INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'07
28 - 31 AUGUST 2007, CITE DES SCIENCES ET DE L'INDUSTRIE, PARIS, FRANCE

DECISION MAKING WITH INTERDEPENDENT OBJECTIVES IN DESIGN FOR X

Stefan Bauer[1], Harald Meerkamm[1]
[1]University Erlangen-Nuremberg, Institute of Engineering Design

ABSTRACT
Decision making tasks in the product development process (e. g. the choice of solution principles or the specification of materials and geometry) are often difficult because the basic objectives (cost, service life or accuracy, etc) which have to be fulfilled are interdependent. There are objectives which support each other, but often, several desirable objectives compete against each other.
Obviously, it is important to know those interdependencies and their holistic interactions exactly. Otherwise, when choosing and weighting the different objectives which have to be fulfilled by the product, it is hard to find the right strategy matching the needs of the considered market segment. Nevertheless, although it is relatively easy to rate the degree of interaction between two objectives based on adequate experience, the whole structure of interactions between several interdependent objectives from different DfX areas can hardly be understood or managed.
Hence, in this paper a method is to be introduced, with which complex decision making tasks dealing with interdependent objectives (or criteria) can be visualized in an easy way. A further goal of this contribution is to show how this method of visualization can be used to represent hierarchies of objectives graphically in an easy way. Furthermore, the paper will figure out how this visualization method could be used to show the connection between design parameters to set (e.g. size of a part or the type of material) and the resulting objectives (e.g. costs, service life ore accuracy).
Beside the presentation of the current state of the implementation of the method, practical applications of this visualization method are to be discussed. For example, the visualization can be used to graphically define product strategies (e.g. cheap model ore high-performance model) by balancing between the basic DfX objectives and to calculate corresponding weighting factors considering existing interdependencies.
In the end, a practical example will be used to illustrate how the visualization method works and to show the potential of the introduced concept.

Keywords: Design for X, Multi-Criteria Decision Making, Multi-Criteria Evaluation

1 MULTI-CRITERIA DECISION MAKING TASKS IN THE SURROUNDING FIELD OF DESIGN FOR X

1.1 Fundamentals

1.1.1 Design for X
DESIGN FOR X (DfX) is a frequently used term behind which a very complex topic is concealing. So far no explicit definition of the term "DfX" exists. According to Hubka [1] a knowledge system is understood by DfX, in which cognitions, how individual properties of technical systems are achieved by engineering design, are collected and organized in an appropriate form. According to [2], [3], and [4], the term "X" may thereby be regarded as a replacement character that denotes a phase of the product lifecycle (e.g. assembly) or a specific property of the product (e.g. costs). By Huang [5] however, who circumscribes the term DfX with "making decisions in product development related to products, processes and plants", the decision making process is in the foreground. So according to these definitions, DfX stands for all endeavors towards making the right decisions in the product development process on basis of a sufficient and universally applicable knowledge basis.

1.1.2 Properties and characteristics

For interpretation of the terms "properties" and "characteristics", here categorically the definitions introduced in [6] shall apply:

- Characteristics: Define the product. Can be directly determined by the designer.
- Properties: Describe the product's behavior. Cannot be directly determined by the designer.

Because decisions in product development also directly extend to process parameters (manufacturing process, manufacturing accuracy), the definition shall be extended to the process prospect:

All product and process-defining parameters and values, which are directly determined by the product developer (or in arrangement with production specialists) are in the following referred to as "characteristics".

As "properties" all consequences pertaining to the product and to (manufacturing) processes shall be considered, which directly result from the determination of characteristics.

1.1.3 Objectives

"Objectives" are terminology-based to be distinguished from "properties". The discrimination shall be made in terms of [15]: While "properties" are of product-specific nature (e.g. weight, assembly properties, or handling properties) and directly verifiable by testing, simulations, or measurements, relate "objectives" rather to the quality of the processing of development project activities. A collection of such basic (development) objectives is found under the designation "universal criteria" in [15]. Mentioned are there the objectives "costs" "quality", "flexibility", "risk", "time" "efficiency", and "environmental effects".

Now if we set up a hierarchy of objectives as suggested by Zangenmeister [22] for example, objectives as understood in this sense will be superior to the (desired) product properties.

1.1.4 Horizontal and vertical dependencies between properties, characteristics, and objectives

Hierarchical structuring of characteristics, properties, and objectives shows the strong interdependency of those variables (figure 1). For a more detailed consideration of the relation between characteristics and properties, reference may be made to [6] and [7].

The four levels diagrammed in figure 1 are of basic nature. The levels "objectives" and "properties" may be subdivided into several hierarchy levels if required. Also is it thinkable in turn to logically hierarchically structure characteristics.

Hierarchic (vertical) dependencies between characteristics, properties and objectives normally commensurate to m:n relations (see also [7]). For that reason, horizontal interdependencies between the different product properties and objectives come into existence. These horizontal dependencies frequently become noticeable as conflicts of objectives, which to solve is a great challenge in the steps of synthesis. In analytic procedures, particularly in evaluation processes using conventional evaluation methods, horizontal dependencies make the proper weighting of evaluation criteria more difficult.

In practice in this connection, many decision-making problems result in the context of one of the following questions:

<u>In steps of synthesis</u>

- Which objectives of the various DfX sub-areas are to be achieved to what degree, i.e. what is the right strategy for the product to be developed?
- Which product properties need to be determined and how is to be balanced correctly between those in order to achieve the desired objectives?
- Which characteristics must be chosen and how so that the product obtains the desired properties?

<u>In steps of analysis</u>

- Does the conceived/drafted variant of the technical system to be designed actually have the demanded properties?
- Will the conceived/drafted variant of the technical system to be designed satisfy the determined objectives?
- How can with several solution alternatives be found out, which alternative is the best?

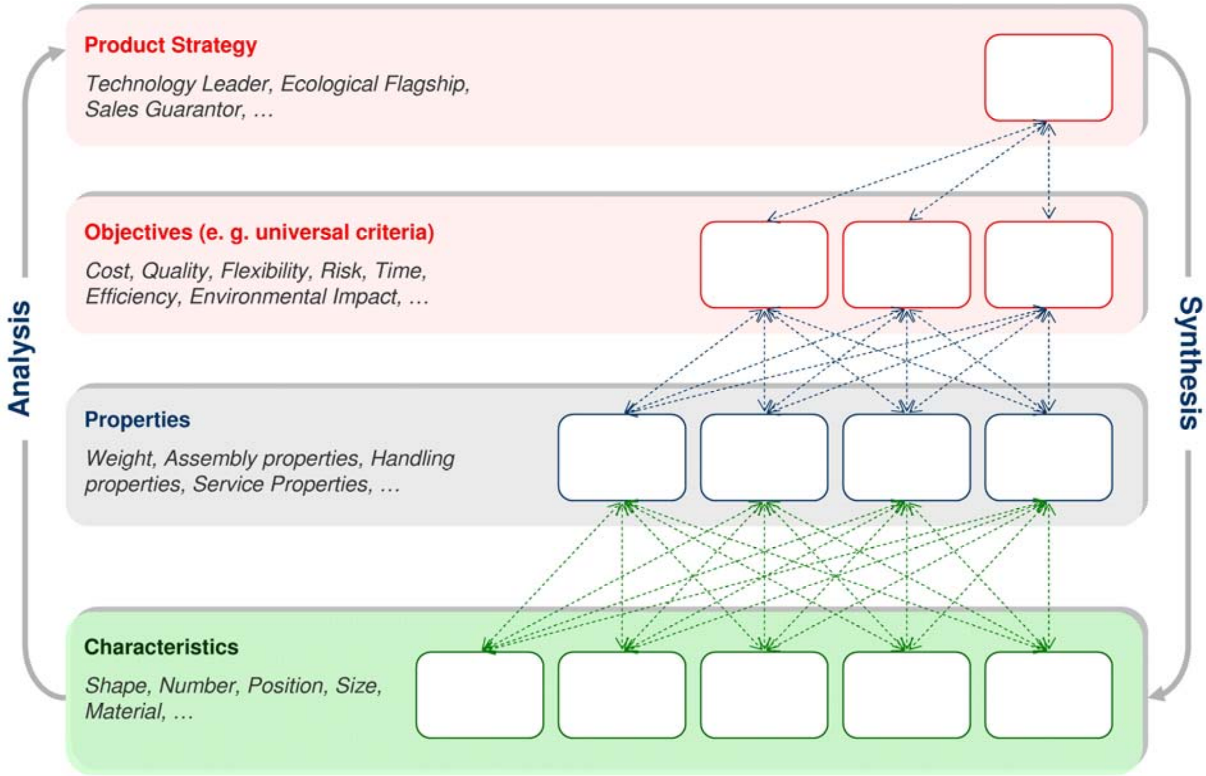

Figure 1 – Correlation between characteristics, properties, and objectives

1.1.5 Requirements and evaluation criteria

In the requirements list, the product properties to be achieved are fixed in first place (e.g. weight, capacity, etc.). Sometimes it is also necessary to directly determine individual characteristics (e.g. important connecting dimensions). These requirements represent the basis for evaluation criteria for the evaluation of the generated product variants.

In the determination of requirements and evaluation criteria respectively, the dependencies shown prove to be problematic, since they often lead to a redundant consideration of individual aspects (through vertical or complementary horizontal relations), or to unrealizable conceptual formulations due to contradictory demands. A detailed treatment of requirements and evaluation criteria is found in [11].

1.2 Implements for decision making tasks

1.2.1 DfX guidelines, methods, and tools

DfX guidelines describe a form of representing the knowledge system mentioned by Hubka [1]. They serve as direction signs that point out the way to the realization of as many as possible desired properties of the product and of the associated processes during the product development processes. Particularly apparent becomes by the application of DfX, which product characteristics should be chosen and how in order to achieve the respective product property considered. The nature and the degree of exactitude of DfX guidelines are depending on the respective product development phase considered.

Systematic approaches for the successful application of DfX guidelines are termed DfX methods. These methods frequently provide support in synthetic and analytic processes. For the aspects of manufacturing and assembly, effective approaches as, for instance, support in the determination of the tree structure and in production-oriented form design [8] already exist. Regarding assembly-oriented design engineering, the decision for the right tree structure (differential, integral, or composite construction) is treated in the early phases while assembly oriented design is treated in the in the later phases, for example by Andreasen [9]. On this basis guidelines and methods for assembly-oriented design engineering are developed. Another known DfX method is DESIGN FOR MANUFACTURE AND ASSEMBLY (DFMA). This is about a systematic procedure, which should help to design components in a way so that they can be produced economically by the most suitable production

process and the number of parts to be assembled can be minimized. The latter should be achieved by a suitable determination and early analysis of design engineering concepts [10].
DfX tools are practical implements for product developers, in which DfX methods are realized. Normally these tools are offered in form of software solutions (cp. [10]). DfX tools first of all provide assistance in the analysis of alternative solutions (a sufficient number of determined characteristics) regarding one or several DfX partial aspects (demanded properties). In this sense for example, calculation and simulation programs (analyses regarding functional capability and strength), cost calculation programs, tolerance analysis programs, or also programs for the analysis of environmental compatibility of a product can be designated as DfX tools for individual aspects.

1.2.2 Multi-criteria evaluation methods

A general definition of a valuation procedure is found for example in [11]: "For a finite set of solutions of arbitrary nature in arbitrary domains and in arbitrary stages of maturation, however of same information content, common evaluation criteria are to be established, those are to be provided with uniform ascertainable and comparable values (valuation numbers), and theirs sums (values) are to be compared in a value comparison in order to ascertain the best solution by the highest value and the worst solution by the lowest value in this way". Thus the valuation procedure represents a central precondition for decision making: The search for the most objective best solution from a selection of several variants. All evaluation methods, for which the described definition applies, have in principle a similar procedure. The execution of the individual steps of the procedure however proceeds very differently. Some of the most customary methods are e.g. the technical-economical evaluation according to Kesselring, weighted point evaluation, or the utility value analysis. The most important element of an evaluation procedure is undoubtedly to be seen in the selection and weighting of evaluation criteria, since exactly here the description of the requirements made on the product and with it the strategy pursued is determined.

1.3 Consideration of dependencies

Most available implements for decision making are not able to handle dependent objective targets directly. However individual papers and approaches exist, which deal with a holistic contemplation of DfX in this sense:
In [12], algorithms for the identification of technological dependency relations and for clearing up of valuation criteria are introduced. For cancellation of contradictory requirements it is recommended to compare the respective criteria and to delete the lesser important criterion. This method of criteria clearing is also used in [11], whereas there the dependencies between the criteria shall be verified by means of a relations test matrix. Problematic with this type of criteria clearing is however that individual aspects can get lost by deleting of criteria. Moreover is the problem of the weighting of complementary criteria methodically not supported. Such an eliminating strategy furthermore disregards a number of acknowledged innovation technics (TRIZ, WOIS), which are based upon the resolution of contradictions as an ideal requisite for innovative solutions.
Andreasen formulated in [4] an approach to explain theoretically DfX and "multiple DfX" (simultaneous consideration of several DfX aspects). For that purpose he introduced fundamental thinking structures and methods for the treatment of "multiple DfX".

2 A NEW TOOL FOR SUPPORTING MULTI-CRITERIA DECISION MAKING TASKS

2.1 Idea

The basis of this method is provided by the concept already introduced in [13] and [14]. According to this, a graphic representation of the entire netting of all interacting requirements of one decision making task shall be generated. For this purpose, requirements (desired product properties) are represented as points in a space. Competing (complementary) requirements thereby show a great (short) distance between each other. This way of visualizing offers a number of potential applications that will be introduced in the following.

2.2 Concept

2.2.1 Setting up of a matrix of interactions

At first, the (desired) product properties are to be compared pairwise in a matrix with regard to their dependency. For that purpose a measuring number between -5 and 5 is assigned. Thereby stands -5 for maximum competition while highly complementary properties are characterized by the assignment of the measuring number +5. Through this matrix of interactions, the entire information about the decision making task to be represented is communicated. For that reason it is important to investigate the information content of this matrix more closely.

For this purpose is to be clarified in which way an interaction (respectively dependency) of two properties is evaluated by a product developer. This shall be made clear by an example: A bicycle to be newly developed shall have among others the properties of "low rolling friction" and "good cross-country mobility". How will a developer now quantify the dependency between these properties? In the mentioned example, this will happen in most cases intuitively due to the prevalent experience with the product group bicycle: The properties are categorized as highly competing. Why? For this purpose, the (in this case probably subconsciously proceeding) argumentation process must be examined. One will firstly reflect about the first property (little rolling friction) and identify, which characteristics are decisive for that property and how they will have to be chosen qualitatively. In the example, one will think of very narrow tires (characteristic), which are pressurized by high air pressure. This corresponds, if you want, to a notional step of synthesis for the achievement of the product property "little rolling friction". In the next step one will analyze what impact the determination of the identified characteristics will have on the second property (good cross-country mobility). Here one will notice in this example that good cross-country mobility would require an exactly oppositional determination of the characteristic "tires": As wide as possible with rather moderate air pressure. Result of this deliberation process is in this case the categorization of the considered pair of properties as highly competing: So it is rated in the matrix of interactions for example by the value -5.

Retained is to be that a quantification of dependencies between product properties (implicit or explicit) is in each case based upon the significant product characteristics. Consequently by editing the matrix of interactions, information about product characteristics is implicitly brought in. As it is shown later, they will also be found in the graphic representation.

In the case of simple known technical systems, the notional conclusion from the desired properties on the characteristics to be chosen and to be determined (step of synthesis) takes place mostly automatically on basis of knowledge from experience. Basically also DfX guidelines, methods or tools are providing support in this conclusion from properties on characteristics. However the danger exists (particularly when estimating interdependencies on basis of experience) that competitions or contradictions between properties are assumed, which would not exist if characteristics were skillfully determined. Particularly then when in conventional, traditional solutions a discrepancy between the considered properties actually exists and unusual, novel characteristics specifications remain unconsidered, such wrong assumptions are preprogrammed. To avoid this, at this point reference is made to innovation technics, e.g. TRIZ or WOIS.

2.2.2 Visualization

On basis of the matrix of interactions, a graphic representation of the considered interacting properties is established. For this purpose, each property is represented by one point in a space (property point). The positions of these property points are calculated so that the representatives of complementary (competing) properties show a short (great) distance between each other.

Thus the fundamental task in generating visualization is the calculation of the pairwise distances between property points. For this purpose, different algorithms were studied respectively implemented.

Multidimensional scaling (MDS)

Multidimensional scaling (MDS) is a collective term for methods by means of which a representation of the objects in a metric space is determined via information about pairwise relations between these objects [17]. This space can be arbitrary dimensional. It is assumed that objects have a position in the space of perception of a person and that they are judged by that person according to several dimensions [18]. The person can describe the objects and their relations among each other, but the representation of the positions of the objects (the so-called configuration) in this space of perception is difficult. MDS was developed with the objective to graphically represent this very configuration by means of a pairwise comparison of the considered objects regarding their relation. For this reason, MDS seems to be predestined for the representation of interdependencies between product properties. By means of an implementation it was also possible to demonstrate that absolutely very useable visualizations of dependent properties can be ascertained. However the fact that these configurations are ambiguous and consequently, that each recalculation of the same task will lead to a different result proves to be problematic.

Forces model

An analogy from mechanics is providing the basis of a new method of own development for calculating the distances between property points. For this purpose each interdependency between two properties is modeled as a force between the representing property points. A force is thereby defined as follows (1):

$$F_{ij}(d_{ij}, w_{ij}) = (d_{ij} - 6 + w_{ij})^3 \cdot |w_{ij}| \quad (1)$$

d_{ij}: Distance of property points P_i and P_j in the visualization space

w_{ij}: Interdependency between properties P_i and P_j as per entry in the interdependency matrix; $w_{ij} \in [-5, 5]$

For the calculation of distances, at first for each property a corresponding property point is placed in the visualization plane. Then the corresponding force for each property pairing according to (1) is determined and entered. The objective is now to calculate those distances d_{mn} for all property pairings, for which the resulting forces at each property point equal zero and consequently the overall system is in equilibrium (figure 2). The arrangement of property points determined in this way proves to be a good visualization of the overall interdependencies and yields in contrast to multidimensional scaling a unique and thus reproducible result.

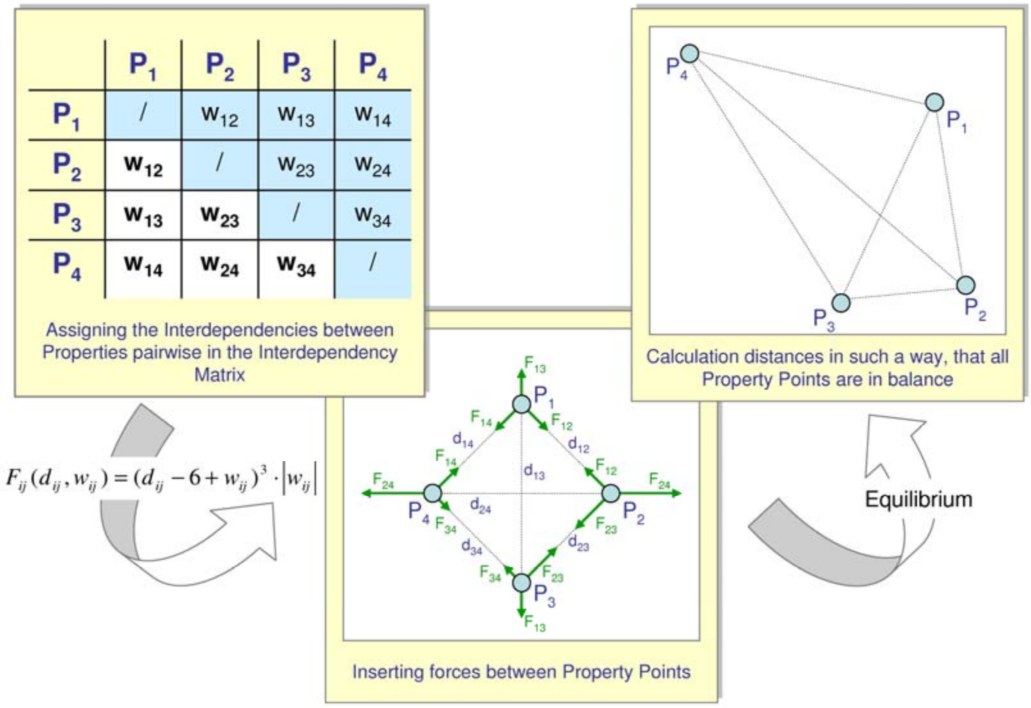

Figure 2 – Approach by the forces model

2.2.3 Interpretation of the visualization

The task is now to interpret the ascertained visualization result. Particularly the significance of occurring structures (clusters, etc.) in the representation and the significance of the dimensions of the visualization space are to be explained.

In figure 3 a visualization of interacting properties (with two dimensions) is mapped and the significance of clusters and dimensions in general is represented.

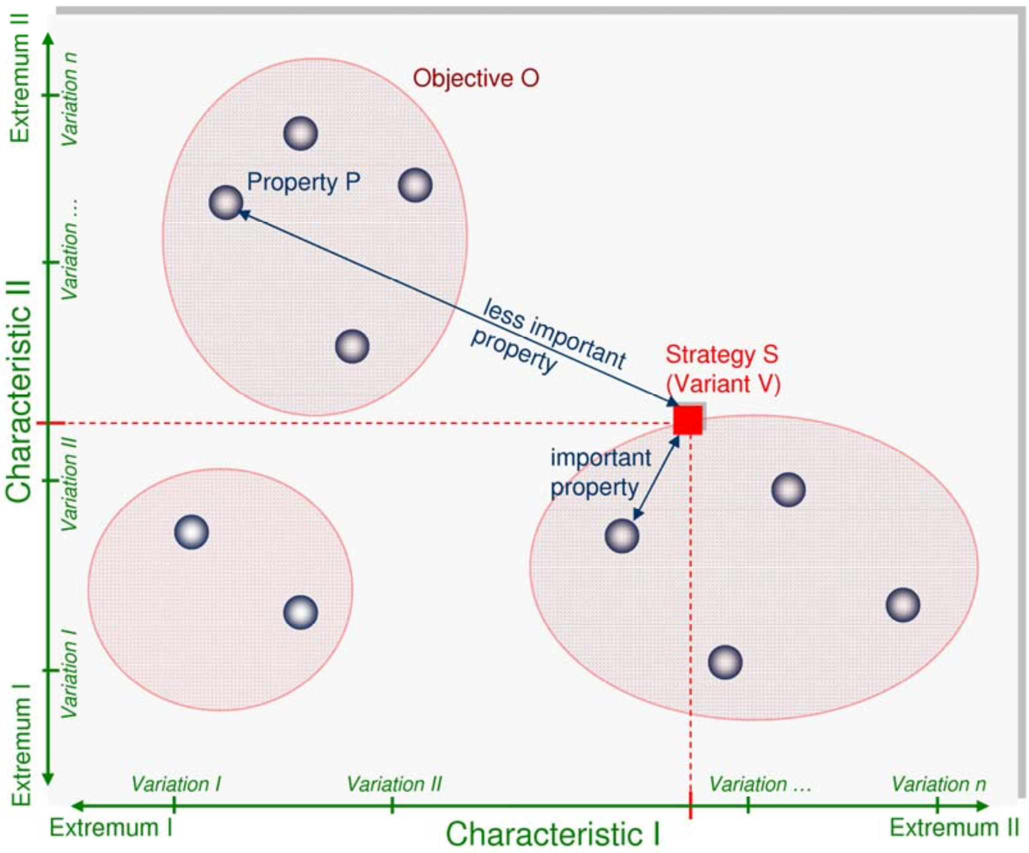

Figure 3 – Interpretation of a visualization result

In the dimensions of the visualization space, all those characteristics are found again that provided the basis in the estimation of the dependencies (implicit or explicit) documented in the interdependency matrix. Hence the dimensionality of the visualization space is determined by the fact of how many characteristics were considered. The extension of the visualization space is here determined by the extreme specifications of the respective characteristics (for example, the characteristic "metallic material" could have the extreme specifications "ordinary steel” and "high-tensile light metal alloys"). Between those extreme specifications lies (depending on the characteristic, discrete or continuous) the set of all variations of a characteristic (see also variation characteristics according to Ehrlenspiel [20]).

Clusters of property points indicate hierarchically higher-positioned goals. In principle it is possible to combine clusters again to hyper-clusters, whereby several levels in the goal hierarchy would be representable.

Here it becomes obvious that visualization is able to completely represent the system of horizontal and vertical dependencies shown in figure 1. Horizontal dependencies between properties respectively goals are represented in visualization by the distance between the corresponding property points respectively clusters. Vertical dependencies can be pointed up by the combination of property points in clusters or by the formation of hyper-clusters. The correlation characteristics – properties particularly becomes then apparent, when you notice that the visualization depicts the relation R, which is mapping characteristics on properties.

Each arbitrary point V_j in the visualization space basically represents a variant of the considered technical system. Thereby applies: A great (short) distance of point V_j to another arbitrary property point P_i means that in the considered variant V_j the property P_i inheres a low (high) importance or weighting respectively.

Thus a technical system is simultaneously represented in two ways in this approach: On the one hand it is defined by the determination of its fundamental characteristics, on the other hand by the definition of its properties and indication of the respective degrees of compliance.

2.2.4 Strategy selection and weighting

On basis of such visualization it is now possible to carry out the determination of weightings for the properties simply by selecting a point (strategy point S) (see figure 3 and figure 4). The distance of a property point from the strategy point is thereby the measure for the significance attributed to that respective property.

Conflicts of objectives cannot be evaded anymore with this approach: When the strategy point is moved towards one property, the distance to all other competing properties enlarges automatically. Thus implicitly the force arises to counteract conflicts of objectives in the choice of the strategy by suitable compromises.

By appropriate choice of basis-providing properties, the visualization of the decision making task on basis of the interdependency can also serve as a basis for the setting up of a product program respectively for the determination of a product strategy. This succeeds then when the different areas can be attributed to certain market segments in the visualization.

From the prioritization determined in the visualization by the choice of the strategy point now in a next step concrete weighting numbers need to be derived for the corresponding criteria. Thereby only it becomes possible to ascertain in a simple way the applicability of different point concepts with regard to the chosen strategy by suitable evaluation methods. The weighting numbers G_i of the depicted desired product properties (i.e. criteria) are modeled in the visualization for this purpose as masses of the respective property points P_i. These masses are determined in such a way that the location of the center of gravity of the mass system coincides with the strategy point (see figure 4).

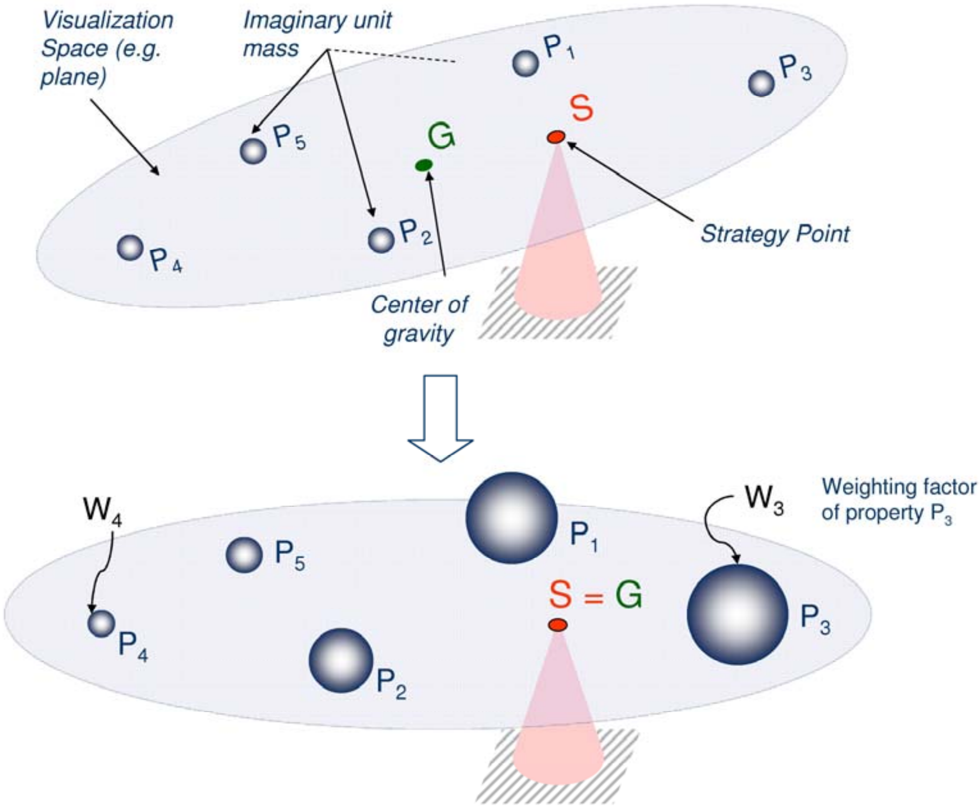

Figure 4 – Determination of weighting factors from the chosen strategy point

This proceeding in particular eliminates the risk of double-weighting of complementary criteria: If an accumulation of criteria exists in an area due to the choice of complementary elements, then in the derivation of weightings according to the center-of-gravity method this is reflected in a distribution of the total weight in the local area on the criteria contained there.

Two on principle deemed to be important, but highly complementary elements would thus be weighted apart less, as the weight intended for the considered aspect is (correctly) allowed for in the sum of the weights of both criteria.

2.3 Actual state of realization

2.3.1 General

The realization of the demonstrated concepts as computing tool was effected up to now by means of the object-oriented programming language JAVA. The applications introduced shall be part of a comprehensive (software-based) system, which also includes a database with DfX guidelines filed in structured form for the context and application-oriented support of steps of synthesis in product development.

2.3.2 Representation of visualization

For calculating the distances between property points, which provides the basis for visualization as described, up to now the two methods introduced in 2.2.2 were considered.
For the implementation of multi-dimensional scaling, the algorithm by Kruskal was used [19]. At this actual state of implementation, an arbitrary number of properties, but only two dimensions (and therewith characteristics) can be incorporated simultaneously by the use of MDS.
The search for the state of equilibrium as explained in the forces model in 2.2.2 was realized by means of the POWELL algorithm. Incorporated are here at this time up to three dimensions and an arbitrary number of properties.

2.3.3 Derivation of weighting factors

The concept presented in 2.2.4 for the automated computation of weighting factors based on a strategy point to be chosen was realized for two- and three-dimensional visualizations.
For this purpose at first initial masses are allocated to the property points. These correspond to a certain distribution, which effects that the masses decrease with increasing distances to the strategy point. Analyzed and implemented were thereby exponential distributions and normal distributions.
In a second step a straight line g is calculated that intersects the connecting straight line h between center of gravity and strategy point perpendicular in the center of gravity. This straight line divides the sum of all property points into two lots: The points in the one half show too light weighting while the points in the other half are weighted too heavily (figure 5).

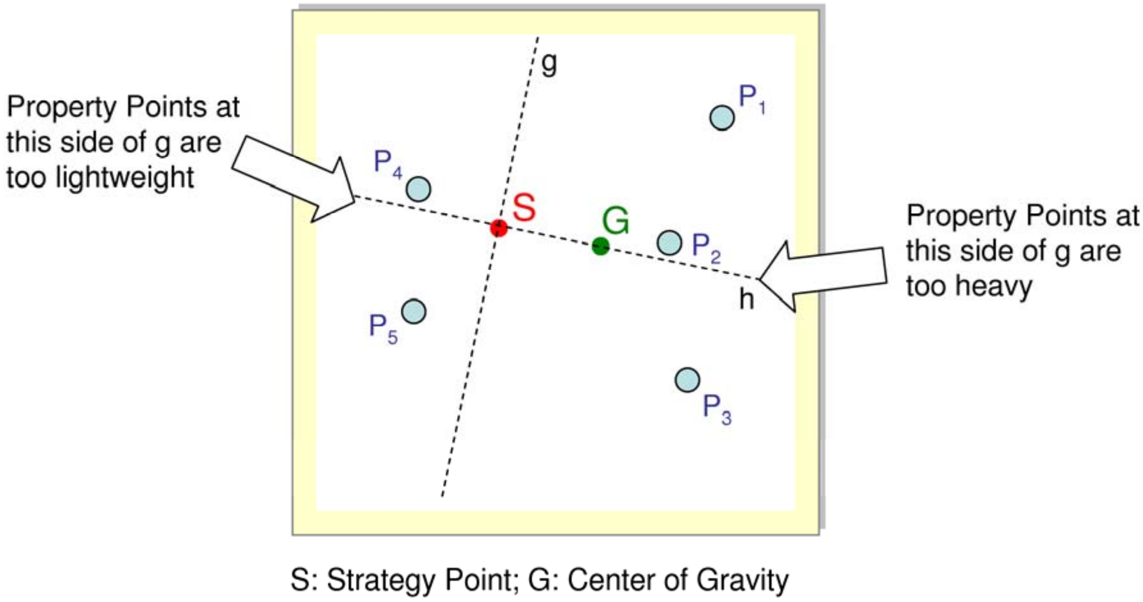

Figure 5 – Clarification of the algorithm for weighting

Iterative systematic re-allocation of weights to property points finally entails in the desired coincidence of strategy point and center of gravity.

2.4 Example

The following example clarifies the introduced method: In the planning phase for a bicycle, the following desired properties are recorded as possible requirements: "low weight", "low rolling friction", "low material costs", "low expenditure in manufacturing", "high degree of safety", "low energy losses", and "good all-terrain applicability".
These are significantly correlating via the characteristics "type of tires" and "materials to be used" to that are be determined (figure 6).

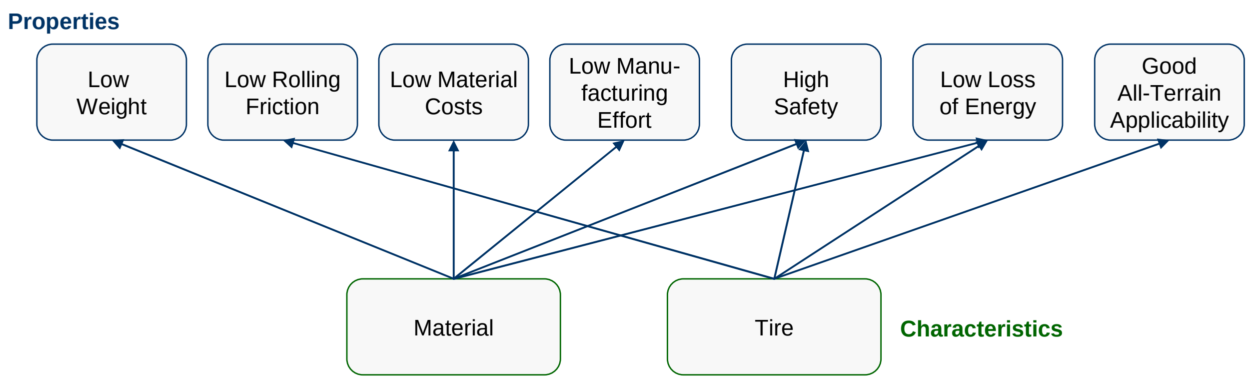

Figure 6 – Correlation characteristics – properties for a bicycle

The dependencies between the individual properties resulting form the relations depicted in figure 6 are formulated in the interdependency matrix. Based thereupon (here by means of multi-dimensional scaling), the corresponding visualization is ascertained (figure 7).

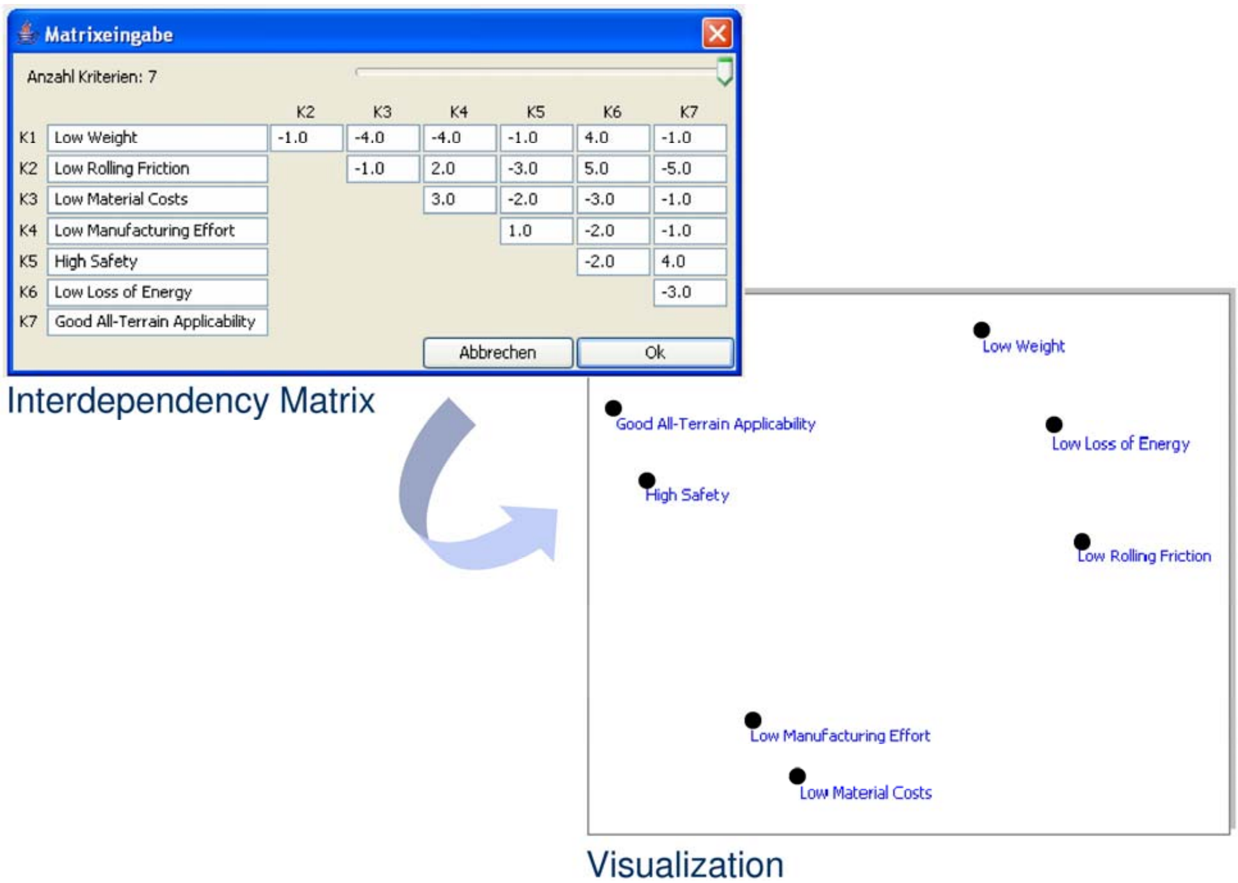

Figure 7 – Interdependency matrix and visualization by the example of a bicycle

In the illustration one recognizes (as desired) that the properties estimated as competing show a great distance from each other, while complementary properties are spatially located close together.

Now it needs to be clarified, how this visualization is to be interpreted. The result is shown in figure 8.

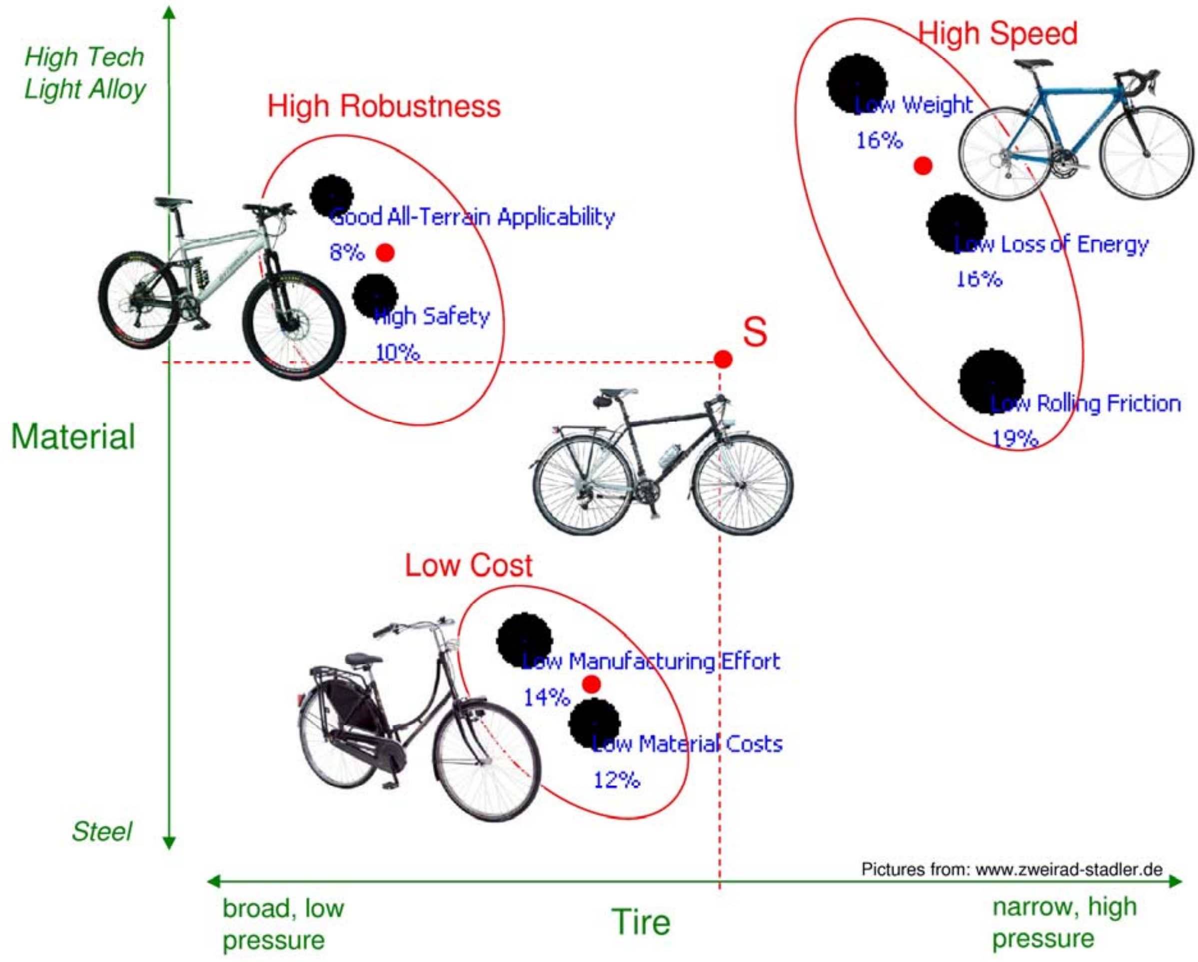

Figure 8 – Interpretation of the visualization, choice of strategy, and weighting

One recognizes clearly that the characteristics "material" and "tires" underlying in the formulation of interdependencies between the properties exist as dimensions. Also clearly visible is that higher-level objectives are depicted in different clusters of properties. Figure 8 furthermore emphasizes how different project strategies and with it variants can be defined, suitable for different market segments.
For the strategy S, weighting factors were ascertained according to the method introduced. In figure 8 they are emphasized by the size of the corresponding property points and indicated as relative weighting factors.

3 CONCLUSION

By the visualization of dependent properties, objectives and characteristics, an excellent tool for supporting in decision making tasks is obtained. Complex coherences become transparent and the often necessary task of having to deliberate about different objective targets is significantly made easier. As it was shown it is also possible to accomplish a weighting of criteria (required product properties) automatically, in which the influence of dependencies is allowed for and taken account of.
For the future it would be desirable to abolish the restriction of the concept to three dimensions. The underlying algorithms would also function for n dimensions, however a visualization concept would have to be established, which for example represents an n-dimensional space with n-1 views. With that it would be possible to unlimitedly depict n:m relations between properties and characteristics.

REFERENCES

[1] Hubka, V.: DESIGN FOR – DF. Fertigungsgerechtes Konstruieren, Report, Beiträge zum 6. Symposium, H. Meerkamm (Hrsg.), Erlangen, S. 1-6, 1995
[2] Tichem, M.: A Design Coordination Approach to DESIGN FOR X. Delft, 1997
[3] Meerkamm, H.; Wartzack, S.: Fertigungsgerechtes Konstruieren - Potenzial und aktuelle Tendenzen. Werkstatt und Betrieb 1-2/00, Carl Hanser Verlag, München, 2000, S. 24-29
[4] Andreasen, M. M.; Mortensen N. H.: Basic thinking patterns and working methods for multiple DfX, Beiträge zum 8. Symposium DfX, Schnaittach, 1997
[5] Huang, G. Q.: DESIGN FOR X, Concurrent Engineering Imperatives. Chapman & Hall, 1996
[6] Weber, C; Werner, H.: Klassifizierung von Cax-Werkzeugen für die Produktentwicklung auf der Basis eines neuartigen Produkt- und Prozessmodells in DESIGN FOR X, Beiträge zum 11. Symposium, H. Meerkamm (Hrsg.), Neukirchen, S. 126-143, 2000
[7] Weber, C; Werner, H.: Schlussfolgerungen für DfX aus der Perspektive eines neuen Ansatzes zur Modellierung von Produkten und Produktentwicklungsprozessen in DESIGN FOR X, Beiträge zum 12. Symposium, H. Meerkamm (Hrsg.), Neukirchen, S. 37-48 , 2001
[8] Pahl, G.; Beitz, W.: Konstruktionslehre, vierte Auflage, Springer Verlag, Berlin, 1997
[9] Andreasen, M. M.; Kähler, S.; Lund, T.: Montagegerechtes Konstruieren, Springer-Verlag, Berlin, 1985
[10] Boothroyd, G.: DESIGN FOR Manufacture and Assembly: The Boothroyd-Dewhurst Experience in DESIGN FOR X, Concurrent Engineering Imperatives. Chapman & Hall, 1996
[11] Breiing, A.; Knosala, R.: Bewerten technischer Systeme, Springer, 1997
[12] Sell, I.: Wenn Bewertungskriterien voneinander nutzenabhängig sind, Konstruktion 50, S. 17-22, Springer Verlag, Berlin, 1998
[13] Bauer, S.: DESIGN FOR X – Ansätze zur Definition und Strukturierung in DESIGN FOR X, Beiträge zum 14. Symposium, H. Meerkamm (Hrsg.), Neukirchen, S. 1-8, 2003
[14] Bauer, S.: Visualisierung von DfX-Anforderungen in der Produktentwicklung auf Basis ihrer Wechselwirkungen – Methoden und Anwendungen in DESIGN FOR X, Beiträge zum 16. Symposium, H. Meerkamm (Hrsg.), Neukirchen, S. 1-10, 2005
[15] Andreasen, M. M.: Concurrent Engineering – effiziente Integration der Aufgaben im Entwicklungsprozess in Handbuch Produktentwicklung, Hanser-Verlag, München/Wien, 2005
[16] Zangemeister, C.: Nutzwertanalyse in der Systemtechnik, Wittmannsche Buchhandlung, 1970
[17] Multidimensionale Skalierung, B.G. Teubner, Stuttgart 1997
[18] Backhaus, K., Erichson, B., et al, Multivariate Analysemethoden, Springer Verlag Berlin, 2000
[19] Joseph Kruskal: On the shortest spanning subtree and the traveling salesman problem. In: Proceedings of the American Mathematical Society. 7 (1956), S. 48–50
[20] Ehrlenspiel K.: Integrierte Produktentwicklung, Hanser-Verlag, München/Wien, 1995

Contact: Dipl.-Ing. Stefan Bauer
University Erlangen-Nurenberg
Institute of Engineering Design
Martensstr. 9
91058 Erlangen
Germany
Phone: +49-(0)9131/85-27987
Fax: +49-(0)9131/85-27988
e-mail: bauer@mfk.uni-erlangen.de
URL: http://www.mfk.uni-erlangen.de