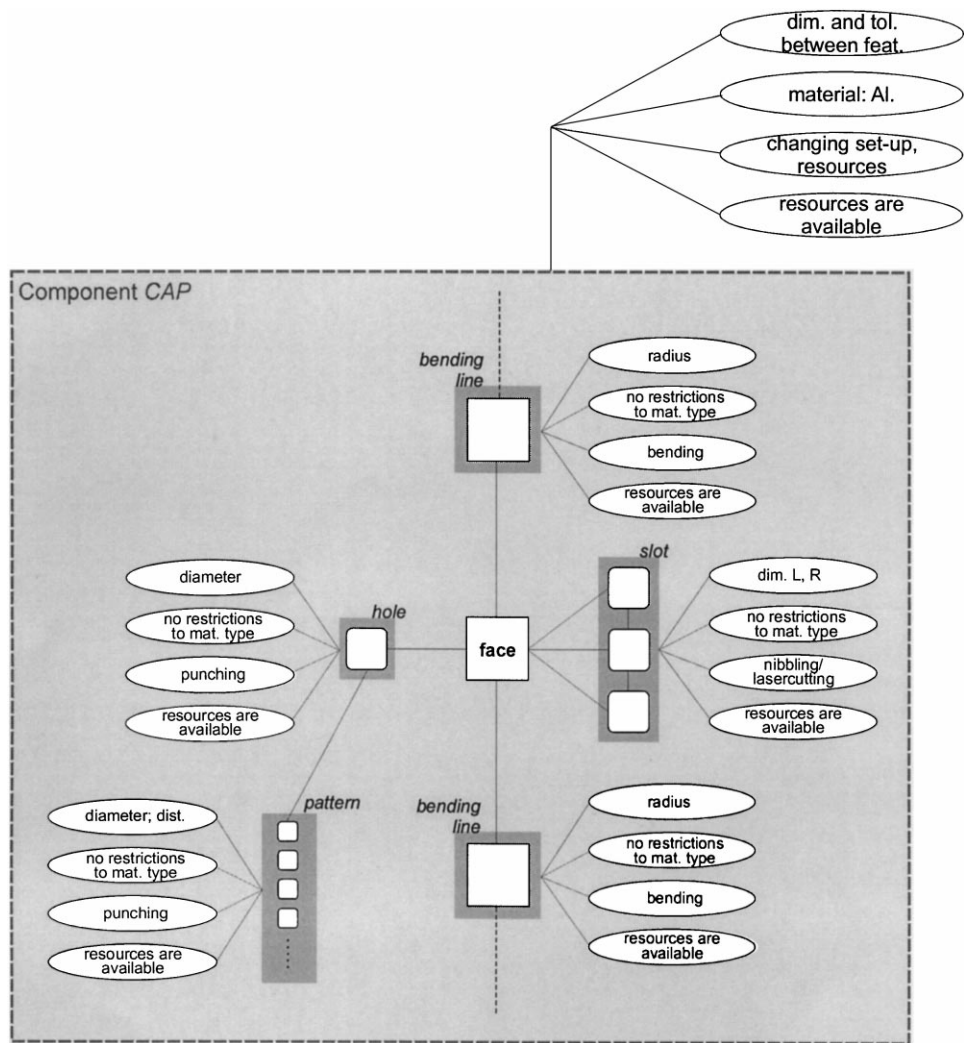


Fig. 10. The cost attributes filled in for a number of features and for the complete component.

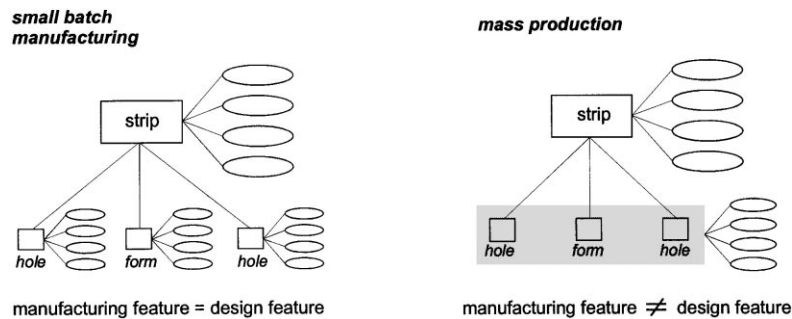


Fig. 11. The cost attributes of the strip; difference between small batch and mass production.

component, the small faces have to be bent first, otherwise collisions occur.

The strip can be manufactured in two different ways, depending on the type of production environment. The strip consists of three features: two holes and one form feature made by a punch operation. These three features can be produced separately, but they can also be produced in one operation. Producing these features in one set-up requires special tooling, which leads to higher costs. Producing the features separately leads to the need of changing resources. Fig. 11 shows that in a small batch environment the cost attributes are allocated to the three features and to the component. In a mass production environment, the costs are allocated to one manufacturing feature (representing three design features) and to the component. A cost effective decision can be made using this structure by taking into account the amount of components that has to be produced.

Finally, the assembly level is explained shortly. The assembly operations are relatively simple. The small strip is welded to the base component and the cap can be placed on the base component. The assembly sequence is of importance, because the strip has to be welded first before the cap can be placed on the base component. The only costs on assembly level are the welding costs (of the strip and base) and the costs of placing the cap and the base together.

As mentioned before, the total product costs are a summation of all values of the cost attributes in the product structure.

11. Concluding remarks

A generic framework for cost estimation and control in product design is presented and is illustrated with a sheet metal example. The characteristics of the generic framework are summarised below:

- Differentiated view of the product costs; this leads to the advantage that the product costs do not depend on one aspect, but on the four mutually dependent cost attributes.

- The costs can be determined on every desired aggregation level; the costs of standard parts can be allocated to the appropriate aggregation level.
- The origin of the product costs can be identified; the extensive cost driving product elements can be found.
- After identification of the most cost driving elements, the causes of the costs can be identified; the causes can be found more accurately due to the differentiated view of the product costs.
- The cost consequences are available immediately; a modification of an element has certain consequences for the related elements. By means of the relations between the elements (in the generic framework) the consequences are directly known.
- Design alternatives can easily be compared regarding the production costs and in this way the most cost effective alternative can be selected.

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