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METHODS, TOOLS, AND PROCESSES FOR THE DESIGN AND DEVELOPMENT OF INDIVIDUALISED PRODUCTS

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Abstract

Specialisation and individualisation are general principles in any system and are currently found in the customers' behaviour regarding any consumer good. The individualisation or customisation of complex mechatronical products demands an integrated approach covering business administration, production technologies, as well as product development and computer support. Within this contribution, we would like to focus on product development in mass customisation, i.e. the offer of individualised products that fulfil each customer wish at conditions of mass production. Therefore we would like to present elements of a general product model, a process for planning the structure or architecture of the product, methods supporting that process, i.e. checklists for degrees of freedom and possibilities of realisation as well as flexible matrices, and a computer tool for the designer. The results are useable for a wide range of cases in the area of the development of variant rich products.

Keywords: Configuration management, variant management, product structuring, product modelling, customisation

1 Introduction

Mass customisation answers the trend towards increasing individuality by combining customised products, which fulfil all individual wishes, with the advantages of mass production, i.e. cost, quality, etc. [1], [2]. While this concept has started and is already implemented in the apparel industry, processes, methods, tools, strategies, and principles have to be adapted and developed for mechanical engineering. This requires a comprehensive and integrated approach covering different aspects such as business administration, production and logistics, as well as product development, which is our focus; product development might be divided into structure planning, i.e. the predominantly customer independent advance development, and the adaptation processes, i.e. the derivation of the individualised product. From a general point of view, several problem fields arise in this context, which are answered by central principles or action fields (Figure 1). Actually, these approaches are elaborated within an interdisciplinary research centre [3], with the example product being a pressure washer. Other insights have been gained by work with automotive seats.

The problems of mass customisation include the increasing efforts to develop and produce the product, the growing complexity of the product and its variants, a limitation of the product scope in order not to go too far, the handling of the complex interdependencies within the product, the general unpredictability of possible customer wishes and respective characteristics of the product, the flexibility of the organisation to react on specific demands, the change from discrete variants to continuous spectra of properties, the possible fuzziness of customer wishes, as well as the time-critical evaluation of demanded product properties. The challenges are answered by a consequent customer integration and interaction in all process steps as well as constant customer retention, the focus on local content by globally distributed miniature plants, these miniature plants themselves implying manageable process chains, utilising new production technologies such as rapid manufacturing, sharing the customer's profile and with that giving him advice in customising his product, a comprehensive documentation of all product data and information, classifications and a cascading of the adaptation and realisation process steps, an evolutionary design that bases on an adaptation and alteration of preceding products, but still allowing substantial and structural changes, as well as an extensive planning of the product structure. The problem and action fields are not to be mapped one to one, though there tends to be some kind of assignment. Product development covers mainly the evolutionary design, the structure planning, and the cascading adaptation.

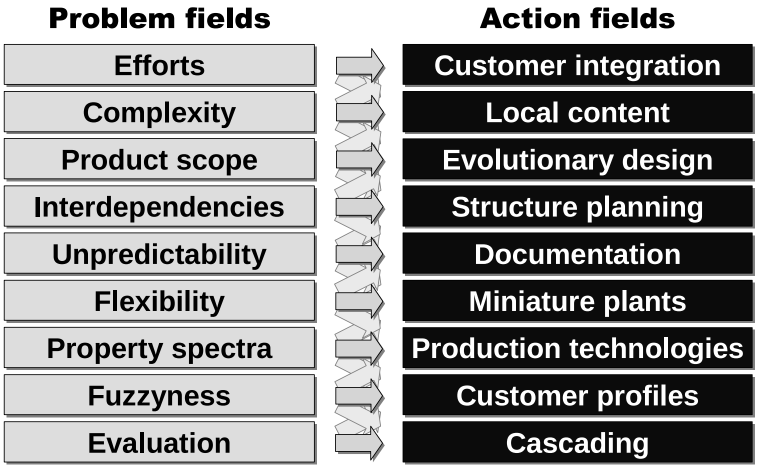

Figure 1. Problem and action fields of mass customization

The focus of this contribution is on the structure planning; its result is a comprehensive and dynamic model of the product spectrum, from which individual products can be easily derived. By that, structure planning consists of processes, models, rules, and tools.

2 Product model

The model has to describe the whole product spectrum, i.e. the product with all its possible specifications. Actually, this "model" might comprise many other models and serve just as a summarising term; it also need not contain a definite description of a complete product, since its purpose is to enable an easy derivation of the individualised product. Quite important insights at the discussion about this model were that there has to be a precise distinction between what has to be modelled and how it is to be modelled, and that it is seemingly not possible to prescribe a model covering all potential cases without inconsistencies (Figure 2). The first aspect supposes that there is a reality that has to be represented by a specific model; this model might be set up in natural language, specification languages, e.g. Express [4], graphically and object oriented, e.g. UML-Unified Modeling Language [5], or in any other way. The problem is that the only possibility to describe the reality is to use one of these languages, which finally influences what is represented. The latter aspect can be best explained when regarding the core product structure in the top left side of Figure 2: a product or component can be generally decomposed (ant. aggregated), e.g. the pressure washer consisting of the housing and the pump, or specified (ant. generalised), e.g. the pressure washer might be a "private" product or a commercial product. These hierarchies proceed on different levels of detail and are interconnected on those levels; this leads to not manageable complexity and by that to redundancies and inconsistencies. This fact becomes even more problematic when the model is extended by e.g. properties ("Are they separate objects or attributes of objects?") or degrees of freedom ("Are selection possibilities explicitly represented or only implicit in the product model?"). Since the ideal representation depends on the particular case, it is not recommended to give one categorical model in one language, but to describe generally the maximum contents of such a model and give an idea of how to adapt the actual model. In the same way, we overcome the first obstacle by describing the single elements of the model with different languages; by that we strive to find an appropriate representation in between the reality and a much too flexible language, which then finally supports the designer.

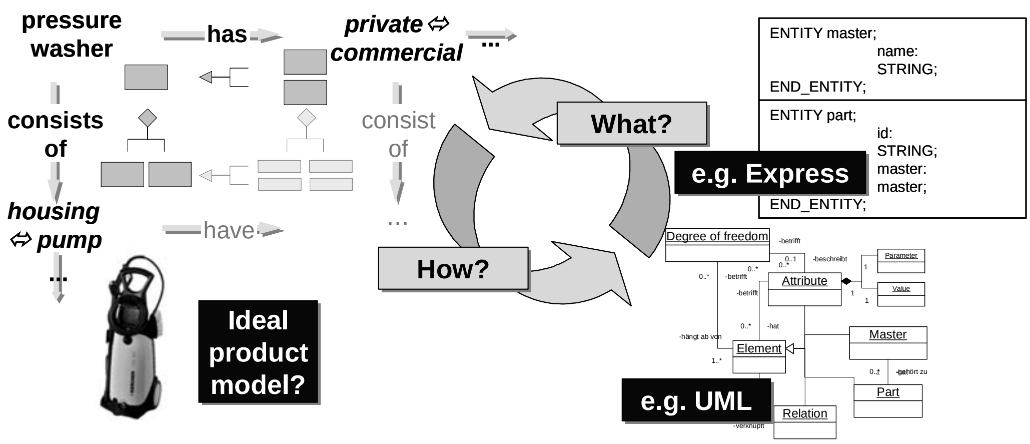

Figure 2. Differentiation between what to describe and how to describe it

The core product model comprises the following list of elements. The models focus is on mass customisation and, as a part of it, variant management. Elements of other models, e.g. for representing the development process, can be added if not already included (e.g. documents or versions). The elements can be almost arbitrarily connected by the relations at the beginning of the list; the relations are themselves regarded as elements of the list, so that they can be explicitly addressed, configured, and customised. The relations might be

- hierarchical: these are the already mentioned decompositions and specialisations; attributes are inherited via these relations, but it has to be explicitly and precisely defined, which attributes and in which direction;
- logical: these relations show dependencies between different elements; the dependencies can be described by logical operations (and, or, not, if…then, etc.), e.g. the large pump not with the small housing; these kind of relation also covers mathematical equations; theoretically, the hierarchical relations can be reduced to these;
- semantic: these relations connect different types of elements, e.g. functions ("generate pressure") and components ("pump");
- technical: they represent concrete technical interfaces between parts on the same level of decomposition, e.g. the pump is connected to the housing via three bolts (with geometrical dimensions etc.); technical interfaces especially have to be regarded as some kind of parts, so that they can explicitly described, standardised, managed, etc.

The (ontology of) elements of the product model in the narrow sense are

- *master* (abstract and specified) and *parts*: master represent abstract classes of otherwise concrete elements of the product, e.g. "pump" or "housing"; if they are on the top level of abstraction, they are called abstract master; if they are partly specialised (e.g.

"engine" specified to "combustion engine" or "electrical engine") they are called specified master; when the specification is completed, i.e. there is a concrete element that can be built in a real product, it is called part (e.g. "engine no. 42"); specified elements might be synonymous *variants* or in relation to each other *alternatives*;

- *products*, *assemblies*, and *components*: this differentiation does only serve to identify the level of decomposition, i.e. a product is not part of a higher element, an assembly is part of a higher element and consists of other elements, and a component cannot be decomposed further;
- *functions* and *principles*: according to design methodology [6], functions are abstract descriptions of the purpose and the operation of an element; principles might be technical (building blocks), physical, biological, etc. and serve to find solutions that can be easily adapted to the specific problem; principles can also be *possibilities of realisation*, describing how to technically realise the degree of freedom (see below);
- *attributes* and *requirements*: these are the actual or target properties of the product; they are composed by *parameter* (e.g. "colour") and *value* (e.g. "red"); the specification can be expressed by these attributes too; theoretically, the other components and relations can be reduced to attributes of the product;
- *degrees of freedom* and *customer wishes*: degrees of freedom representing the possibility of choice of the customer and can be regarded as some kind of attribute (parameter and range of value); by that, they have no value, but a "range of values"; this can be a list (with the special case of a Boolean yes or no), a values margin with either no, one or two limitations, or a mixture of both; customer wishes represent quite blurred expressions that cannot be directly assigned to elements of the product spectrum ("It shall look nice!"), but have to be translated into degrees of freedom;
- further elements: these might be detailed geometrical elements, production steps and resources, service elements, the already mentioned documents or versions, etc.

These elements can be assembled to the product model graphically or within matrices. The general proceeding is to collect the elements, set them in relation to each other, and finally evaluate the relations. The heart of the structure planning is the hierarchical decomposition and specification of the product, the other elements can be assigned to that structure and help in navigating through the structure. As mentioned above, the decomposition and specification can alternate and lead to a quite complex product spectrum. In some cases, a specification or decomposition does not make sense, either when a specification results in too many variants (e.g. a certain car with all options), or when a decomposition is too different for two or more specifications (e.g. the decomposition of a combustion and an electrical engine). To manage this, the master are additionally attributed on one hand with "specified", "specified after decomposition", or "part"; on the other hand with "decomposed", "decomposed after specification", or "component". The classes "specified after decomposition" and "decomposed after specification" allow a fragmentation of the product model itself, which practically helps handling the complexity of the overall product spectrum. E.g. the element engine is removed from the model and separately customised.

3 The structure planning process

The product development in mass customisation is divided into the preceding structure planning and the continuous adaptation processes. The actual structure planning process can be described in respect to the general approach to design [7]; Figure 3 shows the additional results that have to be worked out. As the general approach to design itself and even more with regard to mass customisation, these process steps must not be understood as self-contained units; iterations and recursions are crucial aspects of the proceeding. That is why we have chosen a multi-plane representation of the process; the separate planes might be understood as separate product representations, between which the designer has to switch within the process.

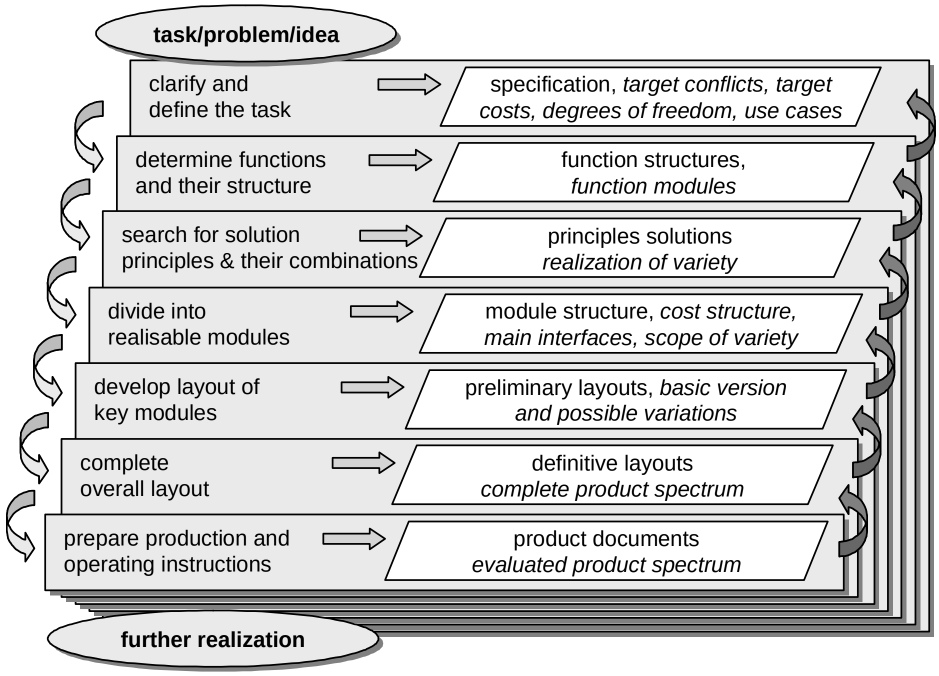

Figure 3. The general approach to design enhanced for mass customisation and variant management

The clarification of the task now contains the collection of the possible degrees of freedom together with possible use cases of the product; this is supported by specific checklists. Additionally, there is an explicit regard of target conflicts and especially target costs. The functional analysis is detailed by the definition of functional modules that can be integrated concerning variants, i.e. components that serve a similar function or that are mostly varied together (e.g. infotainment module, power package, etc.); this is supported by more detailed approaches [8], [9]. The search for "singular" solution principles is extended by the search for principles how to realise the variety and customisation in the product; this again is supported by checklists and catalogues. The dividing into realisable modules is the central part of the structure planning process and refers to the core competences of the designer; the crucial demand is to explicitly regard, describe, and define the interfaces between the elements of the product. Next to the cost structure, the scope of variety, i.e. the range of values of the degrees of freedom is finally specified. Support is provided by forms for interfaces and a collection of design rules and examples. The development of the key modules, as well as the layout of further modules and the final definition of interfaces, leads to a basic version of the product with respective variants; this step can be recursively conducted by the whole approach again, but on the level of the single module. The completion of the overall layout results in the whole product spectrum, which finally has to be limited due to the evaluation of properties (functions, safety, quality, etc.), economics, and production aspects.

Since the adaptation process is part of another project and has its own methodology, only its reference to the product structure and product model shall be considered here. The adaptation can lie between a simple configuration with predefined parts and the request for something completely new that has no clear relation to the existing product spectrum. In between and primarily, there is the specification of degrees of freedom, answered by the flexibility of the miniature plant itself, or the extension of a degree of freedom or the product spectrum itself, but with an identifiable reference to the existing model. This is answered by additional efforts of professional designers extending the product spectrum. The derived individual product definition might be found implicitly in the product spectrum, meaning that all parts and specifications are somewhere comprised, or is stored explicitly within or outside the product spectrum, i.e. there is a separate document comprising (only) the whole individual product definition. In both cases, a consistent filing of this information is essential for the establishing of an effective mass customisation plant.

4 Methods for structure planning

The methods presented in this contribution are restricted to checklists and matrices. The degrees of freedom are to be found with a checklist suggesting different fields and causes for possible variety within the product. The checklist is represented in Table 1. The contents can be referred to as characteristics of the customer, use cases of the product, needs for social differentiation, underlying value system, etc.

Table 1. Checklist for degrees of freedom (variant driver)

criteria	characteristics (examples)
function	equipment, automation, use cases, etc.
design/appearance	color, surface, form, style, type, etc.
technology	energy type, technical features, electronics, software, etc.
performance	power, speed, functional, etc.
measures	length, width, depth, weight, space, etc.
ergonomics	human machine interface, space, operating, display, complexity, etc.
structure	configuration, arrangement, etc.
flexibility	fixed-changeable-adjustable-adjusting, modularity, etc.
comfort	snugness, suspension, climate, etc.
material	appearance, haptics, etc.
ecology	consumption, sustainability, etc.
economy	purchase, running costs, maintenance, delivery time, etc.
life cycle	maintainability, flexibility, number of users, resale, etc.
safety	active, passive, etc.
quality	workmanship, reliability, life span, etc.
region	culture, language, values, laws, standards, climate, use, etc.
service	transport, maintenance, recycling, etc.
personal	size, figure, handedness, handicaps, etc.

The checklist as it stands does not claim to be complete; also the criteria might be not completely independent from each other. But this list shall only serve as stimulation. The possibilities to realise the degrees of freedom within the product spectrum can refer to different dimensions such as the extent of customisation, the scope within the product, the concerned phases in the life cycle, or the flexibility within the whole lifespan. A list of realisation possibilities is proposed in Table 2. The approach will be enhanced by assigning selection criteria to these possibilities of realisation, i.e. between the kind of degree of freedom, further boundary conditions, and the realisation possibilities.

Table 2. Possibilities to realise the degrees of freedom

extend	realisation	description/example
standard	adjustability	adjustment during use, e.g. car seat position
	flexible materials	material adjusts to user, e.g. foam in seat
	software/electronics	easy adaptable, also learning programs
	symmetry/positioning	rotated, translated, or mirrored elements
	exceeding	fulfilment of highest demand
	automatic adjustment	technically elaborated automation
configured	change of surfaces	painting, coating, e.g. colour of product
	exchange of modules	definite decomposition, e.g. car engine
	standard interfaces (space)	definite interfaces, e.g. water connection
	elementary building blocks	standard elements, e.g. Lego, scaffolds
	multiplication	many identical elements, e.g. batteries
	configuration/external parts	independent parts, e.g. accessories
	product models	strong differences, e.g. SUV and convertible
	enabling	limitation, mere economical measure
	non-material interfaces	independent elements, e.g. blue tooth
parametric	change of material	no geometrical change, e.g. metal or plastics
	scaling	simple parameter variation, e.g. tube length
	parametric design	complex parameter variation, e.g. gear box
principle	handcraft adaptation	unplanned in detail, e.g. tuning of a car
	description of principle	design patterns, e.g. physical or biological
	services	functions of and for product, e.g. cleaning

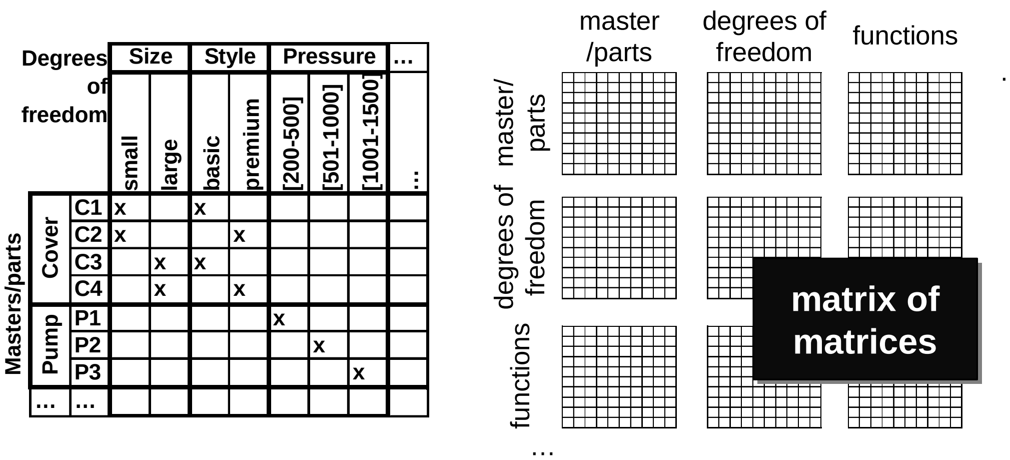

Figure 4. Exemplary matrix and "matrix of matrices"

The connection between the elements, e.g. between degrees of freedom and parts/masters, can be realised in matrices (Figure 4). The matrices can be arranged regarding all the elements, i.e. functions, properties, masters, parts, degrees of freedom, etc., which would finally lead to a "matrix of matrices" [10] and an approach similar to QFD-quality function deployment. The matrices might comprise values and weightings, equations, and even hierarchies. Dependent on the actual case, a specific "path" through the big matrix has to be found. A more detailed approach concerning these matrices might be the early evaluation of product properties, which gains special importance in mass customisation, since certain customer wishes influence the product critically while there is only little time to guarantee crucial product properties. Generally this is supported by a so called "analysis circular" [11]. Customer requirements and required properties as well as the yet carried out evaluation on one hand, the decomposed product and production system and the evaluation criteria on the other hand, when combined lead to critical units as well as critical properties. When integrating variants, these might replace the product structure, which in turn becomes part of the evaluation criteria. By that, critical variants and critical properties can be deduced. This might be the basis for a comprehensive testing. Since these matrices can become very big and the interdependencies quite complex, and since some aspects of the above mentioned product model are hard to represent in the matrices alone, a more sophisticated computer support is needed.

5 Computer support

5.1 Existing tools comprising product structures

The following table (Table 3) shall give a short overview of existing tools and systems that comprise a complex product structure or might be able to represent one. This overview is neither complete nor does it take research approaches into account.

Table 3. Overview of product structure systems

system/description	advantage	disadvantage
product data management (PDM)	large data amounts, central tool and database	too inflexible and rigid, not for early phases, not for individuals
CAD (computer aided design)	focus on design, detailed product model	no complex product structure, no abstract set up of structure
PPS (production planning and control)	large data amounts, variants and complexity regarded	not for early phases or product development, based on existing data
ontology editors (knowledge management)	very flexible management of classes	no direct product regard, abstract, computer background necessary
configuration systems	variants and product structures, for customer/sales	based on existing product structures, focussed on specification
designers workbenches	flexible documentation of development processes	no explicit regard of product variants
standard applications (spreadsheets, etc.)	generally usable, broadly accepted and well known	no guidance, rules, or formats for product structure planning

There are more tools similar to these with similar disadvantages. The list does not devaluate these approaches, but show that the existing tools are not ideally usable for product structure planning in early phases of the development process.

5.2 A conceptual tool for product structure planning

From the mentioned disadvantages and from a close regard of the development of variant rich products, requirements for a computer supported tool can be derived. These are mainly the representation of the above described elements of the product structure, different views (filter & zoom) on the product structure (specification/decomposition), a flexible set up of the structure in early phases of product development, the combination of graphical representations, matrices, and lists, the support of the designer by consistency checks and algorithms, a continuous use throughout the development process and interfaces to other tools, as well as ease of use, giving guidance, and being self-descriptive. Taking this into account, we have developed a prototype tool based on standard applications (Figure 5).

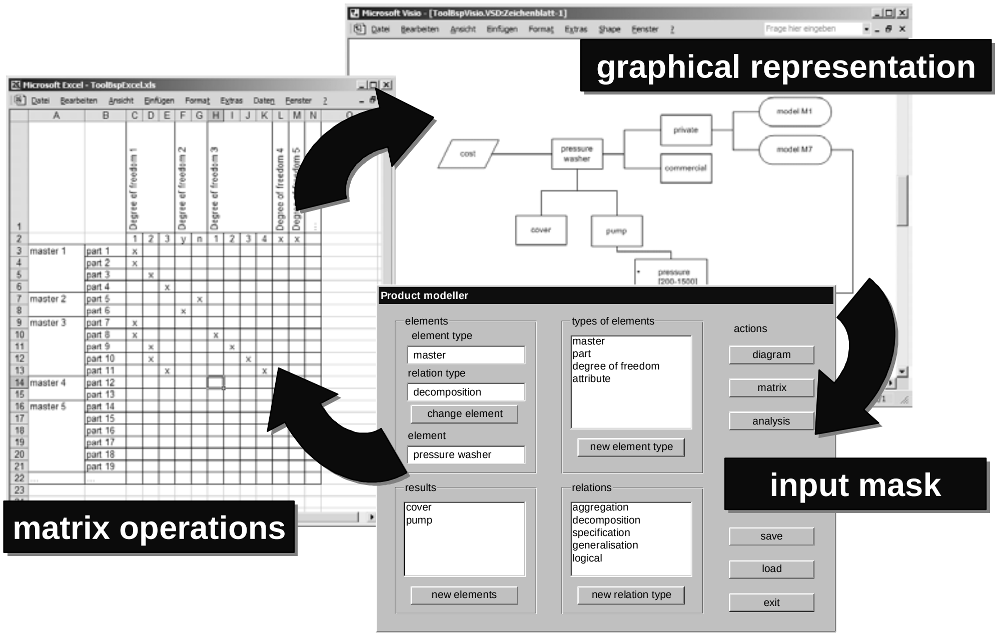

Figure 5. Prototype tool to store, represent, and work with the product structure

The tool comprises an input mask, in which the elements can be easily and systematically entered and specified. A spreadsheet enables the above described matrix approach. The graphical representation allows a general or filtered overview of the structure. A change in one representation propagates through the system to the other applications, so that processing is possible in any form. The use of standard applications helped set up the prototype as well as assuring a certain level of acceptance by the user. After general principles and approaches have been tested, the work on a more sophisticated implementation is in process now.

6 Summary, outlook and related work

The increasing demands on modern products – the trend towards more and more individualisation – have led to a complexity that is hardly manageable without some kind of paradigm shift. This change is not predictable, but mass customisation might be the possibility to cope with the respective problems. It combines approaches of business administration, production engineering, and product development. Regarding the latter, we have presented elements of a product model that is capable of representing comprehensive product spectra flexibly; the model is set up in a process similar to the general approach to design. This is supported by checklists and matrix representations as well as a computer based tool serving generally for structure planning by combining databases with matrices and graphical representations.

Further work aims at the continuously developing product spectrum, i.e. the application of genetic algorithms to the product spectrum in the meaning of the product type represented by the genotype, the individual product being the phenotype. By computer supported simulations and algorithms a continuous evolution of the product spectrum should be possible; first positive experiences have been made. On a more practical level, the mentioned computer tool will be set up in a better engineered implementation. Furthermore, selection criteria will be defined between degrees of freedom and possibilities of realisation as well as a detailed adaptation process. Finally, the evaluation of large product spectra will be optimised by the already addressed matrix approach as well as the application of design for experiments, multivariate analysis methods, and the like.

The presented results partly base on existing approaches in design methodology and complexity management; in the same way, the results can be used for each kind of design of variant rich products, e.g. mass production, plant construction, etc. By that, mass customisation is both a new approach by emphasising special topics and an extreme version of common design efforts. Mass customisation can stand as a separate offer on the market, but it can also be integrated in a larger company as a niche offer simultaneously serving for marketing purposes in the meaning of acquiring actual customer wishes.

7 Acknowledgements

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