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A KNOWLEDGE BASED FRAMEWORK TO ESTIMATE MANUFACTURING COMPLEXITY OF MACHINED PARTS BASED ON EARLY DESIGN CONCEPTS IN CAD SYSTEMS

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Abstract
To achieve the goals of product development in reasonable time and at low costs, designers in midsize metalworking companies today face, among others, the challenge of having to apply available manufacturing processes. In order to achieve this, existing systems often relay on very detailed CAD design models of single parts. One result of these systems is an estimation of manufacturing costs. These systems usually do not compare several design alternatives automatically or even are not suitable for the designers as they are complex to use. So the detailed designs have to be checked for manufacturing costs by other departments. This may lead into longer communication needs or time leaks. Therefore, these systems do not fully use the potential for increased productivity. To assist the development of new products it is necessary, depending on the task to be fulfilled, to integrate systems for estimating manufacturing complexity in early stages of concept CAD models in order to reduce future manufacturing complexity that may lead into reduction of manufacturing efforts and costs.

Keywords: *early design concepts, knowledge-based engineering, design for manufacturing, manufacturing complexity estimation*

1 INTRODUCTION
Design and production of customer specified products in field of small and midsize metalworking companies with small order quantity are usually new designed or existing designs are adopted or – less likely – used from existing variant designs. This leads into a high level of innovation and high pressure in competition and time for those companies.
In contrast to serial production industry the customer specified products mostly need to be built up from the concept stage on. Due to this pressure, mostly the amount of different concepts of the design stays low. And at a very low level of detail only rough estimations of manufacturing complexity mostly based on similarity considerations can take place. Here often one of the first feasible concepts will go into further detailing. Although it is widely known that about 70 percent of the later product costs are defined in the early stages of product design (see *figure 1*) these companies face the reality with their tacit or hidden knowledge for decision making on the design concepts.

2 DEFINITIONS

2.1 Existing Models
Today, it can be observed that between the design department in a company and other department like production preparation or economics usually several iterations occur before enough decisions are made and the final design can be finished. Still today the amount of these iterations is quite high as also time and cost consuming. One possible approach to overwhelm this are integrated CAD/CAM systems. Although the technical drawing – mostly in forms of digital data – remains still the primary mean of communication in small and midsize companies.

Today, not only design guidelines but also cost estimation processes take a major role within the early stages on product design. Traditional approaches start with a precalculation of possible product and production costs, as these are the foundation for offerings to the customer.

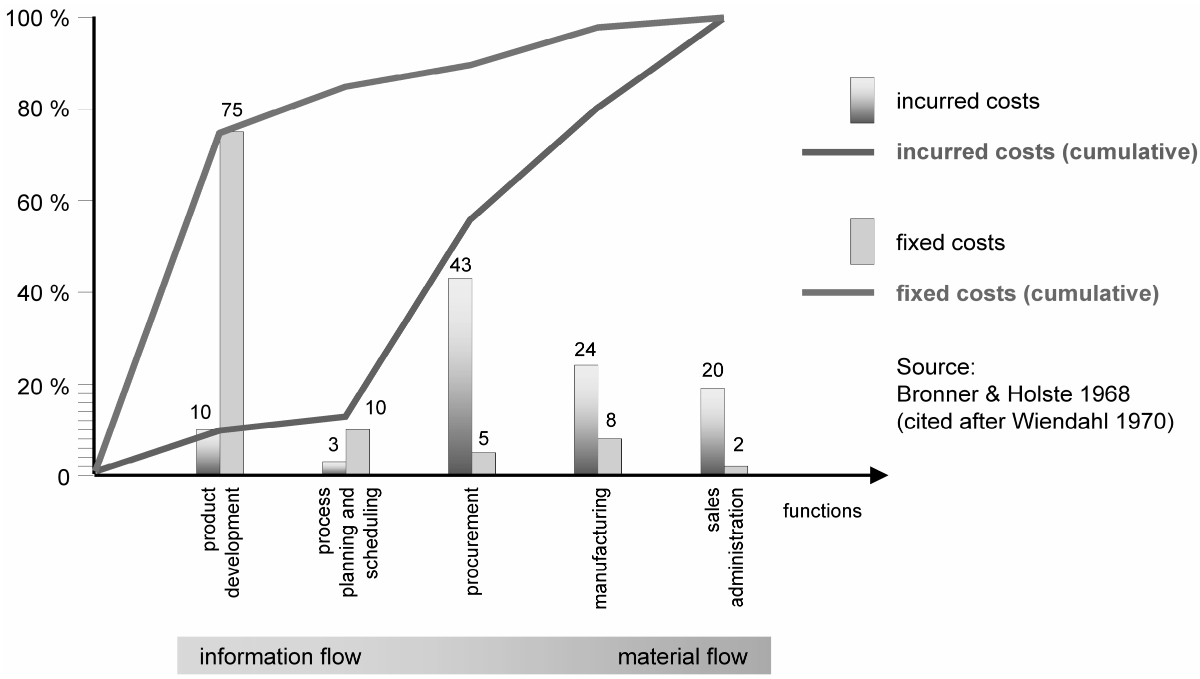

Figure 1. Cost determination and generation in different stages in product development [1]

During several design stages the future costs of the designed product can be calculated with several methods. An excerpt of available methods to estimate product and production costs in literature is shown in *table 1*.

Most of these models base on the foundations of product costing and show different ways to combine the geometry of the product model to the efforts that have to be taken to produce and sale the product.

2.2 Existing Solutions

Today, many approaches for estimation and tracking of product costs are already available as commercial tools or complete software suites. Many solutions focus on analysing designs in several stages and combine those with design accompanying calculations for product cost optimisation. This implies that the cost for manufacturing processes, for buy-in parts and cost unit efforts are known or at least assumed by similarity searches or rule based decision support. This software analyses and evaluates the product models following different criteria, identifies manufacturability, cost drivers, and the estimated manufacturing costs. Also the integration of ERP system interfaces e.g. [47] (or adoption of complete approaches into the ERP system e.g. [27]) is commonly used. Here, information from the ERP forms the database for extensive calculation processes.

Table 1. Cost calculation and cost estimation models

No.	Models	Solution	applies to	works with	Source
1	VDI 2225	design accompanied with cost calculation for new design, variant design, customisation in mechanical engineering	development, design, planning, controlling	based on similar existing designs, comparative costing, overhead calculation	[10]
2	VDI 2235	cost estimation and similarity utilisation for production costs on new design, variant design, customisation, mechanical engineering	development, design, planning, controlling	short cost calculations	[11]
3	DIN 32992 T1	cost calculation in general and overhead cost calculation	development, design, planning and distribution	foundations for cost precalculation, equivalence costing, overhead calculation	[12]
4	DIN 32992 T2	short calculation	development, design, planning and distribution	foundations for short cost calculation, use of statistical data and, similarity of manufacturing processes	[13]
5	DIN 32992 T3	relative cost calculation	development, design, planning and distribution	foundations for relative cost calculation	[14]
6	Cost calculation	cost and benefit calculation cost types and cost unit calculation	controlling and marketing, no design mentioned	overhead calculation, amortisation, price calculation, usage costs etc.	[15]
7	Calculation	cost unit calculation	all units of product development process	diversion calculation, equivalence calculation, overhead calculation, combinations of these, activity based costing, process costing	[16]
8	Offering and project calculation	price definitions, target costing definition, cost control	marketing, sales, design, production preparation	diversion calculation, equivalence calculation, overhead calculation, relative cost, post calculations etc.	[17]
9	Prototype based target cost planning	cost management at the interface between design and controlling	design and controlling	rule based, self learning prototypes for different design tasks, learning based on similar existing designs	[18]
10	Product cost management	modular based variant calculation, mechanical engineering	design and development for variant products	process cost analysis on a controlling based view	[19]
11	Model of a cost information system	cost precalculation of customised products in mechanical engineering	single unit production	similarity search and clustering of similar existing products and related calculations (short calculation and decision tables)	[20]
12	Cost analysis in SFB 396	rationalisation of product development process through enhancement of information content within the product model	design	interactive assignment of predefined parameter, integration of knowledge based system helps to reduce time spend on feature assignment, short calculation with empirical cost parameters	[21]
13	Cost knowing design	design with cost awareness based on requirements from the specification	design, controlling, process planning	cost growing laws and relative cost catalogues, intensive analysis of design and structures	[22]

The controlling and process planning departments use many approaches, e.g. the estimation of costs and the generation of recommendations for further design activities that are communicated to the designer. Calculation usually takes place in controlling departments or within the project management in e.g. matrix organised companies. It's not very common to involve the designer heavily with direct cost estimation analysis of the design, as this is the task of controlling or of project management [2]. Of course, the designer will get the results of these analyses and has to follow the resulting recommendations. The designer usually knows cost drivers. But the knowledge about them is often quite unstructured and the interaction between design and cost drivers is getting more complex as the product gets more detailed.

Table 2. Cost calculation and cost estimation approaches

No.	Approach	Developer, Vendor	Solution	applies to	works with	CAD interface	Integration in product development process	in use	Source
1	Computer Aided Probabilistic Evaluation (CAPE)	DaimlerChrysler AG	decision support in early phases of product development, compare design alternatives, probability of reaching target costs	concept and design of any technical product, used for electrical components and buy-in parts as well as cost structures of assemblies, project management, controlling	system analysis and based on that rating a model of cost estimations with different methods connected with probability estimations	no	requires company wide resources, ERP etc. that have to be integrated into the calculation, complex to handle	for automotive parts in mass production, applies to the cost model, that is specific to the task, framework is generic	[23]
2	Price H	Price Systems	offering calculation, investment calculation, design-to-cost analysis, make or buy decision	development costs and manufacturing costs of hardware, project management, economics dept.	statistical cost estimations from template libraries, parametrical cost estimation	no	requires company wide resources, ERP etc. that have to be integrated into the calculation, complex to handle	mass production, hardware and software	[24], [25], [26]
3	DELMIA (formerly EAI-Delta)	Dassault Systems	cost calculation of different alternatives, systematic approach for cost estimation,	design and process planning, project management, economics dept.	material, assembly, manufacturing costs,	CATIAV5, EDM/PDM-System vis-data	product structure and visualisation data can be added, no associativity, better communication between design and process planning	mass production, big companies	[27]
4	DEVIPLAN	EPFL	cost calculation of simple rotative parts for offering and production cost calculation	design, process planning	cost estimations from CAM-feature template libraries and not CAM-feature based costs	AutoCAD	CAM-based	small and mid size companies, simple rotative parts	[28], [29]
5	LICCOS (PICANT)	wbk	design accompanied with cost precalculation	design in mechanical engineering	overhead calculation, border cost calculation, process cost calculation	Pro/E, CATIA,	requires process model for calculation	small and mid size companies, prototypes	[26]
6	FEKIS	TU Munich	supply of cost information during design for cost optimised design	design of single and serial production parts in mechanical engineering with a high similarity	foundation is a rough knowledge based process plan, uses feature technology for estimating machined material volume	Pro/E with special programmed features	use of special, knowledge enabled features that can get evaluated and analysed afterwards from procedures	prototype	[30], [31], [32], [33]
7	XKIS	TU Munich	cost estimation for production costs during design,	mechanical engineering design, cost calculation and process planning, generation of work and process plans	similarity search in part libraries, Taxonomy of parts, manufacturing library, process library, etc., based on basic design areas (features)	Pro/E, CADAM (2D)	searches base on an existing CAD model	small and mid size companies, quite old approach, takes time to implement	[32], [33], [34]
8	ASCET	IPA FhG	in the design process integrated economical estimation	mechanical engineering design	in early stages with regression analyses, then prob. feature based cost calculation on similarity search for manufacturing costs in early stages, later on statistical approaches mixed in	Konsys2000	similarity search	not defined	[35], [36]
9	KICK	University Paderborn	common cost and process cost estimation within the CAD system	design, mechanical engineering	rule based framework calculating costs with company specific decision tables. Product structure has to be defined and detailed	yes, not defined	product structure browser analyses geometry and supports designer with assignment of material, machining process, structure etc.	large and mid size companies	[37], [38], [39], [40]
10	Prototype based target cost planning	Dittmar, J.	cost management at the interface between design and controlling	design and controlling of	rule based prototypes for different design tasks	planned, not established	not defined	not defined	[41]
11	VESKONN	Wilhelms-Universität Münster	distributed system to support design cost evaluation	design	cost functions are mapped with trained neural network components that connect to design features, in case of new designs n.n. assumes costs	not defined	neural net is trained with data from post calculations	companies with high pressure and vibration technology	[42], [43]
12	Neural Networks for Cost estimation	Bode	supports decision making on several calculation types	controlling and cost planning	only a view design parameters are defined as input vectors for several neural networks that contain different calculation methods	not defined, universal through ASCII files	neural net is trained with data from existing calculations and assumes new calculations	bearings	[44], [45]
13	HKB	Mirakon	rationalisation of product development process through enhancement of information content within the product model	design and all phases of through product development process, mechanical and process engineering	feature based approach within knowledge based systems and databases, contains process modeller and related calculation modules	not defined, universal through ASCII, bmp, dxf files	web based interface with several domain specific modules to connect to databases	large and mid size companies, university	[46]
14	Cost Process Optimisation	Facton	Optimisation of product costs during design	controlling and cost planning rather then design dept.	cost prototypes that collect cost data from different sources over all product development stages	JT, Step	requires integration into ERP system	several mechanical engineering companies	[47]

Most of the listed approaches in *table 2* have only a low CAD system integration or use CAD data in form of post or neutral data formats. This is remarkable because many listed approaches intent to support the designer while designing. Some of the mentioned approaches consider process planning within CAM systems and are able to relate manufacturing process costs to CAD geometry. Unfortunately, CAM is mostly not situated at the concept stage of product development.

It seems that most of mentioned approaches follow industry's deep wish to see the cost evaluation of future products very early and the belief in those numbers is very strong. So therefore, the existing approaches point in that direction by taking into account that the built up systems will grow extensively and will get complex. This complexity might be a fact that organisations within small and mid-size companies may change quickly and these approaches may take lots of effort to get changed over as well.

3 INTEGRATED COMPLEXITY ESTIMATION (ICE)

3.1 Assumptions

With today's globalisation of industries the cost estimations become more complex. This is because at the beginning of the concept design stages it may not be possible to define clearly where in the world the production will take place. And – as widely known – the manufacturing costs differ significantly from country to country. *Figure 1* and approaches in *table 1* and *table 2* mostly consider costs.
From the economical point of view, costs are the rated usage of production factors [3]. In these terms it can be stated that the designer, when defining the product concepts in CAD, also defines the usage or the amount of production factors. As there are many different and linked production factors available, the sum of all will be complex to estimate. Usually, the controlling department defines the underlying costs and proposes the rating of these factors. Some influences on the product costs are e.g. a make-or-buy decision or the decision where to manufacture the product. Normally, designers do not deal with these decisions. Nevertheless, the designer can estimate the usage of production factors in a specific – mostly geometry based – domain. Here it can be possible to estimate this usage in terms of machining efforts, component amount usage etc. So for procurement, manufacturing and sales the consideration of emerging efforts (here especially the manufacturing complexity) may be more useful for making design decisions than costs.
Considering manufacturing expertise during the early stages of design may help to reduce the usage of production factors. Such information can improve not only the quality of a design, but it can also ensure the generation of an easy to manufacture design. This implies to lower the final cost of the designed product. By evaluating how easily an evolving conceptual design can be made, potential errors can be avoided before any detailed design efforts come up [4]. Conceptual design is understood here as first design evaluations within a CAD system (not on finding principle solutions or hand sketches).

3.2 Definitions

On one hand, the foundations of integrated CAD/CAM systems have to be established and the financial means have to be made available. On the other hand the systems have to fulfil their tasks robustly, and error free. The produced CAD data and related information have to be reliable, as these are the main product model information for further work. For these product models, especially in terms of reliability and quality of data, the design department has to ensure the supply for correct input information all over the process of product development. The designer founds himself in a situation where many information streams have to be bundled and an appropriate technical solution must come out. Standards and norms (on company level or on a global level) support the designer with paper-based or electronically provided items which are more or less complex to use. According to [5] this is one precondition of design for manufacturing (DfM). So the aim can be defined in supporting the designer to have the possibility to estimate manufacturing complexity on early concepts in 3D CAD in a very simple way within single parts as well as within assemblies. The approach will base on manufacturing technologies that are commonly used within the production of semi-large power generators or electrical motors, e.g. laser cutting, welding, milling, turning (large scale), drilling. The estimation of costs is not in the main focus of this approach, as manufacturing costs depend on several outside and inside companies' factors that need more support in direction of a knowledge and/or information management systems. This might exceed department investments or is over-scaled and definitely expands communication efforts, which will drive other cost factors within a company [6] p. 176f.

3.3 The Framework

As to be seen in *table 2* most today existing approaches try to estimate manufacturing costs in several stages in product design. It also can be seen that the integration of costs into design brings up different aspects that are mostly complex to handle. Now, by taking away the costs side from the designer and focus on the manufacturing steps that have to be realised within production and bringing in the feature based approaches (where features get loaded with fix or variable attributes for later manufacturing information analyses), a different approach can be evaluated. Hence, the target of this project – in the domain of the design of power generator drives – is the development and the realisation of a framework that allows the designer to estimate and to compare the future manufacturing complexity of several design concept variants in a simple way. So the framework represents an Integrated Complexity Estimation (ICE) for manufacturing within a CAD system. This is possible without bothering the designer with the handling of calculation and optimisation systems, because

- the framework runs the estimations in the background of the design process automatically or on demand,
- the applications of the framework act similar to a feature in the CAD system, so designers see a behaviour that they are familiar with, and
- the interface will have an integrated input assistant, which provides tools, data, and methods.

ICE avoids the usual way of creating a detailed CAD model, handing it over to a cost estimation system, waiting for the calculation results, which then are not automatically reflected to the designer or even in the CAD model. It may help the designer to avoid high manufacturing complexity already in the conceptualisation phase. As a consequence, the product can be developed better and more rapidly already in the early phases of the CAD design process. As the application of the manufacturing complexity analysis behaves like a feature within the CAD model, it allows real time part compare between several models that contain altered design concepts.
This approach is different to approaches that use non-geometrical information on special features like in [7] or a feature based recognition. Today simple features like holes may contain already process information [8]. But sketch-based 3D geometry (e.g. of a rotor structure) still has to be enhanced with additional information and can not easily determined with the classical feature approach [9].

3.4 Enhancing Geometry Information

Once one initial concept is built up as a parametric CAD model, the designer uses the ICE framework to assign some manufacturing processes like welding, laser cutting, milling, or turning to the geometry of single parts or to the geometry of assemblies. The manufacturing process information derives from a database and may differ in layout and quality.
As an example for those manufacturing processes a welding process will be named here. This process can have different qualities like single layer or double layer welding seams or even build-up welding. The regular welding process is mostly applicable to geometry edges, while the build-up welding relates to faces. Also existing knowledge about the material that has to be welded and the process time (e.g. when machine welded in millimetre of seam per minute for a specific material combination) has to be considered when building up the database.
So the definition within the database contains an ID, a name and quality as well as selection mask (e.g. welding suites for edges, milling suites for faces) and connected to that the appropriate geometry analysis function (e.g. edges with length analysis and faces with area analyses). The user defines a certain set of edges or faces by selecting the geometry via standard CAD geometry filter functions. That allows the user to easily pick even a large amount of geometry. A generated CAD application supports search and assignment of the chosen manufacturing process from the database to the geometry by using object attributes and knowledge based checkers. The checkers can be seen as software agents – small autonomous program pieces – to ensure that the geometry does not loose the attributes by geometry changes. The checker also provides methods for the analyses of the related geometry (e.g. for regular welding the actual length of the edge). Multiple assignments of different process information to the same geometry are possible (e.g. for laser cutting and turning or milling with different qualities). Selected geometry may occur within an assembly component or as one single part. Both situations can be handled by transferring the assigned technology attribute down to component level (*figure 2*).

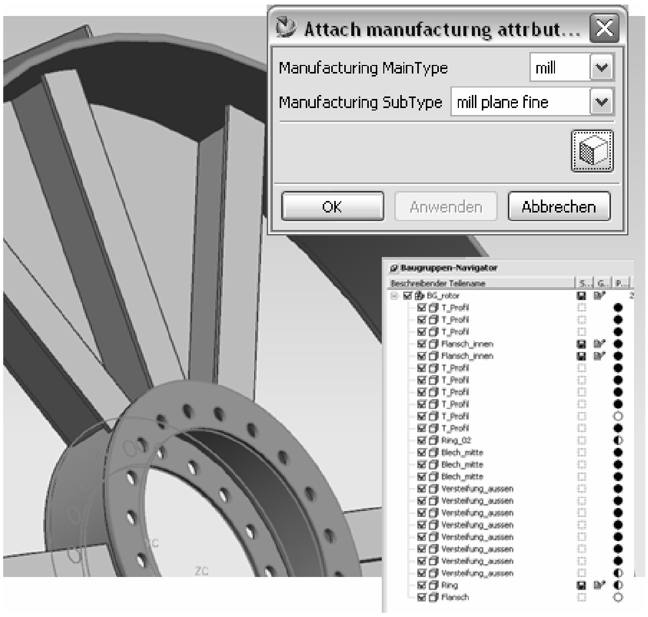

Figure 2. Assignment of technology information within an assembly on the initial CAD model

Now, the design concept will be altered within CAD to derive different variants. This is a common procedure as most of exiting CAD data are reused or altered for different variants or revisions (*figure 3*). The CAD model keeps the formerly signed information associative to the geometry. If a checker looses its references during substantial changes, the user will be asked automatically to assign new references.

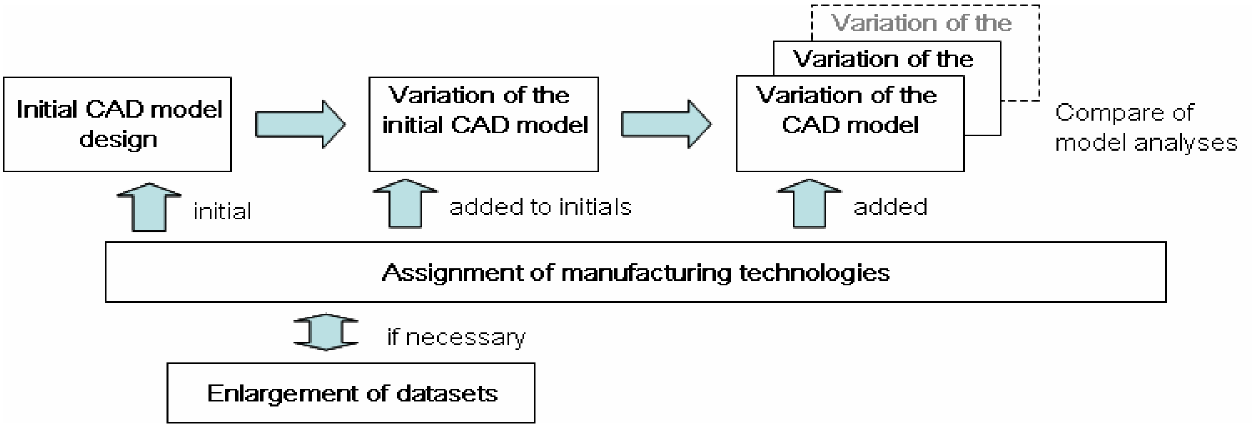

Figure 3. The process of using the integrated complexity estimation framework

If a certain technology is not available in the database, a key user like a designer or process planner may define new technology data sets (*figure 4*). So the system gets extended and keeps this data set available for future activities. The technology data base can be hosted within the LAN (local area network) of the design department and should get extended only by the mentioned experienced key users. Otherwise the consistency of the database information might be lost over time. Of course, the definition of such data set bases on designer's knowledge and knowledge outside the design department. A knowledge transfer from the process planning department may be helpful for the first usage of the framework. There, most of the needed information should already exist in several formats. These have to be converted in consistent sets of data, if not already. Changes to the information may be handled with a revision algorithm or more simply by comments.

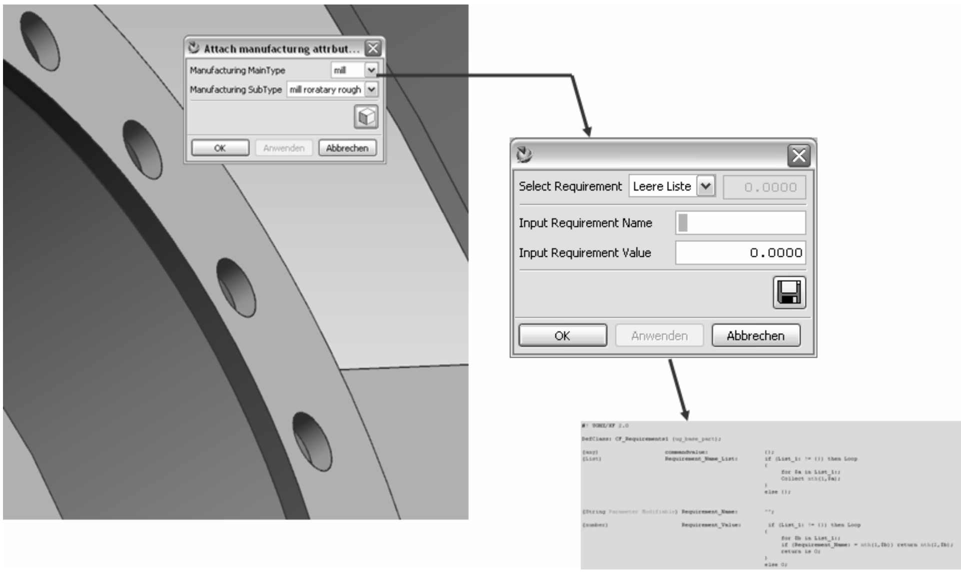

Figure 4. Creation of a new technology data set

The attribute assignment works through an application that will consistently exist within the CAD model during changes of the design concepts. So when altering a design and when new geometry comes in, most of the faces and edges will still keep their attributes or get the attributes handed over by the already mentioned checkers. This puts the designer into a position where only very few additional attributes have to be newly assigned (*figure 3*). ICE bases on a simple knowledge-based system that easily handles geometry configuration. But here in this approach only the geometry attribute assignment, related analyses and calculations are handled, not the geometry itself.

3.5 Evaluating the Manufacturing Complexity

When the designer has evaluated some design alternatives, another generated ICE application reads all attributes, asks for checker information and derives the related set of data from the manufacturing process data base and calculates a grade of manufacturing complexity.

The results are shown as a simple manufacturing complexity estimation of parts and can be reported through a dialog (similar to geometry analysis within CAD systems, *figure 5*) or through a template based modular web site that is created on demand.

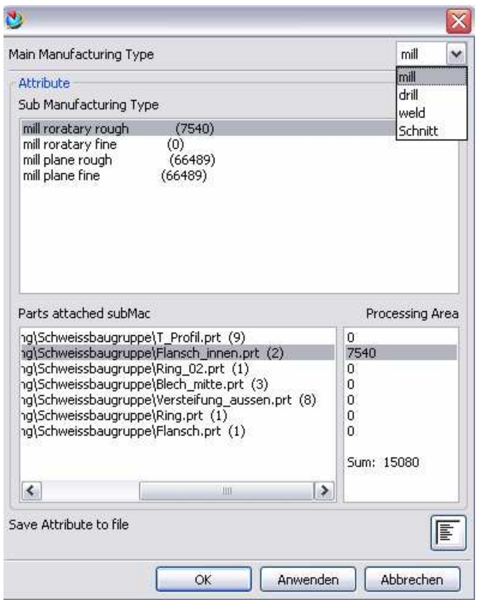

Figure 5. Analysis of the geometry split up into used technology for one concept

The sum of manufacturing efforts consists of the technology related geometry analyses of the attributed faces or edges within the assembly. The analysed functionality will behave also like a feature in the CAD system and provides the results as parameters within the CAD model.
The degree of complexity is dynamic and will be defined as the sum of all subsumed geometric analyses results compared to the same sum in a different coexisting variant. With a factorisation of different technology data sets, the results may look up on single technologies applied or several technologies. In ratio with the analyses results from other variants it is possible to estimate, whether a solution will have more effort to manufacture or less. The degree of manufacturing complexity of one variant by itself is on high level of abstraction and contains only a vague information value. But compared to other design alternatives it becomes meaningful. If design changes are made, results vary and may show better or worse solutions for manufacturing.
This instantly helps the designer to check if design alternatives may lead to more manufacturing efforts or less and supports the decision making during the concept evaluation and product detailing without stressing communication within the company.

4 CONCLUSIONS

The described concept for the support of design as well as an implementation of the ICE framework aims to an easy and simple estimation of manufacturing complexity. Test implementations of this framework have been done exemplary for the CAD system Unigraphics. Designers have the possibility to estimate manufacturing complexity on early concepts in 3D CAD very easy. Efforts to integrate the framework into the CAD system are low. The connection to ERP or other applications was knowingly resigned. That does not imply that the described framework will replace existing cost estimation approaches. As the first mentioned are used more in controlling, process management and project management the framework should coexist within the design department.
Nevertheless, the concept needs a high grade of integration within the CAD system. As different CAD systems are built up with different architectures and functionality, applications of this concept have to be customised, mainly through a specific API. Exchanging the information of technology can easily be realised, as this exists in form of system independent data in databases, spreadsheets, or ASCII files. The presented approach does not imply a company wide usage, as it has been mainly designed for the design department only. Here a rough estimation of future manufacturing complexity is often adequate to follow a certain development direction in terms of manufacturing. Although, during the development of the framework, simple data sets of costs have been added to the existing records that may be able to sum up approximately costs of technologies in use, the usage of production factors is seen so far without underlying costs. The assignment of technology data sets to the initial geometry is done manually by now. Here further investigations to the feature based assignment of technology (as seen in some approaches in *table 1* and *table 2*) could be done. The concept will not include dependencies from supplier networks or estimations on supplier strategies, as the usage of production factors might be the same but costs may differ. When further evaluation testing has been finished, the future work will deal with the extension of the framework for a confidence indicator based on simple statistical analyses. Also the connection to existing databases of machining and manufacturing technologies available in process planning should be developed. Here it is important not to extend the number of available data for the usage of the framework as more the usage of already existing data that shapes the day-to-day business of these departments.

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