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AN AUTOMATED COST ESTIMATING SYSTEM FOR VARIANT DESIGN BASED ON THE METHOD OF SUCCESSIVE CALCULUS

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Abstract

For many products the adaption to customer specifications is essential and requires flexible product design and manufacture while maintaining competitive pricing. A large category of design work in industry has the character of redesign of an existing product concept in terms of dimensional changes, topology variations and configuration of components. In order to evaluate design proposals, costs, which are controlled by the product design, selected materials and manufacturing processes, need to be estimated. Cost estimates are normally based on the manufacturing process plans, which can only be formed when production preparation is finalised. The widespread industrial use of solid modelling opens up new possibilities to automate this process. The purpose of this work is to demonstrate and test a method to extract product information from a CAD model to allow process planning and cost calculation to be carried out automatically for a given class of products. With such a system cost estimates can be made available to the designer the instant a design proposal has been presented. This allows for design iterations to be carried out in order to govern the design work towards solutions with an optimal balance between product and production properties.

Keywords: Design evaluation, CAPP, cost estimation, successive calculus.

1 Introduction

Cost is one of the most fundamental criteria for the evaluation of design proposals [1]. Still, cost is often calculated late in the product development process, when not only the concept is chosen, but also most details are fixed. This means that the cost information feed back to the designer often arrives too late to be taken into account and guide the design towards solutions, which are cost-effective and easily produced.

Different methods exist for cost estimation [2] and much work is currently being done to estimate cost early in the product development cycle. Reference [3] have developed a generic framework for cost estimation and cost control which supports the storage of costs data in a generic way. A multidisciplinary design tool with integration of geometric modelling and activity-based costing for addressing costs in the early stages of technology development is presented by [4]. To handle the uncertainty in cost estimation [5] has applied the method of fuzzy logic.

For many industrial products the cost of material is dominating and easy to estimate, while the production cost presents more difficulties. Estimation of production cost is normally based on the process planning created by production engineers. By using computer-aided process planning (CAPP) the effort is reduced in converting CAD models into process plans, but the lack of interface standards aggravates the system integration. An information model to define the interfaces is presented by [6].

The method used here for process planning and cost estimation is based on extracting information from a parametric solid geometry model. Information about the topology, features and parameters is imported into a CAPP system consisting of generic process plans for different groups of products. The information from the CAD model provides input to a rule-based system and adapts the generic process plans. The values of parameters, which are identified as cost drivers, are imported into the process plans and the material and manufacturing costs are estimated using *the method of successive calculus* [7] to accommodate uncertainties at the early design stages. Design variants can be evaluated at the early stage of the design process and the designer can obtain a balance between product and production properties and the product cost. The method is demonstrated and tested with an example of submarine bulkhead stiffeners. For a brief description of the method of successive calculus see section 4.

2 Knowledge, information flow and information transfer

Redesign of an existing product is the most common design problem in industry [8]. Tasks, which are repetitive, time-consuming, involves information handling and do not involve creative problem solving, could be automated by writing application programs in a CAD systems internal programming language [9] or by using commercial KBE systems [10]. To reduce the cost and the risk of critical vendor dependence, we are attempting a different approach where all vital knowledge is stored in commonly used software programs with a high degree of accessibility and knowledge transportability.

The automated system for cost estimation is part of an overall system for order-based generation of variant product designs. In the proposed system (figure 1) design documentation, process plans and cost estimation for different variant design are created and the design could be evaluated to optimise product properties, production properties and the product cost. The system for cost estimation presented in this paper can operate either as part of the overall system or as a stand-alone application program.

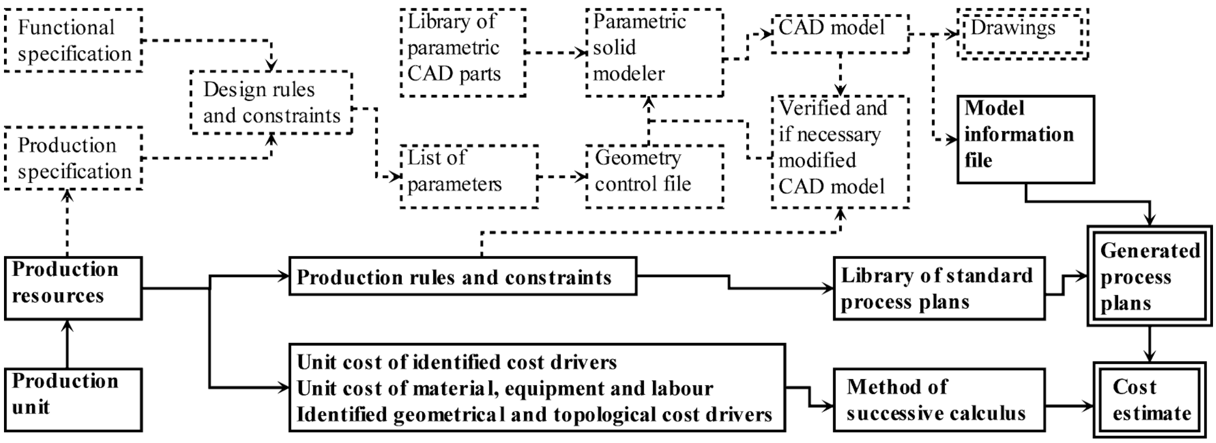

Figure 1. – Information flows and transformations in the proposed overall system. The dashed lines represent information flows and transformations of sub-systems that are not discussed in this paper. The solid lines represent the sub-system for automated cost estimation.

2.1 GEnerative Process Planning And Cost Estimation, GEPPACE

Implementation of the method should be done concurrently with the development of product platforms for variant design. The core of the GEPPACE method is the nomenclature for encoding of objects, which is created and implemented in a parallel process for parametric

CAD models, generic standard process plans and worksheets for cost estimation. In operation, CAD model information is extracted and transferred to the generic standard process plans and worksheets for cost estimation with a program for information transfer (figure 2).

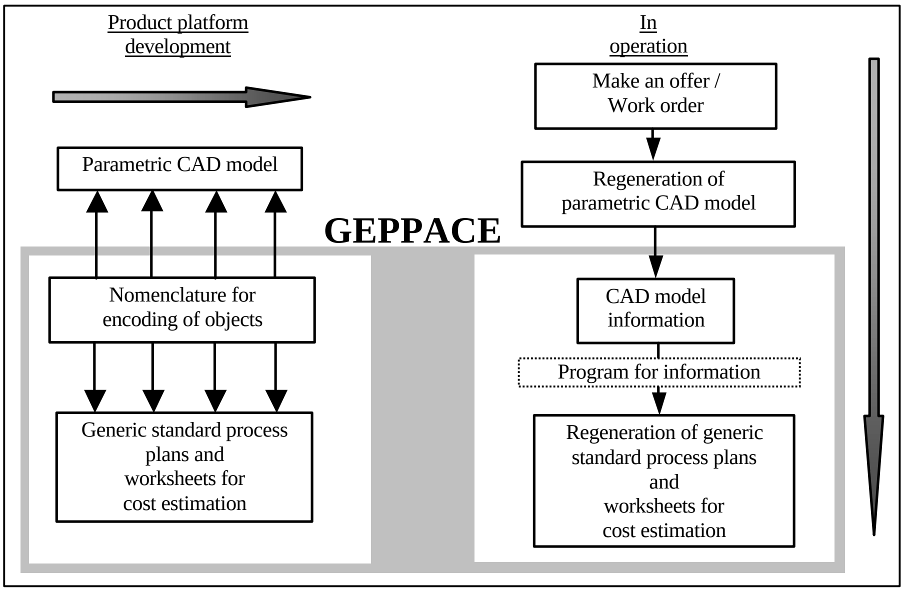

Figure 2. – GEPPACE, implementation and in operation.

2.2 Information extraction and nomenclature for CAD model objects

There are two approaches to identify features in a CAD model for process planning, which will determine the sequence of operation: *feature recognition* and *design by feature* [11]. Feature recognition searches an existing solid model's data structure for combination of geometric elements and tries to identify predefined manufacturing features, which correspond to operations. In design by feature the process of converting features to operations is implemented in the construction of the solid model by using standard shape features, which correspond to manufacturing operations. The present work is based on the method of *designing by feature*.

Many CAD systems support extraction of CAD model information in text format and allow renaming of assemblies, parts, features and parameters. Some programs have commands for saving model information in a text file. Otherwise there is often an application program interface (API), which can be used for adapting the program to save model information in a text file or a database.

An alternative method for information extraction, which is proposed and used in this system, is the renaming of assemblies, parts, features and parameters by text strings with predefined positions for classification of objects using a predefined nomenclature. The nomenclature structure and encoding of objects depend on the company needs and the product. Often there are restrictions, e.g. a maximum number of characters in variable names and the use of special characters, due to the different application programs, which are used to build the system.

For information extraction and information transfer an application program, developed in a common programming language, is used. The application program searches the text files or the database for CAD model information, and matches the information with the information in the generic standard process plans and worksheets for cost estimation. The application program does not have to be developed for every new product and should preferably not contain any rules about the regeneration of process plans or worksheets for cost estimation, as that would make the system less transparent and less accessible to the user.

The model information text files may contain help features, which are of no interest to process planning. In combination with a future wish of allowing manual changes of the CAD model, which should be captured in the process planning and cost estimation, the system has to be selective and open. For a search tool, which scans a text file, this is made possible by using prefixes. In the case of application the prefix II_ is used to identify parameters and the prefix III_ is used to identify features.

3 Process planning

The basis for the cost estimation is the automated generation of process plans. In this work a distinction is drawn between *process planning* and *operational planning*. Process planning is the initial step, which involves selection of operations and their sequence, selection of production resources and a rough prediction of the manufacturing time. The result is sometimes called routing sheets. Operational planning is a detailed description of each operation. This often includes operation sequences in a machine, tooling, fixtures, sketches of set up, machine settings and generation of NC-programs.

Computer-aided process planning systems (CAPP) are used for automating the task of process planning and much research has been done on mapping CAD model data to a process planning system [12]. There are two general approaches: *variant CAPP* and *generative CAPP* [13]. Variant CAPP is based on group technology and standard process plans and often includes manual editing. Generative CAPP utilises decision logic, formulas, manufacturing rules and geometry-based data. In a fully generative CAPP system, there is no need for human assistance or standard plans.

The CAPP system in this work consists of a database with generic standard process plans for a group of parts or assemblies with the same sequence of operations. Individually the numbers of operation can differ. This reduces the number of standard process plans. Figure 3 shows an example of a process plan. Respective text strings with the prefix III_ given in the column "Operation/Parameter", activate the required operations. There could also be operations, which are dependent on other operations and have no corresponding feature in the CAD model, e.g. grinding of sharp edges after a cutting operation or different control operations. Procedural rules stated as "If-Then" handle these operations and are accomplished with logic operators. Manufacturing features are preferred, but not necessary, depending on the rules in the generic standard process plans. When manufacturing features are used, the operations are implicitly stated in the process plans. Parameters, which have an effect on the selection of production resources or are needed for the cost estimation, are also given. Their values are then imported when the process plans are generated.

Name						Standard process plan number 01				
Bill of materials										
Component/Material			Quantity	Dimension						
Opnr	Active	Pgrp	Setup time	Process time	Ref.	Operation/ Parameter	Value	Calc.	Result	Rule
10	No	2810				III_Cut1_Rol1				if Cut1 or Rol1
						II_Cut1_UNI1_depth				
		Cutting steel plate, plasma				II_Cut1_UNI1_length				
						II_Cut1_UNI1_thickness				
20	No	2815				III_Edg1				if Edp1
						II_Edg1_Uni1_angle				
		Edge preparation				II_Edg1_Uni1_depth				
30	No	2817				III_Rol1				if Rol1
						II_Rol1_Kne1_depth				
		Bending flange, hydraul								

Figure 3. – Example of a process plan.

Every plan is a separate worksheet and a set of standard process plans is stored in the same workbook. For evaluation of different production units a set of standard process plans for each production unit can be made.

The CAPP system is based on standard process plans in accordance with variant CAPP but also utilises properties of generative CAPP, such as decision logic and geometry-based data. Based on these facts our system is classified as a *generative CAPP system*.

When a process plan is to be generated automatically for a part or an assembly, the system first identifies which standard process plan is to be used. The plan is retrieved from the set of generic standard process plans and modified in correspondence with the CAD model. Parametric values are extracted from the CAD model and the finalised process plan is saved in a new set of generated process plans. In the present system status, one process plan is created for every part or assembly. A numeric code in the beginning of part or assembly names determine which standard process plan to be used for a part or assembly (figure 4). Alternately the coupling could be done by a computerised dialogue system by which the user interacts and specifies the standard process plan to be used.

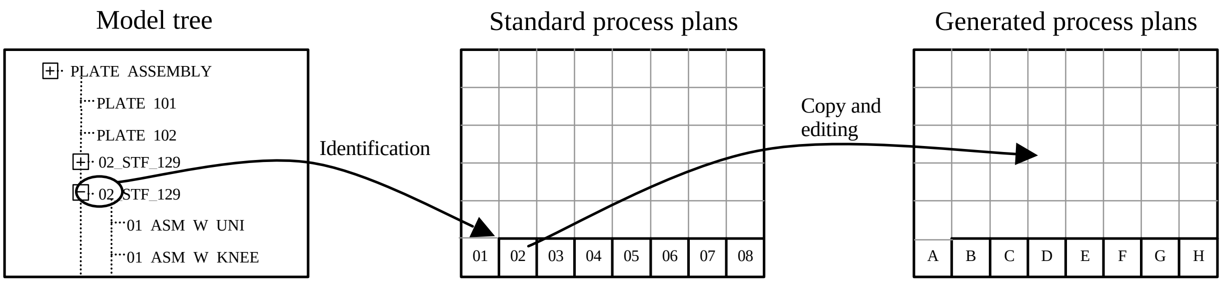

Figure 4. – Identification and generation of process plans.

The system is prepared for manual changes of the CAD geometry through the use of prefixes and a descriptive nomenclature. Manual changes could be activated and handled by a dialogue system. The descriptive nomenclature supplies the engineer with information necessary for adaption of process plans corresponding to the manual changes.

4 Cost estimation

All methods for calculation of production costs prior to manufacture are more or less a simplification with underlying uncertainties. Cost calculations based on operational planning and all relevant production data requires extensive work. With the method of successive calculus [7], costs can be estimated with less effort and the uncertainty is calculated for evaluation. The method supports a systematic breakdown of cost items if a more precise estimate is to be made at a later stage and accommodates uncertainties at the early design stages. The method of successive calculus is based on two statistical assumptions: 1) Cost predictions always involve uncertainties of a statistical nature, and 2) When a number of uncertain values are added up, the uncertainty will even out.

Implementation of the method of successive calculus is done by dividing the cost object in a reasonable number of independent items. For each item a triple estimate of a minimum (min.), a maximum (max.) and a most likely value is done and the mean value (M) and variance (S) is calculated with the following equations [7]:

$$M = \frac{\text{min.} + 3 \times \text{most likely} + \text{max.}}{5} \tag{1}$$

$$S = \frac{\text{max.} - \text{min.}}{5} \tag{2}$$

The extreme values of minimum and maximum should reflect both the 1% and the 99% confidence value. Other limits may be used on condition that the equations are adjusted accordingly.

In the GEPPACE system the basis for cost estimation is the generated process plans. All operations are proposed to be divided into an equivalent subset of cost items (figure 5). These subsets should be chosen so that costs will differ among the alternatives when evaluating variant design proposals. Cost drivers, which are primarily geometrical, but could be topological, are identified and declared in the process plans. Costs and production data are estimated (in the cases where exact values are not available) by the triple estimate of production groups, material and wages. The data are stored in different tables in the workbook with standard process plans. In the same way as with standard process plans, different cost tables could be established for different production units. The cost could then be estimated and evaluated in relation to where the product is to be manufactured.

Total											
Item/ factor	Text	min.	most likely	max	m	s	s/m	M	s_0	S	s^2
1	Raw material										
	Volyme										
	Waste factor										
	Unit price										
Material in total											
2	Operation 10: Active? No										
	Geometry cost driver										
	Work rate										
	Labour cost										
Labour cycle cost in total											
	Setup time										
	Labour cost										
Labour setup cost in total											
	Geometry cost driver										
	Work rate										
	Machine cost (variable)										
Variable machine cost in total											
	Tool cost										
	Fixture cost										
	Machine deprication										
Equipment cost in total											
Base case total			Mean value			Variance					
	Overall correction factor										
Grand total result			Mean value			Variance					

Figure 5. – Subset of cost items for an operation.

When executed, geometrical and topological values are extracted from the parametric solid model and pasted into the system by the application program for information extraction and transfer. The cost, in terms of mean value and variance, is calculated for each part and assembly and the total cost is summed up. The variance indicates the precision in the calculation. If the variance is not acceptable the method of successive calculus supports a systematic refinement of the calculation where items with large variance are broken down into sub-items. The process is successively carried out until the uncertainty is acceptable or no more detailing is possible.

5 Case study

As a case study an order-based design of a submarine bulkhead and its vertical structural members, which consists of cut, rolled and welded steel plating, was studied. The structural members were modelled in a common software application as parametric solid models using methods, which permit dimensional and topological changes [14]. A nomenclature was defined and implemented in the CAD model and in the standard process plans. As an example the CAD model was regenerated with two different specifications, as shown in figure 6.

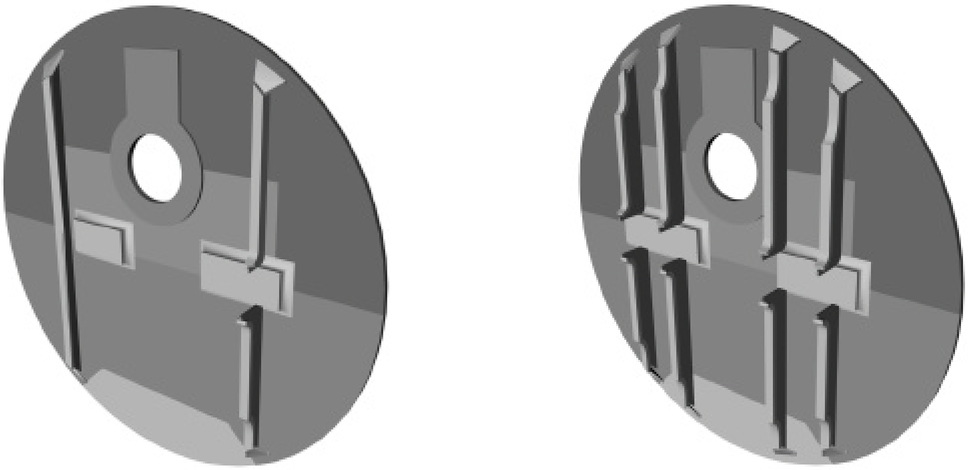

Figure 6. – Two variants of a submarine bulkhead.

Standard process plans with the integration of a system for cost estimation, by the method of successive calculus, was created in a common spreadsheet software application as seen in figure 7. The operations are activated in either of two ways: if there is a corresponding feature in the CAD model or in accordance with rules where operations are interrelated (e.g. If Cut Then Grinding). Geometrical and topological cost drivers were identified and corresponding parameters stated in the standard process plan. Production data and costs for production resources were gathered in tables.

Name						Standard process plan number 01				
Bill of materials										
Component/Material			Quantity	Dimension						
Opnr	Active	Pgrp	Setup time	Process time	Ref.	Operation/ Parameter	Value	Calc.	Result	Rule
10	No	2810				III_Cut1_Rol1				if Cut1 or Rol1
						II_Cut1_UNI1_depth				
		Cutting steel plate, plasma				II_Cut1_UNI1_length				
						II_Cut1_UNI1_thickness				
20	No	2815				III_Edg1				if Edp1
						II_Edg1_Uni1_angle				
		Edge preparation				II_Edg1_Uni1_depth				

	Total							0			0
Item/ factor	Text	min.	most likely	max	m	s	s/m	M	S_0	S	S^2
1	Raw material										
	Volyme	2	2	2	2.00	0.00	0.00		0.00	0.00	
	Waste factor	1.2	1.3	1.5	1.32	0.06	0.05		31.44	31.44	
	Unit price	200	270	300	262.00	20.00	0.08		52.80	52.80	
Material in total								691.68		61.45	3776.31
2	Operation 10: Active? No										
	Geometry cost driver	45	45	45	45.00	0.00	0.00		0.00	0.00	
	Work rate	0.01	0.02	0.04	0.02	0.01	0.27		0.00	0.00	
	Labour cost	150	175	185	172.00	7.00	0.04		0.00	0.00	
Labour cycle cost								0.00		0.00	0.00
	Setup time	2	3	4	3.00	0.40	0.13		0.00	0.00	
	Labour cost	150	175	185	172.00	7.00	0.04		0.00	0.00	
Labour setup cost								0.00		0.00	0.00
	Geometry cost driver	45	45	45	45.00	0.00	0.00		0.00	0.00	
	Work rate	0.01	0.02	0.04	0.02	0.01	0.27		0.00	0.00	
	Machine cost (variable)	75	80	92	81.40	3.40	0.04		0.00	0.00	
Variable machine cost								0.00		0.00	0.00
	Tool cost	5	7	10				0.00	0.00	0.00	0.00
	Fixture cost	17	18	19				0.00	0.00	0.00	0.00
	Machine depriciation	10	12	15				0.00	0.00	0.00	0.00
Base case total			Mean value	0.00		Variance	0.00				
	Overall correction factor	1.015	1.0195	1.025	1.02	0.002	0.002			0.00	0.00
Grand total result			Mean value	0.00		Variance	0.00				
3	Operation 20: Active? No										
	Geometry cost driver	100	100	100	100.00	0.00	0.00		0.00	0.00	
	Work rate	0.02	0.03	0.04	0.03	0.00	0.13		0.00	0.00	
	Labour cost	150	175	185	172.00	7.00	0.04		0.00	0.00	
Labour cycle cost								0.00		0.00	0.00

Figure 7. – Worksheet with standard process plan and system for cost estimation.

An application program with a graphical user interface (figure 8) was developed for information transfer. With the application program the user can open the model tree and check features, parameters and their values, which provide system transparency. Process plans and a summary of the cost estimation are presented in two horizontally separated windows. The search routine for scanning the CAD geometry file is configured for the specific product class and for the CAD system used. Reconfiguration for other products and/or CAD systems can be done using the same principles and with a moderate work effort.

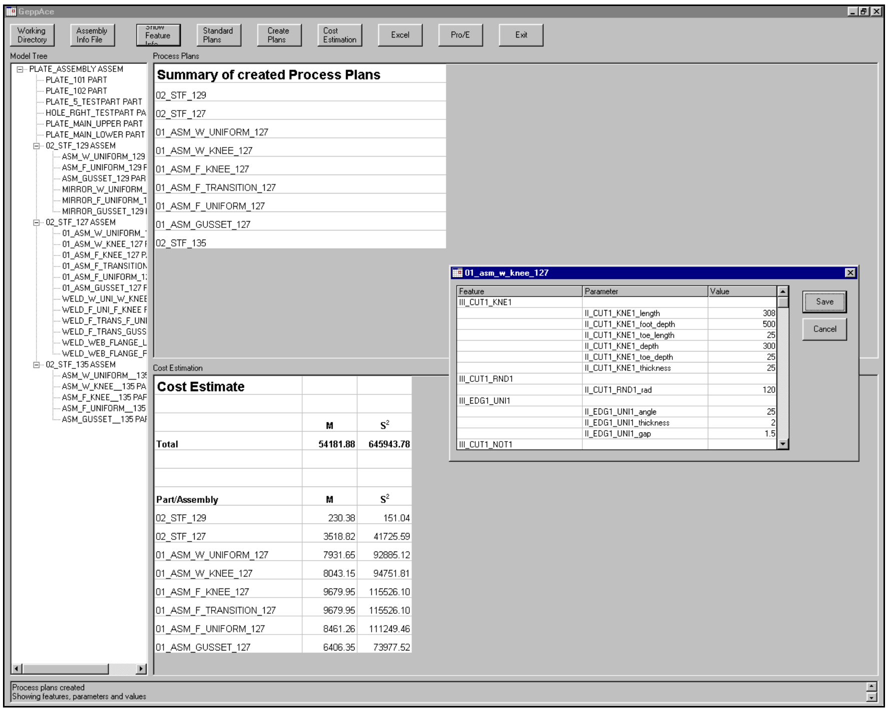

Figure 8. – Graphical user interface of the application program.

The cost estimates of the two variants are presented in figure 9. The program execution proceeds in the following steps:

- Model information files are exported from the CAD system.
- The files are searched and information is transferred to the identified standard process plans.
- The process plans are regenerated based on the imported information and the rules within the plans.
- Values of cost drivers are extracted from the CAD model and transferred to the system for cost estimation.
- The cost is calculated, with the method of successive calculus, for each part and assembly and summarized for the whole product.

Cost Estimate		
	M	S^2
Total	**34769,88**	**946114,71**
Part/Assembly	**M**	**S^2**
02_STF_129	1407,86	39735,41
01_ASM_W_UNIFORM_129	8552,94	458951,52
01_ASM_F_UNIFORM_129	4260,49	110044,07
01_ASM_GUSSET_129_1	481,86	1093,55
01_ASM_GUSSET_129_2	481,86	1093,55
02_STF_127	1639,35	51335,29
01_ASM_W_UNIFORM_127	3857,94	89897,26
01_ASM_GUSSET_135	481,86	1093,55

Cost Estimate		
	M	S^2
Total	**81201,97**	**1354396,61**
Part/Assembly	**M**	**S^2**
02_STF_127_1	1639,35	51335,29
01_ASM_W_UNIFORM_127_1	3857,94	89897,26
01_ASM_W_KNEE_127_1	965,19	4586,60
01_ASM_F_KNEE_127_1	558,56	684,23
01_ASM_F_TRANSITION_127_1	829,08	2007,15
01_ASM_F_UNIFORM_127_1	1878,10	19850,19
01_ASM_GUSSET_127_1	481,86	1093,55
01_ASM_GUSSET_127_8	481,86	1093,55

Figure 9. – Cost estimates for the two variants in figure 6.

6 Results

Our work has resulted in a method and an application program, where knowledge about the design and manufacturing processes of a product is stored and reused in the redesign of the product with the possibility to make automated cost estimations. The method is demonstrated with a system consisting of a database with generic process plans, in which the method of successive calculus is used for cost estimation, and an application program for information transfer. The method supports the designer with information about the manufacturing process at an early stage of the design process, which is a step towards solutions with an optimal balance between product and production properties in a cost-effective way.

7 Conclusions

Using CAD model objects encoded by a nomenclature, a CAPP system consisting of standard process plans can be developed for variant design. All manufacturing operations are proposed to be divided into an equivalent subset of cost items, for which geometrical and topological manufacturing cost drivers are identified and addressed in the CAD models. With the method of successive calculus in terms of estimating costs and production data by a triple estimate of a minimum, a maximum and a most likely value, a system for automated cost estimation for variant design can be developed. A first proposal of process plans as well as cost estimates can be produced automatically by the designer the instant a design proposal is available. This allows for design iterations that will guide the designer towards cost effective solutions, which are in accordance with manufacturing restrictions. A cost estimate based on the method of successive calculus facilitates the work also when exact data are not available. The uncertainty of the prediction is taken into account and through the calculation of variance, items are pointed out for successive break down to gain a refined cost estimate.

8 Acknowledgements

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