NEW GUIDELINE VDI 2206 – A FLEXIBLE PROCEDURE MODEL FOR THE DESIGN OF MECHATRONIC SYSTEMS

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Abstract

Mechatronics - the synergetic integration of different engineering domains such as mechanics, electronics and information technology can create new products and stimulate innovative solutions. In order to yield this potential, experts from the involved domains need a mechatronic-specific guideline for the systematic design of mechatronic systems. In industry guidelines are unfortunately not accepted in the intended way; adaptability to the present design situation is missed. The contribution presents a flexible procedure model taking the specific needs of mechatronic design into account and offering elements for individual adaptation. The procedure model is part of the new guideline VDI 2206.

Keywords: Adaptive Design, Design Methodology, Design Process, Integrated Product Development, Mechatronics

1. Introduction

Innovative products demand the synergetic integration of different engineering domains such as mechanics, electronics and information technology; this is expressed by the term of mechatronics. For the systematic design of mechatronic products the design engineer in practice need a guideline to select the suitable procedures, methods and tools for his/her individual design task.

Surveys show however that guidelines are often not accepted and used by industry in the way they are expected. Practicians claim that the proposed procedures are too rigid, often phase-oriented and cannot be adapted to the individual design situation. The results of the empirical design research confirm that there is no "optimal form of the design process the design engineer can follow according to a fixed flowchart" [1]. Successful design processes are individually influenced and can vary strongly from a general pattern like the guideline VDI 2221 [2], [3]. Therefore new research approaches try to provide procedures and methods in a flexible and situation-specific way, e.g. [4], [5].

The design of mechatronic systems differs from the design of products which are mainly coined by one engineering domain: Mechatronic systems are especially complex due to the great number of connected elements. These elements are realized furthermore in different engineering domains (heterogeneity). In order to manage complexity and heterogeneity the methods of modelling and model analysis – among others – are very important. They need to be integrated in design procedures for mechatronic systems. Existing guidelines like the VDI 2221 or VDI 2422 [6] do not fulfil the special requirements of mechatronics in a sufficient way. The wide spectrum of mechatronic-specific research and industrial developments of the last decade is not yet considered in these guidelines.

Two main questions are raised:

- How should a guideline look like offering methodical support in a flexible and situation-specific way and being accepted and used by industry?

- What are the specific requirements of mechatronics to the design? How should procedure models by designed to meet these requirements?

Facing these questions the committee of the Association of German Engineers (VDI) has worked out a new guideline, the VDI 2206 „Design Methodology for Mechatronic Systems" [7]. The following objectives are in the foreground:

- Supporting the design of mechatronic systems by integrating mechatronic-specific procedures, methods and tools and by structuring the variety of findings in the mechatronic field.

- Proposing a flexible procedure model which can be adapted to the individual design task.

- Complementing existing guidelines, especially the VDI 2221 and VDI 2422; latest findings of design research should be integrated.

This contribution explains the main elements of the procedure model of the VDI 2206 and exemplifies its practical application.

2. Specific Requirements to the Design of Mechatronic Systems

Before introducing the procedure model the requirements of mechatronics to its design will be pointed out. These requirements can be grouped into two categories: 1) impacts of complexity and 2) impacts of heterogeneity.

2.1 Impacts of Complexity

Mechatronic systems are characterised by high complexity due to the cross-linkage of different engineering domains. The complexity is caused by the increasing number of connected elements. Mechatronics does not only improve behavior, precision or the cost-value ratio of known solution principles. It especially creates new functions: Active suspension and electronic stability features in the automotive industry or fly-by-wire in aeronautics are only possible thanks to the permanent interaction of mechanical, electronic and software elements. Therefore complexity is a necessary accompaniment in mechatronics and leads to four requirements:

1. Procedure with changing level of detail and abstraction: During the design process the designing engineers need the reciprocal action between the overall context and the detail focus. Because of the cross-linkage to other elements new detail solutions and findings have to be checked permanently in the overall context as well.

2. Methods of structuring and hierarchisation: Mechatronic systems should be structured in order to reduce complexity and to minimise interactions, e.g. the hierarchical structure in basic elements, systems and linked systems [8].

3. Early modelling and simulation: Interactions between sub-systems, e.g. coupling of engine management and brake system for the electronic stability program (ESP), can only be anticipated by the early modelling and simulation of the system behavior. Suited methods and software tools are necessary.

4. Integration and verification/validation of properties: The design results have to be integrated to an overall system and to be checked continuously by means of the specified solution concept and the requirements. It is to be assured that the actual system characteristics match with those wanted. Hardware-in-the-Loop (HIL) plays an important role to analyse real and virtual components in a common environment.

2.2 Impacts of Heterogeneity

Solutions and components are coming from different engineering domains such as mechanics, electronics and information technology. These involved domains are working on the basis of established, specific design methods, their own ways of thinking, nomenclatures and experiences. The integration of heterogeneous components to mechatronic systems is a big challenge expressed by four requirements:

1. Cross-domain collaboration in teams: Communication and co-operation between the involved disciplines is required to bring together synergetic knowledge and to design an entirely optimised solution.

2. Cross-domain specification: Experts from different disciplines need a common method to specify the results of product conceptualisation in a cross-domain way [9].

3. Partitioning: The partitioning, i.e. the distribution into working principles/solution elements of the involved domains and their assignment to functions, is an important step. Especially the heterogeneous partitioning needs methodical support.

4. Exchange/integration of models: The design results – modelled by the domains with different model languages and tools – need to be integrated. Procedures e.g. MechaSTEP [10] and new languages e.g. Modelica [11] are necessary.

3. A Flexible Procedure Model for the Design of Mechatronic Systems

These requirements lead to a specific procedure model for the design of mechatronic systems. It is characterised by two levels of design support and elements for adaptation to individual design tasks.

3.1 Design Support on the Micro-Level and Macro-Level

The design process distinguishes between the problem solving process of the individual designer (micro-level) and the generic process related to design phases and corresponding product states (macro-level). The micro-level supports the designer in an action-oriented way: alternation between systematic and associative ways of proceeding, reacting in unforeseen situations, structuring design sub-tasks etc. The macro-level helps to survey the total design process: setting mile-stones, planning and controlling the design progress etc.

Micro-level

The presented cycle of problem solving on the micro-level (cf. figure 1) comes from systems engineering. Its basic validity for the planning and realisation of problem solving processes was confirmed from the point of view of psychology [12]. The cycle of problem solving comprises the following steps:

Situation analysis and/or take-over of target: A basic cycle starts either with the situation analysis or the take over of the target: An externally pre-set target can be taken over by the

acting group and/or the individual; the situation analysis will follow (proceeding oriented to the target condition). Otherwise a first unclear situation will be analysed and the target will be formulated respectively (proceeding oriented to the actual condition).
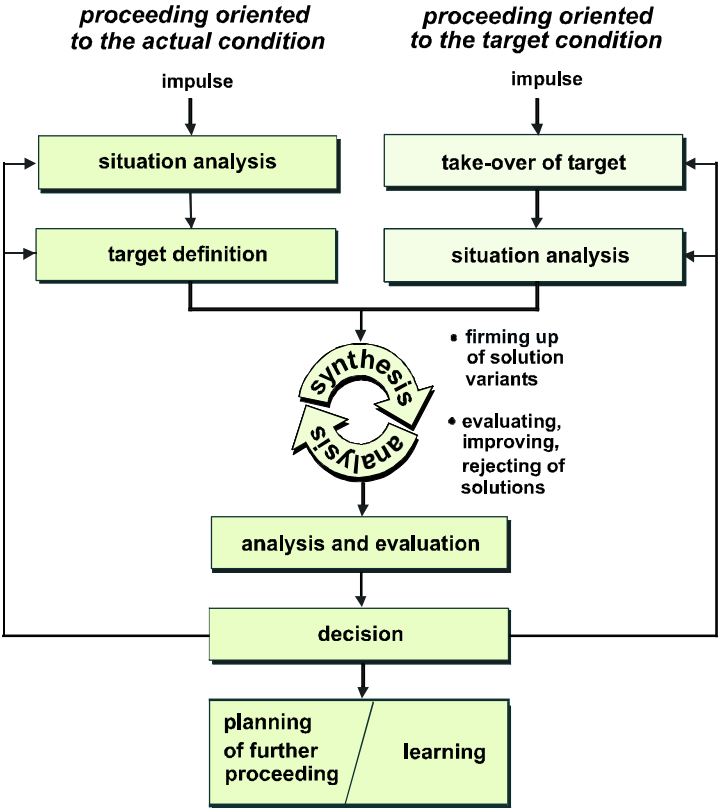

Figure 1. Cycle of problem solving on the micro-level [13]

Analysis and synthesis: It is the aim to search for solutions for the given problem and to elaborate alternative solution variants. This process represents in practice a permanent interaction of synthesis and analysis steps which the design engineers carry out - partly conscious, partly unconscious as well. During the solution search additional aspects of the problem can be recognized that might require a return to the situation analysis and target formulation or the consideration of supplementary criteria.

Analysis and evaluation: The solution variants are subject of a detailed evaluation phase. If certain solution ideas differ too strongly to be compared appropriately, a return to the phase of solution search should be considered. The evaluation of the solution variants is done on the basis of the evaluation criteria defined within the target formulation and solution search. The result consists of a proposition for one or several solution alternatives.

Decision: It must be found out whether the previous process of the problem solution has led to a satisfactory result. If that is not the case, one must return to the situation analysis and target formulation. Otherwise one, maybe also several solution alternatives are chosen and represent the basis for the further planning.

Planning of the further proceeding resp. learning: The further procedure leads in many cases more or less continuously to further cycles of problem solutions and thus to an efficient, situation-adapted process. Beside the evaluation of the design result the process itself should be analysed critically as well. By understanding the positive and negative impacts on the

process, knowledge for coming design tasks can be generated. This helps to improve future design processes in a systematic way.

Macro-level

The v-shaped model is well-established in the domain of software engineering [14]. There are three reasons why it seemed to be suited for mechatronics:

1. The v-shaped model illustrates the top-down-approach (system design: dividing into sub-functions) and the bottom-up-approach (system integration: integrating of results to the overall system) in an obvious way.

2. It allows to point out the need of permanent verification/validation between the requirements/specified functions (left hand side) and the actual (virtual and/or real) system (right hand side).

3. It is already used by the industry in the context of mechatronics which helps to increase the acceptance of the guideline.

Therefore the v-shaped model was chosen and has been adapted to mechatronic needs. It describes the generic procedure for the design of mechatronic systems which has to be specified according to the individual design task (figure 2).
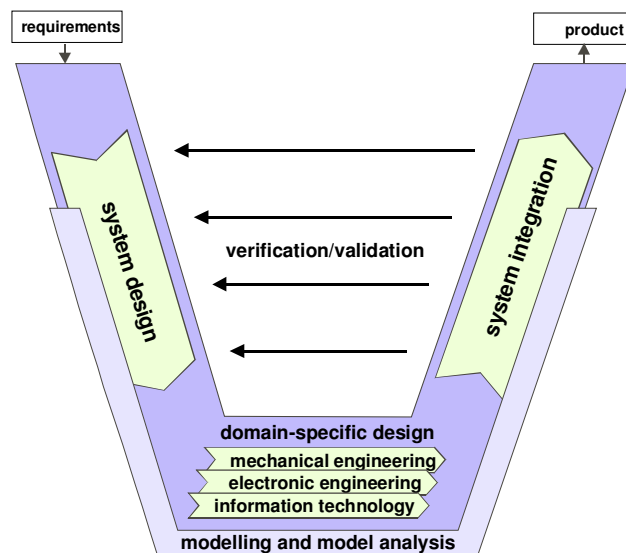

Figure 2. V-shaped model on the macro-level

Requirements: Starting point is an individual design task. The task has been clarified/defined and described with the help of requirements. These requirements represent at the same time the measure for the evaluation of the later product.

System design: The object is to define a cross-domain solution concept which describes the essential physical and logical characteristics of the future product. The overall function of a system will be divided into sub-functions. Suitable working principles and/or solution elements are assigned to these sub-functions and the fulfilling of the functions regarding the overall system context is evaluated. In mechanical engineering this phase is called "conceptualisation", but this term has not the same meaning within software and electronic engineering. Therefore "system design" has been chosen as a cross-domain term. The integration of the involved disciplines is supported by methods and tools: Structuring mechatronic systems in modules in order to reduce complexity [8], using a common language to specify the solution concept [9], early modelling and tool-supported simulation [10] [11],

organisational support (project teams, integration of external design partners etc.). These methods and tools are described in detail in [7].

Domain-specific design: The solution concept which has been developed conjointly by the involved domains will be worked out in detail mostly separately in the concerned domains. Elaborate design and calculations are necessary in order to guarantee the functional performance, in particular that with critical functions.

System integration: The results from the specific domains are integrated to an overall system in order to analyse the interrelations.

Verification/validation: The design progress has to be checked continuously by means of the specified solution concept and the requirements. It is to be assured that the actual system characteristics match with those wanted.

Modelling and model analysis: The described phases are flanked by the modelling and analysis of the system characteristics with the aid of models and computer-aided tools for simulation.

Product: The product is the result of a macro-cycle sucessfully passed through. It does not exclusively mean the finished, really existing manufactured item, but the ongoing concretion of the future product (product maturity). Degrees of maturity are, for example, concept model, functional model etc.

This procedure model differs from the classic phase-oriented procedure e.g. [2]: First it clearly distinguishes between micro- and macro-level supporting both the designer and the design management. Second the macro-model combines top-down and bottom-up approach. Mechatronic design is often bottom-up-driven (integration of components from different disciplines by interfaces). New mechatronic functions (functional and spatial integration) need however the combination of top-down-proceeding to create and bottom-up-proceeding to evaluate. Third the model is not understood as a rigid plan, it integrates elements for adaptation.

3.2 Elements for Adaptation to Individual Design Tasks

The feed-back of practicians in industry and the findings of empirical design research motivated to integrate two elements of adaptation to the procedure model: varying the number and the specification of macro-cycles and integrating user-specific process modules.

Macro-cycles according to the degree of maturity

The introduced v-shaped model on the macro-level is understood as a generic procedure pattern. A complex mechatronic product will normally not be finished within one macro-cycle. Rather several passes are necessary (figure 3).

During a first cycle, for example, the system will be specified functionally, first working principles and/or solution elements are selected and specified roughly and at the same time checked for consistency in the system context. First laboratory samples are the result. These results are worked out in detail within a second cycle (detailed specification of the structures, behavior and shape simulation) in order to generate early prototypes. The macro-cycles can be adapted to the specific design task: According to the company convention, the type and complexity of product etc. the number of macro-cycles and the corresponding product maturity gates can be specified individually. It allows to vary the level of abstraction of the procedure model from a generic level (one macro-cycle) to a more detailed level (several macro-cycles) e.g. for project management and design controlling.
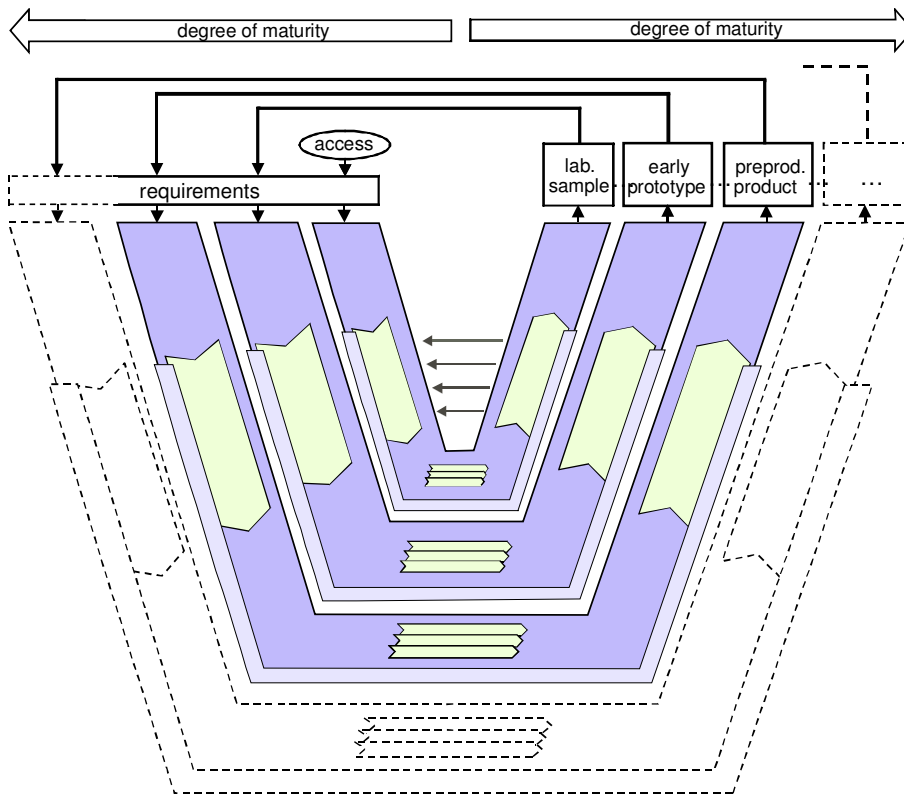
Figure 3. Proceeding with several passes (macro-cycles) and increasing product maturity

User-specific process modules for repeating operation steps

The main phases in the v-model are not yet specified in detail. This has to be done by the individual designer or team. Especially design procedures which occur regularly during the design can be described in terms of partly predefined process modules. These process modules – representing procedures and methods for different design tasks – can be organized in a data base (figure 4).
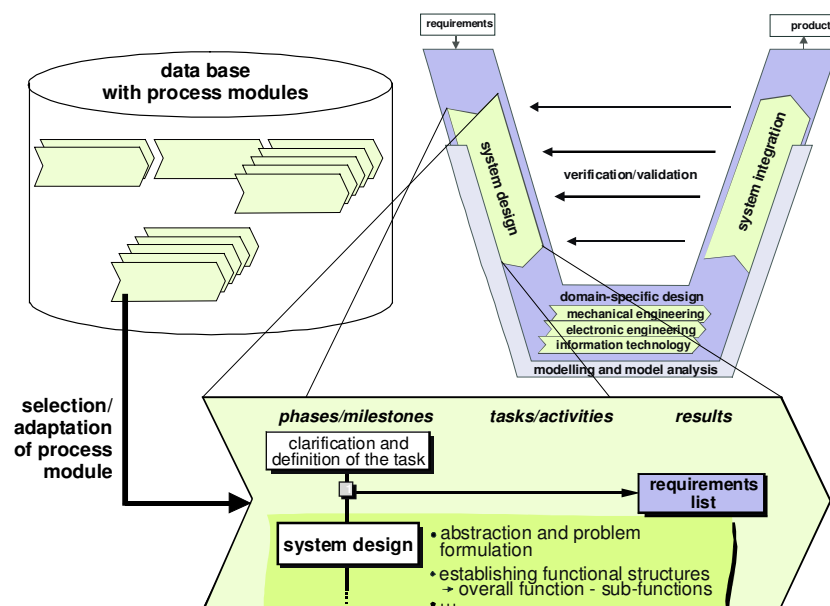

Figure 4. Configuration of process modules for individual operation steps

According to the individual design task the designer can choose the appropriate process modules meeting his requirements; if necessary he can adapt them or create new ones. In figure 4 the process module "system design" is selected and specified. The description can be e.g. phase-milestone-diagrams, checklists, process-flow-diagrams etc. Process modules motivate the designer to organise repeating design steps systematically, but not in a rigid way. Individual design procedures can be generated combining and adapting appropriate process modules. Experiences from former projects can be reused and company-own or product-own process standards can be established.

4. Practical Application of the Procedure Model

The guideline provides the methodical frame and illustrates the practical application with the help of examples. The following example shows the design task "design of the drive unit for a varnishing line" (figure 5) [15]. The focus is on the sub-function "create and control a oscillating translation movement of the spray head". Solution variants have to be found and evaluated, the dynamic behavior of the controlled system has to be analysed. The varnish has to be layed on in a very equal way. Therefore the spray head has to be moved with constant speed on a defined distance. It is a mechatronic task to control speed and to minimize unwanted oscillations.
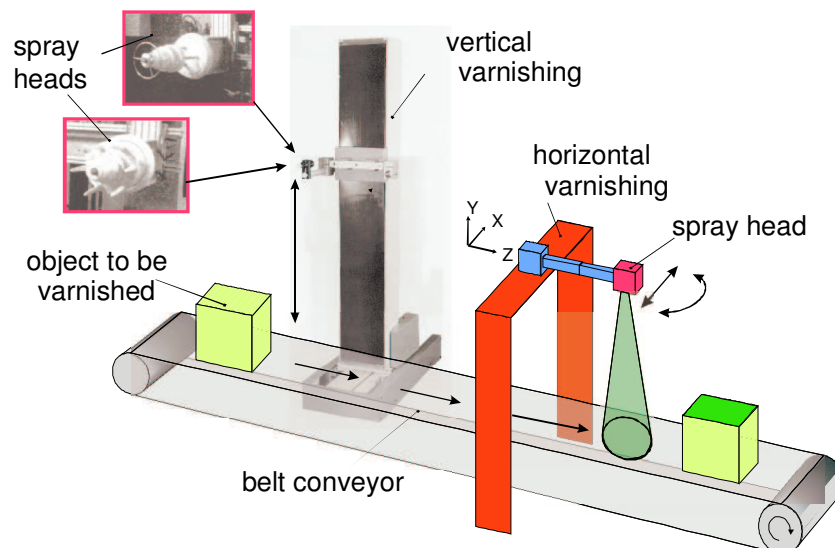

Figure 5. Design sketch and main functions of a varnishing line

For this design task mainly the two design phases "system design" and "modelling/system analysis" are mainly concerned. Therefore the designer will select among the predefined process modules the most similar ones and adapt them if needed to the present situation (figure 6).
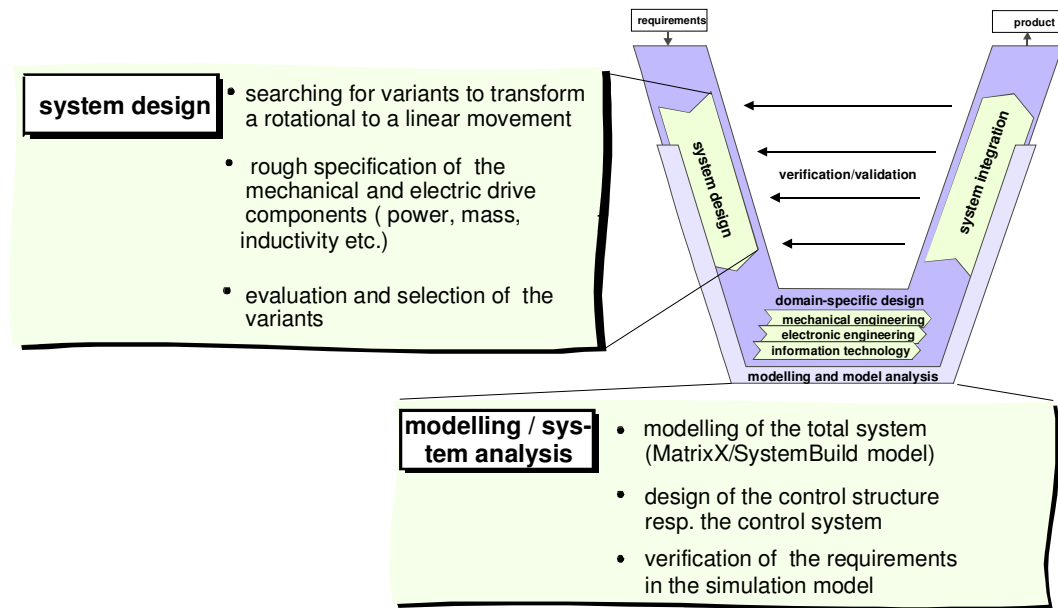
Figure 6. Design-specific v-shaped model with the detailed process modules "system design" and "modelling/system analysis"

5. Conclusion

Mechatronics offers success potentials for the creation of new products, makes however special requirements to the design process: Mechatronic systems are characterised by high complexity due to the great number of connected elements which are realized furthermore in different engineering domains (heterogeneity). In order to manage these requirements a procedure model for the systematic design of mechatronic systems is needed. Adaptability to the individual design task has to be supported to ensure acceptance and use in industry.

The contribution presented the main elements of the flexible procedure model as a part of the new guideline VDI 2206. The Elements are: 1) general cycle of problem solving on the micro-level, 2) v-shaped model on the macro-level, 3) macro-cycles according to the degree of maturity and 4) user-specific process modules for recurring operation steps.

The guideline is a step towards a mechatronic-specific methodology comprising basis of mechatronic systems, procedure model, methods of modelling and model analysis, computer-aided tools and selected aspects of mechatronic organisation. The "green print" of VDI 2206 is published in March 2003, the "white print" with translation in English is scheduled for 2004. Discussion within the design research community is greatly appreciated. Especially the feed-back of practicians in industry is important in order to evaluate and to improve the methodology.

6. Acknowledgements

Parts of this contribution originate from the guideline VDI 2206. The guideline has been worked out by the guideline committee with about 40 well-known specialists in the field of mechatronics. The authors want to thank all members of the guideline committee, especially the core team, for the excellent collaboration and the supply of knowledge, tables and figures. Thanks are also given to the VDI for the organizational support.

References

[1] Dörner D., „Gedächtnis und Konstruieren", Pahl G. (Hrsg.): Psychologische und Pädagogische Fragen beim methodischen Konstruieren, Ergebnisse des Ladenburger Diskurses, Mai 1992 - Oktober 1993, TÜV Rheinland, Köln, 1994.

[2] VDI 2221, „Methodik zum Entwickeln und Konstruieren technischer Systeme und Produkte", Beuth Verlag, Berlin, 1993.

[3] Birkhofer H. and Lindemann U., „Empirical Design Research - what we know and what we want to know, Critical Enthusiasm - Contributions to Design Science", A 'festschrift' for Mogens Myrup Andreasen the occasion of his 60th birthday, 17. December 1999, Trondheim/Lyngby, Norwegian University of Science and Technology, 1999.

[4] Birkhofer H., Lindemann U., Albers A. and Meier M., "Product Development as a Structured and Interactive Network of Knowledge – a Revolutionary approach", Proceedings ICED 2001, Glasgow, 2001.

[5] Lindemann U., "Flexible Adaptation of Methods within the Design Process", Proceedings DESIGN 2002, Dubrovnik – Croatia, Zagreb, 2002.

[6] VDI 2422, „Entwicklungsmethodik für Geräte mit Steuerung durch Mikroelektronik", Beuth Verlag, Berlin, 1994.

[7] VDI 2206, „Entwicklungsmethodik für mechatronische Systeme", Entwurf, Beuth Verlag, Berlin, 1993.

[8] Liu-Henke X., Lückel J. and Jäker K.P., „Development of an Active Suspension/Tilt System for a Mechatronic Railway Carriage", Proceedings IFAC ´00, Darmstadt, 2000.

[9] Gausemeier J., Flath M. and Möhringer S., „Modelling and Evaluation of Principle Solutions of Mechatronic Systems, Exemplified by Tyre Pressure Control in Automotive Systems", Proceedings ICED 2001, Glasgow, 2001.

[10] PAS 1013, „MechaSTEP - STEP Datenmodelle zur Simulation mechatronischer Systeme", Publicly Available Specification, Beuth-Verlag, Berlin, 2001.

[11] Modelica: Object-oriented language for the modelling of multidisziplinary systems, http//:www.modelica.org.

[12] Kranach M. von, Ochsenbein G. and Valach L., „The Groupe as Selfactive System: Outline of a Theorie of Groupeaction", European Journal of Social Psychology, 16, 1986, pp. 193-229.

[13] Daenzer W.F. and Huber F., „Systems Engineering - Methoden und Praxis", 8. verbesserte Auflage, Verlag Industrielle Organisation, Zürich, 1994.

[14] Bröhl A.-P. (Hrsg.), „Das V-Modell – der Standard für die Softwareentwicklung", 2. Auflage, Oldenbourg, München, 1995.

[15] Nordmann R., „Maschinenelemente und Mechatronik", 2. Auflage, Shaker Verlag, Aachen, 2001.

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