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A design language for synthesis and systematization

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Summary

This paper establishes a proposal for a basic theory of technical systems and a design language for synthesis and modelling. Based upon this language is made an explanation and comparison of current design related areas like product modelling, feature based design, object parameters, and configuration.

1 Introduction

The area of design methodology posseses a strong basis for solving many of today's tasks related to design rationalisation, especially when information technology is introduced. There seems to exist a design language based on methodology and systematics, which has the ability to describe machines and serve for synthesis and modelling. This language may be based on a basic approach proposed by several authors, namely the structure/behaviour /function approach. To this may be added the Domain Theory, Andreasen [1], which is a machine modelling theory of genetic nature, i.e. it describes the synthesis of a machine.

A study of the synthesis activity and design models leads to a proposal for at design language, Mortensen [2], proposing that we may "spell a machine" by a structure of characteristics. Even if this proposal is unfinished, it gives us concepts and models which are powerful in the "spelling" of machines, which are necessary for creating digital models of machines.

This paper is closely related to a line of papers presented on earlier symposiums, in discussions on design of machine elements and in a contribution to discussions on a unified design theory, see the list of references. The paper is rising questions to the proper understanding of product modelling, feature based design, object parameters *(Sachmerkmale)* and configuration.

2 Structure, behaviour, and function

A central question in design is of course how we shall explain, describe, or synthesise a machine. We find basic approaches hereto, proposed early by several authors. Cybernetics and System Theory have stated that the concepts of structure, behaviour, and function are of central importance for synthesis and modelling of artefacts during the design activity. In the following the thinking line of Mortensen [2] is utilised.

Klaus [3] defines structure as *"Menge der die Elementen eines Systems miteinander verbindenden Relationen"* and behaviour as *"Menge der z.B. durch äussere Einwirkungen hervorgerufenen aufeinanderfolgende Zustände eines dynamischen selbstregulierenden Systems".* And Klaus defines: *"Die Funktion eines dynamischen System ist die Abstraktionsklasse der möglischen Verhaltungsweisen dieses Systems".*

Hubka [4] was inspired from this cybernetic approach and defines behaviour as "the sum of reactions to stimuli" and function as "the powerful behaviour of the system". Hansen [5] defines structure as *"inneren Aufbau eines technischen Gebildes"* and function as *"die für einen bestimmten Zweck genutzte Eigenschaft eines technischen Gebildes, die Menge X der Eingangsgrössen in die Menge Y der Ausgangsgrössen unter bestimmten Bedingungen zu* *überführen".* Similar definitions are found by Klir [6] and Ropohl [7]. Ropohl defines that the structure is determined, when the sub system types and relations types are determined.

As mentioned, Klaus [3] sees behaviour as the set of system states, where a state is a set of values of system characteristics. Gero [9] sees behaviour as an object's actions or processes under given circumstances. Klir [6] sees behaviour as the relation between response and stimuli. This leads to Mortensen's distinction between internal behaviour and external behaviour. Hubka [4] calls the internal behaviour *Wirkungsweise* and the external *Auswirkung* or effect.

Gero defines function as the purposeful part of a behaviour, where behaviour depends on the artefact's structures, states, and surroundings. Gero explains the design process as a search for a structure (i.e. a design), which expected behaviour is in accordance to the wanted function. During design and realisation, we have to verify that the actual behaviour is in accordance to the expected behaviour.

Andreasen [8] sees an interesting parallel between function and quality. Function is the user/designers utilisation of certain behaviours, where quality is the users appreciation of the objects properties, i.e. the non-active behaviours. Gero underlines this in the statement: "There is no function in structure" and "It is naive to imagine a (direct) relation between function and structure". [9].

Mortensen [2, 10] uses the illustration, fig. 1., to show the relations between a general systems terminology and his proposal for a design language (see section 5).

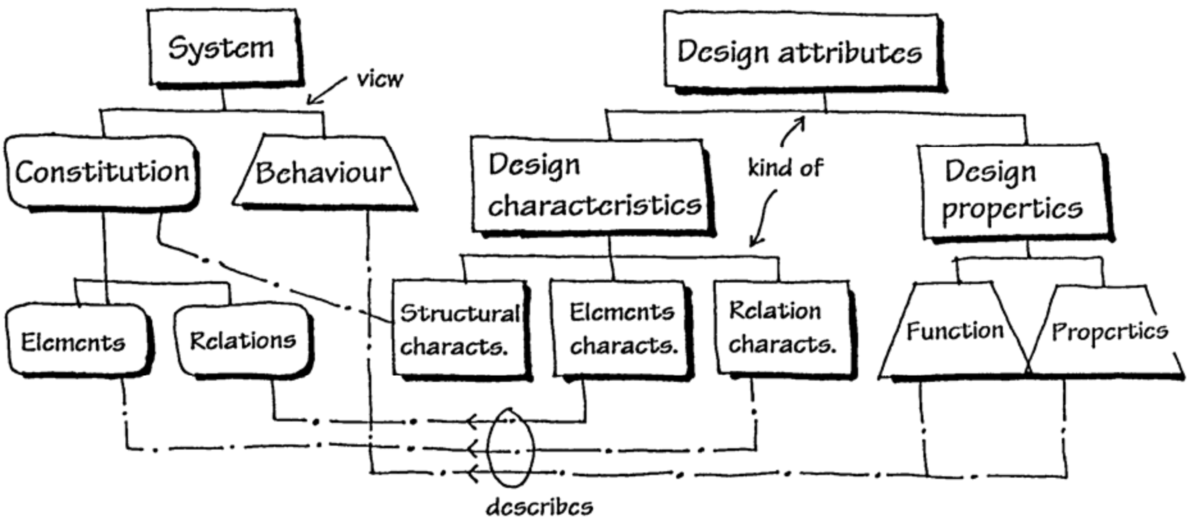


Figure 1 System theory concepts and Design language terminology proposed by Mortensen [10].

3 Domain theory

Until now structure and elements have been seen from a systems point of view. For getting closer we need to make statements on the artefact's nature, i.e. create a Theory of Technical Systems. Hubka [4], Andreasen [1], Hansen [5], and Roth [11] claim that there exist classes of characteristics, which define an artefact and thereby its elements and relations, called respectively, Basic design properties, Design characteristics, *Strukturelle Daten* and *Produktdefinierende Daten.*

The nature of the artefact, its beschaffenheit as Mortensen [2] chooses to call it in English(!), needs description of its structure, where structure is the class of attributes which define the system as an entirety, plus identification of the characteristics of the elements and of the relations. The basic idea is that an identification of elements and relations are not sufficient for identification, we also need a description of their structure.

In German design methodology there are many proposals for set of design characteristics to be determined during design (working principle, logical relationships, function structure etc.) Andreasen [12] claims, inspired by Hubka, that we only need three systems viewpoints on a machine for determining the machine. These three system viewpoints are:

- System of transformation, i.e. the structure of changes of material, energy and/or information realised in the use of the machine
- System of organs, i.e. the structure of organs, which creates the necessary effects (external behaviour) for establishing the transformations
- System of parts, i.e. the structure of parts, which realise or materialise the organs.

In each of these systems there are a behaviour. In transformation systems it is the actual transformation result (output operand), in organ systems it is the effect or function realised by the organs, and in part systems it is the tasks solved by the part, see Mortensen [2], and see fig. 2.

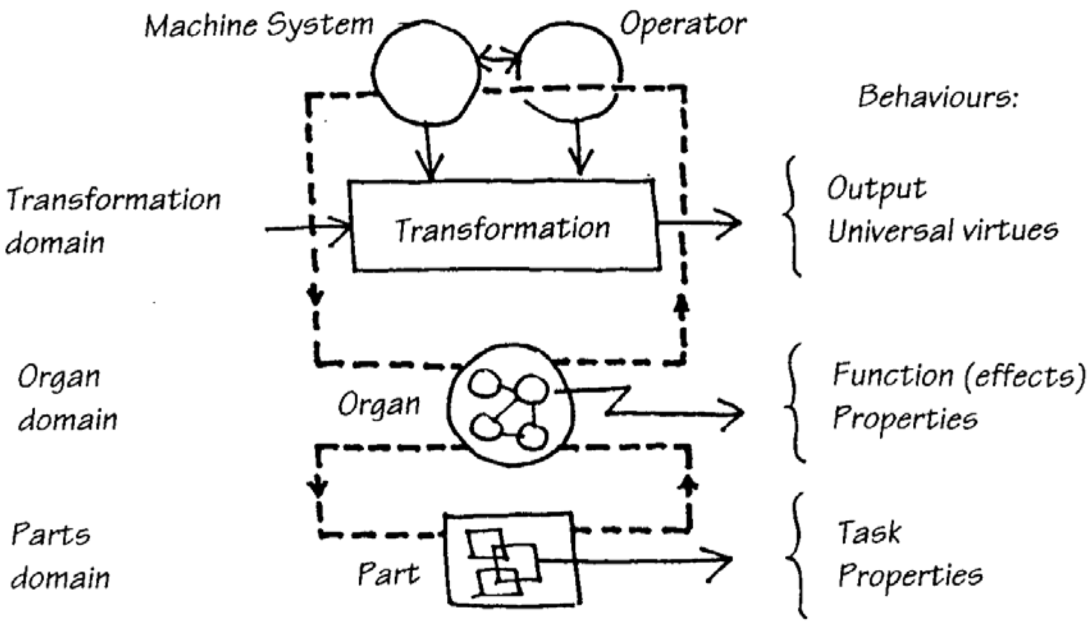


Figure 2 Illustration of the domain theory. Three system views and three types of behaviour are shown, Andreasen [12].

4 Classification and design

The Domain Theory proposes three system models for the synthesis of machines. How shall such a model be build up? In the following we will present patterns which should be mirrored in such models, and their reasons.

The model shall show the system's structure. In a systems engineering approach this means that synthesis of a machine is a successively identification of a solution for a system, leading to a set of sub-systems to be solved, Svendsen [13]. An important law is here Hubka's law [1], which may be modelled in the so-called Funktions/Means-tree [12].

The model shall define its elements by characteristics. It is well known from design methodology that a solution principle, its layout, and detailed design can be characterised by certain parameters. It is also known that choice of other parameters leads to solution alternatives (variation principle, Koller [14], and that a solution becomes gradually clarified by choice of characteristics (intentional) and their destinction or *Prägung* (extensional characteristics, at lowest level quantitative). It is possible to make solutions catalogues, Roth [15], where the classifying characteristics are the same as those we use in description of solutions, and we see that more concrete solutions contain more distinct *characteristics (Merkmale mit Prägung)*. But we also know that the same object or solution may belong to different classifications, i.e. objects have many behaviours and therefore more functionalities.

But a central question is if we can create a full definition based upon characteristics. Full does not only mean complete, but also a description with syntax and semantics, so that the designer and a computer can read and interpretate the model. It is an established ideal procedure in design methodology to create a functional structure *(Funktionsstruktur)*, consider a set of organs *(Funktionsträgern)* and then to solve all lower levels of functionality in the detailing phase, leading to a complete and unambiguous part *structure (Baustruktur)*. In this procedure we would not find it worthwhile to add all functions to the functional structure and document each solution consideration. But the part structure must be complete and correct.

Mortensen [2] in his thesis declares that there does not exist a set of design characteristics which cover the modelling of all objects. The necessary characteristics depend on the physical domain and application area. Mortensen also declares that the pattern of characteristics do not have a general trait.

As an example we may look upon a mechanical object, a snap action connection. This artefact may be modelled in the organ domain by the characteristics proposed by Ersoy [16], namely wirk surfaces, wirk movement, wirk field etc., and an added skeleton for defining where these organ elements shall be arranged. In the part domain we may create a part model, which explains how the parts form, surfaces, dimensions, and material are related to the organ's wirk elements, for instance that a beam is a material field with a E-module, which can create a wirk element for transfer of forces.

The work on the Domain Theory's product modelling approach has many open questions. In the following we have a closer look upon it's product modelling benefits.

5 A design language

In the design area we have used many types of models to capture and define the artefact we design, and for simulation and reasoning about the properties of the design. These models have covered our needs in a rather uneven way, Roth [11] and many models have shoved low degree of semantic and syntax, leaving an unsure interpretation to the human mind.

Today we face the situation that we want to use computers for supporting design. It means that the human operator shall share, at least in the interpretation, models with the computer. We have suddenly recognised the need for semantics and syntax and we see a close link between models and languages. So our current attempts (schematics, technical drawings, feature language, STEP, etc.) are not pointing in the right direction.

The ideal conditions for a design language, Mortensen [10] are:
- allow alternation between entirety/elements modelling and abstract/concrete modelling
- allow alternation between different classes of models and model representations, especially allow the creation of different view models (for instance a control theory view upon a machine).
- allow gradual determination *(Prägung)* of the design model content
- allow that modelling is based upon entities which have functional and structural significance
- allow that part of the design reasoning can be captured and documented in design models

As pointed out by Duffy et al [17] design and designing may be seen in four domains, fig. 3: A reality domain, a phenomena domain, an information modelling domain, and a domain where the model is brought into a computer. The main topic of this article is the theory domain, i.e. how do we describe an artefact? Each of the four domains has its own language.

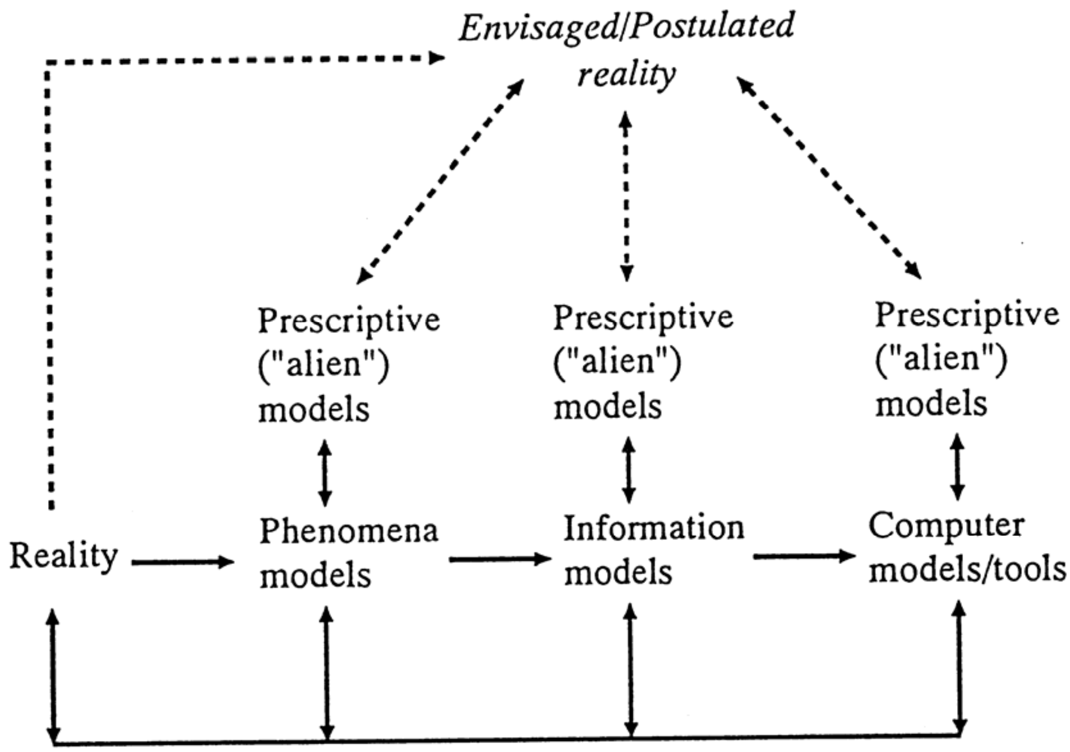


Figure 3 A research approach (Duffy et al [17]) in which phenomena seen in reality are transformed into models of phenomena, information models, and computer models and tools.

A design language shall ideally seen cover two domains, namely being able to describe artefacts in the phenomena domain and transfer this description into an information model which can be treated by the computer.

As mentioned above Mortensen [2] does not see the possibility to create a generic design language, but points out that each family of products might have its own language. However he has established a generic pattern of language elements for and for organ elements.

In the following we will take a starting point in the Design Language concepts (fig. 1), the idea of three Domains, its multiple function approach, - and make a confrontation with a row of application areas which are of importance.

6 Functional reasoning

A core method in design methodology is functional reasoning. We have here (section 2) introduced the concept that a reasoning from function to structure actually has behaviour as an in between step. And the Domain Theory points out that there are three distinct classes of structures and behaviours in a machine and therefore three types of functionality and functional reasoning.

When we reason about function we may chose between looking upon function as the internal changes or the external effects. We have choosed the effect approach defining function as an artefacts ability to deliver a distinct effect.
In earlier publications about the Domain Theory a functional domain was added as a fourth domain. This was in accordance to current design methodology, where establishing a functional structure is seen as a step of synthesis. But as seen in section 2 we cannot synthesise or define an artefact by behavioural characteristics. We have seen it as a fault in the Domain Theory, therefor we now work with three domains.

An explanation of the functional structure approach could be the following. Besides the mentioned interpretation, function may be seen as an abstraction of an organ *(Funktionsträger)* into what it does, what it delivers or what "it is". Therefore German literature discusses functional elements *(Funktionselemente)* and similar concepts, seeing these as artefacts (components, parts or features of a part). From this point of view a functional structure might be seen as a very abstract organ structure, but this idea is unsharp.

It is interesting to see how few attempts the design research literature makes to explain the functionality of a part. Normally more parts constitute an organ and therefore a part has no functionality in itself. An exception is a part which also constitutes an organ, like a beam, column, spring, and similar. Mortensen [2] uses the word task for a parts functionality and he allocates a task ("deliver wirk surface", "create wirk movement") to a part's wirk elements.

We may conclude that in relation to functional reasoning the Theory of Technical Systems gives a certain clarification and an expansion, which the authors see as a core in a theory of detailed design.

7 Object parameters *(Sachmerkmale)*

Object parameters are brought together in lists or tables, where a table determines and make demarcation of a set of materialised objects, which are showing similarity *(ähnlich-keit)*. The lists or tables are used by companies and designers, who want to utilise some of the objects in their design, i.e. make an architecture based upon these (standard) objects. Some definitions are necessary here (DIN 4000 part 1), see also fig. 4:

> A characteristic is a certain property, used for description and differentiation of objects in an object group.

A characteristic may be intentional (like colour) or extensional (like red, green, blue...). In German the extension is called *Ausprägung.*

An object parameter *(Ein Sachmerkmal)* is a characteristic, which describes the object independent from its context. It might be called a “eigen-characteristic”.

A relational characteristic is a characteristic, which characterise the object in relation to its context.

A set of objects may be described and defined (identified) by an object parameter list *(Sachmerkmal-Leiste).* A picture *(Bild)* belonging hereto is a graphical representation of an object, which shows how this object in its design *(Gestalt)* differentiate from other objects or object groups, and which shows the necessary set of characteristics. Figure 5 shows examples of an object parameter list.

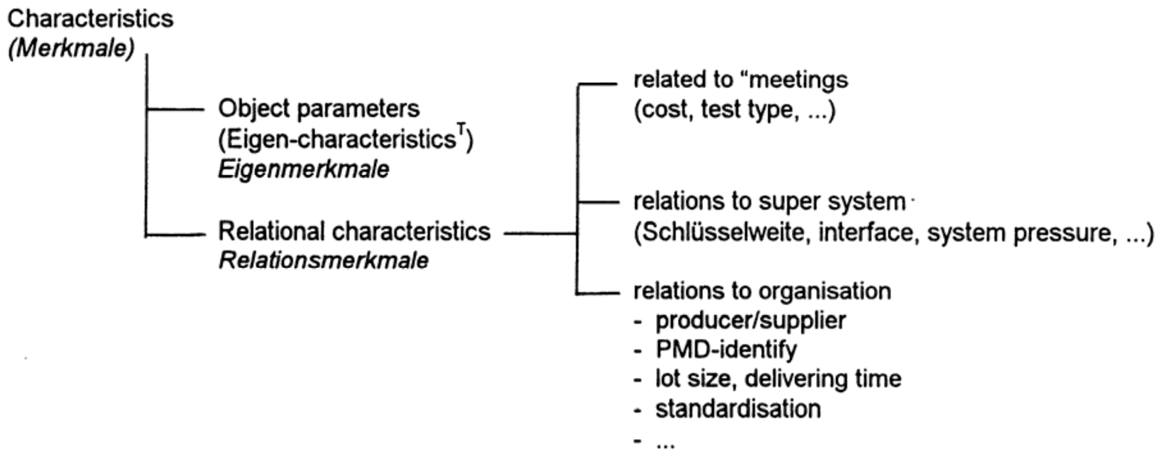


Figure 4 Object parameters as defined in DIN 4000 and our interpretation of rational characteristics.

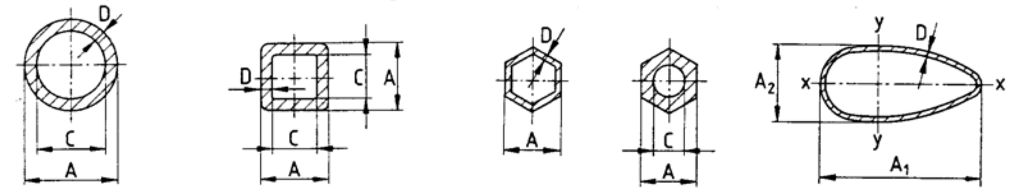
In the following we will confront the concept of object parameters with TTS, using the indice T for words belonging to TTS. DIN 4000 does not distinguish characteristic *(Merkmale)* and property *(Eigenschaft).* The following may be seen from the examples and the use:

1. Object parameters may be both characteristics^T and properties^T, see fig. 5, where Nenndruck is a relational property^T, Wiederstandsmoment a property ^{T} and the rest characteristics ^{T}.
2. The relational characteristics can be of many kinds, see the detailing in fig. 4.
3. The pictorial definition has a language which is not precisely related to TTS, see the table below:

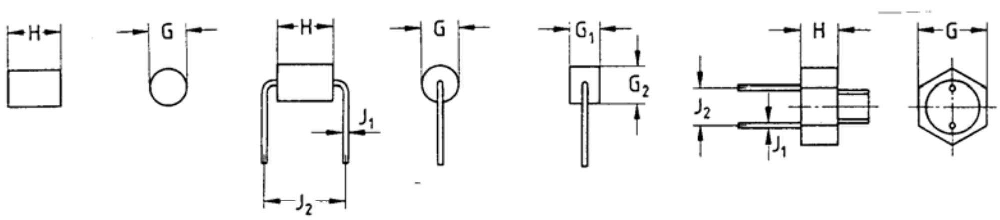
Table 1 Comparing DIN 4000 characteristics to TTS

DIN 4000: Characteristics		TTS
Teilgeometrie	Part geometry	Form of a part
Form	Form	Form
Stellung	Position	Position relative to skeleton
Ausführung	Design	Design (form) variant
Funktionselement	Functional element	Wirk element

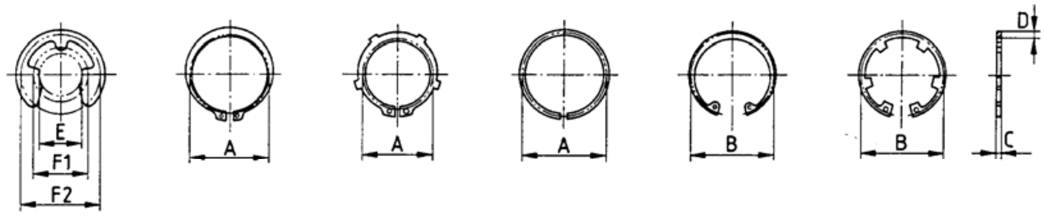
4. The set of characteristics is not a full set of structural characteristics ^{T}. It means there exist additional documents and specifications, often specific for a supplier, which specify fully.
5. The DIN 4000 has in it’s text no defined purpose except its ability to define classes!



Sachmerkmal-Leiste DIN 4000 – 4 – 11									
Kenn-buchstabe	A	B	C	D	E	F	G	H	J
Sach-merkmal-Benennung	Außen-durchmesser oder Außen-Breite und -Höhe oder SW A_1, A_2	zul. Abw. zu A	Innen-durchmesser oder Innen-Breite und -Höhe C_1, C_2	Wanddicke	zul. Abw. zu D	Nenndruck	Wider-stands-moment W_x, W_y	Werkstoff	Oberfläche und/oder Schutzart
Referenz-hinweis									
Einheit	mm	mm	mm	mm	mm oder %	bar	cm^3	–	–



Sachmerkmal-Leiste DIN 4000 – 6 – 5									
Kenn-buchstabe	A	B	C	D	E	F	G	H	J
Sach-merkmal-Benennung	Nenn-widerstand R_N bei Umgeb.-Temp. ϑ_u	zulässige Ab-weichungen zu A	Bezugs-widerstand R_b bei Bezugs-Temp. ϑ_b	Temperatur-koeff. α_R	Anw.-Klasse nach DIN 40 040 oder Temperatur-bereich	Betriebs-spannung U_{max} bei Umgeb.-Temp. ϑ_u	Durchmesser oder SW oder Breite und Dicke (Höhe) max. G_1, G_2	Länge oder Höhe max.	Anschluß-maße oder Anschluß-art J_1, J_2
Referenz-hinweis									
Einheit	Ω; °C	%	Ω; °C	%/K	–; °C	V; °C	mm; –	mm	mm; –



1 von 2	Sachmerkmal-Leiste DIN 4000-3-4.1									
	für Sicherungsringe mit rechteckigem Querschnitt									
Merkmal-Kennung	BLD	A	B	C	D	E	F 1	F 2	G	H
Merkmal-Benennung	Bild-Kennung	Wellen-durch-messer (Nenn-maß)	Boh-rungs-durch-messer (Nenn-maß)	Dicke	Breite	Wellen-nut-durch-messer (Nenn-maß)	Kleinster zuge-höriger Wellen-durch-messer	Größter zuge-höriger Wellen-durch-messer	–	Werk-stoff
Einheit	–	mm	mm	mm	mm	mm	mm	mm	–	–

Figure 5 Examples of object parameter lists and pictures for tubes (DIN 4000-4-11), electrical resistances (DIN 4000-6-5), and Seeger rings (DIN 4000-3-4.1).

We see object parameter lists as a subset of a part definition, fitted for a specific, tradition determined market use, where certain parameters are interesting for the user. Some of these parameters are structural, some behavioural. There exist no unambiguous definition of object parameters. The set used in an object parameter list is determined by the use situation: What is necessary for using the object in a traditional way and ensuring it's correctness and qualities?

Objects are related to a technical area *(Sachgebiet).* The allocation of objects to a technical area is a matter of the object's narrow or broad utilisation. One may believe that there exist

objects belonging to more technical areas. Without market insight one may not identify a technical area and determine the characteristics.

If we would like to be advised as designers from the object list, there are several things missing (fig. 5):
- parts are not explained as contribution to an organ. For instance the Seeger ring is a type of connection organ, needing a groove and a shoulder
- parts are not explained in proper exposed situations. The tube is not shown with water under pressure inside. What are the allowed force-directions for the Seeger ring?
- composed parts, which have functionality (i.e. organs) have no function statement.

We see here that a theoretical approach to object characteristics gives a deeper understanding of their nature.

8 Configuration

Compared to the area of object parameters we add a great complexity when we proceed to the area of configuration. Basically configuration is the activity to create a product based upon given elements (modules, units), obtaining specific properties defined by the customer or a designer using a configuration system. Normally the elements have more alternatives. A specific configuration should lead to a valid architecture, therefor a set of rules has to be derived, controlling the process.

There exist more types of configuration, one of these is sales configuration. Here the customer specifies certain attributes, and a computer system propose an architecture, i.e. a composed product. The product family may be specified by a product family master plan, Riitahuhta & Andreasen [18], which may be seen as a total specification of structure, elements and relations.

Many companies create modules as elements of the product family. These elements may have functionality and defined, uncomplex relations. The ultimate dream seems to be that a company's suppliers deliver assembly ready modules in accordance to companies architectural definition. So now we are in the same area as object parameter lists. How shall we specify a module in such a way that a user or a configuration system directly can use it for configuration?

The user/configuration system might want to know the following related to a module:
- functionality
- selected characteristics and properties
- a full structural specification of the module
- methods for determining properties or at least a list of properties.

The two first might be sufficient for the configuration. The two last might belong to the supplier company.

Setting up the rules for configuration we might see that modules are interrelated by
- transformation objects (material, energy, and information), flowing from one module to another
- organ relations (forces, movements, current, positions, etc.) from one module to another
- connections, i.e. the physical relations (connecting organs) between modules.

It seems from the authors experience that a critical point in utilisation of configuration support systems is the company's ability to "spell the product family" in a proper way. Often the configuration software is based upon a non-technical vocabulary. It is important to recognise that that object oriented modelling do not give an answer to this, compare fig. 2, as this approach is not an artefact theory able to explain how to spell the product. We need TTS.

9 Features

The efforts to utilise features for design and production planning may be seen as an attempt to create a design language. Surprisingly there has not been proposals to relate design methodology to feature thinking and features have been seen as a concept which could not be defined!

If we assume that there exist as proposed above a product model formulated by characteristics then we may be able to interpretate the literature's feature definition: ”Something” in the product is related to a "meaning", as follows:

- ”Something” seems to be a set of characteristics, for instance form characteristics
- ”a meaning” seems to be related to the product life, for instance a production system, the meaning being: "This geometry may be produced by this production method".

Based upon this, Andreasen & Mortensen [19] proposed at the 7. Symposium a feature definition:

> A feature is a relation (according to an engineering purpose) between a set of product characteristics (semantic readable) and another set of product or product life system characteristics (semantic readable)

It means that for instance a production feature might be a set of part characteristics, related to a set of production process characteristics (tools, movement, velocity etc.), combined to the knowledge that this part can be produced by this process with a certain quality.

The feature concept proposed here is easily expanded to several types of highly interesting features, which may be the core of a designer's workbench.

10 Conclusion

This paper raised the question of the existence of a basic theory for synthesis and modelling of machines. Contributions to the Theory of Technical Systems are sketched and it is made probably that a design language should exist. Using examples from design areas where systematisation and "spelling the machine" are necessary it is shown what type of clarification there could be in using TTS concepts and theories.

The TTS is still in its conceptual stage. Many types of clarifications are necessary before we can make genetic product models and use the Domain Theory and the Design Language for a transparent traceable design process.

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