DIMENSIONS OF OBJECTIVES IN INTERDISCIPLINARY PRODUCT DEVELOPMENT PROJECTS

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ABSTRACT
Interdisciplinary product development is a complex and uncertainty-affected system and objectives are central elements of it. In consequence the handling of these objectives, characterized by a high connectivity and dynamic, demands for a multi-dimensional view on objectives. This paper examines the nature of objectives and generates a conceptualization of four generalized dimensions of objectives: degree of maturity, degree of rigidity, leverage and impact. Based on these dimensions the approach of objective dimension matrices (ODM) is deduced. ODM considers product development as a socio-technical system and therefore enables a systematic handling of objectives in order to understand their role in interdisciplinary product development projects. The capability of ODM is demonstrated by its application within the development of a new humanoid robot.

Keywords: objectives, objective dimension matrices, interdisciplinary product development

1 INTRODUCTION
Objectives are central elements of every design process. Especially in interdisciplinary product development projects, efficiency requires both the purposive definition of objectives meeting customer needs and the durable definition of objectives a designer can trust in. Claiming a purposive and durable definition is fundamentally complicated, due to the complexity and the uncertainty product design is naturally confronted with.

The research presented in this paper considers the analysis of dimensions of objectives. Based on these dimensions, an approach is deduced that facilitates the characterization of objectives and supports the continuous process of their definition, development, prioritization and concretization. The research bases on the system triple of product engineering [1] consisting of the three systems: system of objectives, operation system and system of objects. This allows a socio-technical view on product design as well as the consideration of the aspects of complexity and uncertainty.

The paper proceeds as follows. Section 2 gives a brief overview of the role of objectives as elements of the system of product engineering. In this context especially the influence of complexity and uncertainty is discussed. In section 3 the identified aspects of objectives are combined to four objective dimensions that are briefly defined and described. In section 4 the interdependencies between these dimensions are analyzed. Based on the results an approach is developed that allows the stepwise increase to a four-dimensional view on objectives. Section 5 shows the application of the approach using the example of an interdisciplinary project concerning the development of a humanoid robot. Section 6 concludes.

2 OBJECTIVES IN PRODUCT DESIGN
Objectives in product design behave dynamically. Sudin et al. [2] summarize that new requirements are often included as the design process proceeds into an advanced state, because it is not possible to know the problem fully until the solution is created. The requirements are changed (i.e. developed, explored and expanded) during the design process into a more complete description (final specification). This statement leads to the following conclusions: (1) objectives interact with both the product solutions and the process including designers and users (high connectivity), (2) objectives are changing (high dynamics) and (3) objectives depend on a reached knowledge status (uncertainty).

Thus, complexity does not only results from objectives influencing each other, but also because there are strong interdependencies between objectives and the design objects as well as between objectives and the design process. For this reason the research presented in this paper bases on the system triple

of product engineering. It describes product design as a continuous interaction of three systems. Including the designers and the design activities, the operation system is simultaneously developing two different systems: the system of objectives and the system of objects. Hence, besides the final product, the development process continuously brings out information, new objectives are based on, as well as it brings out objects, new information is based on.
Similar to the objectives, important design objects cannot all be identified beforehand, but demand a flexible, explorative and iterative design process [3]. Thus, all three systems and their interactions are affected by uncertainty. The research of Engelhardt et al. [4] confirms this statement by concluding that there is a high level of uncertainty regarding both, the processes to be expected as well as the properties of a product.
According to de Weck et al. [5] the term uncertainty is an amorphous concept that is used to express both the probability that certain assumptions made during design are incorrect as well as the presence of entirely unknown facts that might have a bearing on the future state of the product and its success in the market. Due to this, Hastings and McManus [6] divided uncertainty in two overarching classes: (1) the lack of knowledge, meaning facts that are not known, or are known only imprecisely and that are needed to complete the system architecture in a rational way and (2) the lack of definition that can be described by things about the system in question that have not been decided or specified.
Thus, uncertainty can be mitigated by gaining necessary information and reducing the lack of knowledge or by making necessary decisions and reducing the lack of definition. Transferred to the system triple of product engineering the following picture results (see figure 1). The operation system includes designers, e.g. members of different domains working together in an interdisciplinary product development project [1]. Based on their knowledge and additional information gained from relevant objects, they are able to decide about first product-specific objectives. So they build up the initial system of objectives, which defines a vague solution space of their development task. The solution space is a designer’s mental model and therefor an element of the operating system. In the next step the designers have to find different solutions, whereupon every solution contains certain decisions. Solutions are described by virtual or physical objects that in turn lead to new information the designers can use to refine the system of objectives. By running this refinement cycle uncertainty can be mitigated continuously. Lindemann and Lorenz [7] describe the continuous refinement as a probe and learn framework. They conclude that especially in innovation projects this iterative experimenting loop is repeated until necessary information is generated and the product is modified to reach the final market.

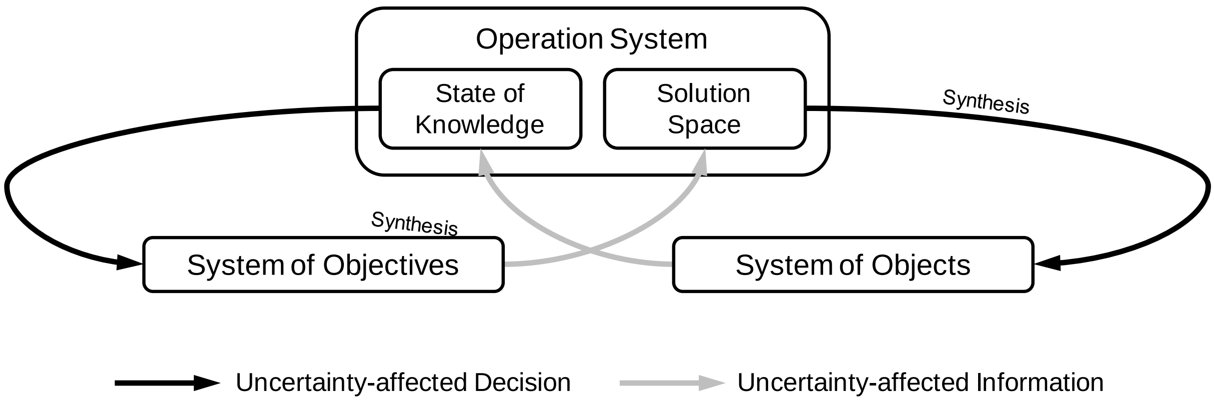

Figure 1. System Triple of Product Engineering Describing the Continuous Mitigation of Uncertainty by Information Gaining and Decision Making

As described above, objectives play a key role in the context of product development. On the one hand there are systemic interdependencies leading to high connectivity and high dynamics. On the other hand objectives are strongly affected by a natural uncertainty. In order to enable a systematic handling of these objectives, it is necessary to understand their characteristics. Therefore, a conceptualization of generalized dimensions of objectives is needed to understand the complexity of objectives in interdisciplinary product development.

3 OBJECTIVE DIMENSIONS

In this section the conceptualization of four dimensions of objectives is presented. As described before, product development requires a continuous refinement of objectives determined by the gaining of information and the making of decisions. Their continuous refinement indicates that objectives are characterized by a certain degree of maturity. Furthermore objectives can be more or less easily changed. So they are also characterized by a certain degree of rigidity. These two identified dimensions are not necessarily coupled to each other. In the following it will be shown that it might be important to define objectives by a high degree of rigidity, although the degree of maturity is still low. The difficulty of changing objectives depends on their interconnectedness within the system triple. It is often difficult to propagate the consequences when changing an objective. Every change has a certain impact on the system of objectives, as well as on the operation system and on the system of objects. With a closer view to the operation system it has been exposed that the authority to influence objectives is distributed to various people. Thus, every designer possesses a different leverage to change an objective.

Altogether, four different generalized objective dimensions have been identified: (1) the degree of maturity, (2) the degree of rigidity, (3) the leverage and (4) the impact.

3.1 Degree of Maturity

The degree of maturity describes the completeness regarding the understanding and realization of an element of the system of objectives. Thus, there is a maturity of objectives and a corresponding maturity of objects.

The term product's degree of maturity is being increasingly discussed within design research. The product's maturity is primly connected to the system of objects, but there are also direct interdependencies to the objectives' degree of maturity. Weber [8], for example, uses the CPM/PDD-approach to conjoin a characteristics-related maturity that indicates the completeness of product definition and a properties-related maturity that indicates the compliance of present state of solution with requirement.

According to Krehmer et al. [9] the product's degree of maturity is the degree of fulfilling the customer's needs in consideration of additional requirements resulting from the choice of a certain solution, it is seen as the performance of a product related to its use. They conclude that the product's degree of maturity is the captured state of the product concerning defined indicators at an arbitrary moment. Thus, the degree of maturity only can be measured by reducing the lack of definition regarding adequate indicators.

3.2 Degree of Rigidity

The degree of rigidity indicates the willingness to hold on to an element of the system of objectives. In consequence, it is an indicator for the trustworthiness or rather the changeability of an objective.

On the one hand defining a high degree of rigidity prioritizes objectives. On the other hand an initially low degree of rigidity avoids a premature limitation of the solution space. Hence, the right defining of the degree of rigidity is not trivial. In design practice there is an affinity to define objectives by a high degree of rigidity, due to a better ability to plan and control.

Eriksson and Brannemo [10], for example, analyzed the collaborative decision making process at a large Swedish company. In their interviews they received statements like 'We make decisions with great uncertainties but act as if we are sure.' or 'The management level in the organization writes things in stone too early.' Such situations can be avoided by initially defining a high degree of rigidity only for a few superior objectives and increasing the degree of rigidity of further objectives according to their degree of maturity.

3.3 Leverage

Leverage indicates the potential to define/change elements of the system of objectives regarding ability and/or authorization.

The development of objectives is task of the operation system, which consists of different system elements. Amongst others, these system elements are the different stakeholders influencing the decisions of objectives' development. In a series of case studies on decision making in complex product development Jupp et al. [11] found out that during negotiation the stakeholder's ability to influence the course of action was predominantly based on their level of interest and power within the project. Here, the dimension representing the level of power respectively the level of ability to influence decisions is called leverage.

In their analysis Jupp et al. differentiates endogenous and exogenous decision making processes. Endogenous processes are often characterized by informal face-to-face meetings, in early stages major design decision even made independently by only one responsible person. In these cases the decision makers have a high leverage. Decision making processes across system boundaries (e.g. personal, functional or organizational boundaries) mostly occur in negotiation between different interest groups. The leverage of these groups depends on a combination of their organizational-determined power and their specific expertise. For example, even a supplier can strongly influence objectives, if his component part plays a critical role in a certain design project.

3.4 Impact

Impact is the (anticipated) consequences of an event or decision in terms of necessarily resulting (change) effort/cost/time for the respective system of objectives and/or objects.

The impact is a measure related to the objectives' connectivity within the system of objectives and their direct and indirect interdependency to the system of objects. Thus, the impact considers questions like: 'What would happen to the system of objects, if we define (or change) this objective in this way?' and 'What systems, subsystems or elements will be concerned how much?' In cases of an adequate knowledge status, these questions can be answered by developing predictions [12, 13], but especially in interdisciplinary projects there are often both, a lack of information and even a lack of awareness according impacts.

Eckert et al. [14] conclude that in complex engineering domains, like in the development of a helicopter, no single person in the company has a detailed overview of all the systems, such that they would be able to assess the impact of a proposed change and predict its likely consequences and cost. They claim to be aware not only of the impact of individual change chains, but of the impact of complex change networks.

4 OBJECTIVE DIMENSION MATRICES (ODM)

The four objective dimensions presented above have been considered as independent factors so far. But especially the interdependencies between the dimensions determine the product development process basically and essentially. Therefore, a simultaneous observation of all four dimensions is strongly recommended.

In this section an approach is presented that supports analyzing and defining the objective dimensions and their interrelationships. Due to the necessity of handling four dimensions simultaneously, the approach proposes the application of multiple matrices each representing the interrelation of only two certain dimensions. The different two-dimensional matrices are run through sequentially, so that complexity is increased stepwise to a four-dimensional view.

Four objective dimensions lead to six different objective dimension matrices (ODM) with six different conclusions. Their structures and advantages are described in the following.

4.1 Impact-Leverage-Matrix

The impact-leverage-matrix (see figure 2) combines the consequences of an event or decision with the designer's potential to exert influence on it. Thus, the impact-leverage-matrix indicates the required attention an objective should be paid to. In interdisciplinary product development projects there are a high number of objectives concerning different systems and domains. The effective and efficient coordination of these many objectives is an essential key factor for successful product development. Since it seems to be impossible to have all these objectives in mind, it is necessary to focus on certain ones. Here, the impact-leverage-matrix can be applied to classify objectives into crucial, important, unimportant or trivial objectives and therefore directing the available attention. Especially in interdisciplinary product development it is essential to be aware of one's own objectives as well as of the objectives of others.

4.2 Maturity-Rigidity-Matrix

The maturity-rigidity-matrix (see figure 2) supports the process of finding and keeping balance between the degree of maturity and the degree of rigidity. Therefore it helps to increase efficiency and reduce risk.

As mentioned before, the handling of objectives is complicated by a dilemma based on the nature of uncertainty in product design: On the one hand the objective's degree of maturity cannot be increased efficiently as long as its degree of rigidity is still low (lack of definition). On the other hand the objective's degree of rigidity cannot be increased effectively as long as its degree of maturity is still low (lack of knowledge).

Thus, there are two contrary ways to start: (1) if the lack of definition preponderates, the objective has to be defined first, even though the knowledge status is insufficient. This procedure should be applied carefully to only a small number of crucial or important objectives, in order to keep flexibility and to reduce risk. (2) If the lack of knowledge causes an inability to define an objective by a high degree of rigidity, information has to be acquired first. This information can be secondary information gained by available sources such as literature and internet or primary information that is directly created by the development of objects and their analysis. Normally, these objects are models representing special aspects of the future product. The analysis of the objects leads to additional knowledge and consequently to new definitions. This way of objectives' development corresponds to the continuous refinement in product design described in figure 1.

In further product development, objectives that already reached a high degree of rigidity have to be concretized next, i.e. they get quantified or they get reinforced by detailed new sub-objectives. Whereas objectives that already reached a high degree of maturity have to be prioritized next, i.e. they get definitely set. When both dimensions have reached a high level, the objective finally needs to get finalized, which means to explicate and realize it.

The maturity-rigidity-matrix considers four objective-related activities: definition, development, concretization and prioritization. Each of these activities is supported by one of the four remaining matrices presented in the following sections.

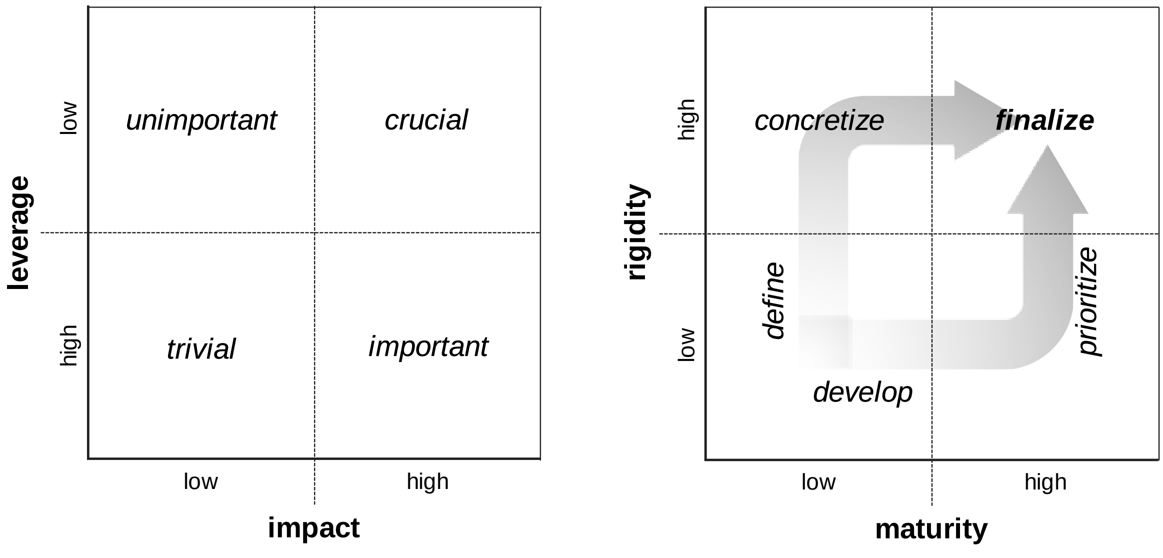

Figure 2. Impact-Leverage-Matrix (left) and Maturity-Rigidity-Matrix (right)

4.3 Rigidity-Impact-Matrix and Maturity-Impact-Matrix

The rigidity-impact-matrix and the maturity-impact-matrix (see figure 3) are similar to each other but not equal. In both matrices the estimated impact of an objective determines the objective that should be defined or developed with major efforts. This is reasonable in two different ways. (1) The rigidity of objectives with a high impact should be increased as early as possible in order to reduce system complexity. Objectives with a lower impact therefore serve as absorbers of necessary changes in order to hold on to the previously defined objectives with higher impact. (2) The maturity of objectives with a high impact should be increased as early as possible in order to clarify the actual impact. In general, the required proper estimation of the actual impact needs further knowledge. If an objective's impact

was estimated wrong, a necessary change will lead to extensive additional effort/cost/time at worst case.
As shown in figure 3, there are possibilities to change an objective's impact or to estimate an objective's impact right. Because of the relevance of objectives in product development, especially the objectives with a high impact should be finally verificated/validated.

4.4 Rigidity-Leverage-Matrix and Maturity-Leverage-Matrix

Both matrices, the rigidity-leverage-matrix and the maturity-leverage-matrix (see figure 3), represent one of the essential social aspects of the socio-technical system of product development. The maturity-leverage-matrix combines the potential to define/change objectives with the continuous progress in product development projects whereas the rigidity-leverage-matrix combines the potential to define/change objectives with discrete decision situations. Both aspects are crucial for success in today's interdisciplinary product development since the leading actors of the operation system more than ever are networked human beings.
Being aware of one's own leverage and the leverage of others concerning the elements of the system of objectives increases the performance of the operation system significantly. If a designer's leverage regarding a specific objective is low and there is someone else who owns a high leverage, an exchange of solution space becomes possible. The leverage becomes even more important in discrete decision situations (e.g. milestone-meetings), especially when new objectives get defined or existing objectives get changed/concretized.

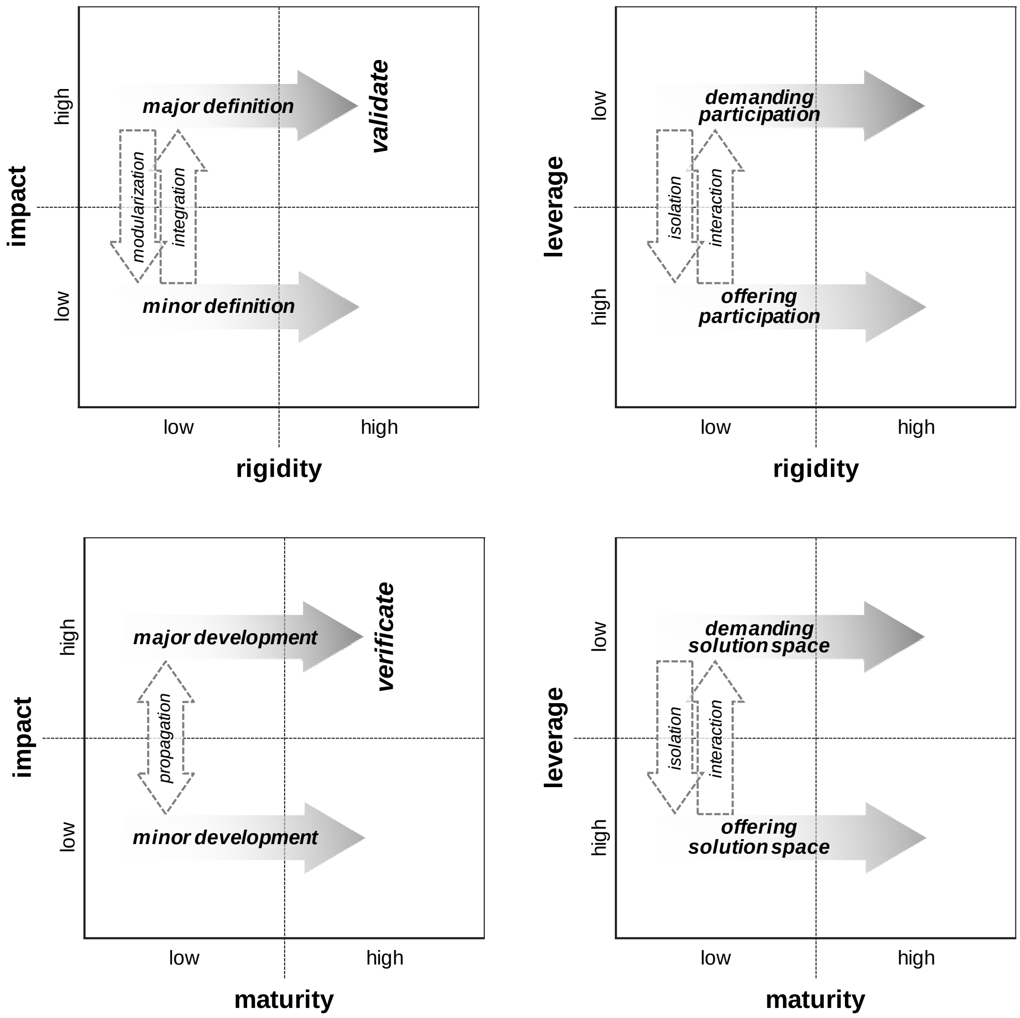

Figure 3. Rigidity-Impact-Matrix and Maturity-Impact-Matrix (left), Rigidity-Leverage-Matrix and Maturity-Leverage-Matrix (right)

5 ODM APPLICATION IN PROJECT WORK

This section briefly describes the application of the presented dimensions of objectives and the deduced objective dimension matrices (ODM). In order to depict the capability of this approach an insight of the development of a new humanoid robot, as a complex mechatronic system that requires interdisciplinary cooperation, will be presented.

5.1 Description of the Project Context

The Collaborative Research Center 588 'Humanoid Robots - Learning and Cooperating Multimodal Robots' (CRC 588) was established on the 1st of July 2001 by the Deutsche Forschungsgemeinschaft (DFG) and will run until June 30th, 2012. The goal of this project is to generate concepts, methods and concrete mechatronical components for a humanoid robot, which will be able to share his activity space with a human partner.

More than 40 scientists and 13 institutes are involved in this project. They belong to the department of Informatics, the Faculty of Electrical and Information Engineering, the Faculty of Mechanical Engineering and Faculty of Humanities and Social Sciences as well as Fraunhofer Institute of Optronics, System Technologies and Image Exploitation (IOSB) and the Forschungszentrum Informatik Karlsruhe (FZI).

On the basis of nearly 10 years of successful integrated research on the field of humanoid robotics, combined with the associated gain in experience, the primarily formulated objective becomes tangible now. Three generations and one evolution step of platform-based humanoid robots and their continuously improved skills proof the performance of the whole CRC 588 and point out simultaneously the next challenging revolution: a fully autonomous two legged humanoid robot named ARMAR IV (see figure 4).

Figure 4. Humanoid Robot ARMAR IV

5.2 Definition of the Initial System of Objectives

The development of ARMAR IV started in June 2008 when the interdisciplinary core team, responsible for the development of the new robot, met to define the initial system of objectives. Being aware of the high impact of these initial objectives, the essential question the core team had to answer was: 'Do we have enough knowledge about two legged humanoid robots to define objectives at the highest impact?' Due to a beforehand literature research on two legged robots in combination with the knowledge of earlier development projects, the definition of a consistent initial system of objectives became possible. In further discussions about the project's main objectives 'autonomous', 'two legged' and 'humanoid' the core team derived several sub-systems of objectives. To give an overview over the included elements a more exemplary excerpt of the initial system of objectives is shown in figure 5.

After explicating this first system of objectives it became necessary to prioritize the single objectives in order to set the right solution space. As almost every objective has a very high impact the decisive question was: 'Which objectives can or may be affected by ourselves?' addressing the leverage of

each objective with an overall project point of view. Among others, two objectives turned out to be crucial objectives because of the estimated high impact and low leverage: ’energy supply on-board‘ and ‘brushless high-torque-drives’. Both objectives had to be realized by a buying-in solution, whereas the potential supplier had been unknown at this moment. A focused internet research concerning these objectives revealed on the one hand an acceptable amount of potential suppliers. On the other hand the core team recognized that some battery-suppliers offer fully customized energy supply solutions. Thus, the interaction with the supplier increased the leverage of this specific objective tremendously. For this, the supplier had to be included into the development by providing them with the necessary sub-system of objectives. With this increased influence on the objective ’energy supply on-board‘, the objective’s prioritization could be reduced from crucial to important at clearly decreased impact.
On the basis of this first understanding of the elements of the systems of objectives (increased maturity of objectives) and the defined prioritization (increased rigidity) the core team finalized these first steps by documenting and communicating the results.

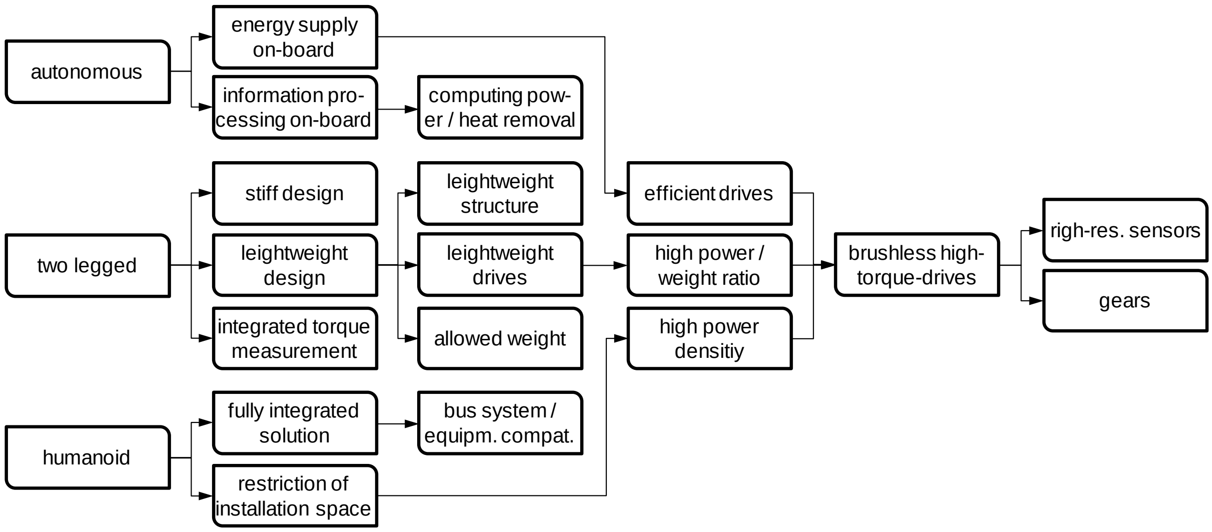

Figure 5. Excerpt of the Initial System of Objectives

5.3 Development of the Drive Units

Product development means continuous increase of the maturity of the system of objectives with the superior ambition of being finally able to realize these objectives and to increase the maturity of the system of objects. Product development therefore means as well drawing knowledge from developed objects and turning that knowledge into further objectives to adapt the solution space (see figure 1). The result of the final realization of the system of objectives is the intended product as part of the system of objects.
After defining the initial system of objectives the designers asked themselves: ’Where to start the development?’ what questions in the presented approach’s language: ’The maturity and rigidity of which sub-system of objectives should be increased first?’ This question demands for several discipline specific perspectives in order to accomplish the project’s main objectives. Asked for their important or crucial objectives, the designers of the three disciplines informatics, mechanical and electrical engineering gave quite differing answers such as ’computing power and heat removal‘, ’integrated lightweight and stiff design‘ and ’bus system and equipment compatibility‘. With the help of this initial revealing step, the designers of the different disciplines were able to explain why they were purchasing the objectives as well as which individual leverage they own. This increased understanding of the objectives and their interrelationship allowed a more detailed estimation of their impact and a further prioritization of the objectives. Consequently, the development of the drive units was prioritized due to the limited leverage (buy-in-solution), the high impact based on the high system integration (sensor/drive/gear) and the very low maturity of the objective (high uncertainty - lack of knowledge).
The first step on the development of the drive units was to decrease the objective’s impact by modularizing the drive units and their environment as well as arranging a weekly interdisciplinary meeting of the designers. After several months of straight forward development two crucial problems

occurred that were not solvable at this particular time because of an ostensible low leverage: (1) the drive supplier's concept for mechanical integration was not suitable at all. (2) The integrated sensors for commutating exceeded the allowed design space. Both objectives - the way of integration and the choice of the sensors - were actually not changeable by the designers. Contacting the supplier and describing them the current objectives and problems increased the designer's leverage once again so that the first problem could be solved whereas the second one could be transformed into an another problem: (1) an alternative mechanical integration concept was recently available. (2) The drives were also available without integrated sensors. The supplier's second offer enabled the designer to develop their specific sensor solution that satisfies the design space. Because of the high impact of the sensor solution with respect of the whole drive unit, the core team decided to verify the developed solution.

Therefore the designer developed a test setup as an element of the system of objects that should increase the maturity of the system of objectives: the test setup was to verify the functionality of the whole drive unit and hereby the functionality of the sensor solution as well. After a first test the electrical engineer realized, that the resolution of the chosen sensor was too low. As he was not sure whether he may change the sensor or not, the electrical engineer demanded solution space of the mechanical engineer. The mechanical engineer indicated subsequently the integrability of the new sensor (high leverage). After a successful test of the new sensor as well as the whole drive unit (increased maturity of objective), the electrical and the mechanical engineer finalized this episode by documenting and communicating the concretized sub-objectives (increased rigidity).

After this exhausting episode the development of the drive units run through only with concretization of objectives and without major changes.

6 CONCLUSION AND OUTLOOK

This paper has described product development as a complex and uncertainty-affected system. It has been shown that the design process is determined by a continuous gaining of information and making of decisions. This includes an also continuous refinement of objectives that increases the complexity of the system of objectives gradually. As presented, a systematic handling of these objectives becomes possible with characterizing them by four generalized dimensions: the degree of maturity, the degree of rigidity, the leverage and the impact.

The sequential utilization of the objective dimension matrices (ODM) allows focusing on initially just one dimension, followed by a stepwise increase of complexity to a final four-dimensional view on objectives. The application of ODM in the context of the interdisciplinary development of a humanoid robot has shown that ODM supports the explicit description and analysis of interdependencies between objectives and the operation system as well as between objectives and the system of objects. In conclusion ODM has raised the understanding and awareness of the role of objectives in interdisciplinary design processes and thereby realized a higher level of transparency in handling objectives within the system of objectives.

Future research work considers the relationship between dynamic objectives and iterations in design processes. Furthermore the interdependencies within the system of objectives will be analysed in detail, in order to realize a software tool supporting the handling of objectives in interdisciplinary product development.

ACKNOWLEDGMENTS

We are grateful for the support provided by the CRC 588 and the Deutsche Forschungsgemeinschaft (DFG).

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