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MODELING OF USE PHASE VARIABILITY AND APPLICATION IN ROBUST DESIGN AND ECODESIGN

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1. Introduction

The use phase is of particular significance in product development. The benefit for the user and the main reason the product is developed, produced and bought is predominantly found during this phase. Economic costs and ecological impacts, factors present in all phases of the product lifecycle, form the eco-efficiency parameters of the product. Lower costs and environmental impacts, as well as greater benefits, lead to higher eco-efficiency. In many cases, costs can be kept low by optimizing the fit of the product to its use.
The technical processes realized are primarily defined by the use phase of the product life cycle. Methodological support for use phase modeling has the potential to be used as a basis for design activities that aim to optimize the eco-efficiency of a product.
The use phase model usually only considers one or a few unsystematically collected use cases. A more thorough analysis is often conducted to identify requirements, but the retrieved data are put into the list of requirements without discerning different scenarios of use. This paper introduces a method to handle variable use scenarios by structuring relevant parameters of different use cases in a matrix. Such a structure can be used for products that exhibit a wide variety of use cases. Great variability in usage scenarios can frequently be found in the development of part systems, which are product systems that are used as input for higher-level product systems, like a pump which may be used in a whole family of high pressure cleaners.
This approach can be used as a basis for a variety of design activities, of which two intended uses are presented. The first intended use aims to facilitate modularization decisions based on the modeling of usage scenarios presented and is part of Robust Design research. The second intended use presented in this paper will enable designers, especially in the field of part systems, to better assess the environmental impacts of their products. It is part of the EcoDesign field of research. The first application is focused on enabling activities of synthesis in design, while the second application aims to analyze existing products.
The following section introduces fundamental terms and models. They are used to establish the scenario matrix, which is evaluated using a short example. Its intended uses in the research fields of Robust Design and EcoDesign are shown. Finally, possible sources of information for the proposed model are discussed.

2. Modeling utilization processes

An adequate process model is needed for detailed analysis and description of utilization processes. The Collaborative Research Centre (CRC) 805, "Control of Uncertainty in Load-Carrying Systems in

Mechanical Engineering", founded by the Deutsche Forschungsgemeinschaft (DFG), developed a process model with a focus on description and visualization of uncertainty in all states of the product lifecycle; it has proved useful [Eifler et al. 2012].

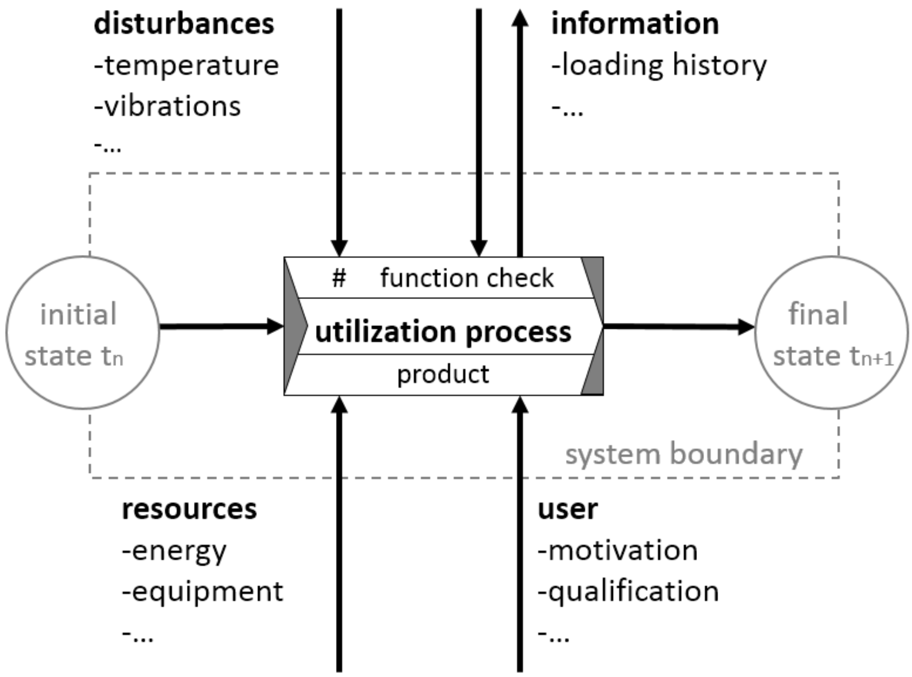

Figure 1. CRC 805 process model

The process model contains the following information (Figure 1):

- **Utilization process:** Time-dependent transformation of the operand properties from an initial state to a changed final state.
- **Operand:** Operands are physical objects that can be described by their properties, for example, a length or a temperature of a component.
- **Product:** The product is the operator that is used to realize the utilization process.
  Influence parameters: These parameters affect either the process or the product behavior. The used process model contains several categories to differentiate influence parameters in order to collect information in a structured and easy to interpret way. The categories are:
  Disturbances: Disturbances have an effect on product, process or user. They can be intentional or unintentional and occur during interaction with the environment or other processes.
  Information: There are two kinds of information in this category. One contains information that is needed to realize the process, for example, a user manual, and the second contains additional information about the product loading history or sum of utilization time.
  Resources: Information about the resources needed to realize the process.
  User: Information about the user who wants the process to be executed.
- **System boundary:** The system boundary represents the differentiation between the process and its environment.

3. The Scenario Matrix

Customer demands for individualization and customization are increasing. A common way to accomplish these demands economically is to develop modular products that can be configured by the customer to cover a wide range of utilization processes with only a few modules.

The CRC 805 process model provides a systematic representation of individual utilization processes. Therefore, each scenario must be described in a new process model, which leads to a number of process models that equals the number of utilization processes.

Variable utilization processes require an appropriate description that enables the designer to document the information of all utilization scenarios in a systematic way as well as having easy data access for further processing and design tasks. Therefore the 1:1 relation between scenario and process model has to be transformed into an n:1 relation that includes all information at once (Figure 2).
This initial situation is the motivation for the development of the *scenario matrix* introduced in this paper.

3.1 Approach

The data contained in the CRC 805 process model can be classified into the utilization process and the influencing parameters (disturbances, information, resources and user). Generally, different scenarios are characterized by deviations in at least one of these categories. Additionally, a scenario may consist of a combination of independent utilization processes.
Complexity management suggests using matrix-based models to collect and process huge amounts of product or process data [Lindemann et al. 2009]. It provides an approach that is well known, accepted and approved by the design community and is therefore considered a useful approach for describing variable utilization processes as well.

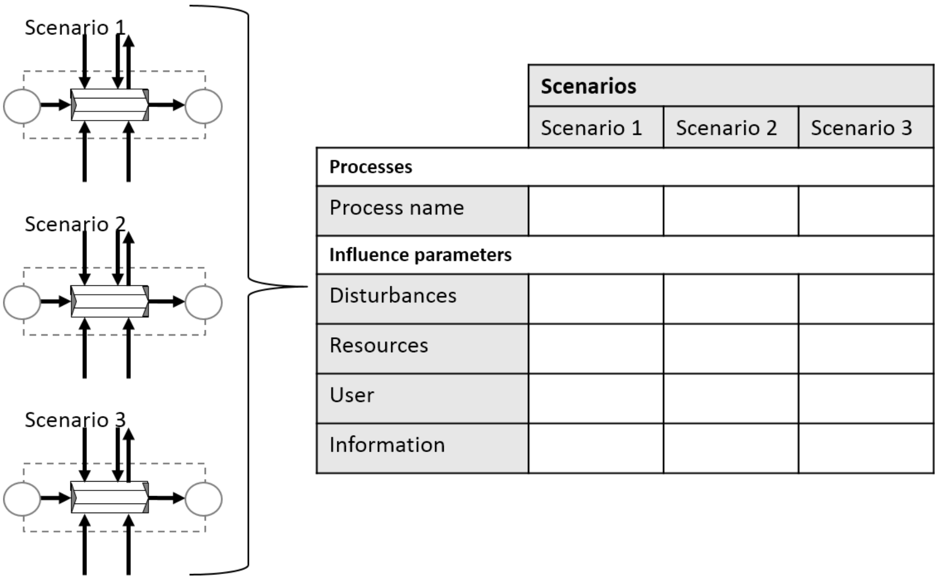

Figure 2. Transferring different utilization processes into the scenario matrix

Figure 2 shows a depiction of the scenario matrix. Its rows consist of the two categories of information:

- **Processes**
  This category lists all independent utilization processes that occur in the scenarios. To express the relation between a specific scenario and a specific utilization process, the field in the matrix has to be marked (see also Figure 2); combinations of utilization processes can then be considered.
- **Influence parameters**
  According to the CRC 805 process model, the influence parameters are differentiated into four subcategories that all contain factors that have an affect on a process in the utilization phase. The information has to be put in the corresponding field of the matrix.

The columns consist of the occurring Scenarios and can theoretically be infinitely expanded. It is recommended that all scenarios are given a unique, identifying name or number to prevent confusion.

3.2 Considering uncertainty

The scenario matrix can be used to systematically document occurring processes and influence parameters.

Besides access to utilization process data, data quality is also of interest. For most utilization processes, it is characteristic that there is insufficient process data available. This creates issues for the designer who is required to develop a product that fits exactly with customer demands and needs. Therefore, it would be useful to assess the available data instead of just entering it into the matrix. This procedure can be carried out while creating a scenario matrix.
As in the CRC 805 uncertainty model [Engelhardt et al. 2010], uncertainty can be categorized into 3 phases (Figure 3):

- **Ignorance**
  In this state there is no trusted information available, so values and deviations can only be estimated.
- **Incertitude**
  Incertitude is the intermediate level of uncertainty. Descriptions in this state are characterized by interval values; the distribution within the interval is unknown.
- **Stochastic uncertainty**
  This kind of uncertainty occurs if a value and its distribution are known.

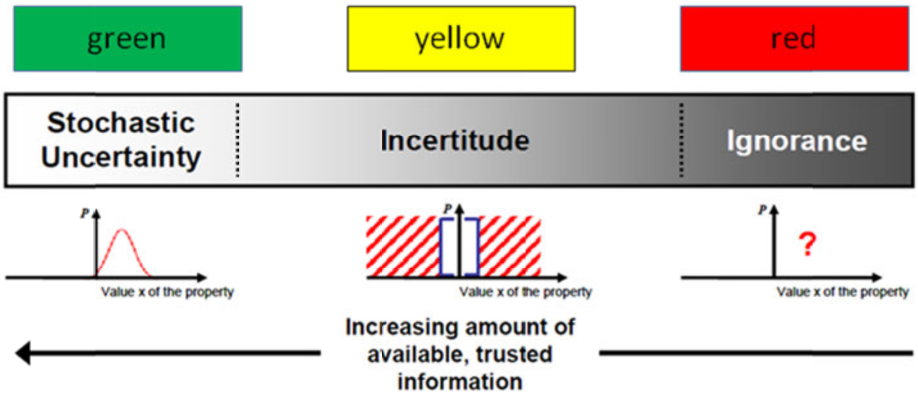

Figure 3. CRC 805 Uncertainty model

A three-colored code is proposed to consider the state of uncertainty within the representation of utilization process data in the scenario matrix. It represents the three states of uncertainty mentioned previously and provides data quality visualization that is easy to adapt. Using this code, the designer has an overview of the quality of the information, which helps to determine the focus of analysis of the use phase.

3.3 Illustrative evaluation

The benefit of using the scenario matrix as will be illustrated using a high pressure cleaner and three use scenarios.

Product

The high-pressure cleaner is a multi-functional product mostly for private use. It comes in a basic version and there is a lot of supplementary equipment available to realize a huge variety of utilization processes. This makes it a perfect example for evaluating the scenario matrix.

Processes

The three processes considered are:

- **Cleaning a terrace:** Cleaning a terrace or similar flat area outside a house is one of the standard utilization processes of high-pressure cleaners.
- **Removing rust or paint:** A process that illustrates the huge variability of a high-pressure cleaner is its application in sandblasting processes, such as removing rust or paint.
- **Cleaning a bike:** This process requires different cleaning tools and is of special interest for an investigation of its environmental impacts.

The result of the use phase model of the high-pressure cleaner is shown in Figure 4.

		scenarios		
		Scenario 1	Scenario 2	Scenario 3
processes				
Cleaning a terrace		X		
Remove paint or rust			X	
Cleaning a mountainbike				X
influence parameters				
disturbances	temperature	-5 – 40°C	-5 – 40°C	-5 – 40°C
	radiation	UV	UV	UV
	moisture	Spray water	Spray water filled with sand particles	Emulsion of water and oil
	dirt	organic material / mineral material	Paint rests / Rust particles	organic material / mineral material
	blast material		sand	
	cleansing agent	?		?
resources	energy	835 – 1770 W	?	?
	equipment	High pressure cleaner	High pressure cleaner / Sandblasting module	High pressure cleaner / rim brush
	water	drinking water / well water / rainwater	drinking water / well water / rainwater	drinking water / well water / rainwater
user	motivation	interest of safety/ optical reasons	Prevent corrosion / optical reasons	Asure function / optical reasons
	qualification	none	none	none
information	Use duration per year	4 hours	1 hour	0,5 – 15 hours

Figure 4. Illustrative depiction of the scenario matrix, containing data of three utilization scenarios for a high-pressure cleaner

Figure 5 is an illustrative depiction of a scenario matrix with statements about the occurring categories of uncertainty.

disturbances	temperature	-5 – 40°C	-5 – 40°C	-5 – 40°C
	radiation	UV	UV	UV
	moisture	Spray water	Spray water filled with sand particles	Emulsion of water and oil
	dirt	organic material / mineral material	Paint rests / Rust particles	organic material / mineral material
	blast material		sand	
	cleansing agent	?		?
resources	energy	835 – 1770 W		

Figure 5. Illustrative rating of information using the scenario matrix

4. Applications in Robust Design

In the use phase, the product behavior is expected to be robust against disturbances and misuse. One of the challenges in product development is to accomplish these expectations while managing increasing complexity combined with decreasing time to market. This evolution has to be supported by adequate design principles and methodology, which are the focus of CRC 805.

Uncertainty occurs when process properties of a system cannot be determined [Hanselka et al. 2010]. According to this hypothesis, uncertainty only occurs in processes. Regarding this, designing robust products is closely related to knowledge of uncertainty occurring in the utilization phase. The task of robust design in this context is to detect, rate and control uncertainty.

4.1 The influence matrix

The scenario matrix contains information about different use processes, influence parameters and quality of information in the use phase. For the development of robust products, this information is the basis for investigating the influence of parameters on the components of the product. This step marks the connection between the utilization process and the product, which is used to realize a certain process and is of great interest to the designer.

The influence matrix proposed in this paper supports the identification of the most affected component as well as the identification of most influencing parameter considering uncertainty.

To create the influence matrix the following steps have to be carried out:

- **Influence parameters** (Figure 6, No. 1)
  The influence parameters listed in the scenario matrix build the columns in the influence matrix. Each parameter can be appended with information about its uncertainty, which can be used to weight the influence values (Figure 6, No. 4).
- **Assemblies** (Figure 6, No. 2)
  The rows of the influence matrix are built by the assemblies of the product. Depending on the task, assemblies can be considered in different depths of detail, for example, in function groups or components.
- **Interdependency matrix** (Figure 6, No. 3)
  The interdependency between influence parameters and assemblies can be investigated by using the rating algorithm known from quality function deployment, which provides 4 values to represent different stages of influences. To evaluate the influences, every component and the occurring influence parameters have to be rated. The rating value has to be multiplied with the uncertainty value. The resulting value represents influence in uncertainty.
- **Sum of component points** (Figure 6, No. 5)
  To identify the most affected component, the points along each row first must be summed up. The most affected component is then characterized by the highest sum of points.
- **Sum of parameter points** (Figure 6, No. 6)
  The parameter with the highest influence can be found by summing up all points in each column.

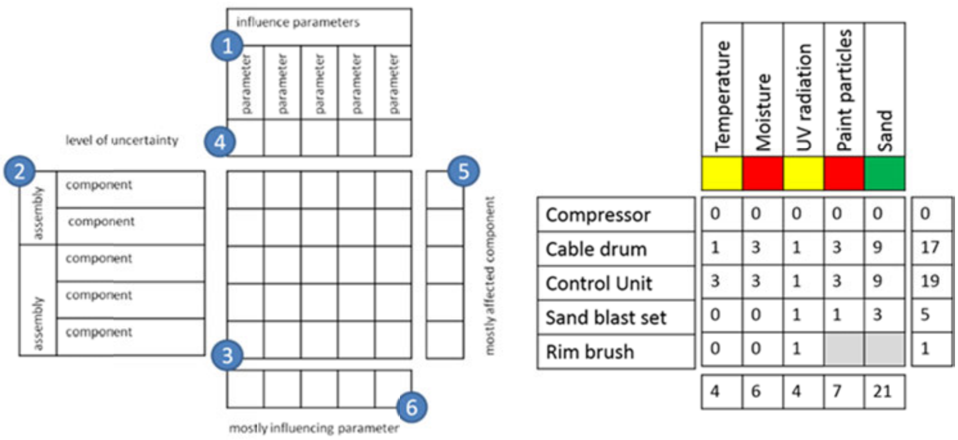

Figure 6. Structure of the influence matrix (left) and illustrative depiction of its application on the high-pressure cleaner (right)

The illustrative application of the influence matrix based on the high-pressure cleaner (Figure 6) demonstrates its benefits in product development. The control unit is the most affected component and therefore it has to be the focus of further development to assure its robustness against the occurring influence parameters, especially sand. Generally, critical combinations of parameters and components are marked by high influence combined with high uncertainty. Another outcome is the identification of sand as the mostly influencing parameter. Taking this into account, one strategy to increase the robustness of the product could be to find another working principle to realize the same functionality.

5. Applications in EcoDesign

The aim of EcoDesign research is to provide methods that include ecological considerations in product design without neglecting economic issues. A commonly used method to analyze the environmental impacts of a product is Life Cycle Assessment (LCA). LCA is based on a model in which environmental impacts are directly connected to elementary flows, which connect the environment or ecosphere to the technosphere: the system of technical processes [DIN EN ISO 14044 2006]. In this model, technical processes generate elementary flows, for example, CO_2 emissions or intake of iron ore, which lead to environmental issues, like global warming and resource depletion. Analysis of the environmental impact of a product system is conducted by modeling the processes of the products life cycle for occurring environmental flows.
Knowing the relations between a given product and its environmental impacts is the first step of the EcoDesign approach described in [Birkhofer et al. 2012]. This knowledge allows the identification of ecological weaknesses and levers that can be used to influence ecological impacts. Conducting an ecological assessment is a challenge, even for well-known products with limited variety in the use phase.
Past research supported modeling of the use phase and its relation to elementary flows, for example, the UPA matrix and analysis with causal chains [Oberender 2006]. These methods are part of a tight-knit methodology that enables designers to gain a highly detailed view of environmental impacts in a product use phase. However, this detailed view comes at the cost of a laborious analysis process. An analysis of different scenarios is possible within the methodology but it further increases the complexity of its application.
The method proposed in this paper is designed to enable the use of synergies by presenting information that is valuable in a large number of design tasks. As mentioned previously, EcoDesign heavily focuses on elementary flows that are connected to the entries in the matrix. For example, energy consumption may be the main cause for environmental impacts in one scenario while another scenario may feature additives, like detergents, that are discharged into the environment as the biggest ecological weakness. In a scenario with detergents, energy consumption will potentially be lower due to lower cleaning pressures. Only a differentiated but universally applicable presentation of information can lead to decisions on product differentiation (for example, excluding the detergent, using the cleaning function from one product system and providing an optimized alternative product) or optimization of the overall environmental impact. The gathering of information is usually a weak point in the ecological assessment of product systems. Synergies between Robust Design and EcoDesign can be used to qualify assumptions, for example about energy consumption and detergent use, which are assumed to be ecological weaknesses in different scenarios. This is illustrated in Figure 7.

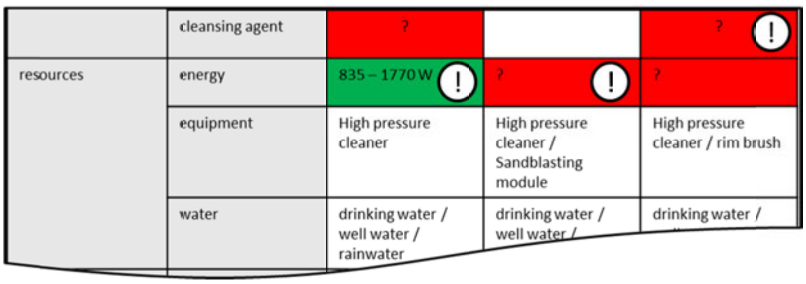

Figure 7. Environmental points of interest in the scenario matrix

The proposed method is particularly useful in the EcoDesign of part systems. Two practical issues when assessing the environmental impacts of part systems are the diversity of use cases, which is peculiar to part systems, and the lack of information about the use cases [Sarnes and Kloberdanz 2013]. Support for handling these problems is yet to be developed. A component, especially one that fulfills a very basic function, can be used in a great number of higher-level technical systems. Experience shows that the drivers of environmental impacts that can be attributed to a specific component depend very much on the system environment. For example, the main driver for the environmental impact of a component installed in a vehicle will usually be its mass, which increases the driving resistance of the higher-level system (the vehicle) and thus the overall fuel consumption. The same component installed in a stationary system will exhibit very different drivers of environmental impacts. Gaining an understanding of the whole product system and its connections to environmental impacts enables the product designer to make informed decisions regarding the environmental aspects of a product.

The method to model variability in usage scenarios proposed in this paper can be used as the basis for addressing the assessment of environmental impacts of part systems by reducing the overall complexity of issue handling. Further steps are needed to connect the information contained in the scenario matrix with environmental impacts. Past research led to support in this area, for example, by providing generic process databases for material, fuel and energy production or by reducing the complexity of the LCA method, which led to a group of methods called Shortened Life Cycle Assessment (SLCA).

6. Collecting Information

To use the proposed matrix, the collection of suitable information about the relevant use cases is necessary. Depending on the product nature and the type of pending design project (original design, adaptive design, and variant design), there are a wide variety of ways to obtain the needed information. In Section 3, three kinds of information availability were described. For most product development processes, a mixture of all three kinds seems to be characteristic. Original design projects will usually have the worst information availability, but this disadvantage can be offset if reference products are well known. At the beginning of every original product development project perceived use case of the product has to be known to be able to draw up a list of requirements.

In the case of part systems, the position relative to downstream usage processes may be an important parameter. The resulting diversity of the part system will increase the number of usage types that have to be described, hindering the development of more eco-efficient products.

6.1 Empirical information gathering

Usually a certain amount of *informal and formal flows* of information can be found in every design situation. Every contact of an enterprise's departments with a customer or a user will lead to a better understanding of the relevant use cases. Some of these contacts will be formalized relationships, for example, communication between sales departments and customers; other contacts may be based on informal acquaintanceships in an industrial sector. However, there has to be a transfer of information flows back to the product development process for there to be a benefit from these sources.

Analyzing returning products is another way to access empirical information about different usage types. Repair, remanufacturing or centralized disposal processes in an enterprise are valuable sources for clues. These procedures will seldom lead to specific information, but they can help to move from ignorance to incertitude.

Under *Voice of Customer* exists an extensive methodology that aims to capture the attributes and requirements of customers to optimize the value the product provides to the customer. This is usually accomplished by conducting different types of surveys, such as mail-out surveys, in-person interviews or telephone surveys [Yang 2008].

[Ookawa et al. 2013] and previous papers propose the use of Part agent systems that connect a single product artifact with a software agent to gather information about individual part systems and their usage history to support decisions in the market of reused parts. In the German research initiative Industrial Revolution 4.0 a similar concept is used, called the *Cyber Physical systems* concept. These combinations of a physical system and a digital system are used to control industrial manufacturing processes. In the SemProM project [Wahlster 2013], they are used to aggregate a history of the product life cycle. Depending on the characteristics of actual implementation of such concepts, they can theoretically be used to gain access to a large amount of empirical data on individual products and components, which can be analyzed and aggregated to obtain a very acurate picture of actual usage types. The effectiveness of Big Data solutions depends largely on the kinds of data gathered.

6.2 Anticipating use cases

If sufficient amounts of empirical data remain unobtainable, several methods can be used to anticipate the possible types of usage types of a technical system.
A systematic *process analysis* based on the process model described in Section 2, is the simplest form of methodical analysis of the use cases. In this case, the model works as a type of checklist to guide product developers while considering possible use cases.
Checklists that are usually used to identify requirements can also be used to anticipate use cases. Such checklists [Roth 2000], [Pahl et al. 2003] vary in their degrees of comprehensiveness.
To complete established use cases, variants of the *scenario technique* or systematic variation can be used.

7. Summary

This paper introduced a technique called the scenario matrix to represent diverse use cases of a technical system, based on the CRC 805 process model. Applications in two fields of research design, Robust Design and EcoDesign, were presented. An overview of different sources of information was given. Future research will focus on enabling the applications presented for the scenario matrix.

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